TRAINING COURSE SERIES No. 10

Ultrasonic Testing of Materials at Level 2

Manual for the Syllabi Contained in IAEA-TECDOC-628, "Training Guidelines in Non-destructive Testing Techniques"

31-05

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1999

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FOREWORD

The International Atomic Energy Agency (IAEA) has been active in the promotion of non-destructive testing (NDT) technology for many years. The prime reason for this interest has been the need for stringent quality control standards for the safe operation of nuclear installations. The IAEA has successfully executed a number of regional projects of which NDT was an important part. These were the Regional Co-operative Arrangements for the Promotion of Nuclear Science and Technology in Latin America (ARCAL), the Regional Co-operative Agreement for Asia and the Pacific (RCA), the African Regional Co-operative Agreement (AFRA) and lately the NDT Regional Project in West Asia. Through these projects a large number of persons have been trained in Member States and a state of self-sufficiency in this area of technology has been achieved in many of them.

There has long been a realization of the need to have well established training guidelines and related books in order, firstly, to guide IAEA experts who were involved in this training programme and, secondly, to achieve some level of international uniformity and harmonization of training materials and consequent competence of personnel.

The syllabi for training courses have been published in the form of two TECDOC publications. The first was IAEA-TECDOC-407, which contained syllabi for the basic five methods, i.e. liquid penetrant testing, magnetic particle testing, eddy current testing, radiographic testing and ultrasonic testing. The second is IAEA-TECDOC-628, which is a revision of IAEA-TECDOC-407 and includes additional methods of visual testing and leak testing. IAEA-TECDOC-628, as well as most of the international standards on the subject of training and certification of NDT personnel including ISO 9712, define three levels of competence, namely, Level 1, Level 2 and Level 3. Among these, Level 1 is the lowest and Level 3 the highest. The intermediate Level 2 is considered to be the most appropriate for persons who, in addition to other duties, are expected to independently undertake practical testing in the relevant method of NDT, make accept/reject decisions in accordance with relevant standards and specifications and be able to train and supervise the Level 1 staff under them.

The next logical step is to compile the textbooks and training manuals in accordance with these syllabi. Work in this regard has been undertaken and a manual on radiographic testing was issued in 1992 in the Training Course Series.

This publication is a continuation of that effort. Earlier training notes on this subject existed in the form of IAEA-TECDOC-462, which was compiled in accordance with the syllabus of IAEA-TECDOC-407. These fulfilled the training needs of the member countries of RCA for quite some time. The present book is in fact an expanded and updated version of the older document. An effort has been made to bring it as close as possible to the syllabus requirements of IAEA-TECDOC-628. This has been done by putting in additional material wherever needed and then rearranging the whole in accordance with the format of Level 2 Ultrasonic Testing syllabus in IAEA-TECDOC-628. A new Section on Special Techniques has been added in which the present status of development of various new techniques of ultrasonic testing, automated ultrasonic inspection and the basic concepts of data processing have been introduced. An extensive bibliography at the end covers all the references which have been used in the compilation as well as those which can be consulted for further information on ultrasonic testing of materials.

These training materials were compiled by A.A. Khan and his colleagues at the National Centre for NDT of Pakistan Atomic Energy Commission. Various chapters of the draft were then

circulated to the national co-ordinators for the NDT sub-project in different countries of the RCA region. The national co-ordinators themselves or through the experts available in their countries scrutinized the material, making alterations wherever considered necessary. The draft was then finalized after incorporation of the recommendations of the national co-ordinators. Finally the draft was discussed at a national co-ordinators meeting held in Melbourne, Australia, in July 1995. The draft was then finalized for publication.

During the process of compilation of the training notes guidance and support was also provided by a large number of persons especially from the NCNDT, OAEP Thailand and the RCA Co-ordinator's Office in Vienna.

The IAEA wishes to express its appreciation to all those who have contributed to the production of these Training Course Notes and to the governments and organizations whose financial and technical support made this publication possible.

The IAEA officer responsible for this publication was A.A. Khan of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

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1. GENERAL KNOWLEDGE

1.1. BASIC PRINCIPLES OF NON-DESTRUCTIVE TESTING

1.1.1 Definition and Importance of NDT

1.1.1.1 Definition and nature of NDT

Non-destructive testing is the use of physical methods which will test materials, components and assemblies for flaws in their structure without damaging their future usefulness. NDT is concerned with revealing flaws in the structure of a product. It, however, cannot predict where flaws will develop due to the design itself.

All NDT methods have the following common characteristics:

i) The application of a testing medium to the product to be tested.

ii) The changes in the testing medium due to the defects in the structure of the product.

iii) A means by which it detects these changes.

iv) Interpretation of these changes to obtain information about the flaws in the structure of the product.

1.1.1.2 Importance of NDT

NDT plays an important role in the quality control of a product. It is used during all the stages of manufacturing of a product. It is used to monitor the quality of the:

i) Raw materials which are used in the construction of the product.

ii) Fabrication processes which are used to manufacture the product.

iii) Finished product before it is put into service.

Use of NDT during all stages of manufacturing results in the following benefits:

i) It increases the safety and reliability of the product during operation.

ii) It decreases the cost of the product by reducing scrap and conserving materials, labour and energy.

iii) It enhances the reputation of the manufacturer as producer of quality goods.

All of the above factors boost the sales of the product which bring more economical benefits to the manufacturer.

NDT is also used widely for routine or periodic determination of quality of the plants and structures during service. This not only increases the safety of operation but also eliminates any forced shut down of the plants.

1.1.2 Types of NDT Methods

The methods of NDT range from the simple to the complicated. Visual inspection is the simplest of all. Surface imperfections invisible to the eye may be revealed by penetrant or magnetic methods. If really serious surface defects are found, there is often little point in proceeding to more complicated examinations of the interior by ultrasonics or radiography. NDT methods may be divided into groups for the purposes of these notes: conventional and non-conventional. To the first group may belong the methods which are commonly used and include Visual or Optical Inspection, Dye Penetrant Testing, Magnetic Particle Testing, Eddy Current Testing, Radiographic Testing and Ultrasonic Testing. The second group of NDT methods are those used only for specialized applications and consequently are limited in use. Some of these methods which are being mentioned here merely as a curiosity for the reader include Neutron Radiography, Acoustic Emission, Thermal and Infrared Testing, Strain Sensing, Microwave Techniques, Leak Testing, Holography etc. It must also be remembered that no one of these methods can give us solutions to all the possible problems, i.e. they are not optional alternatives but rather complementary to each other. The basic principles, typical applications, advantages and limitations of the methods of group one will now be briefly described.

1.1.3 Visual testing (VT)

Often overlooked in any listing of NDT methods, visual inspection is one of the most common and most powerful means of non-destructive testing. Visual testing requires adequate illumination of the test surface and proper eye-sight of the tester. To be most effective visual inspection does however, merit special attention because it requires training (knowledge of product and process, anticipated service conditions, acceptance criteria, record keeping, for example) and it has its own range of equipment and instrumentation. It is also a fact that all defects found by other NDT methods ultimately must be substantiated by visual inspection. Visual testing can be classified as direct visual testing, remote visual testing and translucent visual testing. The most common NDT methods MT and PT are indeed simply scientific ways of enhancing the indication to make it more visible. Often the equipment needed is simple (Figure 1.1): a portable light, a mirror on stem, a 2 x or 4 x hand lens, one illuminated magnifier with magnification 5x or 10x. For internal inspection, light lens systems such as borescopes allow remote surfaces to be examined . More sophisticated devices of this nature using fibre optics permit the introduction of the device into very small access holes and channels. Most of these systems provide for the attachment of a camera to permit permanent recording.

The applications of visual testing include:

1) Checking of the surface condition of the test specimen.

2) Checking of alignment of matting surfaces.

3) Checking of shape of the component.

4) Checking for evidence of leaking.

5) Checking for internal defects.

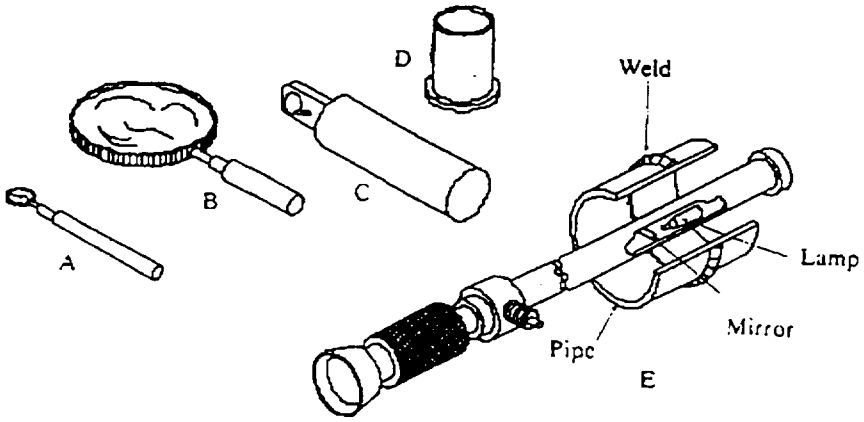


Figure 1.1 : Various Optical Aids used in Visual Inspection.

A Mirror on stem: may be flat for normal view or concave for limited magnification.

B Hand magnifying glass (magnification usually 2-3x).

C Illuminated magnifier; field of view more restricted than D (magnification 5-10x).

D Inspection glass, usually fitted with a scale for measurement; the front surface is placed in contact with the work (magnification 5-10x).

E Borescope or intrascope with built-in illumination (magnification 2-3x).

1.1.4 Liquid penetrant testing (PT)

This is a method which can be employed for the detection of open-to-surface discontinuities in any industrial product which is made from a non-porous material. This method is widely used for testing of non-magnetic materials. In this method a liquid penetrant is applied to the surface of the product for a certain predetermined time, after which the excess penetrant is removed from the surface. The surface is then dried and a developer is applied to it. The penetrant which remains in the discontinuity is absorbed by the developer to indicate the presence as well as the location, size and nature of the discontinuity. The process is illustrated in Figure 1.2.

Penetrants used in liquid penetrant are either visible dye penetrant or fluorescent dye penetrant. The inspection of the presence of indications dye visible by penetrant is made under white light while inspection of presence of indications by fluorescent dye penetrant is made under ultraviolet (or black) light under darkened conditions. The liquid penetrant processes are further sub-divided according to the method of washing of the specimen. The penetrants can be: (i) water-washable, (ii) post-emulsifiable, i.e. an emulsifier is added to the excess penetrant on surface of the specimen to make it water-washable, and (iii) solvent removable, i.e. the excess penetrant is needed to be dissolved in a solvent to remove it from the test specimen surface. In order of decreasing sensitivity and decreasing cost, the liquid penetrant processes can be listed as:

1) Post emulsifiable fluorescent dye penetrant.

2) Solvent removable fluorescent dye penetrant.

3) Water washable fluorescent dye penetrant.

4) Post emulsifiable visible dye penetrant.

5) Solvent removable visible dye penetrant.

6) Water washable visible dye penetrant.

Some of the advantages of liquid penetrant testing are as follows:

1) It is extremely sensitive to surface defects if properly used.

2) Materials and equipment used in liquid penetrant testing are relatively inexpensive.

3) Liquid penetrant process is relatively simple and trouble free.

4) In liquid penetrant testing part geometry is not a problem.

Some of the limitations of liquid penetrant testing are as follows:

1) Defects must be open to the surface.

2) Material of the test specimen should be non-porous.

3) Liquid penetrant process is fairly dirty.

4) Inspection cost is relatively high.

In liquid penetrant testing there is no easy method to produce permanent record.

1.1.5 Magnetic particle testing (MT)

Magnetic particle testing is used for the testing of materials which can be easily magnetized. This method is capable of detecting open to surface and just below the surface flaws. In this method the test specimen is first magnetized either by using a permanent or an electromagnet or by passing electric current through or around the specimen. The magnetic field thus introduced into the specimen is composed of magnetic lines of force. Whenever there is a flaw which interrupts the flow of magnetic lines of force, some of these lines must exit and re-enter the specimen. These points of exit and re-entry form opposite magnetic poles. Whenever minute magnetic particles are sprinkled onto the surface of such a specimen, these particles are attracted by these magnetic poles to create a visual indication approximating the size and shape of the flaw. Figure 1.3 illustrates the basic principles of this method:

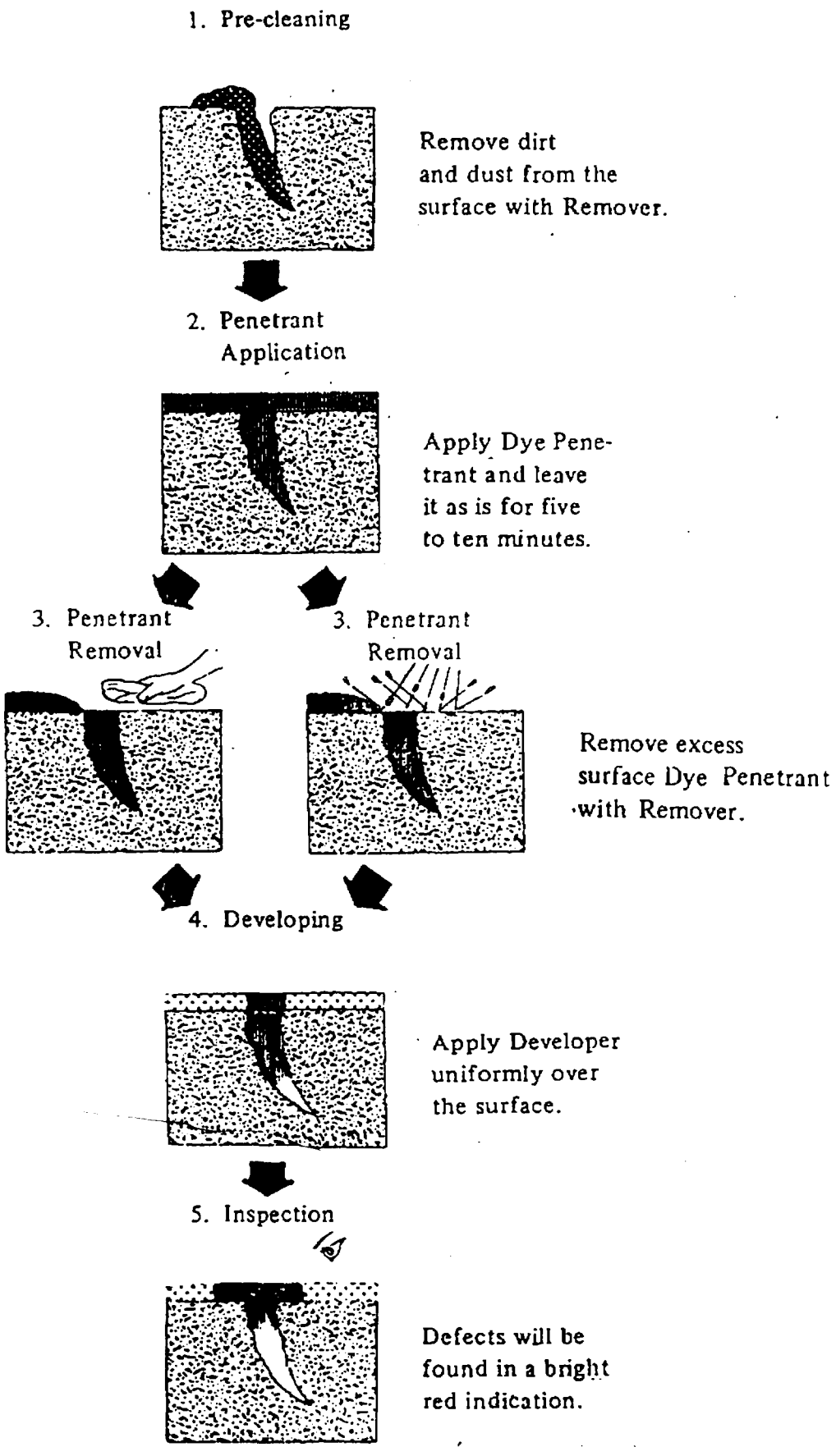


Figure 1.2 : Different stages of liquid penetrant process.

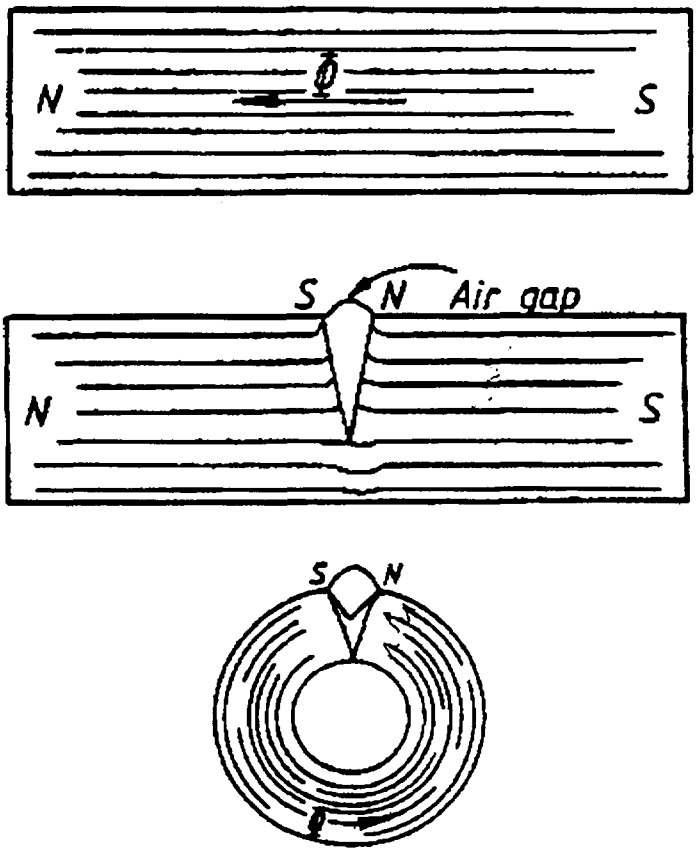


Figure 1.3 : Basic principle of magnetic particle testing.

Depending on the application, there are different magnetization techniques used in magnetic particle testing. These techniques can be grouped into the following two categories:

a) Direct current techniques: These are the techniques in which the current flows through the test specimen and the magnetic field produced by this flow of current is used for the detection of defects. These techniques are shown in Figure 1.4 (a, b & c).

b) Magnetic Flux Flow Techniques: In these technique magnetic flux is induced into the specimen either by the use of a permanent magnet or by flowing current through a coil or a conductor. These techniques are shown in Figure 1.4 (d, g).

Advantages of magnetic particle testing include the following:

1) It can detect open to the surface as well as near the surface defects.
2) It can be used without the removal of thin protective coatings.
3) It does not need very stringent pre-cleaning operation.
4) It is quicker.
5) It is more sensitive.
6) There are fewer process variables so liability to operator error is less.

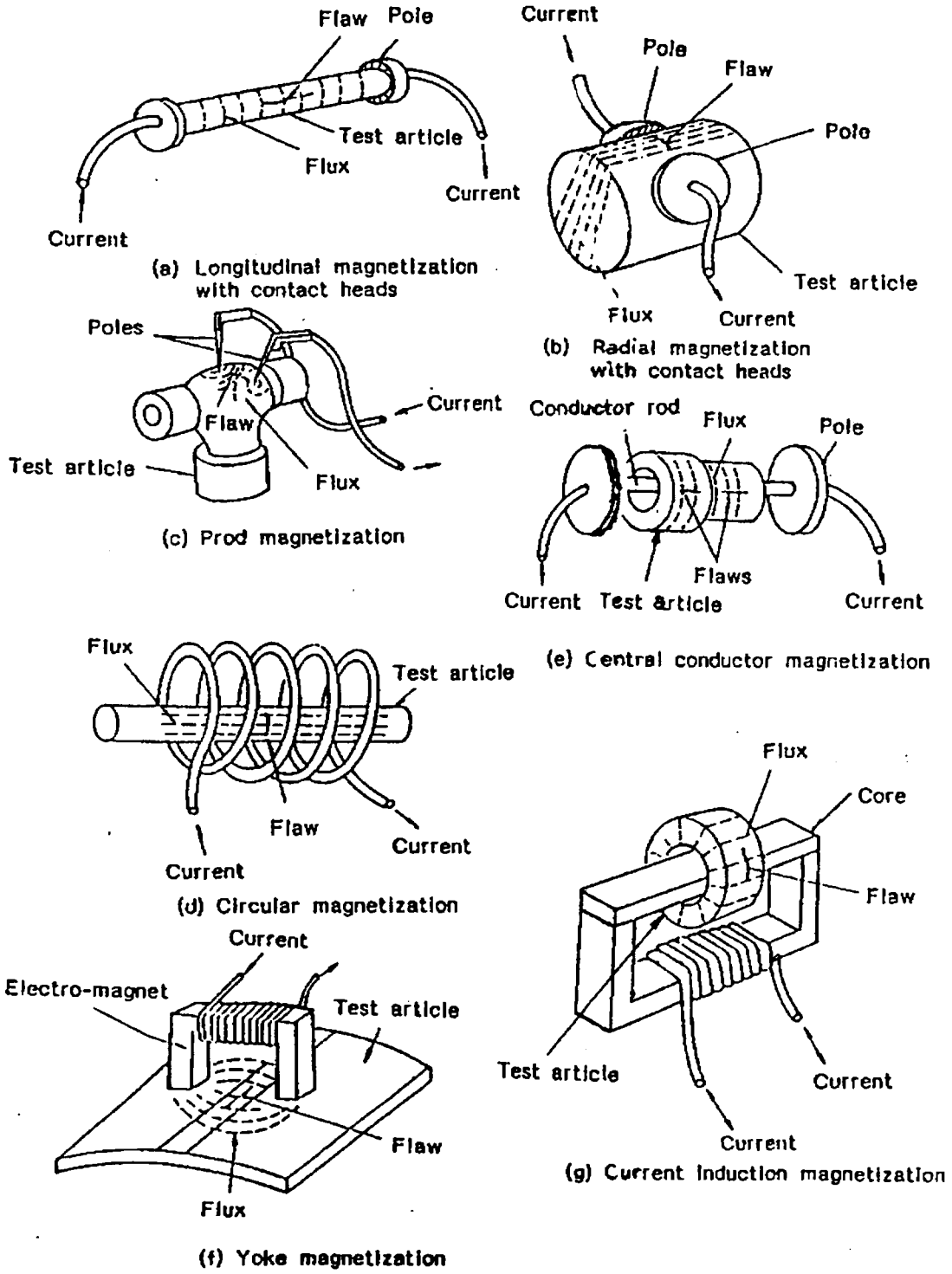


Figure 1.4 : Different magnetizations used in magnetic particle testing.

Some of the limitations of magnetic particle testing include the following:

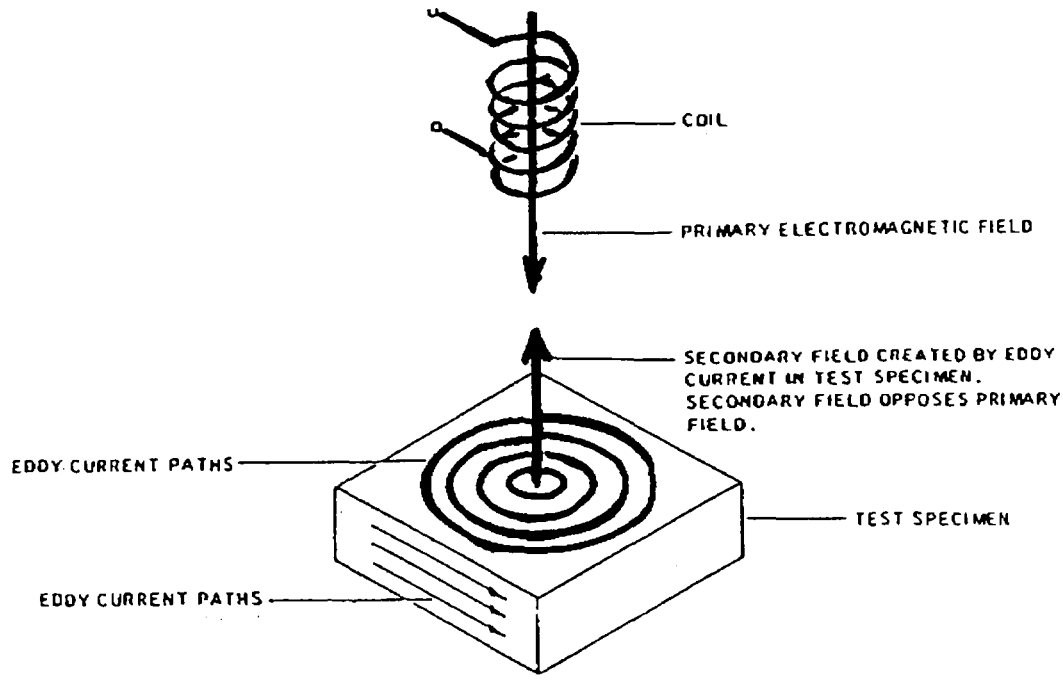
1) It cannot be used on non-magnetic materials.

2) It is restricted and sensitive to defects lying at 45° to 90° to the lines of magnetic flux.

3) Equipment used in magnetic particle testing is more expensive.

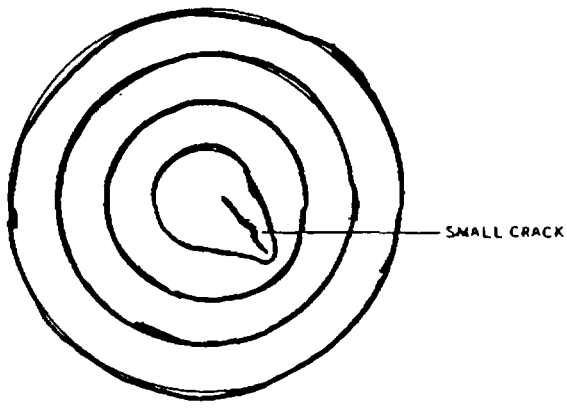
1.1.6 Eddy current testing (ET)

This method is widely used to detect surface flaws, to sort materials, to measure thin walls from one surface only, to measure thin coatings and in some applications to measure case depth. This method is applicable to electrically conductive materials only. In the method eddy currents are produced in the product by bringing it close to an alternating current carrying coil. The alternating magnetic field of the coil is modified by the magnetic fields of the eddy currents. This modification, which depends on the condition of the part near to the coil, is then shown as a meter reading or cathode ray tube presentation. Figure 1.5 gives the basic principles of eddy current testing.



(a)

Figure 1.5 : (a) Generation of eddy currents in the test specimen.



(b)

Figure 1.5 : (b) Distortion eddy currents due to defect.

There are three types of probes (Figure 1.6) used in eddy current testing. Internal probes are usually used for the in-service testing of heat exchanger tubes. Encircling probes are commonly used for the testing of rods and tubes during manufacturing. The uses of surface probes include the location of cracks, sorting of materials, measurement of wall and coating thickness, and case depth measurement.

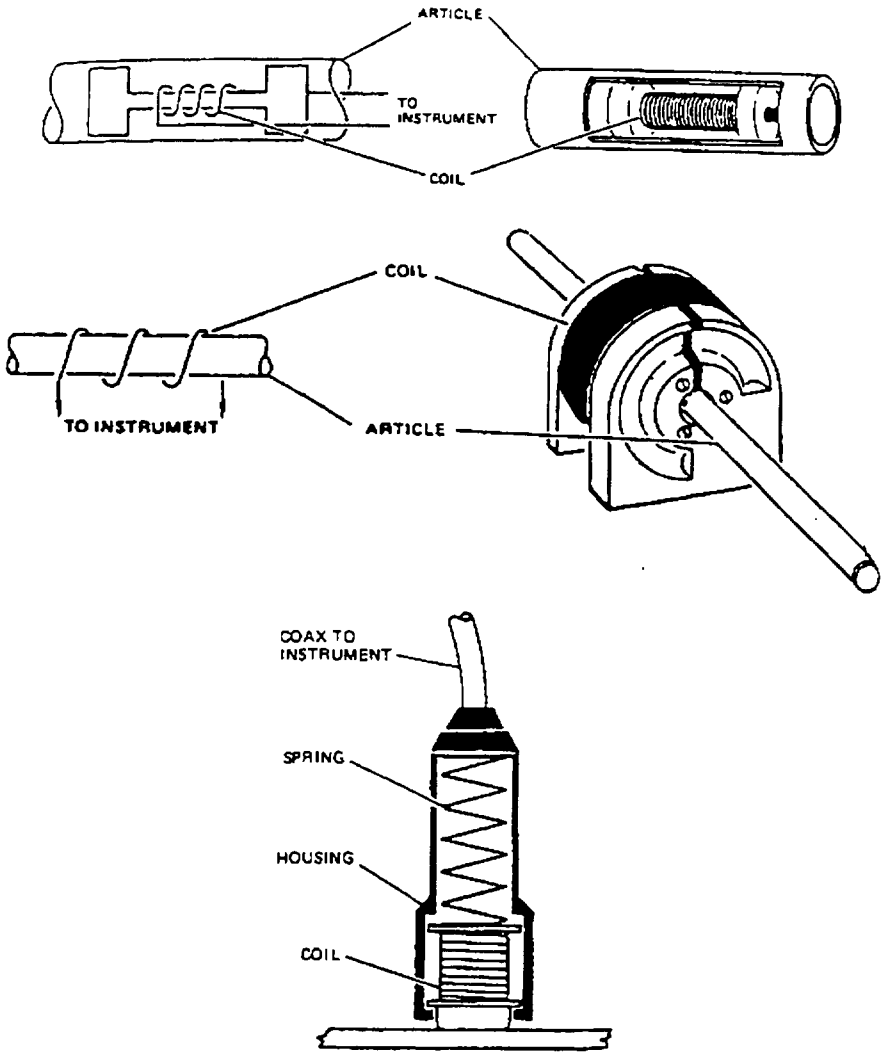


Figure 1.6 : Types of probes used in eddy current testing.

This method is used:

1) For the detection of defects in tubings;
2) for sorting materials;
3) for measurement of thin wall thicknesses from one surface only;
4) for measuring thin coatings and
5) for measuring case depth.

Some of the advantages of eddy current testing include:

1) It gives instantaneous response.
2) It can be easily automated.
3) It is versatile.
4) No contact between the probe and the test specimen is required.
5) Its equipment can be made portable.

Some of the limitations of eddy current testing include the following:

1) It requires highly skilled operator.
2) It is applicable to conductive materials only.
3) Its depth of penetration is limited.
4) Its application to ferromagnetic materials is difficult.

1.1.7 Radiographic testing method (RT)

The radiographic testing method is used for the detection of internal flaws in many different materials and configurations. An appropriate radiographic film is placed behind the test specimen (Figure 1.7) and is exposed by passing either X-rays or gamma rays through it. The intensity of the X-rays or gamma rays while passing through the product is modified according to the internal structure of the specimen and thus the exposed film, after processing, reveals the shadow picture, known as a radiograph, of the product. It is then interpreted to obtain data about the flaws present in the specimen. This method is used on wide variety of products such as forgings, castings and weldments.

Radiographic testing is used for the detection of internal flaws in many different materials and configurations. It is used on wide variety of products such as forgings, castings and weldments.

Some of the advantages of radiographic testing are:

1) It can be used to inspect large areas at one time.
2) It is useful on wide variety of materials.
3) It can be used for checking internal malstructure, misassembly or misalignment.
4) It provides permanent record.
5) Devices for checking the quality of radiograph are available.
6) Interpretation of radiographs can be done in comfortable conditions.

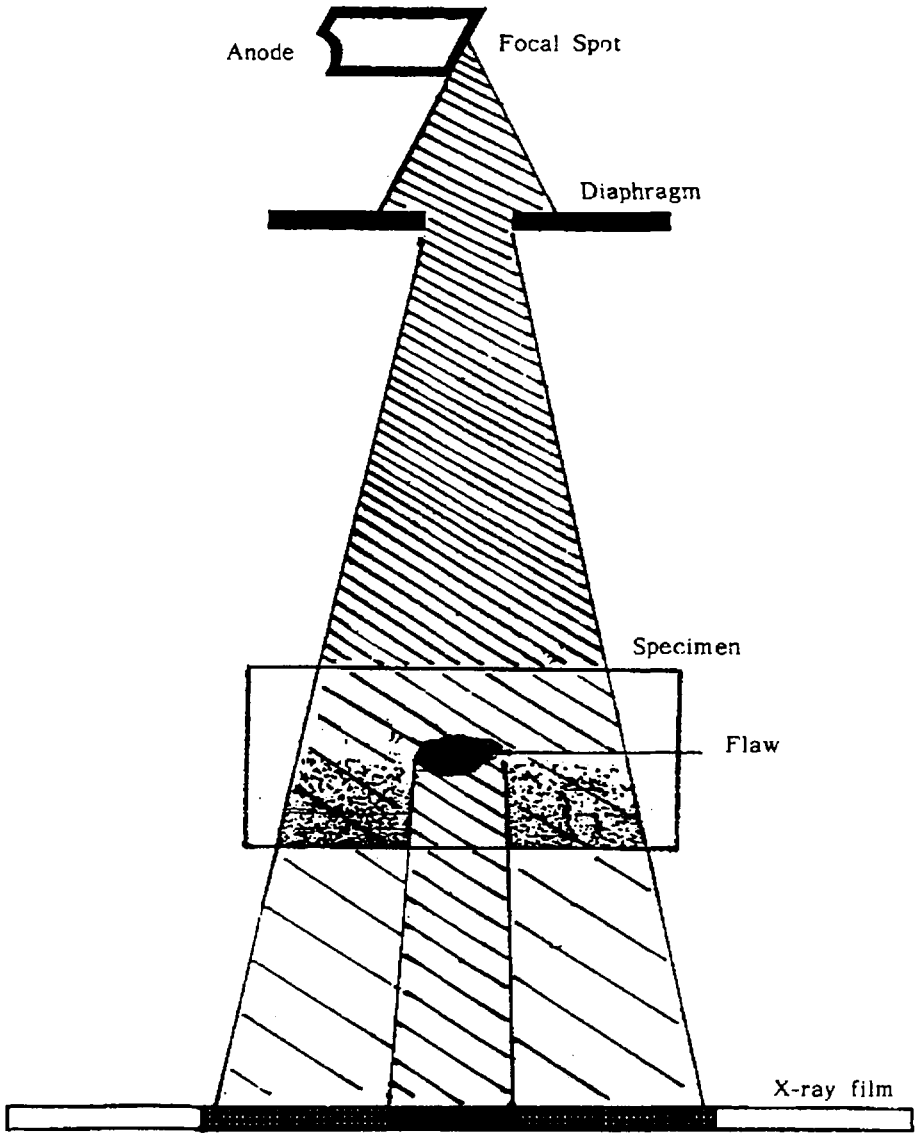


Figure 1.7: Arrangement for radiographic testing method.

Some of the limitations of this method are:

1) X-Rays and gamma-rays are hazardous to human health.
2) It cannot detect planar defects readily.
3) Access to both sides of the specimen is required in this method.
4) Thickness range that can be inspected with this method is limited.
5) Certain areas in many items cannot be radiographed because of the geometric consideration.
6) Sensitivity of inspection decreases with thickness of the test specimen.
7) It is more costly.
8) It cannot be easily automated.
9) It requires considerable skill for the interpretation of the radiographs.

1.1.7.1. Personal safety and radiation protection

Nuclear radiations are harmful to living tissues. The damage done by radiations is sinister as human senses are not capable of detecting even lethal doses of radiation. The dose of radiations absorbed by human body is expressed in mSv (1 mSv = 100 rem = 1J/kg) which takes into account the biological effectiveness of different types of radiations such as alpha particles, gamma rays, X-rays and neutrons etc. The overall outcome of exposure to radiation is initiated by damage to the cell which is the basic unit of the organism. The effects of radiation may be deterministic or stochastic, early or late, of somatic or genetic type.

Somatic effects depend upon three main factors:

(a) First of these factors is the rate at which the dose is administered. Cells begin the repair processes as soon as some degree of damage has been received. When the body is able to keep up with the damage, no injury or pathological change will be seen in the irradiated individuals. However, the same amount of radiation given all at once would produce a more severe reaction.

(b) The second is the extent and part of the body irradiated. It is known that certain cells are more sensitive to radiation than others. Hence the overall effect of radiation depends on the extent and part of the body irradiated.

(c) The third important factor is the age of the affected individual, persons growing physically are in an accelerated stage of cells reproduction and most of the cells in the body are dividing and hence sensitive to radiation. For this reason an exposure of a given amount should be considered more serious for a young person than for an adult.

The somatic effects can either be immediate or delayed. Given below is a summary of immediate effects when the whole body is acutely irradiated with a range of radiation doses:

0-0.25 Sv: No manifested injuries and no clinical effects. Increase of frequency of chromosomal observations in peripheral lymphocytes above 0.15 Sv whole body dose.

0.5-1 Sv: Some changes in blood count picture i.e. reduction in lymphocytes and neutrophils with delayed recovery. Delayed effects may shorten life expectancy. No clinical symptoms .

1-2 Sv: Mild degree of ARS (acute radiation syndrome). Nausea, fatigue, dizziness. Vomiting in 10-50% cases within 24 hours starting 2 hours after exposure or later. Latent period about 3 to 4 weeks. Following the latent period, clinical symptoms appear in a more severe manifestation. No disability.

2-4 Sv: Moderate ARS: nausea, fatigue, dizziness, loss of appetite. Vomiting within 2 hours in 70-90% of exposed persons. Latent period of 2 to 3 weeks where the victim seems relaxed and recovering. The critical period follows with epilation, loss of appetite and general weakness accompanied by fever, inflammation of the mouth and throat, diarrhoea, nose bleeding. Death due to infections could occur in 0-50% of the exposed individuals within 2 months without proper treatment with antibiotics and fluid replacement .

4-6 Sv: Severe ARS: Nausea, weakness, loss of appetite, vomiting within one hour with 100% incidence. Mild diarrhoea in less than 10% of exposed persons with an onset of 3 to 8 hours following the whole body exposure. Headache in 50% of the exposed persons within 4 to 24 hours. Fever in 80 - 100% cases within 1 to 2 hours. Drop of lymphocytes to about 500 on 2^{nd} - 3^{rd} day. Latent period of 1 to 2 weeks followed by severe clinical picture, fever, infections (pneumonia). Death in 50 to 80% of patients within 2 months.

>8 Sv : Lethal ARS: Severe nausea, fatigue and vomiting within 10 minutes followed by fever and diarrhoea and hemorrhage with no latent period. Rate of survival is very poor and death occurs within 2 weeks in 90-100% of exposed individuals. At whole body doses >15 Sv damage on the central nervous system characterized by cramps, involuntary movements of the muscles (ataxia) followed by coma (lethargy). Death occurs within 2 days due to irreversible circulatory cerebral odema and probably heart failure.

In case of protracted or low dose exposure, ionizing radiation may not produce immediate consequences but some delayed effects may appear a long time after the exposure. These types of effects may be late deterministic effects (life cataract) or stochastic effects (radiation induced cancer or genetic effects).

Genetic effects may be explained in the following way. It is a fact that children inherit characteristics such as appearance, strength, resistance to disease, temperament, etc. from their parents. This happens because each of the parents contributes a characteristic gene to the reproduction process. The genes are contained in the sperm and egg cells of the parents producing them. Radiation can modify and damage the genes. However, genetic effects have never been manifested and proved in exposed to radiation human population groups (neither in A-bomb survivors).

In accordance with the recommendations of the International Commission on Radiological Protection, (ICRP), the dose limit of ionizing radiation is that, which in the light of present knowledge and in the opinion of competent medical authority, is not expected to cause injury to a person at any time during his lifetime and carries negligible probability of cancer induction and genetic malformations.

(1) Occupational workers

As per Schedule II of the IAEA Safety Series No. 115, following criteria and dose limits apply:

II-5: The occupational exposure of any worker shall be so controlled that the following limits be not exceeded:

(a) an effective dose of 20 mSv per year averaged over five consecutive years;

(b) an effective dose of 50 mSv in any single year;

(c) an equivalent dose to the lens of the eye of 150 mSv in a year; and

(d) an equivalent dose to the extremities (hands and feet) or the skin of 500 mSv in a year.

II-6: For apprentices of 16 to 18 years of age who are training for employment involving exposure to radiation and for students of age 16 to 18 who are required to use sources in the course of their studies, the occupational exposure shall be so controlled that the following limits be not exceeded:

(a) an effective dose of 6 mSv in a year;

(b) an equivalent dose to the lens of the eye of 50 mSv in a year; and

(c) an equivalent dose to the extremities or the skin of 150 mSv in a year.

II-7: When, in special circumstances, a temporary change in the dose limitation requirements is approved pursuant to Appendix I:

(a) the dose averaging period mentioned in para. II-5 (a) may exceptionally be up to 10 consecutive years as specified by the Regulatory Authority, and the effective dose for any worker shall not exceed 20 mSv per year averaged over this period and shall not exceed 50 mSv in any single year, and the circumstances shall be reviewed when the dose accumulated by any worker since the start of the extended averaging period reaches 100 mSv; or

(b) the temporary change in the dose limitation shall be as specified by the Regulatory Authority but shall not exceed 50 mSv in any year and the period of the temporary change shall not exceed 5 years.

The occupational dose constrain for the whole body exposures in forty years of working lifetime of an individual is 1 Sv. The maximum accumulated dose to a radiation worker of age N years is given by (N-18) x 20 mSv. This means that no person less than 18 years of age can be employed for radiation work.

Radiation workers such as radiographers are subjected to ionizing radiation while performing their work. The amount of radiation dose received depends on various parameters and conditions such as time, distance, shielding and working procedure. Thus, to ensure the safety of radiographers, it is important that supervisors or radiation protection officers continuously observe and record the amount of radiation received by each radiographer working under them. Such an activity is called personnel monitoring.

In general, the main purposes of personnel monitoring are to ensure that the dose limit is not exceeded, to limit the exposure of the individual radiographer, to assist the medical authority in making analysis in the case of accidental over exposure and to provide information about work practices and personal dose history. The other type of monitoring is area monitoring in which the environment around the worker is monitored. This includes checking the equipment containing radioactive sources, and the correctness of the exposure procedures. Personnel monitoring devices include film badges, pocket dosimeters and thermoluminescence dosimeters (TLD), while the area monitoring is done with the help of radiation survey meters.

(2) Non-occupational workers

For all non-occupational workers and members of the public being exposed to external radiation, the above mentioned dose limits must be reduced appreciably to keep limited the spread of radiation effects if any. The criteria and dose limits specified by Schedule II of the IAEA Safety Series No. 15 for this category of personnel are as given below:

II-8: The estimated average doses to the relevant critical groups of members of the public that are attributable to practices shall not exceed the following limits:

(a) an effective dose of 1 mSv in a year;

(b) in special circumstances, an effective dose of up to 5 mSv in a single year provided that the average dose over five consecutive years does not exceed 1mSv per year;

(c) an equivalent dose to the lens of the eye of 15 mSv in a year; and

(d) an equivalent dose to the skin of 50 mSv in a year.

1.1.8 Ultrasonic testing (UT)

Ultrasonic inspection is a non-destructive method in which high frequency sound waves are introduced into the material being inspected. Most ultrasonic inspection is done at frequencies between 0.5 and 20 MHz, well above the range of human hearing which is about 20 Hz to 20 kHz. The sound waves travel through the material with some loss of energy (attenuation) due to material characteristics. The intensity of sound waves is either measured, after reflection (Pulse echo) at interfaces (or flaw) or is measured at the opposite surface of the specimen (Pulse transmission). The reflected beam is detected and analyzed to define the presence and location of flaws. The degree of reflection depends largely on the physical state of matter on the opposite side of the interface, and to a lesser extent on specific physical properties of that matter, for instance, sound waves are almost completely reflected at metal-gas interfaces. Partial reflection occurs at metal-liquid or metal-solid interfaces. Ultrasonic testing has a superior penetrating power than radiography and can detect flaws deep in the test specimen (say up to about 6 to 7 metre of steel). It is quite sensitive to small flaws and allows the precise determination of the location and size of the flaws. The basic principle of ultrasonic testing is illustrated in Figure 1.8.

Ultrasonic testing method is:

1) Mostly used for detection of flaws in materials.

2) Widely used for thickness measurement.

3) Used for the determination of mechanical properties and grain structure of materials.

4) Used for the evaluation of processing variables on materials.

Some of the advantages of ultrasonic testing are:

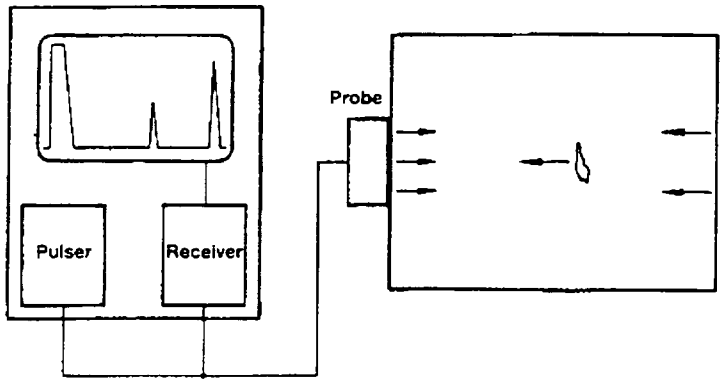
1) It has high sensitivity which permits detection of minute defects.

2) It has high penetrating power (of the order of 6 to 7 metres in steel) which allows examination of extremely thick sections.

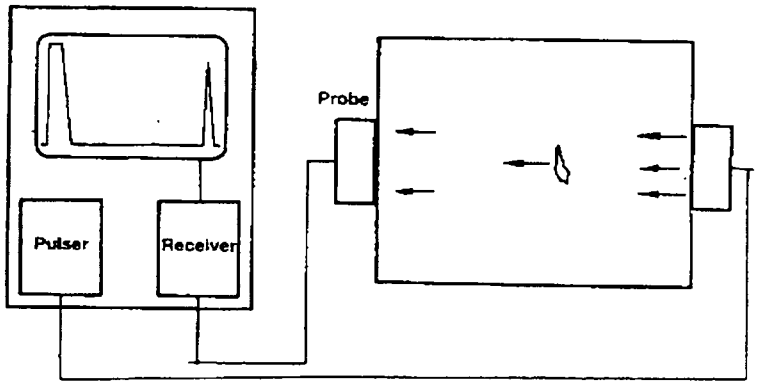
3) It has a high accuracy of measurement of flaw position and size.

4) It has fast response which permits rapid and automatic inspection.

5) It needs access to only one surface of the specimen.



(a) Pulse echo method.



(b) Through transmission method.

Figure 1.8 : Basic components of a pulse echo ultrasonic flaw detector.

Some of the limitations of this method are:

1) Unfavourable geometry of the test specimen causes problems during inspection.
2) Inspection of materials having undesirable internal structure is difficult.
3) It requires the use of a couplant.
4) The probe must be properly coupled during scanning.
5) Defect orientation affects defect detectability.
6) Equipment is quite expensive.
7) Very highly skilled manpower is required.

1.1.9 Comparison of Different NDT Methods

Frequently it may be necessary to use one method of NDT to confirm the findings of another. Therefore, various methods must be considered complementary and not competitive, or as optional alternatives. Each method has its particular merits and limitations and these must be taken into account when any testing programme is planned. Table 1.1 gives a summary of the most frequently used NDT methods.

TABLE 1.1 : COMPARISON OF NON-DESTRUCTIVE TESTING (NDT) METHODS

Method	Applications	Advantages	Limitations
Visual Testing (VT)	Surface discontinuities: cracks, porosity, slag, misalignment, warpage, incorrect size or number.	Inexpensive, fast, simple, apply during processing, can eliminate need for other methods.	Surface only, variable and poor resolution, eye fatigue, distractions, need good illumination.
Penetrant Testing (PT)	Surface discontinuities: cracks, porosity, seams, laps, leaks.	Inexpensive, easy to apply, more sensitive than visual, rapid, portable.	Surface only, not useful on hot, dirty, painted, or very rough surface, requires some skill.
Magnetic Particle Testing (MT)	Surface and near surface discontinuities: crack, void, porosity, inclusions, seams, laps.	Low cost, fast, more sensitive to tight cracks than PT, can do near surface, portable.	Material must be ferromagnetic, surface must be clean and good contact made, part may need demagnetization, alignment of field is important, requires operator skill.
Eddy Current Testing (ET)	Surface and near surface discontinuities: crack, seams, composition, thickness, eccentricity, surface condition.	Extremely rapid, can be automated, very sensitive, surface contact not necessary, permanent record.	Shallow penetration, conductive materials only, may require special equipment, sensitive to geometry, difficult interpretation sometimes.
Radiographic Testing (RT)	Subsurface discontinuities: cracks, voids, inclusions, lack of fusion, incomplete penetration, corrosion, missing components, composition	Easily understood, permanent record, usually moderate cost, can be portable, applicable to wide range of materials.	Cannot detect laminations, radiation hazard and regulations, access to both sides, can be high cost, requires trained operators.

TABLE 1.1 (cont.)

Method	Applications	Advantages	Limitations
Leak Testing	Leaks in systems or subassemblies.	Very sensitive to holes or separations not detected by other methods, can be rapid and inexpensive.	Costs vary widely with method, open systems cannot be tested, type or cause of defect not identified, can require special materials and equipment.
Dynamic Testing /Vibration Analysis	System abnormalities, misalignment, lack of bonding, missing or worn components, loose parts.	Useful in predictive or preventive maintenance, identify problem areas or parts, indicate severity, in-service test, portable.	Special equipment, experience required, some systems are too complex.
Acoustic Emission (AE)	Surface and subsurface discontinuities: crack initiation and growth, leaks, boiling and cavitation, phase changes.	Remote and continuous surveillance, location, severity, permanent record, tests on entire vessel or system.	Contact with system, may need many contact points, complex interpretation, system must be stressed, usually expensive, some systems are too complex.
Thermal Testing	Void or lack of bond or continuity, thin or thick sections, loss of insulation, heat sources.	Detect and locate hot or cold spots and heat generating defects, permanent record that may be quantitative, remote sensing, portable.	Poor resolution, often slow, specialized equipment can be expensive and require highly trained personnel, need reference standards.
Composition & Analysis	Alloy identification, plating identity and thickness.	Rapid, in place, usually not too difficult to do.	Can require considerable technique and experience or very expensive equipment. Very similar alloys difficult to identify.
Miscellaneous	Special	Can solve special problems.	Equipment not readily available, results not readily acceptable or interpretable.

1.2 MATERIALS AND DEFECTS

1.2.1 Structure of metals and alloys

The properties of metals can be explained in terms of the manner in which the atoms of a metal are bonded together. In this bond, called the "metallic bond" which is formed among similar metal atoms when some electrons in the valence shell separate from their atom and exist in a cloud surrounding all the positively chargeαd atoms. These positively charged atoms arrange themselves in a very orderly pattern. The atoms are held together because of their mutual attraction for the negative electron cloud (Figure 1.9).

Because the electrons are free to move in an electric field, metals conduct electricity. Because free electrons absorb and then radiate back most of the light energy that falls on them, metals are opaque and lustrous. Because free electrons can transfer thermal energy, metals conduct heat effectively. The metallic bond is non-specific, which explains why different metals can be alloyed or joined one to another. It is also non-directional, pulling equally hard in all directions. It therefore binds the metal atoms tightly, so that their cores (nuclei and inner shell electrons) fit closely among one another. The close packing favoured by the metallic bond is best realised in certain regular crystalline structures. These structures, although resistant to tension, offer less resistance to shearing forces, and thus they explain the ductility of metals. They are by definition dense, and thus they explain the comparative heaviness of metals.

1.2.1.1 Crystal structure

All matter is considered to be composed of unit substances known as chemical elements. These are the smallest units that are distinguishable on the basis of their chemical activity and physical properties. The elements are composed of atoms which have a distinct structure characteristic of each element. Atoms are too small to be seen with the aid of ordinary microscopes, but the outline of molecules has been detected with such devices as the ion field emission microscope and the electron microscope.

The chemical elements may be roughly classified into three groups: metals, metalloids, and non-metals. Some of the properties that an element must have to be considered a metal are: (1) crystalline structure; (2) high thermal and electrical conductivity; (3) ability to be deformed plastically; (4) metallic Ulster or high reflectivity of light (5) ability to donate electrons and form a positive ion. Metalloids resemble metals in some respects and non-metals in others. Examples of metalloids are carbon, boron and silicon. The remaining elements are known as non-metals. This includes the inert gases, the elements in Group VII A, and N, O ,P and S.

The mechanical properties of metals, then derive from their crystalline structure. That is, the atoms in the solid state of a metal are arranged in definite three dimensional geometric patterns to form crystals or grains of the metal. The network formed by joining the centre of the atoms in a crystal is called the `space lattice' or `crystal lattice' of the metal. The smallest volume in a space lattice which properly represents the position of the atoms with respect to each other is known as the unit cell. There are fourteen types of unit cells but the structures of most of the common and commercially important metals in the solid state are constructed from the following three types of unit cells:

a) Body-centered cubic(BBC)

The body-centered cubic cell is made up of two atoms. Eight are located on the corners of the cube but each of them builds also a part of further seven cells meeting at that corner (8 x $^1/_8$) with the ninth positioned centrally between them (Figure 1.10a). The body-centered cubic is a strong structure, and in general, the metals that are hard and strong are in this form at normal temperatures. These metals include for example chromium, molybdenum, titanium, tungsten, sodium and vanadium. Steel under 723 °C also has this structure.

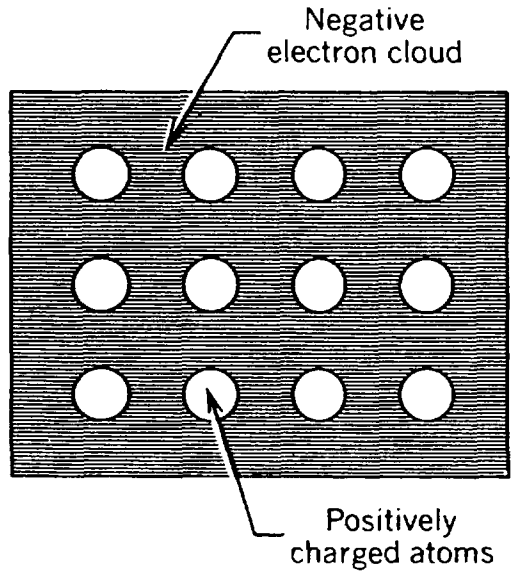


Figure 1.9 : Schematic illustration of a metallic bond.

b) Face-centered cubic (FCC)

Face-centered cubic cells consist of four atoms with eight at the corners (8 x $^1/_8$) and the other six centered in the cube faces but each of them is also a part of the neighbouring cell (6 x $^1/_2$) (Figure 1.10b). This structure is characteristic of ductile metals, which include aluminium, copper, gold, lead, nickel, platinum and silver. Iron, which is body-centered cubic at room temperature, is also of the face-centered structure in the temperature range from about 910 °C to 1,400 °C.

c) Hexagonal close-packed (HCP)

Seven atoms combine to make the hexagonal close-packed unit cell. Six atoms are located in each hexagonal face at each corner (6 x $^1/_3$) and one in the centre of the face (1 x $^1/_2$) and there are two hexagonal faces. The three remaining atoms take up a triangular position in the centre of the cell equidistant from the two faces (Figure 1.10c). The metals with this structure are quite susceptible to work-hardening. Some of the more commonly used metals that crystallize with this structure are cadmium, cobalt, magnesium, titanium and zinc.

1.2.1.2 Grains (crystals) and grain boundaries

When a metal is cooled from the liquid state to the solid state, because cooling cannot be exactly the same for every atom, certain atoms will be attracted to each other to form a unit cell ahead of others. This unit cell becomes the nucleus for crystal formation. As the cooling continues other atoms will take up their positions alongside this nucleus and the crystals, or as it is usually referred to for metals, the grain, will grow in size. This orderly growth of the grain continues in all directions until it runs into interference from other grains that are forming simultaneously about other nuclei. Figure 1.11 illustrates the process of the formation of grains and grain boundaries.

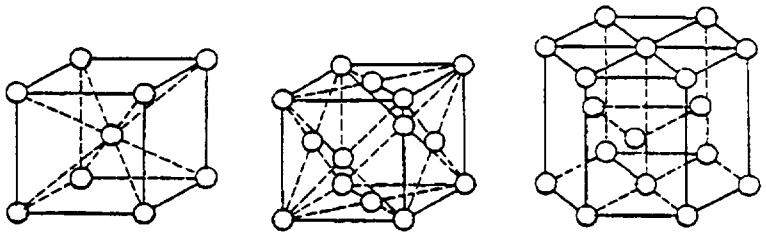


Figure 1.10 : Crystal types.

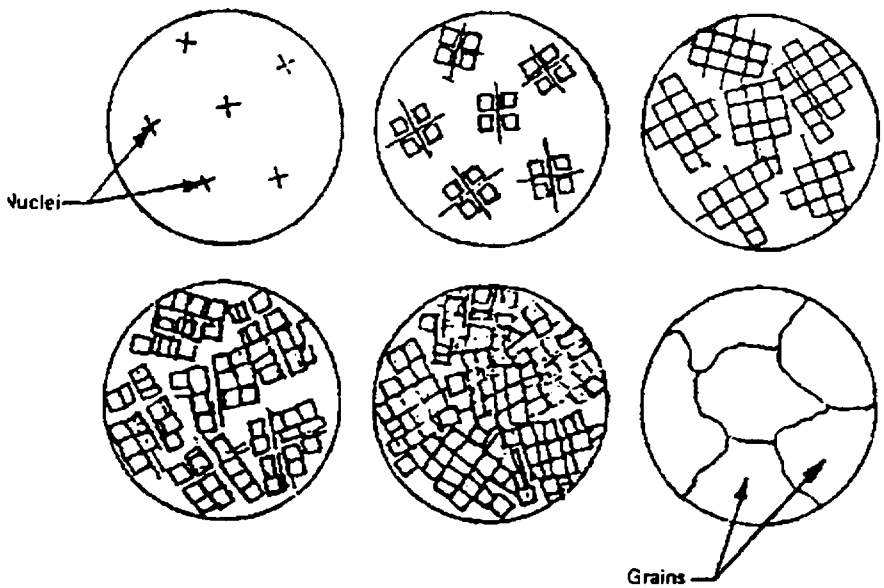


Figure 1.11 : Growth of crystals and grains during solidification.

Although with some metals with special treatment it is possible to grow single crystals several inches in diameter, in most metals at the usual cooling rates, a great number of crystals are nucleated and grow at one time with different orientations.

If two grains that have the same orientation meet, they will join to form a larger grain, but if they are forming about different axes, the last atoms to solidify between the growing grains will be attracted to each and must assume compromise positions in an attempt to satisfy a double desire

to join with each. These misplaced atoms are in layers about the grains and are known as grain boundaries. They are interruptions in the orderly arrangement of the space lattices and offer resistance to deformation of the metal. A fine-grained metal with a large number of interruptions, therefore, will be harder and stronger than a coarse-grained metal of the same composition and condition.

1.2.1.3 Structure of alloys

An alloy is a substance that has metallic properties and is composed of two or more chemical elements, of which at least one is a metal. Most commercially used metallic materials are not pure metals but alloys which consist of more than one elements. Some of them may be non-metallic elements. Fundamentally, three modes of arrangement of atoms or phases exist in alloys. These three modes (phases) are; pure metal, solid solution and intermetallic compound. For simplicity of illustration, an alloy with two elements A and B, shall be considered in the following discussion.

(a) Pure metal

There exist no B-atoms in A-crystal grains and no A-atoms in B-grains, i.e. mixture of pure A- and B-crystal grains. A and B metals are mutually insoluble. This complete lack of intersolubility is theoretically almost impossible (the solubility of one component in an other may be exceedingly small but hardly zero).

(b) Solid solution

Any solution is composed of two parts: a solute and a solvent. The solute is the minor part of the solution or the material which is dissolved, while the solvent constitutes the major portion of the solution. There exist B-atoms (solute) in A-crystal grains (solvent). Solid solutions are of two types: substitutional solid solutions and interstitial solid solutions.

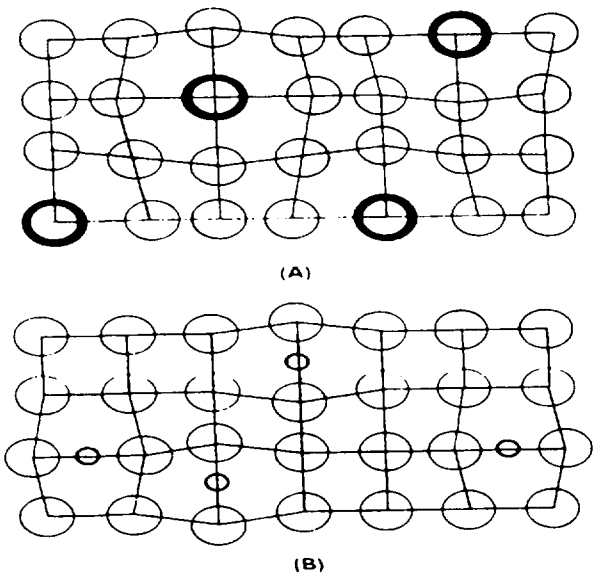


Figure 1.12 : Schematic illustration of substitutional and interstitial solid solutions.

(i) Substitutional solid solution

A substitutional solid solution is a solution of two or more elements with atoms that are nearly of the same size. This requirement is necessary in that the alloying atoms need to replace the regular atoms in the lattice structure as shown in Figure 1.12(A). Examples of substitutional solid solutions are gold dissolved in silver, and copper dissolved in nickel.

(ii) Interstitial solid solution

Interstitial solid solutions are made up of alloying elements or atoms that differ greatly in size. The alloying atoms must be small enough to fit within the lattice structure of the base material. This type of solid solution is called interstitial, and is illustrated in Figure 1.12(B). Small amounts of carbon, nitrogen, and hydrogen can alloy interstitially in iron and other metals.

(c) Intermetallic compounds

These are generally formed between chemically dissimilar metals and are combined by following the rules of chemical valence. Since they generally have strong bond (ionic or covalent), their properties are essentially non-metallic. Elements A and B form an intermetallic compound AB. In contrast to a solid solution, the ratio of the number of A-atoms to B-atoms is fixed (m : n), and the crystal structure is quite different from both A- and B-metal crystals and usually very complicated. Almost all the intermetallic compounds are very hard and brittle due to their complicated crystal structure.

1.2.1.4 Allotropic transformation

Many metals exist in more than one crystal structure. The transformation when a metal changes from one crystal arrangement to another is called an "allotropic transformation" or "phase transformation". Iron exists in three allotropic forms: BCC (below 1330°F or 704°C), FCC (above 1670°F or 911°C), and delta iron (between 2550°F or 1398°C and 2800°F or 1538°C). The exact temperature is determined by the amount of carbon and other alloying elements in the metal.

The properties of iron and steel are governed by the phase transformations they undergo during processing. Understanding these transformations is essential to the successful welding of these metals.

Steel is an iron alloy containing less than two percent carbon. The presence of carbon alters the temperatures at which freezing and phase transformations take place. The addition of other alloying elements also affects the transformation temperatures. Variations in carbon content have a profound affect on both the transformation temperatures and the proportions and distributions of the various phases (austenite, ferrite, and cementite). The iron-carbon phase diagram is shown in Figure 1.13.

On cooling, delta ferrite to Austenite transformation occurs at 2535°F (1390°C) in essentially pure iron, but in steel, the transformation temperature increases with increasing carbon content to a maximum of 2718°F (1492°C). Steels with more than 0.5 percent carbon freeze directly to austenite at a temperature below 2718°F (1492°C), and therefore, delta ferrite does not exist in these steels.

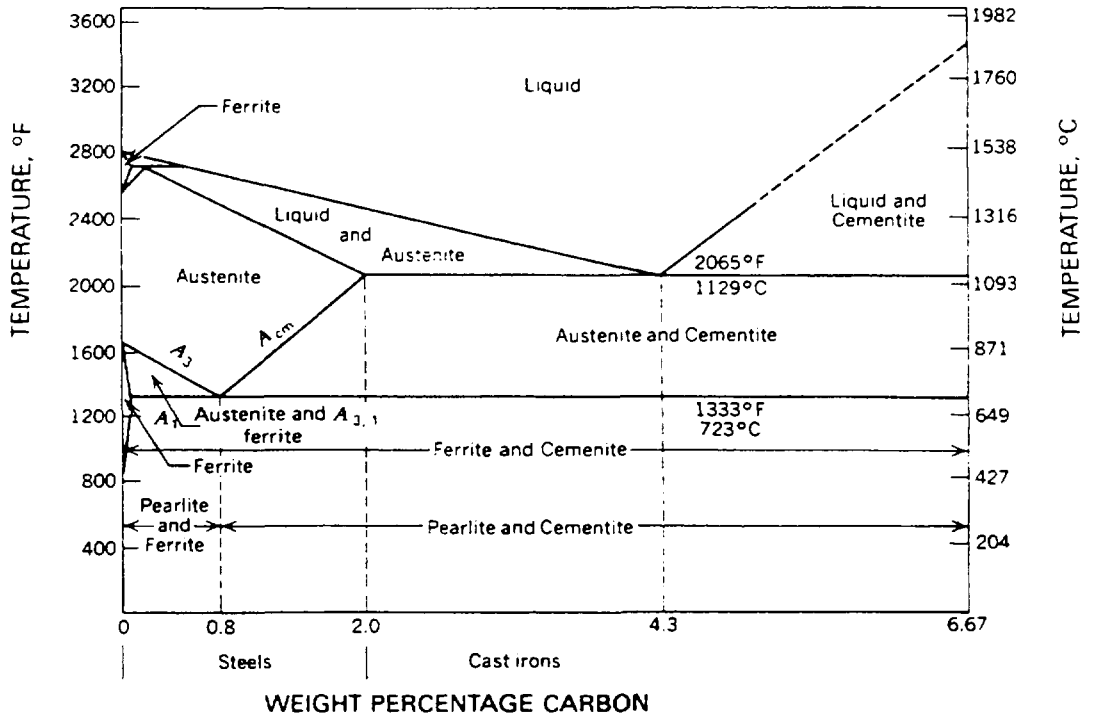


Figure 1.13 : The iron-carbon phase diagram.

On further cooling, austenite transforms to ferrite plus iron carbide. This is one of the most important transformations in steel. Control of it is the basis for most of the heat treatments used for hardening steel. This transformation occurs in essentially pure iron at 1670°F (910°C). In steel with increasing carbon content, however, it takes place over a range of temperatures between boundaries A_3 and A_1, Figure 1.13. The upper limit of this temperature range (A_3) varies from 1670°F (910°C) down to 1333°F (723°C). For example, the A_3 of a 0.10 percent carbon steel is 1600°F (870°C), while for a 0.50 percent carbon steel it is 1430°F (775°C). Thus, both at high and low temperature the presence of carbon promotes the stability of austenite at the expense of delta and alpha ferrite. The lower temperature of the range (A_1) remains at 1330°F (723°C) for all plain carbon steels, regardless of the carbon level.

Austenite can dissolve up to 2.0 percent of carbon in solid solution, but ferrite can dissolve only 0.025 percent. At the A_1 temperature, austenite transforms to ferrite and an intermetallic compound of iron and carbon (Fe_3C), called cementite. Ferrite and cementite in adjacent platelets form a lamellar structure, known as pearlite.

Most of the common alloying elements added to steel further alter the transformation temperatures. Room temperature microstructures of iron-carbon alloys at the equilibrium conditions covered by this diagram include one or more of the following constituents:

(1) Ferrite: A solid solution of carbon in alpha iron.
(2) Pearlite: A mixture of cementite and ferrite that forms in plates or lamellae.
(3) Cementite Iron carbide, Fe_3C: Present in pearlite or as massive carbides in high carbon steels.
(4) Austenite: A solid mixture of carbon in gamma iron.
(5) Leborite: A eutectic mixture of austenite & cementite.

When carbon steels are slowly cooled from the austenitic temperature range, the relative amounts of these three constituents at room temperature depend on the chemical composition. However, austenite decomposition is suppressed when the cooling rate is accelerated. When transformation does begin, it progresses more rapidly, and larger volumes of pearlite are formed. As the cooling rate is further increased, the pearlite lamellae become finer (closely spaced platelets).

At fast cooling rates, still lower transformation temperatures are encountered, and a feathery distribution of carbides in ferrite is formed instead of pearlite. This feathery arrangement of shear needles with fine carbides in a ferrite matrix is called bainite. It has significantly higher strength and hardness and lower ductility than fine pearlitic structures. With very fast cooling rates (severe quenching), martensite forms. Martensite is the hardest austenite decomposition product. When the cooling rate is fast enough to form 100 percent martensite, no further increases in hardness can be achieved by faster quenching.

The decomposition of austenite is an important consideration in the welding of steel alloys because the weld metal and parts of the heat-affected zone undergo this transformation.

1.2.2 Properties of materials (metallic & non-metallic)

1.2.2.1 Metallic materials

Mechanical properties are defined as the properties of a material that reveal its elastic and inelastic (plastic) behaviour when force is applied, thereby indicating its suitability for mechanical applications, for example, modulus of elasticity, tensile strength, elongation, hardness, and fatigue limit. Other mechanical properties, not mentioned specifically above, are yield strength, yield point, impact strength, and reduction of area, to mention a few of the more common terms. In general, any property relating to the strength characteristics of metals is considered to be a mechanical property. Physical properties relate to the physics of a metal such as density, electrical properties, thermal properties, magnetic properties and the like. These and other properties will be described here in slightly more detail.

Elasticity

When stress or force is applied to a metal, it changes shape. For example a metal under a compressive stress will shorten and metal in tension will lengthen. This change in shape is called strain. The ability of metal to strain under load and then return to its original size and shape when unloaded is called elasticity. The elastic limit (proportional limit) is the greatest load a material can withstand and still spring back into its original shape when the load is removed. Within the elastic range stress is proportional to strain and this is known as Hooke's law. The relationship between applied stress or load and the consequent strain or change in length is shown in Figure 1.14. The end of the straight line portion is known as the elastic limit. A point on the curve slightly higher than the elastic limit is known as the yield point or yield strength. The allowable or safe load for a metal in service should be well below the elastic limit. If higher loads are applied, however, the range of elasticity or elastic deformation is exceeded and the metal is now permanently deformed. Now it will not return to its original dimensions even when the load is removed. For this reason, the area of the stress strain curve beyond the elastic limit is called the plastic range. It is this property that makes metals so useful. When enough force is applied by rolling, pressing or hammer blows, metals can be formed, when hot or cold, into

useful shapes. If the application of load is increased in the plastic region a stage comes when the material fractures.

A very important feature of the stress-strain curve must be pointed out. The straight-line or elastic part of the stress-strain curve of a given metal has a constant slope. That is, it cannot be changed by changing the microstructure or heat treatment. This slope, called the modulus of elasticity, measures the stiffness of the metal in the elastic range. Changing the hardness or strength does not change the stiffness of the metal. There is only one condition that changes the stiffness of any given metal, that is temperature. The stiffness of any metal varies inversely with its temperature; that is, as temperature increases, stiffness decreases, and vice versa.

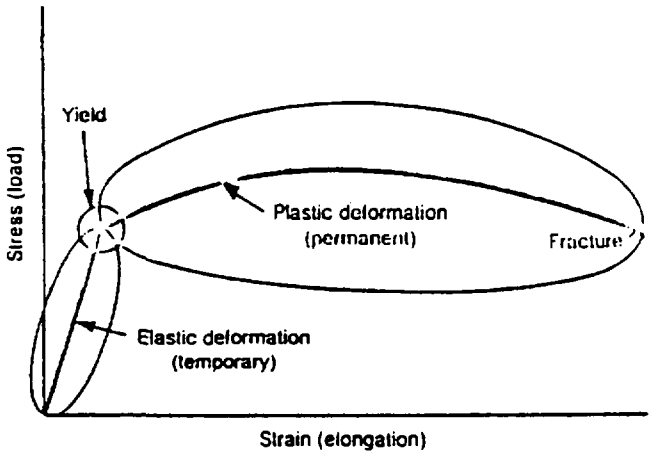


Figure 1.14 : Stress-strain curve showing elastic and plastic portions of a typical curve.

Strength

The strength of a metal is its ability to resist change in shape or size when external forces are applied. There are three basic types of stresses namely tensile, compressive, and shear. When we consider strength, the type of stress to which the material will be subjected must be known. Steel has equal compressive and tensile strength, but cast iron has low tensile strength and high compressive strength. Shear strength is less than tensile strength in virtually all metals.

The tensile strength of a material can be determined by dividing the maximum load by the original cross-sectional area before testing. Thus,

$$\text{Tensile strength} = \frac{\text{Maximum load}}{\text{Original cross-sectional area}} \quad \text{----------} \quad (1.1)$$

Metals are "pulled" on a machine called a tensile tester. A specimen of known dimensions is placed in the tensile testing machine and loaded slowly until it breaks. Instruments are sometimes used to make a continuous record of the load and the amount of strain (proportional change in length). This information is put on a graph called a stress-strain diagram. A stress-strain diagram can be made for any metal.

Hardness

The hardness of a metal is its ability to resist being permanently deformed. There are three ways that hardness is measured; resistance to penetration, elastic hardness, and resistance to abrasion. Hardness varies considerably from material to material. This variation can be illustrated by making an indentation in a soft metal such as aluminium and then in a hard metal such as alloy tool steel. The indentation could be made with an ordinary centre punch and a hammer, giving a light blow of equal force on each of the two specimens. In this case just by visual observation one can tell which specimen is harder. Of course, this is not a reliable method of hardness testing, but it does show one of the principles of hardness testers; measuring penetration of the specimen by an indenter or penetrator, such as a steel ball or diamond point.

Rockwell, Vicker and Brinell hardness testers are the most commonly used types of hardness testers for industrial and metallurgical purposes. Heat treaters, inspectors, and many others in industry often use these machines. The Rockwell hardness test is made by applying two loads to a specimen and measuring the difference in depth of penetration in the specimen between the minor load and the major load.

The Brinell hardness test is made by forcing a steel ball, usually 10 millimetres (mm) in diameter, into the test specimen by using a known load weight and measuring the diameter of the resulting impression. A small microscope is used to measure the diameter of the impressions. Various loads are used for testing different materials, for example, 500 kilograms (kg) for soft materials such as copper and aluminium and 3000 kg for steels and cast irons.

Generally the harder the material is, the greater its tensile strength will be, that is, its ability to resist deformation and rupture, when a load is applied.

Ductility

The property that allows a metal to deform permanently when loaded in tension is called ductility. Any metal that can be drawn into a wire is ductile. Steel, aluminium, gold, silver, and nickel are examples of ductile metals.

The tensile test is used to measure ductility. Tensile specimens are measured for area and length between gauge marks before and after they are pulled. The percent of elongation (increase in length) and the percent of reduction in area (decrease of area at the narrowest point) are measures of ductility. A high percent elongation (about 70 percent) and reduction in area indicates a high ductility. A metal showing less than 20 percent elongation would have low ductility.

Malleability

The ability of a metal to deform permanently when loaded in compression is called malleability. Metals that can be hammered or rolled into sheets are malleable. Most ductile metals are also malleable, but some very malleable metals such as lead are not very ductile and cannot be drawn into wire easily. Metals with low ductility, such as lead, can be extruded or pushed out of a die to form wire and other shapes. Some very malleable metals are lead, tin, gold, silver, iron and copper.

Brittleness

A material that will not deform plastically under load is said to be brittle. Excessive cold-working causes brittleness and loss of ductility. Cast iron does not deform plastically under a breaking load and is therefore brittle.

A very sharp "notch" that concentrates the load in a small area can also reduce plasticity. Notches are common causes of premature failure in parts. Weld undercut, sharp shoulders on machined shafts, and sharp angles on forgings and castings are examples of unwanted notches (stress raisers).

Notch toughness

Notch toughness (impact strength) is the ability of a metal to resist rupture from impact loading when there is a notch or stress raiser present. A metal may show high ductility or strength when tensile tested or be hard or soft when hardness tested, but often the behaviour of metals under shock loads is not seemingly related to those properties. Of course, as a rule, a brittle metal such as grey cast iron will fail under low shock loads; that is, its shock resistance is low, and soft wrought iron or mild steel has a high shock resistance. But soft, coarse-grained metals will have lower shock resistance than fine-grained metals. A notch or groove in a part will lower the shock resistance of a metal, so a specific notch shape and dimension is machined on the test specimen in order to give uniform results.

In general, the tensile strength of a metal changes in proportion to hardness. However, this relationship does not always hold true at high hardness levels or with brittle materials because these materials are more sensitive to stress concentrations, or notches, and may fracture prematurely when stressed in tension.

Conductivity

Conductivity is a measure of the ability of a material to conduct electric current. It is the reciprocal of resistivity. Conductivity is commonly expressed as mhos per metre since the unit of resistivity is the ohm. The conductivity of metallic elements varies inversely with absolute temperature over the normal range of temperatures but at temperatures approaching absolute zero the imperfections and impurities in the lattice structure of a material make the relationship more complicated. Metals and materials exhibit a wide range of conductivity. Between the most conductive substances (silver and copper) and the most resistive (polystyrene for example) the difference amounts to 23 orders of magnitude.

1.2.2.2 Non-metallic materials

Ceramics

Ceramics offer unique properties as engineering materials, notably exceptionally high hardness and resistance to abrasion and corrosion as well as high temperature properties considerably superior to those of any metals. However, they are less ductile, intrinsically brittle and susceptible to thermal shock which can limit their maximum service temperature on applications involving thermal cycling. Resistance to thermal shock is directly dependent on a low coeff[illegible] of thermal expansion and high thermal conductivity, which properties differ appr[illegible] between different ceramic materials.

The fabrication of ceramics does not set particular problems since they can be formed by traditional techniques such as slip casting wet pressing and extrusion; and by such modern methods as injection moulding, isostatic pressing, tape casting and dry pressing.

Ceramics which can be classified (or are usable or potentially usable) as engineering materials currently embrace:

(i) alumina, (ii) beryllia (beryllium oxide) and boron nitride, (iii) porcelain (aluminium silicates), (iv) steatite and forsterite (magnesium silicates), (v) silicon nitride and silicon carbide, (vi) titanium diboride and (vii) vitreous carbon.

Ceramics are finding an increasing use in the fabrication of electronic components, engineering components, medicine and dentistry and jewellery.

Cermets

The use of ceramic-coated metals and ceramic-metal combinations has now assumed significant proportions, particularly in the fields of practical nuclear physics (e.g. parts for nuclear reactors) and jet engine manufacture. Metal ceramic combinations are of two types: a ceramic coating on the metal, or a chemical and mechanical combination of metals and ceramics in a cermet material. Both are essentially attempts to produce satisfactory high-temperature materials, either with reduced costs and better availability or with an overall performance superior to existing metal or ceramic materials on their own. Broadly speaking the mechanical properties of these two types of materials represent extremes. Metals have high tensile strength and shock resistance, but lose these properties rapidly with increasing temperature. Ceramics of the refractory kind have extremely high melting points and excellent general stability, but are low in tensile strength and both mechanical and thermal shock resistance. The demand for materials combining the favourable features of both metals and ceramics is increasing; hence the development of combinations of ceramics with metals over the past few years.

Normally cermets are formed by techniques similar to those employed in powder metallurgy. The ceramic content usually comprises refractory oxides, carbides or nitrides whilst the metal powder component is usually chromium, nickel, molybdenum or titanium. The resulting properties are different from those of either of the separate constituents. A number of cermets have particularly high melting points, best realised in an open flame.

Composites

A composite is a material in which a stronger, sometimes fibrous material is usually combined with another to reinforce or strengthen the resultant mass. The needs of the aerospace industry led to the development and acceptance of composite materials. Low weight, high strength and great rigidity were of paramount interest of military aviation. These same qualities are also in demand in many non-military applications.

The most common forms of composites are based on a plastic matrix. The fibrous reinforcing material may be in sheet form, as in thermoset plastic laminates; filament form, woven or random, as in glass reinforced plastics; or short fibre form as in filled or reinforced thermoplastics. These materials are well established and widely available.

In the case of thermoset laminate composites, phenolic, melamine and epoxide are the main resin systems used with paper, cotton fabric, glass fabric and asbestos as the main alternative reinforcing materials.

Ceramic and metal composites have remained relatively undeveloped as general engineering and constructional materials, largely on account of high cost. There are, however, numerous applications of 'filled' and 'laminated' metal forms which qualify as composites under the general description.

Concrete

Concrete is a mixture of stone and sand held together by a hardened paste of hydraulic cement and water. When the ingredients are thoroughly mixed, they make a plastic mass which can be cast or moulded into a predetermined size and shape. When the cement paste hardens, the concrete becomes very hard like a rock. It has great durability and has the ability to carry high loads especially in compression.

The required strength and properties of concrete can be obtained by careful selection of its ingredients, correct grading of ingredients, accurate water additions and adopting a good workmanship in mixing, transportation, placing, compaction, finishing, and curing of concrete in the construction work.

The main ingredients of concrete are cement, coarse aggregate (i.e. screenings, gravel, etc.), fine aggregate (i.e. sand), chemical admixtures (if necessary) and fibrous materials (as necessary). Aggregates in concrete constitute by far the bulk of the mass.

1.2.3 Discontinuities and defects in metallic materials

Whenever there is a change in the homogeneity and uniformity of properties within a material, it can invariably be attributed to the presence of discontinuities or imperfections (lack of material) within the material. Starting from the dislocations and atomic structure irregularities, the discontinuities can take various shapes and forms such as gas inclusions (microporosity, porosity, blowholes, pipes, voids), cracks, metallic inclusions, lack of penetration, lack of fusion, shrinkage, laps and seams, etc. Discontinuities can be divided into three general categories inherent, processing, and service.

(i) Inherent discontinuities are usually formed when the metal is molten. There are two further sub classifications. Inherent wrought discontinuities relate to the melting and solidification of the original ingot before it is formed into slabs, blooms, and billets. Inherent cast discontinuities relate to the melting, casting and solidification of a cast article usually caused by inherent variables such as inadequate feeding, gating, excessive pouring temperature, and entrapped gases.

(ii) Processing discontinuities are usually related to the various manufacturing processes such as machining, forming, extruding, rolling, welding, heat treating, and plating. During the manufacturing process, many discontinuities that were subsurface will be made open to the surface by machining, grinding, etc.

(iii) Service discontinuities are related to the various service conditions, such as stress, corrosion, fatigue and erosion. The discontinuities may alter the local stress distribution and, in addition, may affect the mechanical or chemical (corrosion resistance) properties.

Discontinuities should be characterized not only by their nature, but also by their shape. Planar type discontinuities, such as cracks, laminations, incomplete fusion, and inadequate joint penetration, create serious notch effects. Three-dimensional discontinuities create almost no notch effect, but amplify stresses by reducing the weldment area. Therefore, the characteristics of discontinuities which should always be considered, include the size, acuity or sharpness, orientation with respect to the principal working stress and residual stress, location with respect to the exterior surfaces and the critical sections of the structure.

All the above discontinuities are described under the individual processes in Sections 1.3 and 1.4.

1.3 PROCESSING AND DEFECTS

1.3.1 Primary processes and related defects

1.3.1.1 Ingot casting and related defects

A casting suitable for working or remelting is called ingot. The moulds into which molten metal is poured to form ingots are made of grey cast iron, meehanite with large graphite flakes, and anodized aluminium alloys. The inside surface of the mould is frequently coated with suitable materials to help form a smooth ingot surface. The cross-sectional shape of the ingot will vary depending upon the intended product. Rectangular ingots are used for making slabs, plate, and sheet, and the ingots may weigh as much as 25,000 lbs. (11343 kg) each. Square ingots are used for producing billets, structural shapes, bars, and rods. The slab or billet is normally the starting point for actual forming of articles or materials. Typical discontinuities found in ingot (Figure 1.15) are non-metallic inclusions, porosity and pipe. Most of these discontinuities in the ingot are in the upper portion and can be easily eliminated by cropping off the top of the ingot. The ingot after the hot top is cropped off is called a bloom. The blooms then can be further processed to form slabs and billets (Figure 1.16).

1.3.1.2 Casting processes

A commonly used method of forming metal objects of complex shapes is by pouring molten metal into a mould in which it sets to the required shape. The mould is then broken away to expose the casting, or the design of the mould is such that it can be separated without damage and re-used. The moulds are usually formed from patterns which can be used many times over, if necessary, and their design is critical in that `feed' and `vent' holes must be carefully

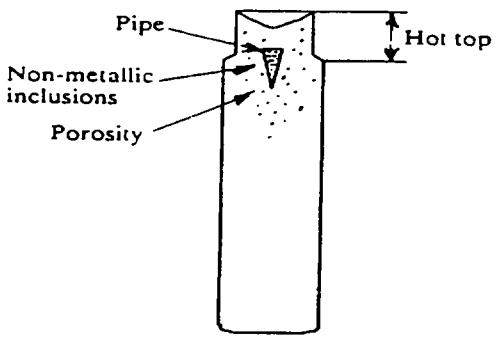


Figure 1.15 : Typical defects in an ingot.

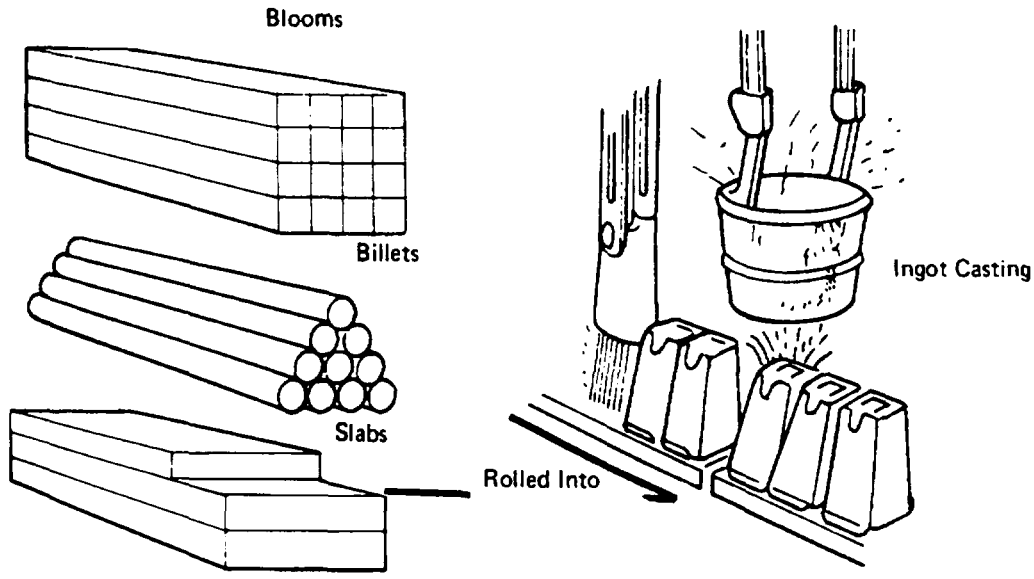


Figure 1.16 : Typical primary material processes.

positioned in the mould to permit the metal to flow freely into all parts (Figure 1.17). Problems that can occur are interaction on cooling. It is also unlikely that the crystal structure of a casting will be optimum in all parts so that its strength may be less than with other methods of fabrication. Various casting processes include sand casting, permanent mould casting, die casting, centrifugal casting and shell mould casting.

Since the casting process is complex and a large number of variables need to be controlled to get a good quality product and since it is not possible to give all the details here, only the principles and salient features of the above mentioned processes of casting are briefly presented.

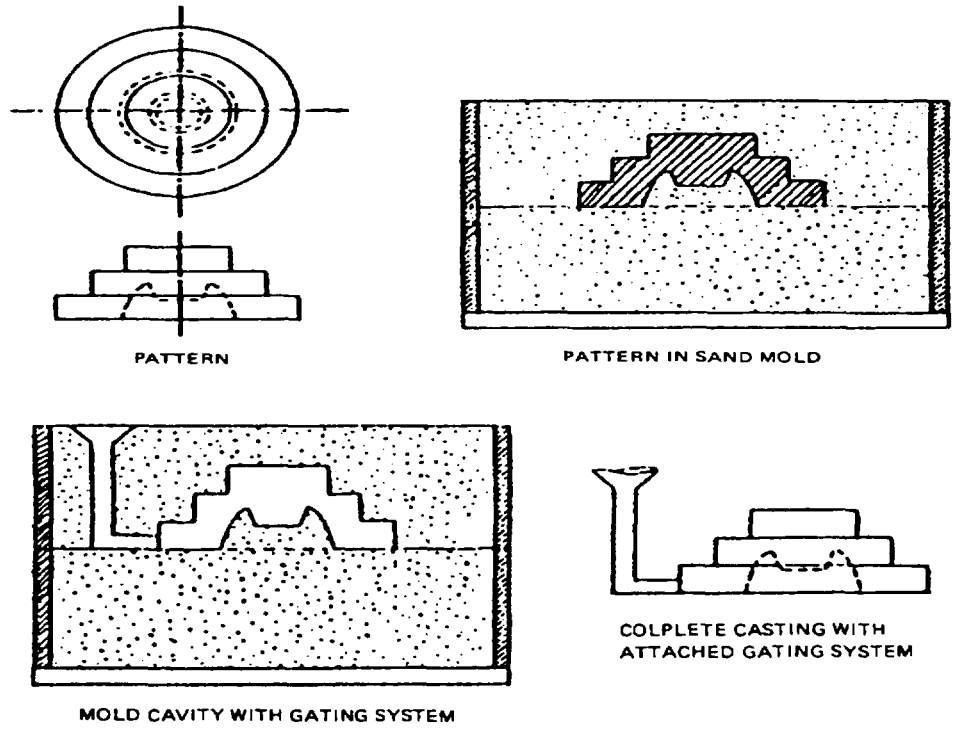


Figure 1.17 : Casting steps.

Sand casting

In this case a sand mould is used for casting the desired shape of the required alloy. A sand mould may be defined as a preformed sand container into which molten metal is poured and allowed to solidify. In general sand moulds are destroyed as the casting is removed from them. Sand moulds make it possible to cast complex shapes that might not be possible otherwise.

Different types of sand moulds can be made for making different castings. Green sand moulds are made from moist sand and are used for practically all ferrous and non-ferrous castings. They have the disadvantage of not being very strong as well as requiring moisture during manufacture which may cause certain defects in the casting. Green sand moulds may be provided with a dry sand on the surface to give `skin-dry moulds'. Purely `dry-sand moulds' can also be made by adding to the sand a binder instead of moisture. Its main advantages include a greater resistance to metal erosion, increased strength and a lessening of the tendency in the casting to acquire moisture-related defects. In some cases silica sand bonded with portland cement may be used to make the moulds.

Methods of preparing sand moulds include `bench moulding', `machine moulding', `floor moulding' and `pit moulding'. `Bench moulding' is used for small castings. This is usually a slow and laborious process since hand ramming with loose pattern is usually used. Small and medium moulds may be made even with the aid of a variety of `machines' which are usually faster and more uniform than bench moulding. Medium to large moulds are made directly on the foundry floor. Very large moulds made in a pit constructed for the purpose are called `pit moulds'.

The sands most commonly used in `sand die casting' contain silica sand which is usually from 50 to 95% of the total material in any moulding sand, zirconate and olivine, etc. The most important properties and characteristics of such sands are `permeability', `cohesiveness' and `refractoriness'. Permeability is a condition of porosity and is related to the passage of gaseous material through the sand as well as to the density of sand grains. Cohesiveness can be defined as the holding together of sand grains or strength of moulding sand and depends upon the size and shape of the sand grains. The property of cohesiveness may be improved by adding to the sand some binders such as clay, resins and gums and drying oil. The third important characteristic of the moulding sand is `refractoriness' which is its ability to withstand a high temperature without fusing. Pure silica sand can withstand a temperature as high as 3148°F. The property of `refractoriness' can be affected by impurities like metallic oxides.

Mould cavities may be produced by packing the moulding material around what are called `patterns'. The `patterns' may be made from wood, metal or other suitable materials. There are a variety of these patterns used in the manufacture of castings. Another important part of the casting process is the `core box' which is a structure made of wood, metal or other suitable material, containing a cavity with the shape of a desired core. Making a sand mould involves the proper packing of moulding sand around a pattern. After the pattern is removed from the sand and the gating arrangement completed, the mould cavity is filled with molten metal to form the casting.

Permanent mould casting

A casting made by pouring molten metal into a mould made of some metallic alloy or other material of permanence is known as a permanent mould casting.

Grey cast iron and meehanite with large graphite flakes are the most commonly used materials in the construction of permanent moulds. This common use is partly due to the ease with which they may be machined. Certain steels, particularly special alloy steels that are heat-treated, often have especially good resistance to erosion. They have excellent refractory properties. Some aluminium alloys on which the surface has been anodized, are also used as moulding materials. Anodizing produces Al_2O_3 which is very refractory and resistant to abrasion. These alloys are very easy to machine and possess a good chilling capacity. The mould is not destroyed on removing the casting and therefore can be re-used many times.

Die casting

Die casting may be defined as the use of a permanent mould (die) into which molten metal is introduced by means of pressure. The term pressure die casting is another name for this method of casting. This pressure is obtained by application of compressed air or by pneumatically or hydraulically operated pistons. This process of casting can be subdivided in two types, e.g. (a) hot chamber die casting; and (b) cold chamber die casting:

(a) Hot chamber die casting

The melting unit is an integral part of the hot chamber machine, and molten metal is introduced directly from this melting unit, by means of plunger mechanism into the die cavity. The process is further characterised by a normal amount of superheat in the metal and the need for a commensurately lower casting pressure. Pressure on the molten metal in hot chamber die casting machines may vary from approximately 500 to 6000 psi (3.5 to 41 MPa). An average of approximately 2000 to 2500 psi (14 to 17 MPa) is common. Air injection pressures are normally limited to about 600 psi (4 MPa) (Figure 1.18).

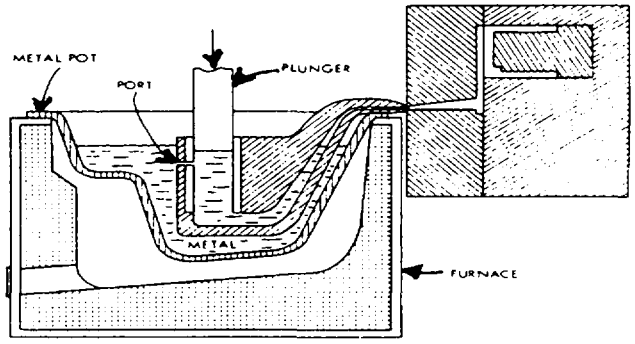


Figure 1.18 : Hot Chamber die casting.

(b) Cold chamber die casting

The melting unit is usually separate in this case, and molten metal must be transferred to the injection mechanism by ladle (Figure 1.19). Further distinctive characteristics of the process are, very high metal pressures and the fact that the casting alloy may be at a temperature somewhat less than normal superheat; the melt may even be in a semimolten condition. Pressure on the casting metal in cold chamber die casting machines may vary from 3000 psi (20.5 MPa) to as high as 25000 psi (172 MPa) and in some cases may reach 100,000 psi (690 MPa). Metallic alloys cast in a semimolten condition require greater pressure to compensate for the reduced fluidity resulting from low pouring temperatures. Lower working temperature and high pressures produce castings of dense structure, free of blow holes and porosity related to

dissolved gases. A piston type plunger mechanism is commonly used to force the semimolten alloy, which has been introduced through the injection port, into the die cavity. The lower temperatures of the melt reduce the possibility of excessive damage to machine parts from thermal shock.

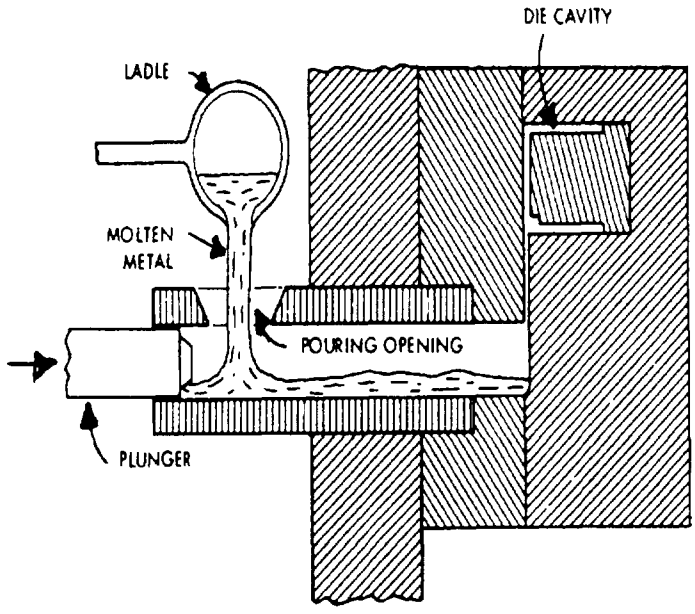


Figure 1.19 : Cold chamber die casting.

Centrifugal casting

Any process in which molten metal is poured and allowed to solidify while the mould is revolving, is a centrifugal casting process. Castings produced under this centrifugal force are called centrifugal castings. There are three recognized centrifugal processes namely `true centrifugal casting', `semicentrifugal or profiled-centrifugal casting' and `centrifuged or pressure casting'. `True centrifugal casting' is that in which castings are made in a hollow, cylindrical mould rotated about an axis common to both casting and mould. Cast-iron pipe is commonly made by this method. In this process the axis of spin may be horizontal, inclined, or vertical. In the true centrifugal casting process the inside circumference is always circular. When the mould is rotated on a horizontal axis, a true cylindrical inside surface is produced. True centrifugal casting is used only on symmetrically shaped objects. Semicentrifugal or profiled-centrifugal casting is similar to the true centrifugal method, except that a central core is used to form the inner surface or surfaces. The casting is not dependent upon centrifugal force for its shape. A good example of semicentrifugal work is a cast wheel-like casting. The axis of spin in the semicentrifugal process is always vertical. Although the yield is better than with static casting, it is not as high as in true centrifugal casting. With this process also only symmetrically shaped objects can be cast.

Centrifuged or pressure casting is applied for non-symmetrical castings. The mould cavity is not rotated about its own axis but about the axis of a central down sprue common to the axis of spin, which feeds metal into the mould cavity under centrifugal force. This process of centrifuging can be done only about a vertical axis. Centrifugal force provides a high pressure to force the metal alloy into the mould cavity.

Centrifugal casting processes can be used to produce parts made of both the ferrous and non-ferrous alloy groups. Cast-iron pipe, gun barrels, automotive cylinder walls, jet engine rings, piston rings and brake drums are common parts centrifugally cast. Advantages include the elimination of foreign inclusions and the production of sounder castings. The chief disadvantages are the shape and size limitations.

Investment casting

This process involves making a one-piece mould from which the pattern is removed by a procedure which melts the pattern. The moulds used in this process are single purpose moulds. The elimination of all parting planes provides improved dimensional tolerances. Since the pattern is removed by melting or burning out, casting precision is increased through eliminating draft, rapping, and shifts. Various other names are given to this process. It is also called 'precision investment casting', 'precision casting' or the 'lost-wax process' and is shown in Figure 1.20.

Various types and grades of wax are the common materials for pattern making for investment casting. Certain plastics that burn without residue are also used as pattern materials. Some low melting point metallic alloys can also be used as pattern materials. In this process of casting the patterns are formed afresh each time by casting or forging the pattern material in dies made of metal, plastic, rubber or wood.

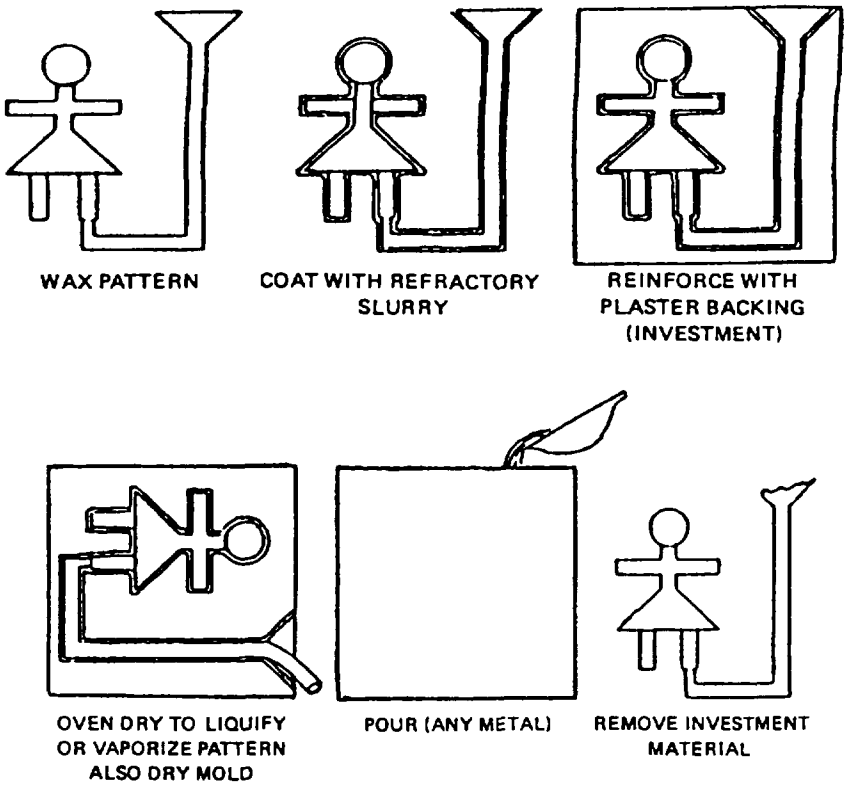


Figure 1.20 : Steps for investment casting.

Patterns are first made of wax or other pattern materials by melting and then injecting it into a metallic or non-metallic die. Then the patterns are welded or joined to gates and runners, which are also of the same material as the pattern. By this welding or joining of the pattern to gates and

runners a tree like pattern is prepared. This tree is now dipped into a refractory sand, placed in a metal flask and sealed to the pallet. Then the investment or moulding material, in viscous slurry form, is poured around the pre-coated tree. When the investment has set, the mould is heated by putting it in an oven at 200°F. By this heating the mould is dried and baked and the pattern is melted and the molten pattern material is taken out of the mould. Now as a final touch to the mould before casting, the mould is placed in a furnace and is heated to a temperature of 1300-1900°F. This removes all the wax residue, if any, sticking to the investment mould. The mould is then heated to the casting temperature.

Shell mould casting

This process involves making a mould that has two or more thin, shell-like parts consisting of thermosetting resin-bonded sand. These shells are single purpose in application and are hard and easily handled and stored. Shells are made so that matching parts fit together easily, held with clamps or adhesives and poured in either a vertical or horizontal position. These moulds may be supported in racks or in a mass of bulky permeable material like sand, steel shots, or gravel.

Metallic patterns are used for the production of shells, as they are subjected to heating temperatures approaching 1,000°F. The pattern must have some provision, in the form of ejector pins, for the removal of shells from the surface of the pattern. Clean dry silica sand is the bulk material used in the making of shell moulds. Grain size and distribution can vary with use. Thermosetting synthetic resins are used as binders for sand. The resins include the phenolformaldehydes, urea formaldehydes, and others.

The sand and resin mix or coated sand is caused to fall against, or is blown against, a heated metal pattern or core box. The temperature of the pattern ranges from 350 to 600°F. Contact of the thermosetting resin with the hot pattern causes an initial set and thus an adhering layer of bonded sand is formed within 5 to 20 seconds. The pattern with this adhering layer of bonded sand is placed into the furnace and is cured by heating to the proper temperature for one to three minutes. The time of curing depends on the shell thickness and the resin type. The assembly is then removed from the furnace and the shell is stripped from the pattern by ejector devices. This stripping is sometimes a problem and can be overcome by using a silicon parting agent.

The main advantages of this process are that the `shell' cast parts have generally a smooth surface and thereby reduce machining costs. These techniques are readily adaptable to mass production by using automatic equipment. The disadvantages can be the initial cost of metal patterns, the higher cost of the resin binders and a general size limitation.

Continuous casting

Although only a small tonnage of castings are produced by continuous casting, it is possible to produce two dimensional shapes in an elongated bar by drawing solidified metal from a water-cooled mould. As shown schematically in Figure 1.21, molten metal enters one end of the mould, and solid metal is drawn from the other. Control of the mould temperature and the speed of drawing is essential for satisfactory results. Exclusion of contact with oxygen, while molten and during solidification, produces high quality metal. Gears and other shapes in small sizes can be cast in bar form and later sliced into multiple parts.

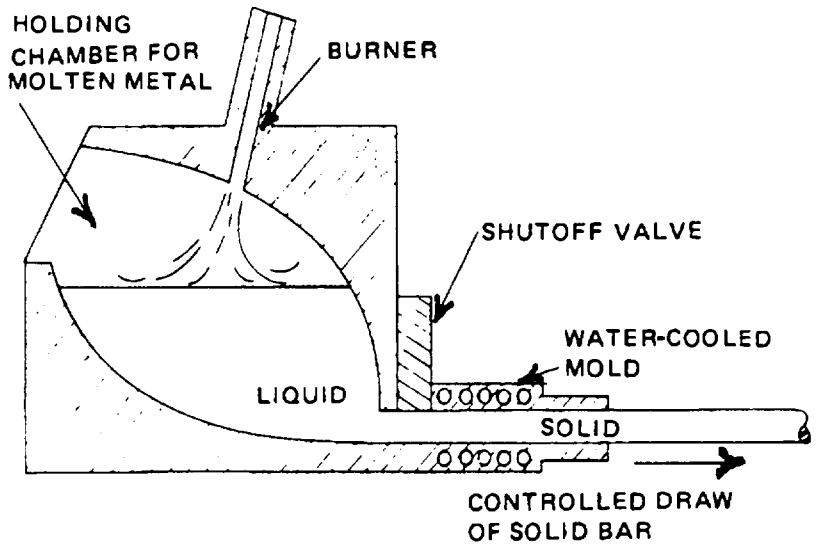


Figure 1.21 : Schematic diagram of continuous casting process.

Casting defects

There are in general three broad categories of casting defects. First are the major or most severe defects which result in scraping or rejection of the casting. The second category is of intermediate defects which permit salvaging of the casting through necessary repair. The third category defects are minor ones which can be easily repaired. The elimination and control of casting defects is a problem that the foundry engineer may approach in several ways. The common procedure is to rely upon salvaging techniques that appear to provide immediate savings. Remedial procedure in the moulding, coremaking, melting or pouring areas of the foundry are frequently neglected but are highly desirable to be controlled to avoid defects. Some of the defects which usually occur in castings are given hereunder:

Porosity

Gas holes are spherical holes of varying size, with bright walls, usually fairly evenly distributed and formed by gas in the metal. The larger holes tend to be found in the heavier section (i.e. last to solidify). If the metal is correct prior to casting, the pinhole type of porosity is probably due to absorption of hydrogen from steam in the mould. The gas in the molten metal is removed by a gas scavenging technique and by keeping casting ladles and moulds dry.

Blowholes

Blowholes are mainly found in three forms: i) Elongated cavities with smooth walls, found on or just below the surface of the topmost part of a casting. These are caused by entrapped air and repetition can be avoided by venting the mould and increasing its permeability. ii) Rounded shape cavities with smooth bright walls are caused by mould or core gases, coupled with insufficient permeability, or venting. They can be avoided by using less oil binder in the mould and ensuring that cores are dry and properly baked and that the sand is properly mixed. iii) Small cavities immediately below the 'skin' of the casting surface are formed by the reaction of the molten metal with moisture in the moulding sand. This can be avoided by reducing the volatile content in mould cores and mould dressing, by ensuring that metal is deoxidized, by using more

permeable sands, by ensuring that moulds and cores are properly vented and by reducing pouring temperature.

Piping

When this term is used in the foundry it refers to the gas inclusion defects encountered in risers or within the casting proper.

Inclusions

These are material discontinuities formed by the inclusion of oxides, dross, and slag in a casting. They are due to careless skimming and pouring, or the use of a dirty ladle, and to turbulence due to improper gating methods when casting alloys, such as aluminium and bronze, that are subject to surface oxide-skin formation. Faulty closing of moulds can cause 'crush' and loose pieces of sand becoming incorporated in the casting. The occurrence of inclusions can be avoided by proper use of equipment and foundry practice.

Sponginess

A defect that occurs during the early stages of solidification of a casting and has the appearance, as the name would imply, of a sponge; it may be local or general in extent. The major cause is failure to obtain directional solidification of the casting towards the desired heat centres, such as risers and ingates; insufficiently high pouring temperature and placing of ingates adjacent to heavy sections.

Shrinkage

A casting defect that occurs during the middle and later stages of solidification of the cast metal. It has a branching formation, is readily distinguishable from that of sponginess, and is a form of void (Figure 1.22). The defect can be avoided by paying particular attention to the direction of solidification and ensuring adequate risers, or other feeding aids, on the heavier sections of a casting. Modification of casting design, i.e. to make cast sections more uniform for the flow and solidification of the metal is helpful in avoiding shrinkage. Moulds and cores are sometimes made too strong and greatly resist the contraction of the cast metal and, in this way, will cause a breakdown in the homogeneity of the metal.

Hot tears

These are discontinuities that result from stresses developed close to the solidification temperature while the metal is still weak. These, again, are attributed to resistance of the mould and core, which hinder contraction of the casting, causing thermal stress. Hot tears resemble ragged cracks. They can be avoided by making cores and moulds more collapsible, avoiding abrupt changes in section and preventing the formation of intense hot spots by designing with more uniform sections (Figure 1.23).

Crack

Well defined and normally straight, they are formed after the metal has become completely solid. Quite large stresses are required to cause fracture, and the walls of such cracks are discoloured according to the temperature of the casting when the cracks formed. Bad casting design coupled with restriction of contraction by the mould, core, or box bars contribute to

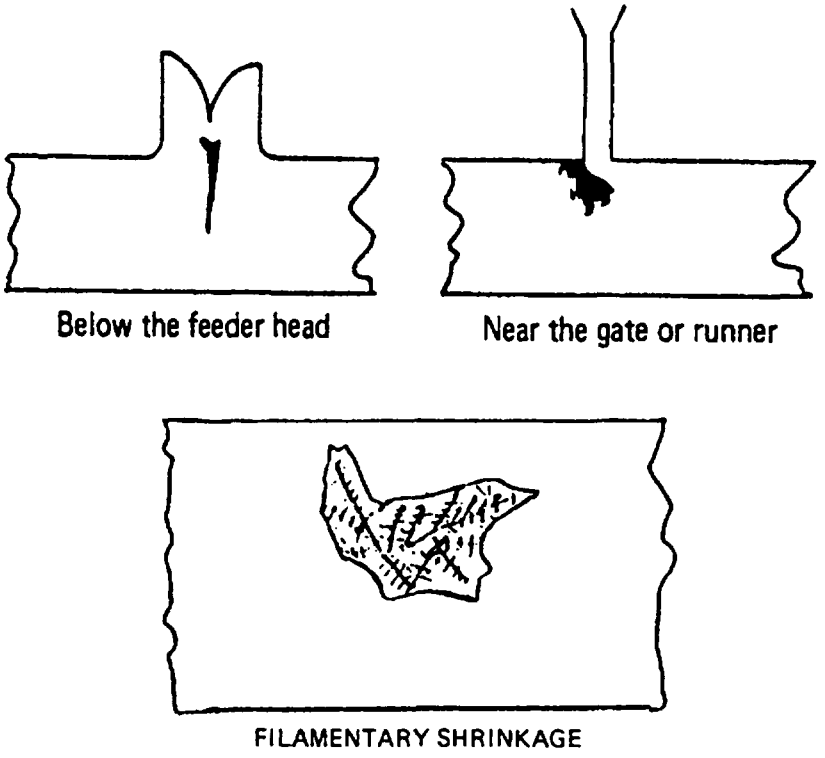


Figure 1.22 : Formation of shrinkage defects.

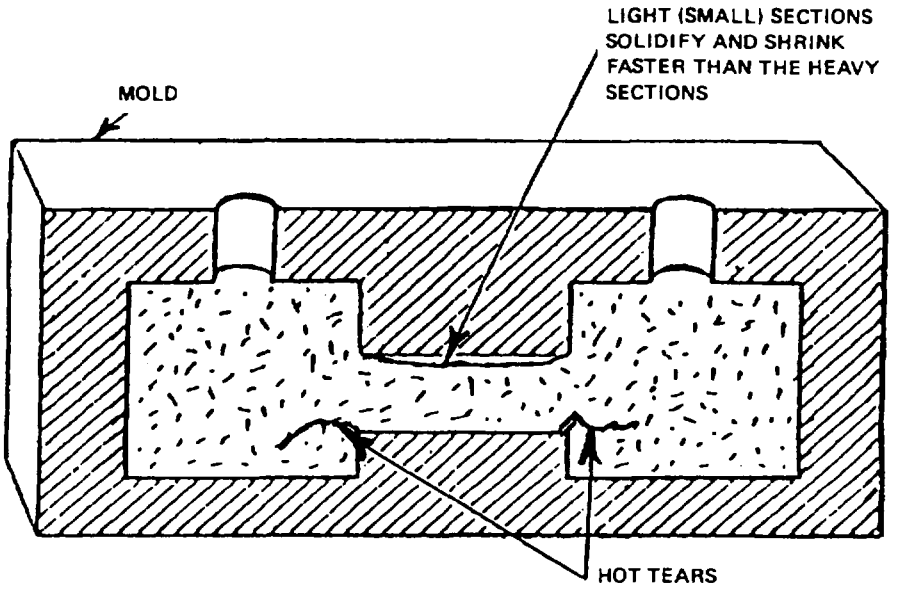


Figure 1.23 : Hot tears.

cracking, and avoidance of these, together with the easing of mould or cores as soon as possible after solidification, will help to prevent build-up of stresses.

Cold shuts

These are discontinuities (a form of lack of fusion) caused by the failure of a stream of molten metal to unite with another stream of metal, or with a solid metal section such as a chaplet (Figure 1.24). They are linear in appearance, with perhaps a curling effect at the ends. A cold shut is caused by the fluidity of the metal being too low (i.e. surfaces too cold) or perhaps unsatisfactory methods of feeding the molten metal.

Cold shuts can often be avoided by raising the pouring temperature or pouring rate or both and reviewing the position, size, and number of ingates and the arrangements for venting the mould.

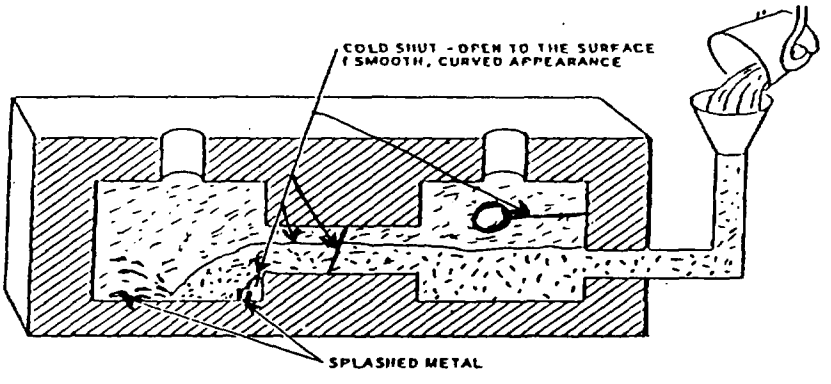


Figure 1.24 : Types of cold shuts.

Unfused chaplet

A chaplet is often used to support a section of a mould or a core within a mould and when the molten metal is poured in, the chaplets should fuse into the casting. When unfused the chaplet will cause a discontinuity in the casting. Design of chaplet and type of chaplet should be reviewed in overcoming this defect.

Misplaced core

An irregularity of wall thickness, e.g. one wall thicker than the other, can be detected by a double wall technique radiograph. It is caused by core out-of-alignment, careless coring-up and closing of mould, or rough handling after the mould is closed.

Segregation

Segregation is a condition resulting from the local concentration of any of the constituents of an alloy. The segregation can be 'general' extending over a considerable part of a casting, 'local' when only the shrinkage voids or hot tears are wholly or partially filled with a constituent of low melting point or 'banded' which is mainly associated with centrifugal castings but can also occasionally occur in static castings.

1.3.1.3 Powder metallurgy processes

The definition for the term powder metallurgy is 'the art of producing metal powders and objects shaped from individual, mixed, or alloyed metal powders, with or without the inclusion of non-metallic constituents, by pressing or moulding objects which may be simultaneously or subsequently heated to produce a coherent mass, either without fusion or with the fusion of a low melting constituent only'. Figure 1.25 shows the steps ordinarily required in the production of a part by the powder metallurgy process. Suitable powder must first be produced. While theoretically any crystalline material may be fabricated by powder metallurgy, the production of suitable powder has presented restrictions in many cases, either because of difficulty in obtaining adequate purity or because of economic reasons. After selection and blending of the powder and manufacture of a die for the shape to be produced, the powder is pressed to size and shape. The application of heat results in crystalline growth and the production of a homogeneous body.

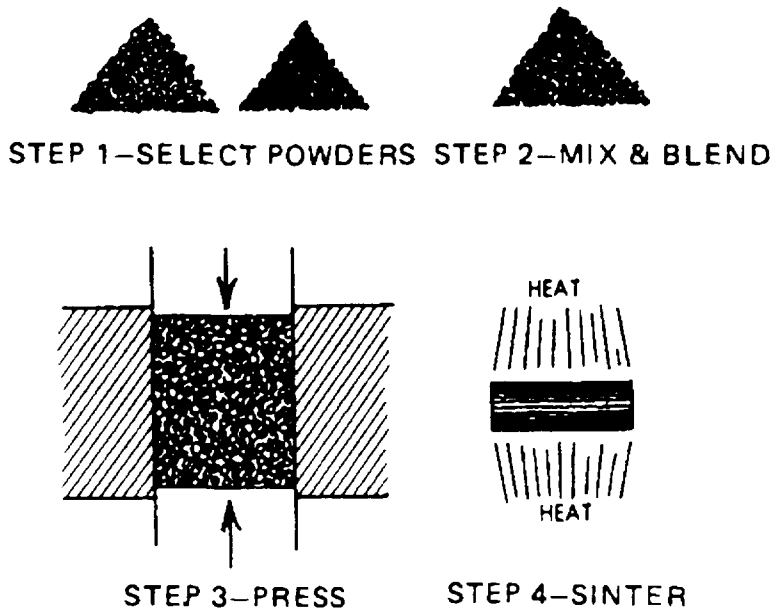


Figure 1.25 : Elements of powder metallurgy.

Mixing and blending

Mixing is required for even a single metal powder to promote homogeneity with a random dispersion of particle sizes and shapes. The mixing and blending is even more important for combinations of materials that depend on uniform alloying to develop final properties. Small amounts of organic materials may be added to reduce segregation, and other materials, both organic and inorganic, may be added to act as lubricants during pressing or sometimes in the final product.

Pressing

Compacting of metallic powders ideally would be done by applying pressure in all directions at one time. This is usually impractical for commercial use, and most compaction is done along a single axis. Pressure is sometimes applied from one direction only, but in other cases opposing motions are used to reduce the effect of sidewall friction. The effectiveness of pressing is most often evaluated by measuring the density of the material and expressing it as a percentage of the theoretical density for solid metal of the type being treated. Densities depend on the particle size

and shape, the material, the pressure, the time, and the temperature. The density variation problem is further complicated by shapes that are other than simple cylinders. Development of pressure by centrifuging may produce more uniform density because each particle of material supplies a force of its own.

Sintering

The term sintering is used to identify the mechanism by which solid particles are bonded by application of pressure or heat, or both. In its broadest sense, the process includes such procedures as welding, brazing, soldering, firing of ceramics, and union of plastic flakes or granules. Each of the procedures other than those involving metal in powder form are important enough and of such wide usage as to have developed their own language and technology. Sintering can be accomplished at room temperature with pressure alone but it is most often performed at elevated temperature, either at the same time or after pressure has been applied. The two most common sintering procedures are: (1) application of heat and pressure together, called hot pressing; and (2) application of heat after the particles have been closely packed, by cold pressing. In hot pressing, the plasticity of the particles is greater, and they recrystallize more readily and thus permit high densities to be achieved with lower pressures than would be necessary at lower temperatures. Cold-pressed parts that are subsequently sintered may be heated in conventional manner by being placed in ordinary furnaces or salt baths.

Deformation

Because of variations of density and other factors, shrinkage of powder metallurgy products during sintering is difficult to control. Parts that require close tolerances must nearly always be finished by some dimensional treatment. Cold working may be used for minor changes of dimensions, but this procedure is limited by the lack of ductility common to powder metallurgy products. Repressing, sometimes referred to as coining, improves the density, strength, and ductility of the material. Even with this process, it is seldom that these properties are equal to those of a similar material produced by fusion. Most commercial deformation working is done by hot working or by cold working with frequent interruptions for recrystallization.

Heat treatment

Powder metallurgy products may be heat treated in the same ways as other materials of similar chemical composition, but the treatments are usually not as effective as for the fusion produced metals, mainly because of the porous structure restricting the heat conductivity. Many of the voids within powder metallurgy products are stress concentration points that not only limit service loads but also increase the stresses arising from thermal gradients during heat treatment. The treatments include resintering for stabilization and homogeneity, annealing for softness, grain refinement for improved ductility, and hardening for improved wear resistance.

Machining

The machinability of sintered materials is usually poor, but machining is sometimes necessary to provide final control of dimensions or to establish shapes that are not practical for the powder metallurgy process. With some types of products, such as the cemented carbides, grinding is the common finishing process both to control size and shape and, in many cases, to eliminate the surface produced in the sintering process.

Impregnation

One important finishing step is that of impregnation. Inorganic materials, such as oils or waxes, may be impregnated into porous metal products for purposes of lubrication. An entirely different kind of product can be produced by impregnating high melting temperature metals with low melting temperature metals. The principal use of this technique is in the production of cemented steels.

Applications of powdered metal products

Powder metallurgy occupies two rather distinct areas. It is a basic shape-producing method for practically all metals, in direct competition with other methods. In addition, for many refractory materials, both metals and non-metals, powder metallurgy is the only practical means of shape production. Tungsten is typical of the refractory metals; it has a melting point of 3,400 °C, and no satisfactory mould or crucible materials exist for using conventional casting techniques at this temperature. Tantalum and molybdenum are similar.

Cemented carbides form one of the most important groups of materials that can be fabricated into solid shapes by powder metallurgy only. The biggest use is for cutting tools and cutting tool tips or inserts, but the cemented carbides are also used for small dies and some applications where wear resistance is important. The principal material used is tungsten carbide, although titanium carbide and tantalum carbide are also used. Some very useful production cutting tools are manufactured by using strong, tough materials as a core and impregnating the surface with titanium carbide or another hard, wear resistant material.

A further area in which powder metallurgy produces products not practical by other means is the manufacture of materials with controlled low density. One of the first mass-produced powder metallurgy products was sintered porous bronze bearings. After cold pressing, sintering, and sizing, the bearings are impregnated with oil, which in service is made available for lubrication. Although not true fluid film bearings, they provide long service with low maintenance. Porous materials are also useful as filters.

Composite electrical materials form a group similar to the cemented carbides. Tungsten and other refractory metals in combination with silver, nickel, graphite, or copper find wide applications as electrical contacts and commutator brushes; powder metallurgy not only provides a means for producing the combination but also provides the finished shape for the parts. Many of the currently used permanent magnetic materials are as well produced by powder metallurgy.

1.3.2 Manufacturing processes and related defects

1.3.2.1 Welding processes

Welding can be defined as the metallurgical method of joining, applied to the general problem of construction and fabrication. It consists of joining two pieces of metal by establishing a metallurgical atom-to-atom bond, as distinguished from a joint held together by friction or mechanical interlocking. This metallurgical atom-to-atom bond is achieved by the application of heat and sometimes pressure.

Many welding processes require the application of heat or pressure, or both, to produce a suitable bond between the parts being joined. The physics of welding deals with the complex

physical phenomena associated with welding, including heat, electricity, magnetism, light, and sound. In making a joint two parts of the same chemical composition may be welded together using no added metal to accomplish the joint. This might be termed as `autogenous' welding. A metal which is of the same composition as the parts being joined may be added, in which event, the process would come under the general heading `homogenous' welding. Finally, an alloy quite different from that of which the parts are made may be used or alternatively the parts themselves may differ significantly in composition. Then this process is called `heterogeneous' welding. Almost every imaginable high energy density heat source has been used at one time or another in welding. Externally applied heat sources of importance include arcs, electron beams, light beams (lasers), exothermic reactions (oxyfuel gas and thermit), and electrical resistance. Welding processes that acquire heat from external sources are usually identified with the type of heat source employed. The welding processes which are commonly used for the welding of metals are described and their features are discussed in the following sections.

Weld design and positions

The loads in a welded structure are transferred from one member to another through welds placed in the joints. The types of joints used in welded construction and the applicable welds are shown in Figure 1.26.

All welds that are encountered in actual construction, except groove welds in pipe, are classified as being flat, horizontal, vertical, or overhead. Groove welds in pipe are classified as horizontal rolled, horizontal fixed, vertical, or inclined fixed. These positions are illustrated in Figures 1.27 and 1.28 and explained below:

(i) Flat position (1G)– The test plates are placed in an approximately horizontal plane and the weld metal deposited from the upper side (Figure 1.27 (A)).

(ii) Horizontal position (2G)– The test plates are placed in an approximately vertical plane with the welding groove approximately horizontal (Figure 1.27 (B)).

(iii) Vertical position (3G)– The test plates are placed in an approximately vertical plane with the welding groove approximately vertical (Figure 1.27 (C)).

(iv) Overhead position (4G)– The test plates are placed in an approximately horizontal plane and the weld metal deposited from the underside (Figure 1.27 (D)).

(v) Horizontal rolled (1G)– the pipe is placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane and the pipe is rolled during welding (Figure 1.27 (A)).

(vi) Vertical (2G)– The pipe is placed with its axis in an approximately vertical position with the welding groove in an approximately horizontal plane (Figure 1.27 (B)).

(vii) Horizontal fixed (5G)– The pipe is placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane and the pipe is not to be rolled or turned during welding (Figure 1.27 (E)).

(viii) Inclined fixed (6G)– The pipe is inclined fixed (45° ± 5°) and not rotating during welding (Figure 1.27 (F)).

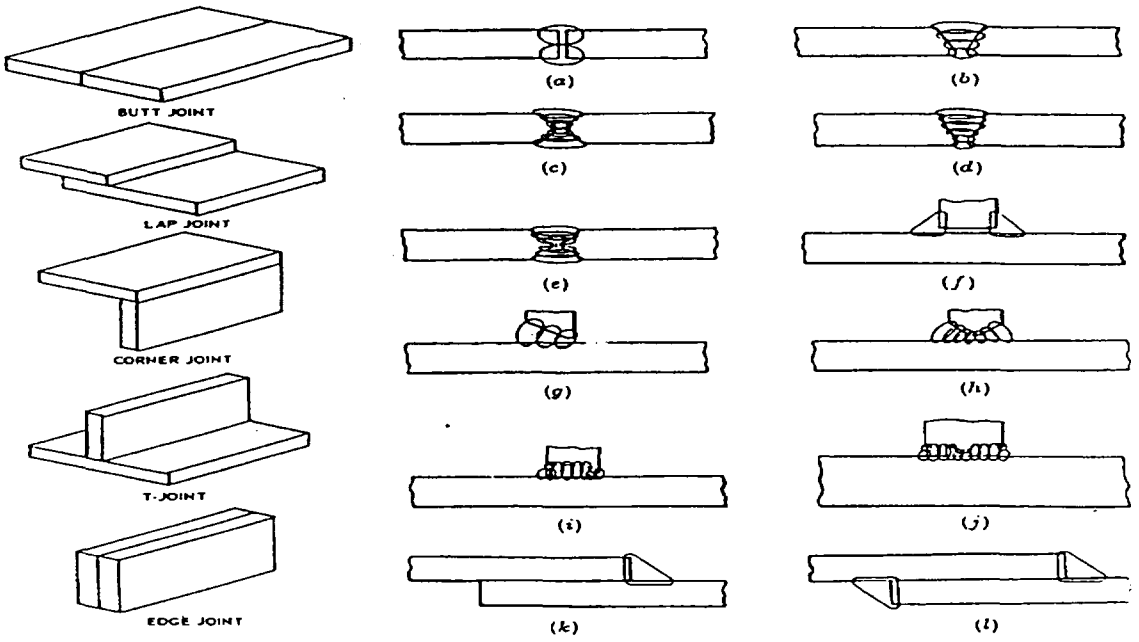


Figure 1.26 : Types of Welding joints; (a) square butt joint, (b) single-v butt joint, (c) double-v butt joint, (d) single-u butt joint, (e) double-u butt joint, (f) square-t joint, (g) single-bevel t-joint, (h) double-bevel t-joint, (i) single-u t-joint, (j) double-u t-joint, (k) single-bead lap joint, (l) double-bead lap joint.

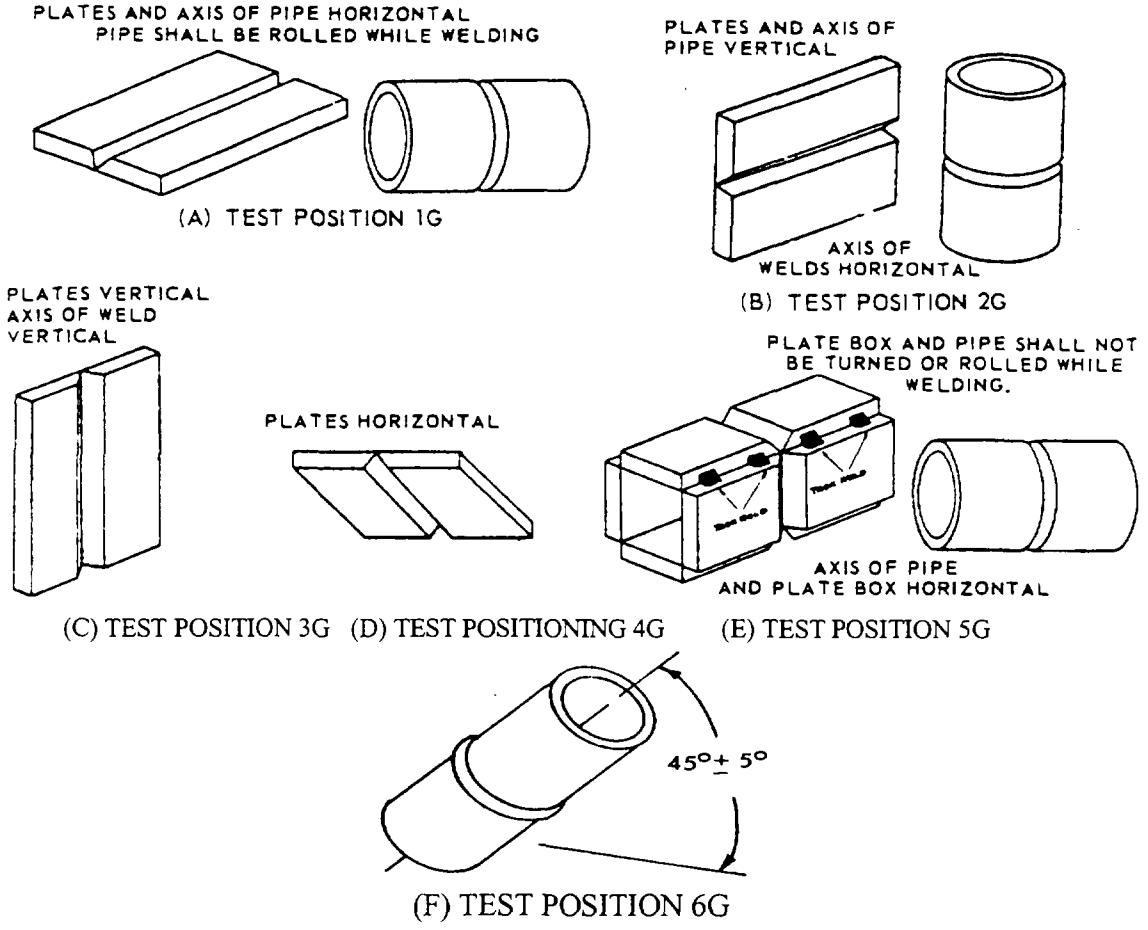


Figure 1.27 : Positions of plates and pipes for groove weld.

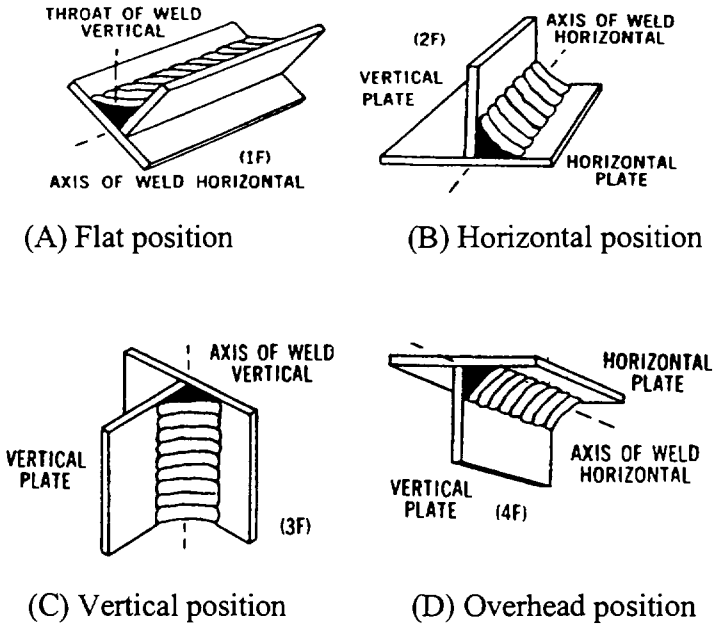
For fillet welds in plates, different positions are defined as below:

(i) Flat position (1F)– The test plates are so placed that each fillet weld is deposited with its axis approximately horizontal and its throat approximately vertical (Figure 1.28 (A)).

(ii) Horizontal position (2F)– The test plates are so placed that each fillet weld is deposited on the upper side of the horizontal surface and against the vertical surface (Figure 1.28 (B)).

(iii) Vertical position (3F)– Each fillet weld is made vertically (Figure 1.28 (C)).

(iv) Overhead position (4F)– The test plates are so placed that each fillet weld is deposited on the underside of the horizontal surface and against the vertical surface (Figure 1.28 (D)).



(A) Flat position (B) Horizontal position

(C) Vertical position (D) Overhead position

Figure 1.28 : Positions of plates for fillet welds.

Shielded metal arc welding (SMAW)

Shielded metal arc welding is an early arc welding process. It is one of the simple and versatile processes for welding ferrous and several non-ferrous base metals. Basically, it is a manual welding process in which the heat for welding is generated by an arc established between a flux covered consumable electrode and the work. The electrode tip, welded puddle, arc and adjacent areas of the work piece are protected from atmospheric contamination by a gaseous shield obtained from the combustion and decomposition of the flux covering. The process is illustrated in Figure 1.29.

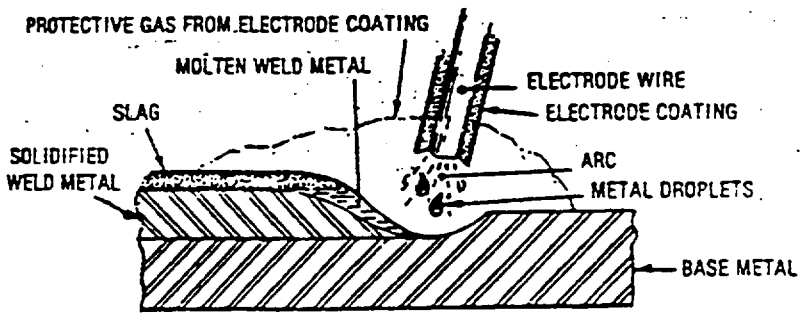


Figure 1.29 : Shielded metal arc welding process.

Covered electrodes are produced in a variety of diameters normally ranging from 1/16 to 5/16 in. (2 to 8 mm). The smaller diameters are used with low currents for joining thin sections and for welding in all positions. The large diameters are designed for conducting high currents to achieve greater deposition rates in the flat and horizontal positions. Special alloy filler metal compositions can be formulated with relative ease by the use of metal powders in the electrode coating.

The SMAW process has several advantages. Using the process, job shops can handle many welding applications with a relatively small variety of electrodes. Other advantages are the simplicity and lightness of the equipment, and its relatively low cost. Also, welds can be made in confined locations or remote from heavy power supplies.

Submerged arc welding (SAW)

In submerged arc welding the arc and molten metal are shielded by an envelope of molten flux and a layer of unfused granular flux particles as shown in Figure 1.30. When the arc is struck, the tip of the continuously fed electrode is submerged in the flux and the arc is therefore not visible. The weld is made without the intense radiation that characterizes an open arc process and with little fumes.

The SAW process is used in both mechanized and semiautomatic operations, although the former is by far more common. High welding currents can be employed to produce high metal deposition rates at substantial cost savings. Welds can only be made in the flat and horizontal positions.

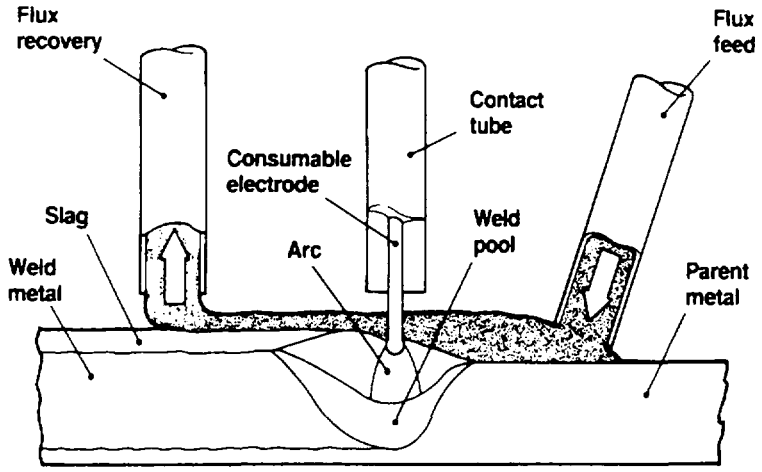


Figure 1.30 : Submerged arc welding process.

The process is most widely employed for welding all grades of carbon, low alloy, and alloy steels. Stainless steel and some nickel alloys are also effectively welded or used as surfacing filler metals with the process. Various filler metal-flux combinations may be selected to provide specific weld metal properties for the intended service. The flux may contain ingredients that when melted react to contribute alloying additions to the weld metal. Approximately one kilogram of flux is consumed for every kilogram of electrode used.

Gas metal arc and flux cored arc welding (GMAW & FCAW)

Gas metal arc welding (GMAW) and flux cored arc welding (FCAW) are two distinct processes, but they have many similarities in application and equipment. Both processes use a continuous solid wire or tubular electrode to provide filler metal, and both use gas to shield the arc and weld metal. In GMAW, the electrode is solid, and all of the shielding gas is (argon, helium) supplied by an external source, as shown in Figure 1.31.

The original gas metal arc process consisted of a continuous operation requiring high current densities to achieve a smooth transfer of molten metal.

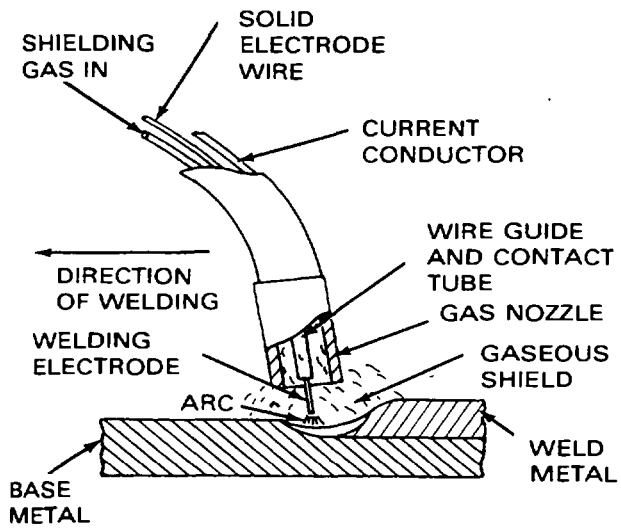


Figure 1.31 : Gas metal arc welding process.

The process permits welding with minimal spatter, uniform penetration, and good out-of-position capability. With FCAW, the electrode is tubular and contains core ingredients that may supply some or all of the shielding gas needed. This process may also use auxiliary gas shielding, depending on the type of electrode employed, the material being welded, and the nature of the welding involved. FCAW is illustrated in Figure 1.32.

Flux cored arc welding uses cored electrodes instead of solid electrodes for joining ferrous metals. The flux core may contain minerals, ferroalloys, and materials that provide shielding gases, deoxidizers, and slag forming materials. The additions to the core promote arc stability, enhance weld metal mechanical properties, and improve weld contour. Many cored electrodes are designed to be used with additional external shielding. Carbon dioxide-rich gases are the most common. Weld metal can be deposited at higher rates, and the welds can be larger and better contoured than those made with solid electrodes, regardless of the shielding gas.

Gas tungsten arc welding (GTAW)

Gas tungsten arc welding uses a non-consumable tungsten electrode which must be shielded with an inert gas. The arc is initiated between the tip of the electrode and work to melt the metal being welded, as well as the filler metal, when used. A gas shield protects the electrode and the

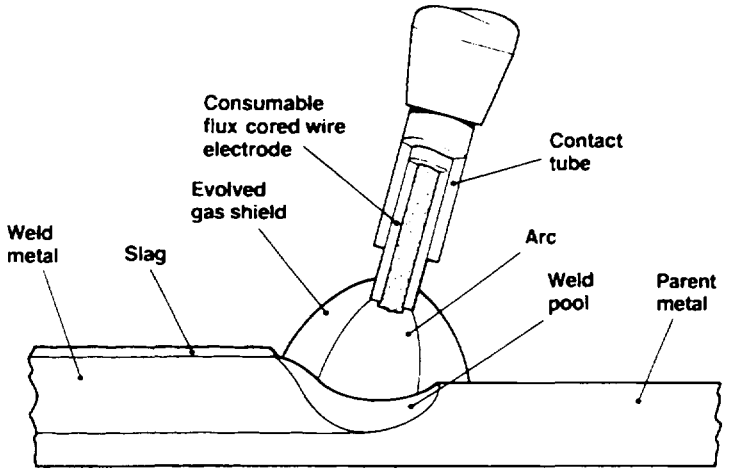


Figure 1.32 : Flux cored arc welding.

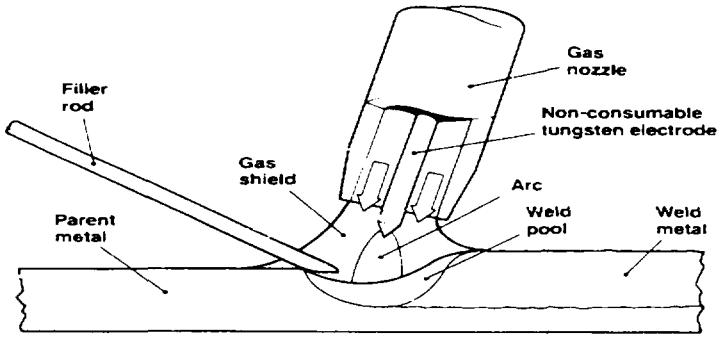


Figure 1.33 : Gas tungsten arc welding.

molten weld pool, and provides the required arc characteristics. This process is illustrated in Figure 1.33 and is also sometimes called TIG welding.

Several types of tungsten electrodes are used with this process. Thoriated and zirconiated electrodes have better electron emission characteristics than pure tungsten, making them more suitable for dc operations.

Electro-slag welding (ESW)

Electroslag welding is s specialized adaptation of submerged arc welding and it is used for joining thick materials in the vertical position. This process is illustrated in Figure 1.34. Strictly speaking it is not an arc welding process at all, because it actually depends on the electrical receptivity of a molten flux bath to produce the heat necessary to melt the filler and base metal.

The process is, however, initiated by an arc, which heats a layer of granular welding flux contained within water cooled moulding shoes or dams and the edges of the joint, thus turning it to a bath of molten slag. The arc is then extinguished, and the conductive slag maintained in a molten condition by its resistance to the electric current passing through from a consumable electrode to the work.

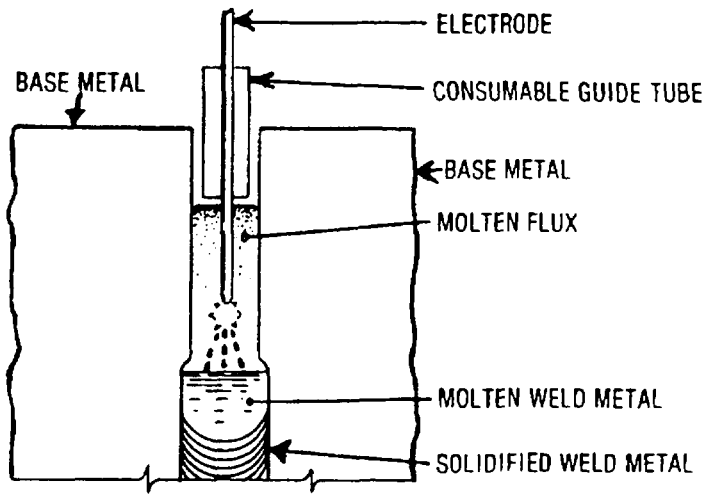


Figure 1.34 : Electroslag welding process.

The principal application of electroslag welding is welding of thick steel plate heavy forgings and large steel castings in the fabrication of machine bases and in the structural steel industry. Its main features are: (i) Extremely high metal deposition rates, (ii) ability to weld very thick materials in one pass, (iii) minimal joint preparation and fit-up requirements, (iv) little or no distortion and (v) low flux consumption.

Stud arc welding (SAW)

In stud welding, basically an arc welding process, the welding arc is generated between a metal stud or similar part and the part to which it is ultimately fused by the welding heat so generated (Figure 1.35). In a way it is also a variation of the shielded metal arc process, the stud representing the electrode. But only the end of the electrode is melted and it becomes a permanent part of the final assembly.

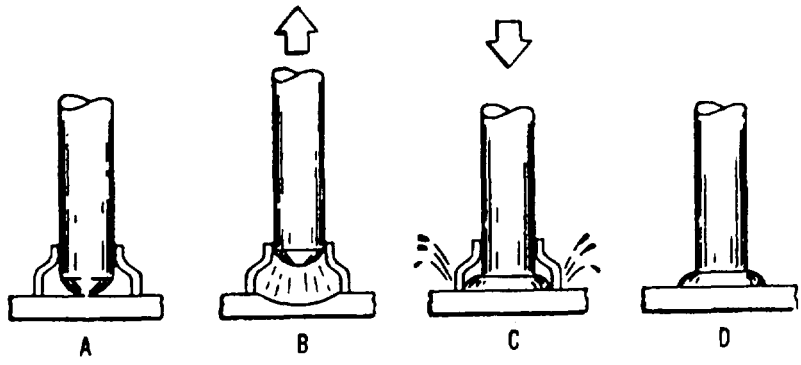


Figure 1.35 : Stud welding sequence.

In operation the stud is retained in a hand held or bench mounted gun and is positioned over the spot where it is to be attached. Upon initiation, current flows through the stud, which, at the same time, is lifted slightly, creating an arc. After a very short arcing period, the stud is plunged into the molten pool created on the base plate, and the gun is withdrawn.

Typical applications of stud welding include securing special lining in tanks, studding boiler tubes, assembling electrical panels, securing water, hydraulic, and electrical lines to buildings, vehicles and large appliances, and securing feet and handles to large appliances.

Plasma arc welding (PAW)

The plasma arc welding process provides a very stable heat source for welding most metals from 0.001 to 0.25 in. (0.02 to 6 mm). This process has advantages over other open arc welding processes, such as SMAW, GMAW, and GTAW, because it has greater energy concentration, improved arc stability, higher heat content, and higher welding speeds. As a result, PAW has greater penetration capabilities than SMAW, GMAW, and GTAW.

The basic elements of the plasma arc torch, illustrated in Figure 1.36, are the tungsten electrode and the orifice. A small flow of argon is supplied through the orifice to form the arc plasma. Shielding of the arc and weld zone is provided by gas flowing through an encircling outer nozzle assembly. The shielding gas can be argon, helium, or mixtures of argon with either hydrogen or helium. The plasma is initiated by an internal low current pilot arc between the electrode and the orifice. The pilot arc ionizes the orifice gas to ignite the primary arc between the electrode and the base metal. The arc plasma is constricted in size by the orifice around the electrode, and is called a transferred arc. If filler metal is used, it is fed into the arc as in the GTAW process.

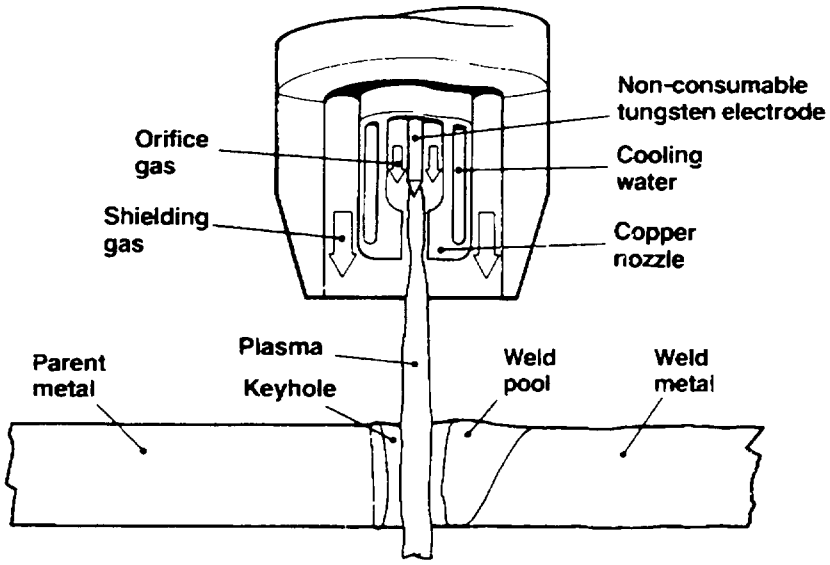


Figure 1.36 : Plasma arc welding.

Resistance welding (RW)

Resistance welding incorporates a group of processes in which the heat for welding is generated by the resistance to the flow of electrical current through the parts being joined. It is most commonly used to weld two overlapping sheets or plates which may have different thicknesses. A pair of electrodes conduct electrical current to the joint. Resistance to the flow of current heats the faying surfaces, forming a weld. These electrodes clamp the sheets under pressure to provide good electrical contact and to contain the molten metal in the joint. The joint surfaces must be clean to obtain consistent electrical contact resistance to obtain uniform weld size and soundness.

The main process variables are welding current, welding time, electrode force, and electrode material and design. High welding currents are required to resistance heat and melt the base metal in a very short time. The time to make a single resistance heat and melt the base metal is very short usually less than one second.

There are four major resistance welding processes, namely, spot welding (RSW), projection welding (RPW), flash welding (RFW), and seam welding (RSEW). These processes are illustrated in Figure 1.37. In RSW, the welding current is concentrated at the point of joining using cylindrical electrodes. Spot welds are usually made one at a time. In RPW, a projection or dimple is formed in one part prior to welding. The projection concentrates the current at the faying surfaces. Large, flat electrodes are used on both sides of the components to produce several welds simultaneously. As an example, a stamped bracket may have three or four projections formed in it so that it can be welded to a sheet with one welding cycle. In seam welding, electrodes in the form of rolls are used to transmit pressure and to send current through the overlapping sheet being moved between them. Flash welding is usually an automatic process. Parts are clamped in place by a welding operator who simply presses a button to start the welding sequence. The usual flash weld joins rods or bars end to end or edge to edge. The flashing action is continued until a molten layer forms on both surfaces. Then the components are forced together rapidly to squeeze out the molten metal. This produces a hot worked joint free of weld metal. The mechanical properties of flash welds are often superior to other types of welds.

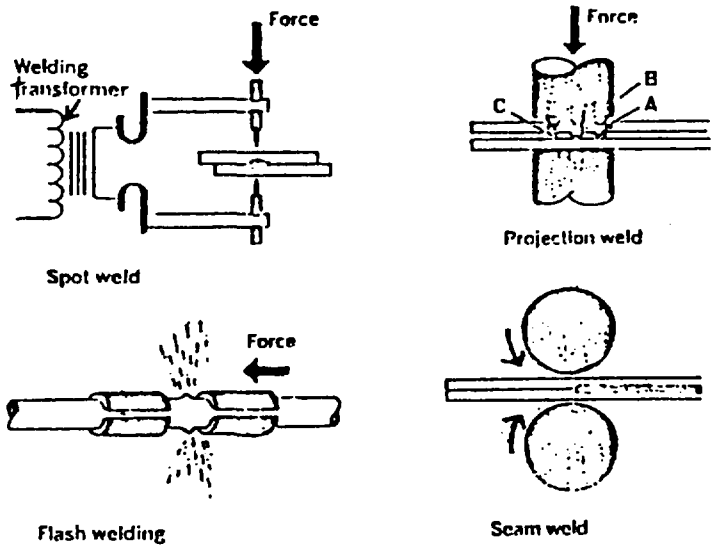


Figure 1.37 : Basic resistance welding methods.

Oxyfuel gas welding (OFW)

Oxyfuel gas welding includes a group of welding processes that use the heat produced by a gas flame or flames for melting the base metal and, if used, the filler metal. Oxyfuel gas welding is an inclusive term used to describe any welding process that uses a fuel gas combined with oxygen to produce a flame having sufficient energy to melt the base metal. The fuel gas and oxygen are mixed in the proper proportions in a chamber which is generally a part of the welding torch assembly. The torch is designed to give the welder complete control of the welding flame to melt the base metal and the filler metal in the joint. This process is illustrated in Figure 1.38.

Oxyfuel gas welding is normally done with acetylene fuel gas. Other fuel gases, such as methyl acetylene propadience and hydrogen, are sometimes used for oxyfuel gas welding of low melting metals. The welding flame must provide high localized energy to produce and sustain a molten weld pool. With proper adjustment, the flames can also supply a protective reducing atmosphere over the molten weld pool.

Oxyfuel gas welding can be used for joining thick plates, but welding is slow and high heat input is required. Welding speed is adequate to produce economical welds in sheet metal and thin-wall and small diameter piping. Thus, OFW is best applied on material of about 1/4 in. (6 mm) maximum thickness.

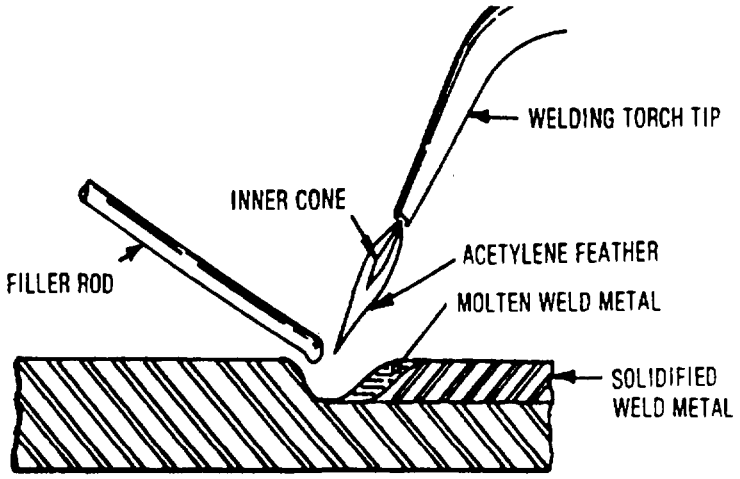


Figure 1.38 : Oxyfuel gas welding process.

Brazing process

Brazing is a metal joining process where the base metal is heated to a temperature of about 425°C. Non-ferrous filler metals, such as brass or silver alloys, are melted by the heat of the base metal and flow by capillary attraction between the closely fitted surfaces of the joint. Heat for brazing is usually applied by flame torches, furnaces, electric induction, electric resistance or dropping the work into a hot salt bath. Filler and flux are either applied manually or are replaced in the form of powder, metallic rings or strips.

Miscellaneous welding processes

There are number of other welding processes sometimes encountered. Some of the important ones of these processes are briefly discussed below:

Electron beam and laser welding

These methods are generally utilized for precision assemblies requiring high-quality welds. The procedure is conducted by focusing an electron beam or laser beam on the joint interface and causing melting and fusion of the metal. Beam welds require that the mating of the components to be welded be fitted closely since there is no filler metal. The weld joint is created by the

fusion of the material penetrated by the beam, therefore, the mating surface should be geometrically prepared so that they are in intimate contact over the entire joint surface.

Electron beam welds are usually made in a vacuum while laser welding is conducted using an inert gas surrounding the laser beam. At the present time, electron beam has the capability for welding thicker specimens (up to 200 mm in steel), but is limited by the size of the vacuum chamber.

Friction welding (FW)

In friction welding the heat for coalescence is produced by direct conversion of mechanical energy to thermal energy at the joint interface. The mechanical energy is generated by the sliding action between rotating or rubbing surfaces. The basic process involves holding a non-rotating workpiece in contact with a rotating workpiece under constant or gradually increasing pressure until the interface reaches welding temperature. The rotation is then stopped. It is a solid state process in which coalescence occurs at a temperature below the melting point of the metals being joined.

Ultrasonic welding (USW)

Ultrasonic welding is a form of friction welding that has long been used to join plastics. Recently, such high frequency vibration has been successfully applied to the welding of metals, mostly non-ferrous metals.

It is known as a cold bonding process, because atomic combination and diffusion occurs while materials are in a semisolid or solid state. Although some heating occurs, welding depends more on the cleaning action of the process than on material heating.

In practice the parts to be welded are clamped under pressure between an anvil and a tip connected to a horn that vibrates at a high frequency. The welding tip and anvil may be contoured to the shape of the parts. The part in direct contact with the tip is rubbed at a high frequency against the stationary part. This vibratory action first erodes oxides and other contaminants on the interface surfaces. Once they are clean the surfaces come into intimate contact, and solid state bonding takes place.

Ultrasonic welding is best suited for joining small parts, sheet and foil. The process is fast, requires no consumables, and, because of its low heat, the result of the processing eliminates the need for further cleaning. In some instances, even coated, painted and badly rusted surfaces can be effectively joined without surface preparation.

Weld defects and discontinuities

During the process of welding, discontinuities of various types may occur. These may be classified under the headings of procedure and process, design, and metallurgical behaviour. The groups should be applied loosely because discontinuities listed in each group may have secondary origins in other groups. Discontinuities related to process, procedure, and design are, for the most part, those that alter stresses in a weld or heat-affected zone. Metallurgical discontinuities may also alter the local stress distribution, and in addition, may affect the mechanical or chemical (corrosion resistance) properties of the weld and heat-affected zone.

Porosity

Molten weld metal has a considerable capacity for dissolving gases which come into contact with it, such as hydrogen, oxygen and nitrogen. As the metal cools its ability to retain the gases diminishes. For instance, in steel the oxygen reacts with the carbon to form carbon monoxide, which is given off as a gas. With the change from the liquid to the solid state, there is reduced solubility with falling temperature. This causes an additional volume of gas to be evolved at a time when the metal is becoming mushy and therefore incapable of permitting the gas to escape freely. Entrapment of the gas causes gas pockets and porosity in the final weld. The type of porosity within a weld is usually designated by the amount and distribution of the pores. Some of the types are classified as follows: (Figure 1.39).

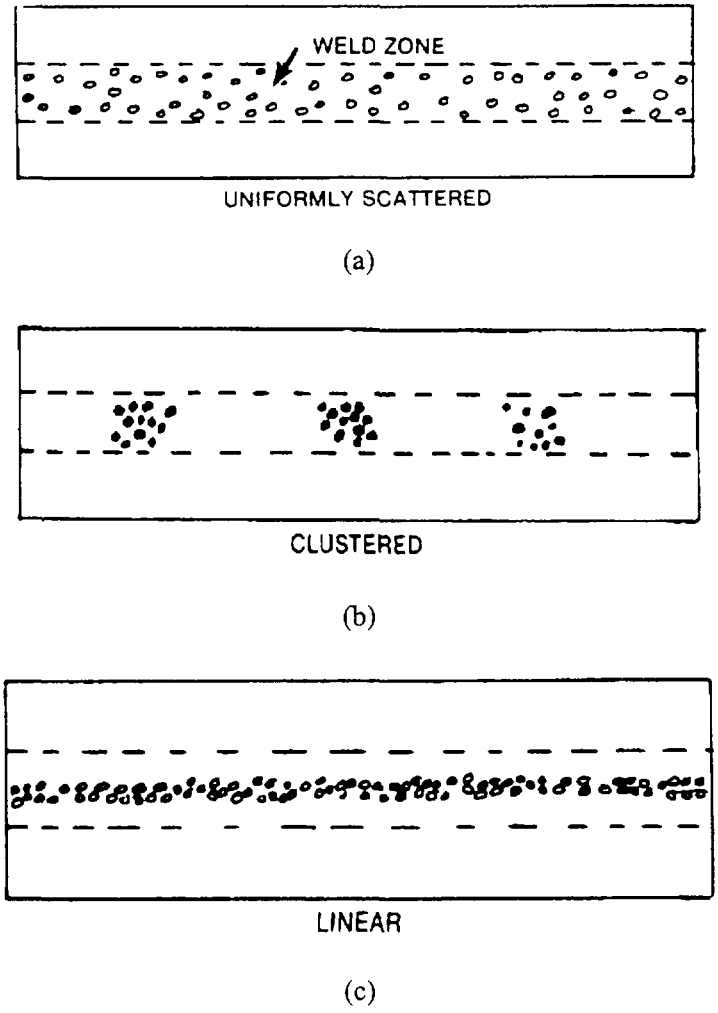


Figure 1.39: Three types of weld porosity.

The common causes of porosity, and suggested methods of preventing it, are summarized in Table 1.2.

Pipe or wormholes

Some gas inclusions have an elongated form known as pipes or wormholes. They are usually almost perpendicular to the weld surface. They can result from the use of wet powdered flux or

TABLE 1.2 : COMMON CAUSES AND REMEDIES OF POROSITY

Causes	Remedies
Excessive hydrogen, nitrogen, or oxygen in welding atmosphere	Use low-hydrogen welding process, filler metals high in deoxidizers; increase shielding gas flow
High solidification rate	Use preheat or increase heat input
Dirty base metal	Clean joint faces and adjacent surfaces
Dirty filler wire	Use specially cleaned and packaged filler wire, and store it in clean area
Improper arc length, welding current, or electrode manipulation	Change welding conditions and techniques
Volatilization of zinc from brass	Use copper-silicon filler metal; reduce heat input
Galvanized steel	Use E6010 electrodes and manipulate the arc heat to volatilize the zinc ahead of the molten weld pool
Excessive moisture in electrode covering or on joint surfaces	Use recommended procedures for baking and storing electrodes. Preheat the base metal
High sulphur base metal	Use electrodes with basic slagging reactions

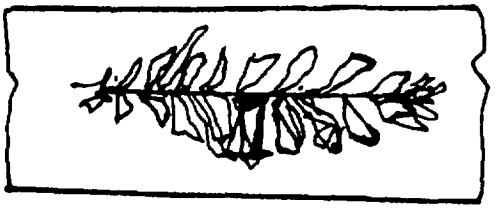


Figure 1.40 : Piping in weld.

from inadequate welding current. Another typical form of pipe has appearance of a branch of a tree (Figure 1.40). These can be caused by use of wet welding electrodes.

Non-metallic inclusions

These may be the result of weld-metal contamination by substances on the surface of the joint or by the atmosphere. But the usual source is the slag formed by the electrode covering or flux used in the welding process. Some slag may be trapped in the deposited metal during its

solidification, particularly if the metal fails to remain molten for a sufficient period to permit the slag to rise to its surface. In multi-pass welding, insufficient cleaning between weld passes can leave a portion of the slag coating in place to be covered by subsequent passes. A particular characteristic of slag inclusions is the 'slag line', intermittent or continuous. Such slag lines are often accompanied by a pronounced lack of fusion to the base metal. In general inclusions may be due to any one of several reasons which include failure to clean the surface of the joint, failure to remove slag from a previous deposit, incorrect edge preparation, incorrect manipulation of the electrode and insufficient arc shielding. The common causes and remedies of inclusion-type discontinuities are shown in Table 1.3.

TABLE 1.3 : COMMON CAUSES AND REMEDIES OF SLAG INCLUSIONS

Causes	Remedies
Failure to remove slag	Clean the surface and previous weld bead
Entrapment of refractory oxides	Power wire brush the previous weld bead
Improper joint design	Increase groove angle of joint
Oxide inclusions	Provide proper gas shielding
Slag flooding ahead of the welding	Reposition work to prevent loss of slag control
Poor electrode manipulative technique	Change electrode or flux to improve slag control
Entrapped pieces of electrode covering	Use undamaged electrodes

Tungsten inclusions

Tungsten inclusions are particles of metallic tungsten embedded in the weld metal which originate from the tungsten electrode used in tungsten arc welding. Causes are excessive welding current allowing the melting and deposition of tungsten in the weld and incorrect polarity of electrode using a d.c. source. Tungsten inclusions can also be caused from dipping the electrode into the molten weld metal or by touching the filler rod to the electrode during welding. Tungsten inclusions frequently occur at the start of welds when the electrode may be cold. Small globular and widely scattered tungsten inclusions are sometimes permissible, but sharp edged inclusions are dangerous.

Lack of fusion

This is due to the lack of union in a weld between the weld metal and parent metal or between parent metal and parent metal or between weld metal and weld metal. Consequently the lack of fusion can be of three types namely lack of side fusion, lack of root fusion and lack of inter-run fusion. The defect results mainly from the presence of slag, oxides, scale, or other non-metallic substances, too low a welding current or incorrect edge preparation. Incomplete fusion can also arise from too high a welding current when the high melt rate encourages the welder to use excessive welding speed. The defect reduces considerably the strength of a joint subjected to

TABLE 1.4 : COMMON CAUSES AND REMEDIES OF INCOMPLETE FUSION

Causes	Remedies
Insufficient heat input, wrong type or size of electrode, improper joint design, or inadequate gas shielding	Follow correct welding procedure specification
Incorrect electrode position	Maintain proper electrode position
Weld metal running ahead of the arc	Reposition work, lower current, or increase weld travel speed
Trapped oxides or slag on weld groove or weld face	Clean weld surface prior to welding

static loading, and under cyclic or shock loading it is quite serious. The causes and remedies for incomplete fusion are summarized in Table 1.4.

Incomplete root penetration

In butt welding, a root opening is usually left at the bottom of the groove (in one-side welding) or at the centre of the weld (in two-side welding). If the opening between the two plates is narrow, it is difficult to achieve complete penetration and fusion at the root of the weld. Therefore there can be a lack of fusion in the root of the weld or a gap left by the failure of the weld metal to fill the root of a butt weld (Figure 1.41). It is caused by the electrode held at an incorrect angle, an electrode too large in diameter, a rate of travel too fast, an insufficient welding current, or an improper joint preparation (e.g. joint misalignment).

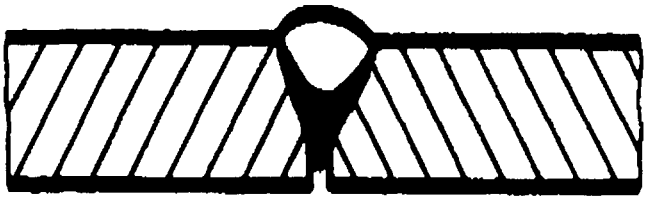


Figure 1.41 : Incomplete root penetration.

Cracks

Cracks are linear ruptures of metal under stress. Although sometimes wide, they are often very narrow separations in the weld or adjacent base metal (see Table 1.5).

Cracks can occur in a wide variety of shapes and types and can be located in numerous positions in and around a welded joint (Figure 1.42).

Cracks associated with welding may be categorized according to whether they originate in the weld itself or in the base metal. Four types commonly occur in the weld metal, i.e. transverse, longitudinal, crater and hat cracks. Base-metal cracks can be divided into seven categories, namely, transverse cracks, lamellar tearing, delaminations and fusion-line cracks.

(a) Transverse cracks

In the weld metal, these are formed when the predominant contraction stresses are in the direction of the weld axis (No. 2 in Figure 1.42). They can be hot cracks, which separate

TABLE 1.5 : COMMON CAUSES AND REMEDIES OF CRACKING

Causes	Remedies
Highly rigid joint	Preheat; relieve residual stresses mechanically; minimize shrinkage stresses using backstep or block welding sequence
Excessive dilution	Change welding current and travel speed; weld with covered electrode negative, butter the joint faces prior to welding
Defective electrodes	Change to new electrode; bake electrodes to remove moisture
Poor fit-up	Reduce root opening; build up the edges with weld metal
Small weld bead	Increase electrode size; raise welding current; reduce travel speed
High sulfur base metal	Use filler metal low in sulfur
Angular distortion	Change to balanced welding on both sides of joint
Crater cracking	Fill crater before extinguishing the arc; use a welding current decay device when terminating the weld bead
Hydrogen in welding atmosphere	Use low-hydrogen welding process; preheat and hold for 2 h after welding or postweld heat treat immediately
Hot cracking	Use low heat input; deposit thin layers; change base metal
Low ductility	Use preheat; anneal the base metal
High residual stresses	Redesign the weldment; change welding sequence; apply intermediate stress-relief heat treatment
High hardenability	Preheat; increase heat input; heat treat without cooling to room temperature
Brittle phases in the microstructure	Solution heat treat prior to welding

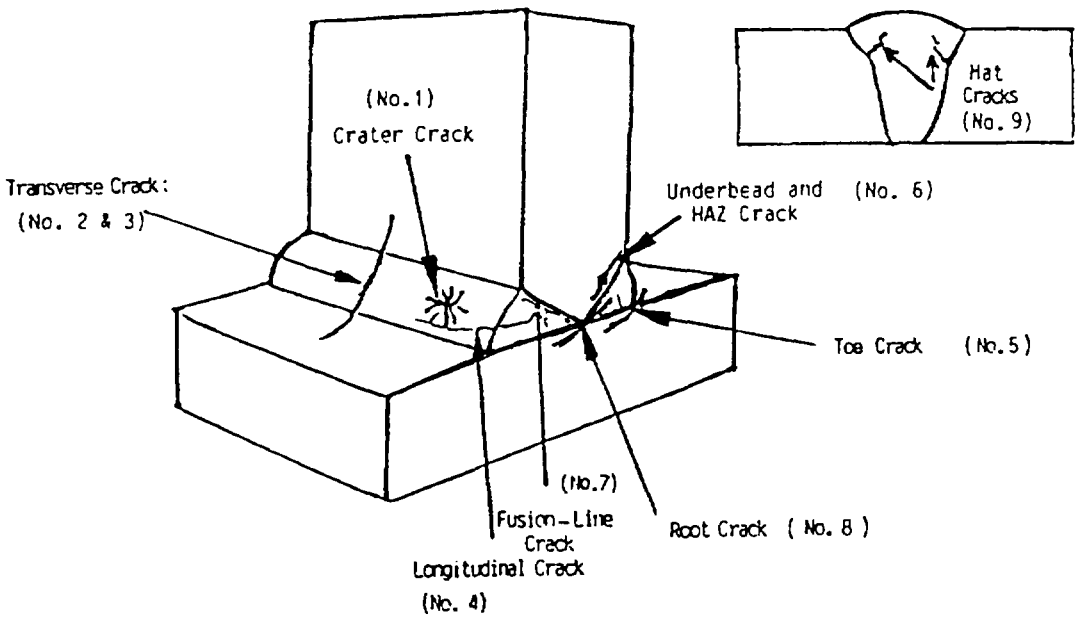


Figure 1.42 : Different types of cracks located in and around a welded joint.

intergranularly as a result of hot shortness or localized planar shrinkage, or they can be transgranular separations produced by stresses exceeding the strength of the material. Transverse cracks lie in a plane normal to the axis of the weld and are usually open to the surface. They usually extend across the entire face of the weld and sometimes propagate into the base metal.

Transverse cracks in base metal (No. 3 in Figure 1.42) occur on the surface in or near the heat-affected zone. They are the result of the high residual stresses induced by thermal cycling during welding. High hardness, excessive restraint, and the presence of hydrogen promote their formation. Such cracks propagate into the weld metal or beyond the heat affected zone into the base metal.

(b) Underbead cracks

These are similar to transverse cracks in that they form in the heat-affected zone because of high hardness, excessive restraint, and the presence of hydrogen. Their orientation follows the contour of the heat-affected zone (No. 6 in Figure 1.42).

(c) Longitudinal cracks

These cracks may exist in three forms, depending on their position in the weld (No. 4 in Figure 1.42). Check cracks are open to the surface and extend only partway through the weld. Root cracks extend from the root to some point within the weld. Full centreline cracks may extend from the root to the face of the weld metal.

Check cracks are caused either by high contraction stresses in the final passes applied to a weld joint or by a hot-cracking mechanism.

Root cracks are the most common form of longitudinal weld-metal cracks because of the relatively small thickness and size of the root pass. If such cracks are not removed, they can propagate through the weld as subsequent passes are applied. This is the usual mechanism by which full centreline cracks are formed.

Centreline cracks may occur at either high or low temperatures. At low temperatures, cracking generally is the result of poor fit-up, overly rigid fit-up, or a small ratio of weld metal to base metal.

All three types of longitudinal cracks usually are oriented perpendicular to the weld face and run along the plane that bisects the welded joint. Seldom are they open at the edge of the joint face, because this requires a fillet weld with an extremely convex bead.

(d) Crater cracks

As the name implies, crater cracks occur in the weld crater formed at the end of a welding pass (No. 1 in Figure 1.42). Generally, this type of crack is caused by failure to fill the crater before breaking the arc. When this happens, the outer edges of the crater cool rapidly, producing stresses sufficient to crack the interior of the crater. This type of crack may be oriented longitudinally or transversely, or may occur as a number of intersecting cracks forming the shape of a star. Longitudinal crater cracks can propagate along axis of the weld to form a centreline crack. In addition, such cracks may propagate upward through the weld if they are not removed before subsequent passes are applied.

(e) Hat cracks

These cracks derive their name from the shape of the weld cross section with which they are usually associated. This type of weld flares out near the weld face, resembling an inverted top hat (No. 9 in Figure 1.42). Hat cracks are the result of using excessive voltage or too low a welding speed. The cracks are located about halfway up through the weld and extend into the weld metal from the fusion line of the joint.

(f) Toe and root cracks

These cracks occur in the root area of the weld or near the boundary between the weld metal and the parent metal (Nos. 5 and 8 in Figure 1.42).

Undercut

During the final or cover pass the exposed upper edges of the beveled weld preparation tend to melt and to run down into the deposited metal in the weld groove. The result is a groove which may be either intermittent or continuous, with more or less sharp edges along the weld reinforcement (Figure 1.43).

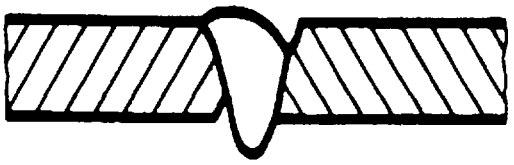


Figure 1.43 : Undercut.

Concavity at the root of the weld

A concave surface at the root of the weld can occur specially in pipe welding (without a cover pass on the root side). Root concavity is commonly produced by the flux cored arc welding (FCAW) process. In overhead welding this condition is a consequence of gravity which causes the molten metal to sag away from the inaccessible upper surface of the weld. It can also occur in downhand welding with a backing strip at the root of the weld groove if slag is trapped between the molten metal and the backing strip (Figure 1.44).

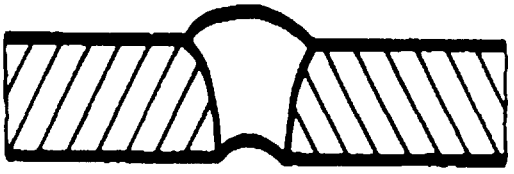


Figure 1.44 : Root concavity.

Excessive penetration

In welds molten metal sometimes runs through the root of the weld groove producing an excessive reinforcement at the back side of the weld. In general this is not continuous but has an irregular shape with characteristic hanging drops of excess metal (Figure 1.45).

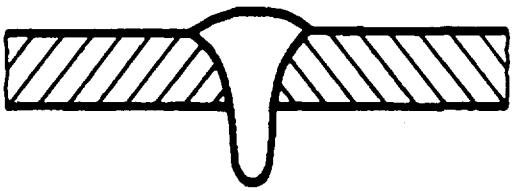


Figure 1.45 : Excessive penetration.

Overlap

Overlap is an imperfection at the toe or root of a weld caused by an overflow of weld metal onto the surface of the parent metal, without fusing with the latter (Figure 1.46). It is caused when the welding rod has been used at an incorrect angle, the electrode has travelled too slowly, or the current was too low.

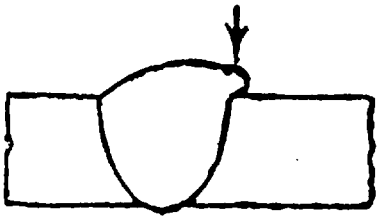


Figure 1.46 : Overlap.

Lamellar tearing

This is a phenomenon that occurs in T-joints where the web plate is welded on both sides with usually full penetration welds. The stresses developed by this configuration result in a separation that takes place in the base metal between the roots of the two welds extending in a plane parallel to the surface of the base metal. Such a discontinuity is often associated with laminations or other planes of weakness in the metal. It is characterized by a step-like tear and caused by the shrinkage of the weld bead stressing the base metal through its thickness. This results initially in decohesion of non-metallic inclusions and then ductile tearing at about 45° between adjacent non-metallic inclusions to produce the step-like tears. Lamellar tearing can occur outside the heat affected zone 5-10 mm below the fusion face (Figure 1.47).

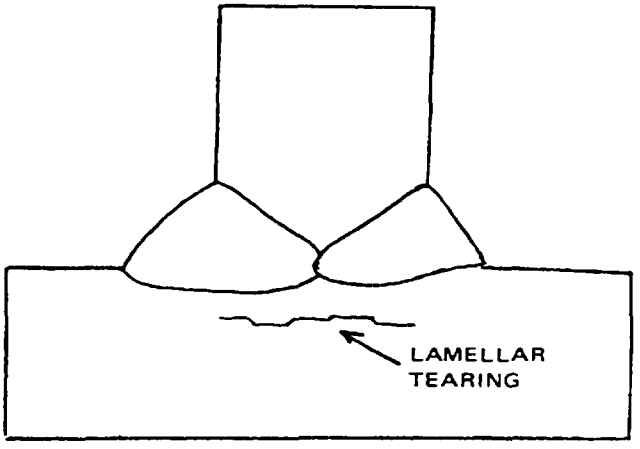


Figure 1.47 : Lamellar tearing.

Burn through

A burn through area is that portion of the weld bead where excessive penetration has caused the weld pool to be blown into the pipe or vessel. It is caused by the factors, such as high current, slow rod speed, incorrect rod manipulation, etc., that produce excessive heat in one area. It is often accompanied by excessive drop through of the metal on the inside of the pipe (Figure 1.48).

Figure 1.48 : Burn through.

Root pass oxidation

Oxidation is the result of insufficient protection of the weld and heat affected zone from the atmosphere. Severe oxidation will occur on stainless steels, for example, reducing corrosion resistance, if the joint is not purged with an inert gas.

1.3.2.2 Forging processes

Forging is the working of metal into a useful shape by hammering or pressing and is the oldest of the metal forming processes. Most forging operations are carried out hot, although some metals are cold-forged. The hot working of metals in the forging process results in an improvement in the mechanical properties. This method of shaping is therefore used in the manufacture of parts requiring good mechanical properties. Improvement in the mechanical properties results from a general consolidation of the metal and closing of gas and contraction cavities by means of mechanical pressure, a refinement of the crystal structure and a destruction of the continuity of intergranular concentrations of impurities and inclusions.

Forging is done on either a hammer or a press. A horizontal press (forging machine) is used in certain instances for forging small parts; otherwise forging machines are vertical, the lower die of which is fixed while the upper die is moveable, being carried on a vertical ram. In the case of hammers the die is raised mechanically and the blow is struck by the die falling freely (Figure 1.49).

Forging may be considered under two categories. First where the working surface of the dies is flat or of uniform curved contour and shaping is done by manipulation using tools of simple shape. This is called `open-die' forging. The second is where impression dies are used and the metal is shaped by being forced into the die impressions. This is called `closed-die' forging. In the first category are forgings of simple, round or rectangular cross-section and forgings of more complicated shapes which are so large that `sinking' of closed dies would be impractical or too costly. Small forgings of complicated final shape may be rough forged on simple dies and then machined to final form if the number required is too small to justify the cost of an impression die. In this category also are hollow forged parts. For these, the centre metal of the rough piece of proper size is either machined out cold (trepanned), or is punched out hot using suitable dies on a press. The part is then forged on a mandrel passing through the centre hole and supported at both ends so that the mandrel acts as the bottom die. In closed die forging on a hammer or vertical press the lower die has an impression corresponding to one half of the part to be made

while the upper die has an impression corresponding to the other half. For relatively simple shapes the dies may have only one impression but more commonly they incorporate a series of impressions in which the part is successively shaped to the final form. Closed die forging is commonly known as 'drop forging'. Around the impressions the dies are shaped to provide space for the excess stock, as it is not practical to have exactly the amount of metal required to fill the impressions. The excess metal that is forced into this space is referred to as 'flashing' or 'flash'. After forging this is trimmed off in suitable dies. The closed die forging business (Figure 1.50) is so competitive that the losses in trim scrap provide one of the most important areas for economy.

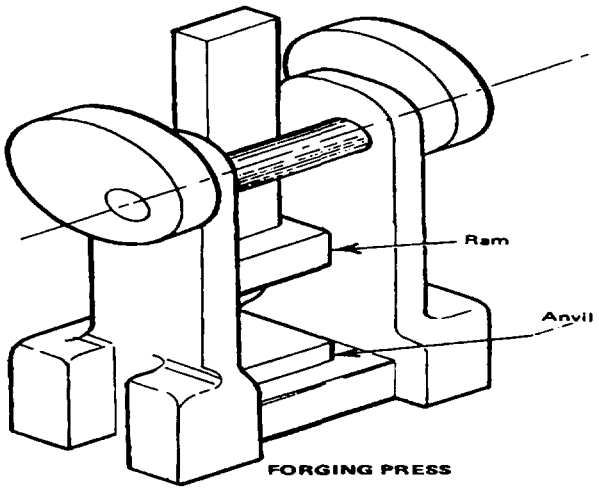


Figure 1.49 : Vertical forging press.

The hot forging process whereby bolts, for example, are headed is referred to as hot upset forging or hot heading. In this process, a bar of uniform cross section is gripped between grooved dies and pressure is applied on the end in the direction of the axis of the bar by means of a heading tool. The metal flows under the applied pressure and fills the cavity between the dies.

1.3.2.3 Rolling processes

The flattening of metal between rollers is used for the production of strip, sheet, plate, bar and sections. Since the metal is formed by a squeezing action, rolling can be considered as a continuous forging process with the rolls acting as hammers and the metal being drawn down.

Rolling may be performed above the temperature of recrystallisation (hot rolling) or below the temperature of recrystallisation (cold rolling). Hot rolling is always used for the initial rolling of the cast ingot. Not only is it easier to break down the ingot to size quickly when it is hot and plastic, but the hot-rolling process closes any casting discontinuities and forge welds their surfaces together. This prevents any faults, which could lead to lamination, being carried forward into subsequent rolling operations. In hot rolling the coarse grains are first elongated and distorted and then formed into equi-axed crystals due to recrystallisation. The crystals elongated and distorted by cold rolling do not recrystallise and the metal therefore remains work-hardened.

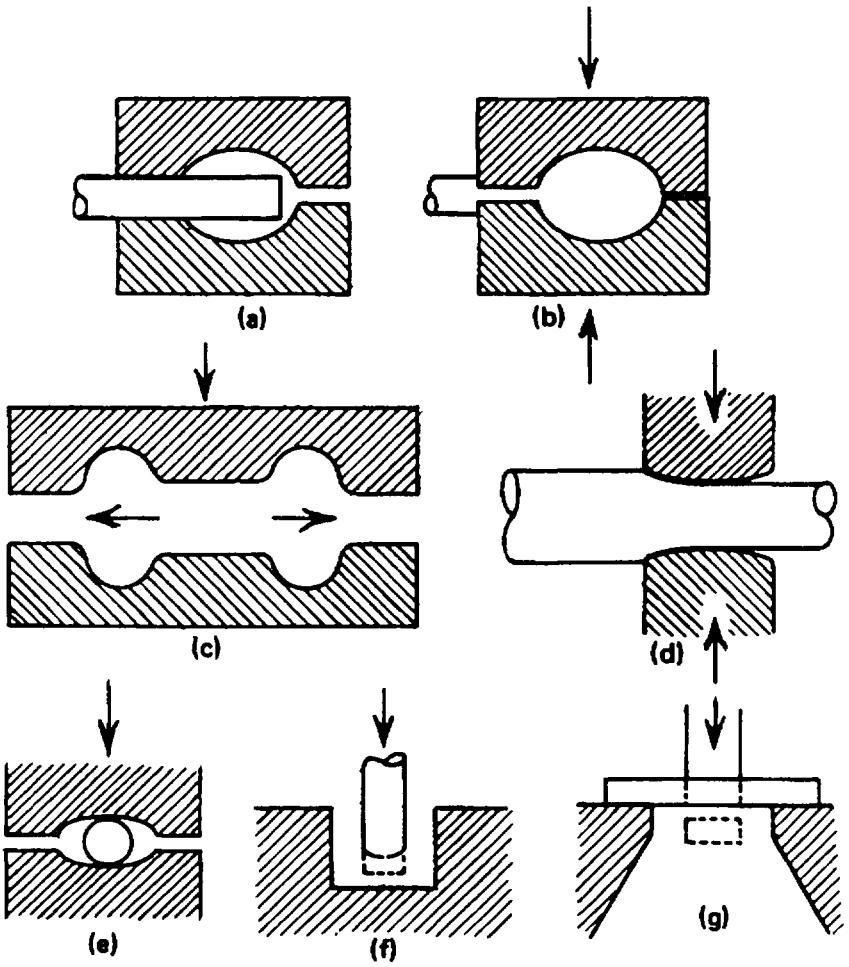


Figure 1.50 : Forging operations; (a,b) edding; (c) fullering; (d) drawing, (e) swaging, (f) back extruding; (g) punching.

Rolling mills are described according to the arrangement of the rolls. The simplest is the two-high reversing mill (Figure 1.51 b). In this the metal is passed through from one side, the rolls are then lowered and their direction of rotation is reversed, and the metal is passed back through them. This cycle is repeated until the metal is of the required thickness. In the three-high mill (Figure 1.51 c) the rolls rotate continuously in one direction. The roller beds rise and fall to pass the metal between the lower two rolls first and then back again between the upper two rolls. The cycle is repeated until the metal is of the required thickness. In the four-high mill (Figure 1.51 d) and the cluster mill (Figure 1.51 e) the additional rolls `back-up' the working rolls and allow them to apply greater pressure on the metal being rolled without deflection. Four-high and cluster mills operate in the same manner as the two-high reversing mill, and are widely used for cold rolling bright finished strip. Some typical rolling-mill processes are slabbing, cogging and re-rolling. Slabbing is the process of breaking down the ingot into slabs ready for re-rolling into strip, sheet and plate. The process is carried out at 1300°C and casting discontinuities in the ingot are welded by the process thus making the slab homogeneous. Cogging is similar to slabbing except that the ingot is rolled into 'blooms' ready for re-rolling into bars and sections. Two-high and four-high reversing mills are usually used for rolling both slabs and blooms. The re-rolling of slabs into strip is usually performed in a continuous strip mill. The slab is reheated to 1300 °C and passed through a water spray and scale-breaking rolls to remove the scale left on the surface of the slab from previous processing. It is then roughed down, and finally passed to the finishing `train' of rolls. The strip is finally coiled ready for further processing. The re-rolling

of sections and bars is usually performed in two-high reversing mills fitted with grooved rolls. Some modern plants handling large quantities of standard section beams and joints are often laid out to provide a continuous train (Figure 1.52).

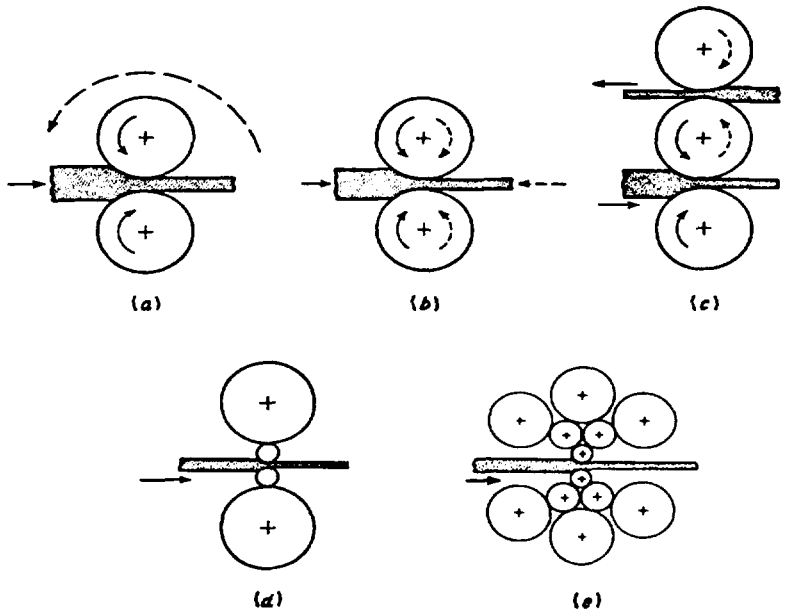


Figure 1.51 : Typical arrangements of rolls for rolling mills; (a) Two-high pullover, (b) two-high reversing, (c) three-high, (d) four-high, (e) cluster.

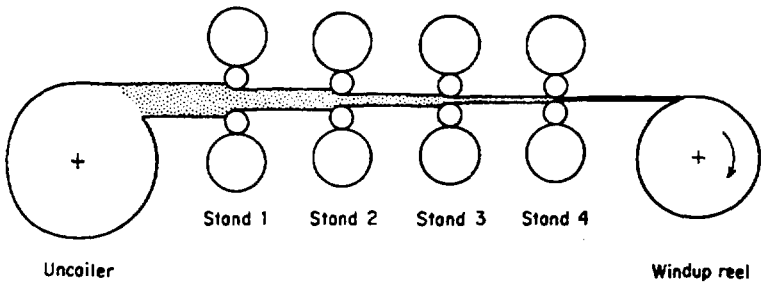


Figure 1.52 : Schematic drawing of strip rolling on a four-stand continuous mill.

Whilst materials that are forged into wire and tube require the property of malleability, materials that are drawn into wire and tube require the property of ductility, combined with a relatively high tensile strength and a low work-hardening capacity as the process is performed cold. The reduction in size of the drawn section is provided by the material being pulled through a die. Rods and bars are drawn using draw-benches (Figure 1.53).

Fine wire, especially the copper wire used for electrical conductors, is drawn on multiple-die machines. A capstan block pulls the wire through each die and passes it onto the next stage in the machine. As the wire becomes finer its length increases and the speed of the last capstan has to be very much higher than the first (Figure 1.54).

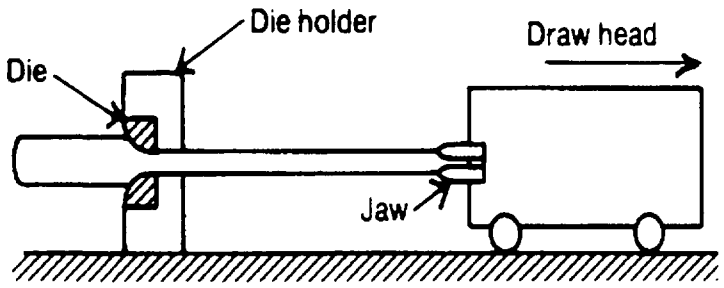


Figure 1.53 : Schematic drawing of a drawbench.

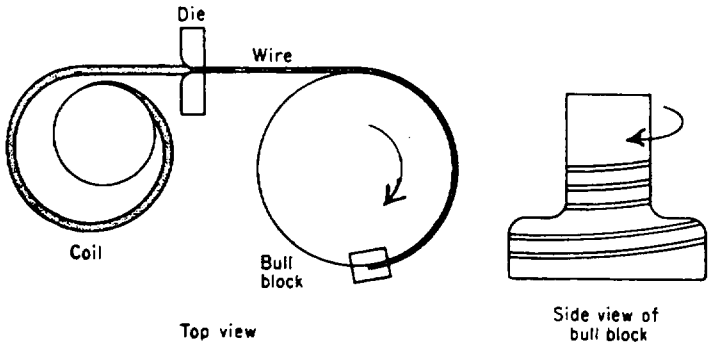


Figure 1.54 : Schematic wiredrawing equipment.

Tube drawing is similar to rod drawing using a draw bench. However, the billet is pierced to start the hole and the tube is drawn over a mandrel. Where longer lengths of tube are required, the stock and the drawn tube have to be coiled. This prohibits the use of a fixed mandrel, and a floating mandrel or plug is used.

1.3.2.4 Extrusion processes

Another process which is similar to rolling is extrusion. In principle, extrusion is similar to squeezing toothpaste from a toothpaste tube. The raw material is a heated cast billet of the required metal. Usually this is either a copper alloy, an aluminium alloy or lead. The pressure necessary to force the metal through the die is provided by the hydraulic ram. Since the billet is reduced to the size of the finished section in one pass through the die, extrusion is a highly productive process. However, the plant is extremely costly and so is its operation and maintenance. Like most hot processes the finish and dimensional accuracy of the section is lower than that associated with cold drawing. Therefore, where greater accuracy is required, the extruded section is given a light draw to strengthen the section and finish, and improve its dimensional accuracy (Figure 1.55 a & b).

The Mannesmann mills, plug rolling mills, three-roll piercing mills, and reeling mills are also used for producing seamless pipe and tubing (Figure 1.56). The Mannesmann mill (Figure 1.56 a) is used extensively for the rotary piercing of steel and copper billets. The process employs two barrel-shaped driven rolls which are set at an angle to each other. An axial thrust is developed as well as rotation to the billet. Because of the low arc of contact with the billet, tensile stresses develop along the axis of the billet. This assists in opening up the center of the billet as it flows around the piercing point to create the tube cavity. Piercing is the most severe

hot-working operation customarily applied to metals. The Mannesmann mill does not provide sufficiently large wall reduction and elongation to produce finished hot-worked tubes. Various types of plug rolling mills which drive the tube over a long mandrel containing a plug (Figure 1.56 b) have been widely adopted. This has led to the development of three-roll piercing machines (Figure 1.56 c) which produce more concentric tubes with smoother inside and outside surfaces than the older Mannesmann design. A reeling mill (Figure 1.56 d) which burnishes the outside and inside surfaces and removes the slight oval shape is usually one of the last steps in the production of pipe or tubing.

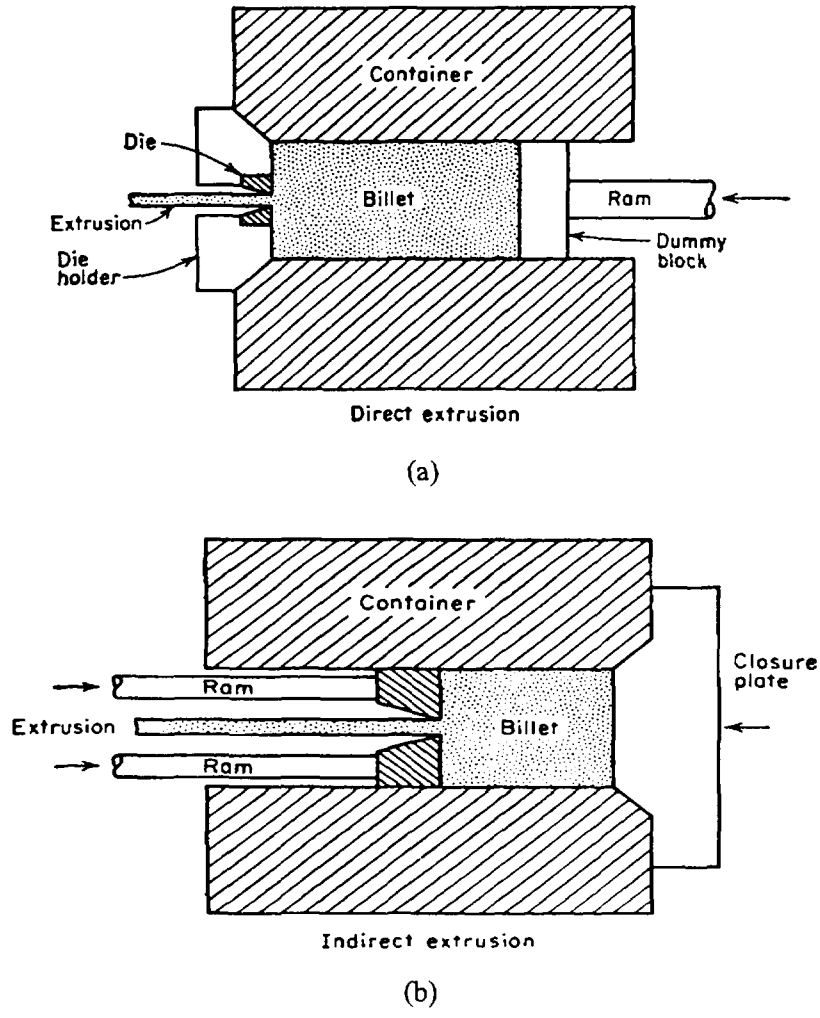


Figure 1.55 : Types of extrusion

1.3.2.5 Spinning processes

A method of making tank heads, television cones, and other deep parts of circular symmetry is called spinning (Figure 1.57 a). The metal blank is clamped against a form block which is rotated at high speed. The blank is progressively formed against the block, either with a manual tool or by means of small diameter work rolls. In the spinning process the blank thickness does not change but its diameter is decreased. The shear spinning process (Figure 1.57 b) is a variant of conventional spinning. In this process the part diameter is the same as the blank diameter but the thickness of the spun part is reduced according to $t = t_0 \sin \alpha$. This process is also known as power spinning, flowturning, and hydrospinning. It is used for large axisymmetrical conical or curvilinear shapes such as rocket-motor casings and missile nose cones.

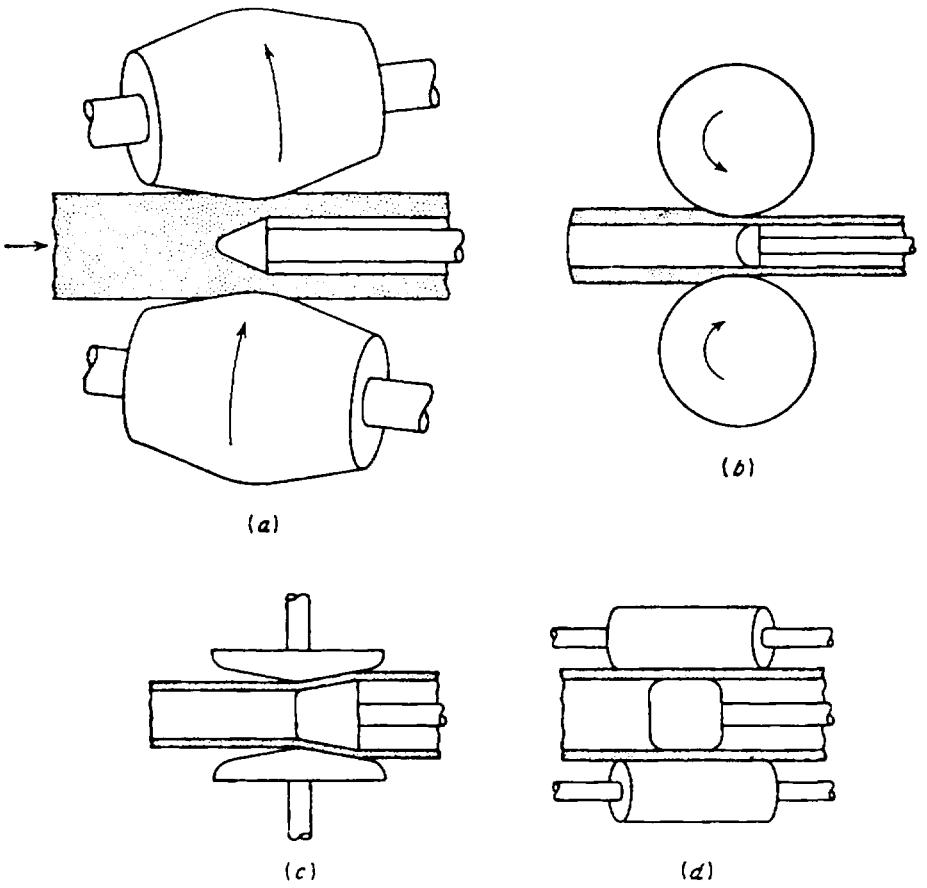


Figure 1.56 : (a) Mannesmann mill, (b) plug rolling mill, (c) three-roll piercing mill, (d) reeling mill.

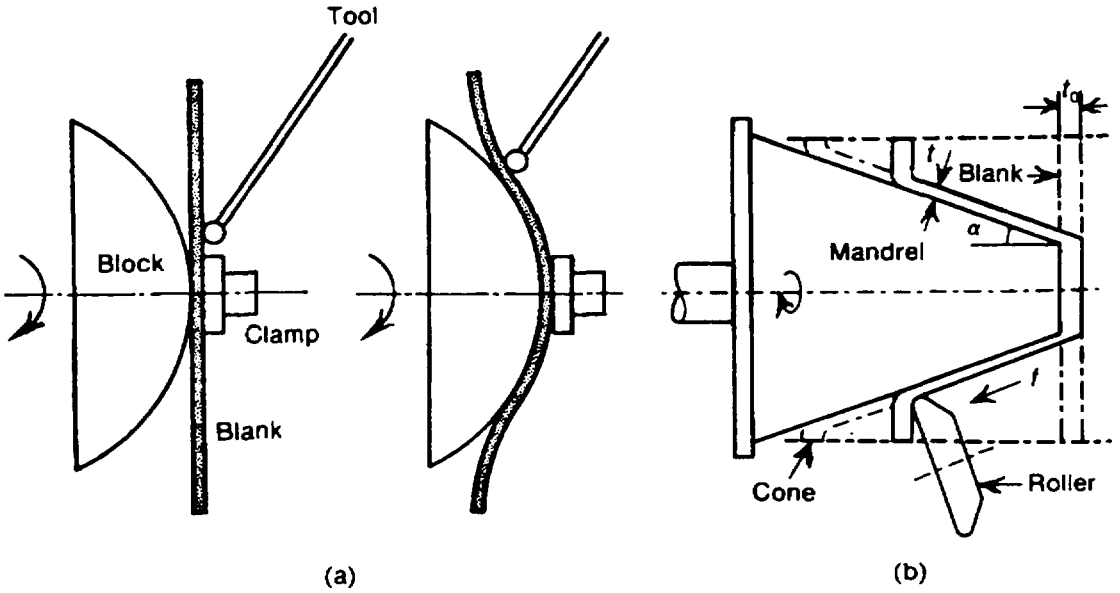


Figure 1.57 : Schematic representation of spinning processes; (a) manual spinning, (b) shear spinning

1.3.2.6 Shearing and blanking

Shearing is the separation of metal by two blades moving as shown in Figure 1.58. In shearing, a narrow strip of metal is severely plastically deformed to the point where it fractures at the surfaces in contact with the blades. The fracture then propagates inward to provide complete separation. The depth to which the punch must penetrate to produce complete shearing is directly related to the ductility of the metal. The penetration is only a small fraction of the sheet thickness for brittle materials, while for very ductile materials it may be slightly greater than the thickness.

The clearance between the blades is an important variable in shearing operations. With the proper clearance the cracks that initiate at the edges of the blades will propagate through the metal and meet near the centre of the thickness to provide a clean fracture surface (Figure 1.58 a,b). Note that even with proper clearance there is still distortion at a sheared edge. Insufficient clearance will produce a ragged fracture and also will require more energy to shear the metal than when there is proper clearance. With excessive clearance there is greater distortion of the edge, and more energy is required because more metal must plastically deform before it fractures. Furthermore, with too large a clearance burrs or sharp projections are likely to form on the sheared edge. A dull cutting edge also increases the tendency for the formation of burrs. The height of the burr increases with increasing clearance and increasing ductility of the metal. Because the quality of the sheared edge influences the formability of the part the control of clearance is important. Clearances generally range between 2 and 10 percent of the thickness of the sheet; the thicker the sheet the larger the clearance.

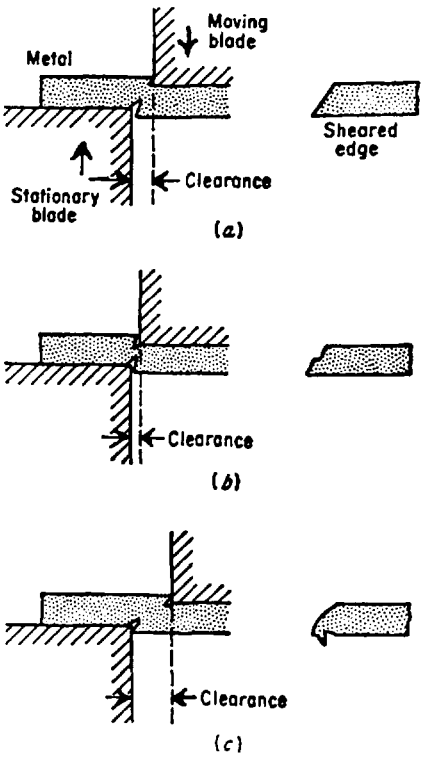


Figure 1.58 : Shearing of metal; (a) proper clearance, (b) insufficient clearance, (c) excessive clearance.

A whole group of press operations are based on the process of shearing. The shearing of closed contours, when the metal inside the contour is the desired part, is called blanking. If the material inside the contour is discarded, then the operation is known as punching, or piercing. Punching indentations into the edge of the sheet is called notching. Parting is the simultaneous cutting along at least two lines which balance each other from the standpoint of side thrust on the parting tool. Slitting is a shearing cut which does not remove any metal from the sheet. Trimming is a secondary operation in which previously formed parts are finished to size, usually by shearing excess metal around the periphery. The removal offering flash in a press is a trimming operation. When the sheared edges of part are trimmed or squared up by removing a thin shaving of metal, the operation is called shaving.

1.3.2.7 Bending processes

Bending is the process by which a straight length is transformed into a curved length. It is a very common forming process for changing sheet and plate into channel, drums, tanks, etc. In addition, bending is part of the deformation in many other forming operations. The definition of the terms used in bending are illustrated in Figure 1.59. The bend radius R is defined as the radius of curvature on the concave, or inside, surface of the bend. For elastic bending below the elastic limit the strain passes through zero halfway through the thickness of the sheet at the neutral axis. In plastic bending beyond the elastic limit the neutral axis moves closer to the inside surface of the bend as the bending proceeds.

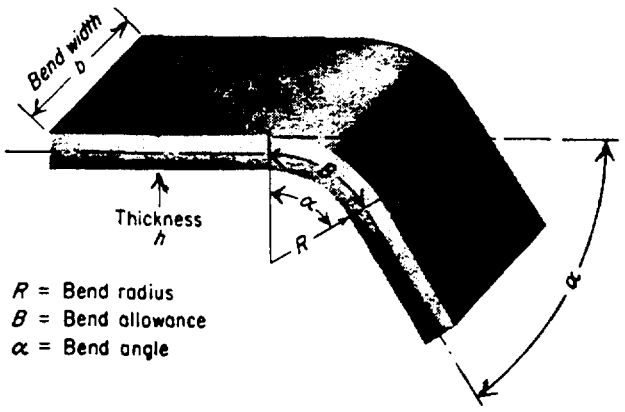


Figure 1.59 : Definition of terms used in bending.

1.3.2.8 Deep drawing processes

Deep drawing is the metalworking process used for shaping of flat sheets into cup-shaped articles such as bathtubs, shell cases, and automobile panels. This is done by placing a blank of appropriate size over a shaped die and pressing the metal into the die with a punch (Figure 1.60). Generally a clamping or hold-down pressure is required to press the blank against the die to prevent wrinkling. This is best done by means of a blank holder or hold-down ring in a double-action press.

1.3.2.9 Forging and rolling defects

Discontinuities in forgings may originate in the slab or billet and be modified by the rolling and forging of the material, or may result from the forging process itself. Some of the defects that can occur in forgings are similar to those in castings since most forgings originate from some form of cast ingot. Given below are some of the more specific defects.

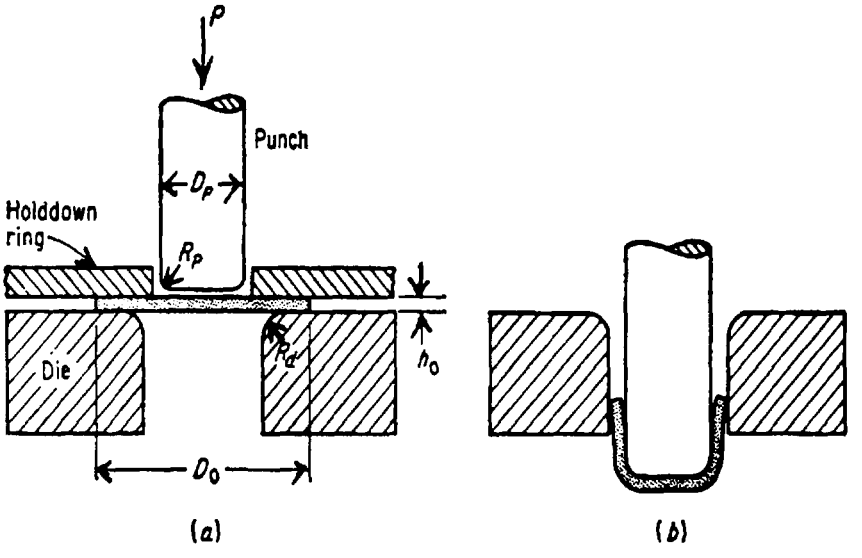


Figure 1.60 : Deepdrawing of a cylindrical cup; (a) before bending, (b) after drawing.

Laminations

Large porosity, pipe and non-metallic inclusions in slabs or billets are flattened and spread out during the rolling and forging processes. These flattened discontinuities are known as laminations (Figure 1.61).

Seams

Surface irregularities, such as cracks, on the slab or billet are stretched out and lengthened during rolling and are then called seams. Seams may also be caused by folding of the metal due to improper rolling. Seams are surface discontinuities and on finished bars will appear as either continuous or broken straight lines. On round bar stock they will appear as straight or slightly spiral lines, either continuous or broken.

Forging laps

Forging laps are the discontinuities caused by the folding of metal in a thin plate on the surface of the forging. They are irregular in contour (Figure 1.61).

Centre bursts

Ruptures that occur in the central region of a forging are called centre bursts. They can arise because of an incorrect forging procedure (e.g. too low a temperature or too drastic a reduction) or from the presence of segregation or brittle phase in the metal being forged Figure (1.61).

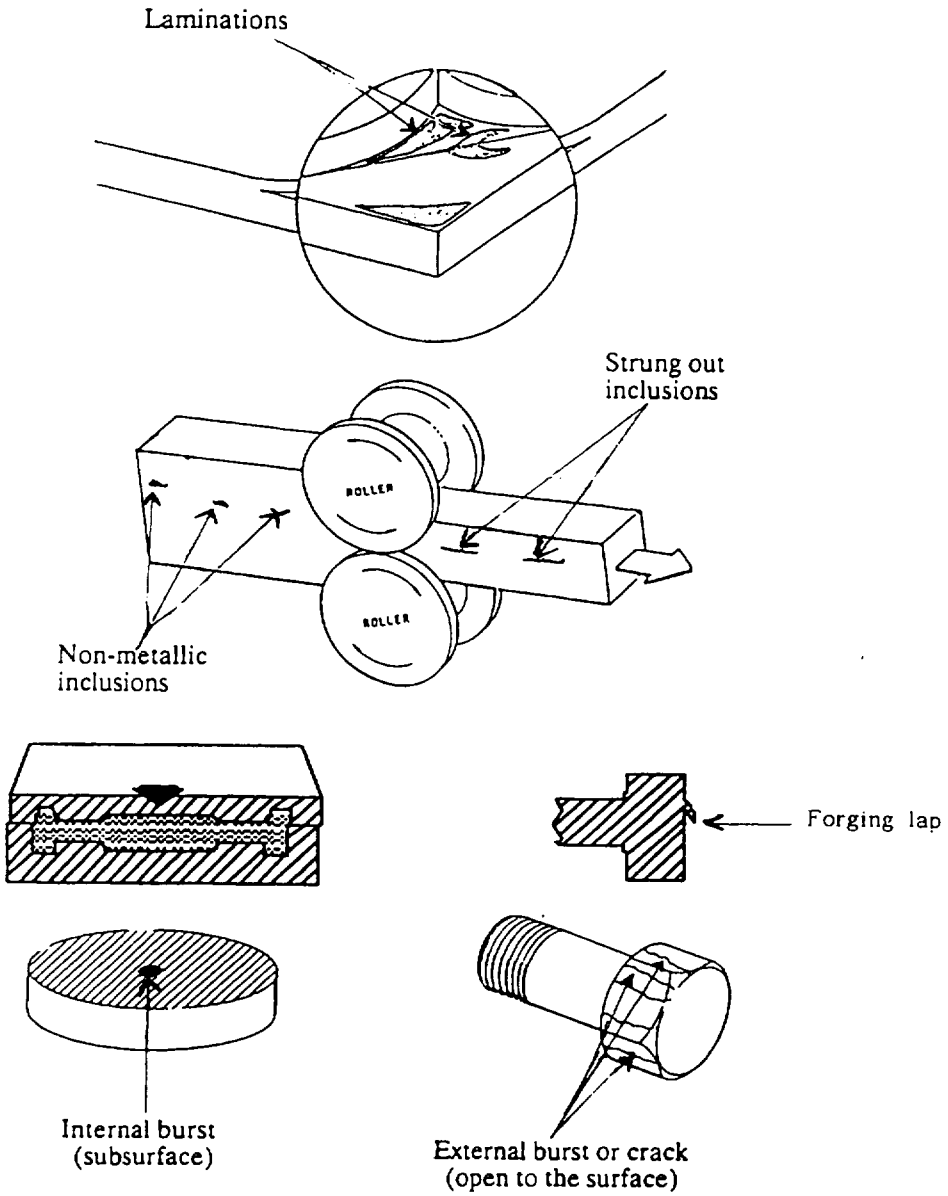


Figure 1.61 : Forging and rolling defects.

Clinks (thermal cracks)

Clinks are cracks due to stresses arising from excessively high temperature gradients within the material. Cracks formed during too rapid cooling originate at the surface and extend into the body of the forging; those formed during too rapid heating occur internally and can be opened up to become diamond-shaped cavities, during subsequent forging.

Hairline cracks (flakes)

Flakes are very fine internal cracks of circular shape that develop and extend with time and are associated with the presence of hydrogen in steel. There is greater susceptibility in larger forgings than in smaller and in certain grades of alloy steel than in carbon steel; they can be avoided by correct treatment.

Hot tears

Surface defects due to metal being ruptured and pulled apart during forging. They may be associated with the presence of local segregation, seams, or brittle phases.

Stringers

Non-metallic inclusions in slabs or billets, that are thinned and lengthened in the direction of rolling by the rolling process are called stringers (Figure 1.61).

Overheating

Normally identified by the facets seen on the fractured surfaces of a test-piece, but in extreme cases can manifest itself as a severely broken-up surface.

Pipe

If there has been insufficient discard from the original ingot, remnant primary pipe will normally show up axially. Secondary pipe that has never been exposed to the atmosphere will be welded-up if there has been sufficient forging.

1.3.2.10 Finishing processes and related defects

Machining process

Machining is a shape-producing process in which a power-driven device causes material to be removed in chip form. Most machining is done with equipment that supports both the workpiece and the cutting tool. Although there are many kinds of machines used in manufacturing industry, the term machine tools has been assigned to that group of equipment designed to hold a cutting tool and a workpiece and establish a suitable set of motions between them to remove materials from the work in chip form. The common combination of motions is shown in Figure 1.62.

Turning and boring

These machines normally rotate the workpiece to produce the cutting motion and feed a single point tool parallel to the work axis or at some angle to it. External cylindrical machining is called turning, internal cylindrical machining is called boring, and making a flat surface by feeding the tool perpendicular to the axis of revolution is termed as facing.

Drilling

A special fluted tool with two or more cutting lips on its exposed end is called a drill and is rotated and advanced axially into the workpiece by use of a drill press. The principal work is the making of, or enlarging of, cylindrical holes.

Milling

There are a great variety of milling machines which like the drill press employ special multi-edge cutters. Except for some special production type milling machines, this equipment permits multi-direction feeding and the cutters perform their principal cutting on their periphery edges.

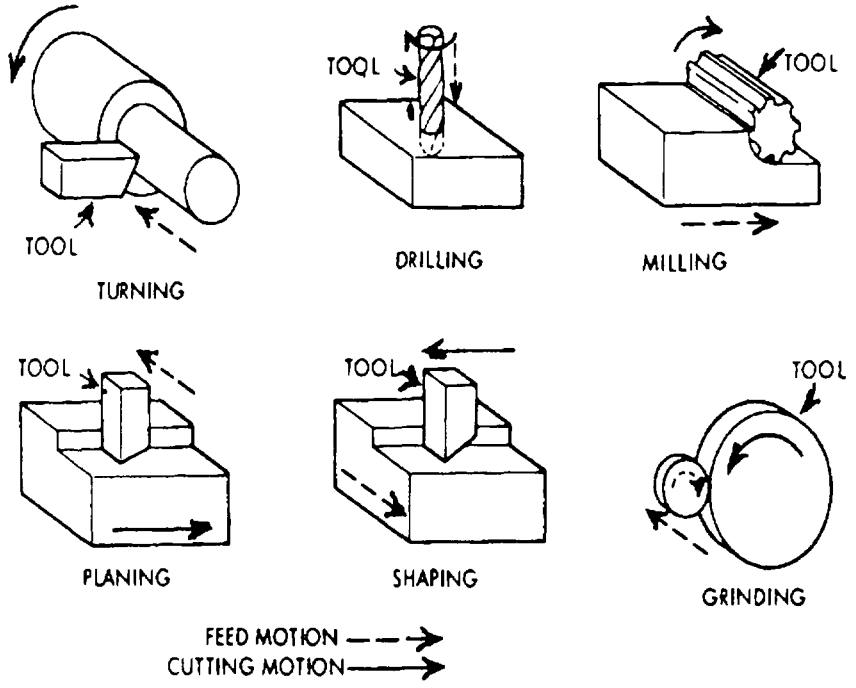


Figure 1.62 : Feed and cutting motions.

Straight line machines

One group of machine tools provide straight line cutting motion for its cutting action. This includes the shaper (straight line motion of the cutter), the planer (straight line motion of the workpiece), and the broach (straight line motion of a special multitooth cutter). Because of the high cost of the special cutter, broaching is used only for production quantity machining but the shaper and planer are more commonly used.

Machine tears are caused by dull machine tools. They will show up as short irregular lines at right angle to the direction of machining. They are the result of tool removing the metal more through a tearing action than through a cutting action.

Grinding processes

Grinding processes employ an abrasive wheel containing many grains of hard material bonded in a matrix. The action of a grinding wheel may be considered as a multiple-edge cutting tool except that the cutting edges are irregularly shaped and randomly spaced around the face of the wheel. Each grain removes a short chip of gradually increasing thickness, but because of the irregular shape of the grain there is considerable ploughing action between each grain and the workpiece.

The depth of cut in grinding usually is very small (a few μm), and this results in very small chips that adhere readily to the wheel or the workpiece. The net effect is that the specific cutting energy for grinding is about 10 times greater than for turning or milling. In grinding, greater than

70 percent of the energy goes into the finished surface. This results in considerable temperature rise and generation of residual stresses.

Grinding cracks are a processing type discontinuity caused by stresses which are built up from excess heat created between grinding wheel and metal. Grinding cracks are fine sharp type cracks and will usually occur at right angles to the rotation of the grinding wheel.

Heat treatment of steel

A number of heat treatment cycles have been developed to alter the structure and hence the properties of iron and steel. Some of usual treatments and the specific properties they develop in iron and steel are discussed in the following (Figure 1.63). The first is annealing. Steel is annealed to soften it for easy machining and to release internal stresses that might have been caused by working of the metal or by unequal contraction in casting. For annealing the steel is heated slowly to a temperature between 800°C and 1000°C. It is then held at this temperature for sufficient time so as to enable the internal changes to take place. It is then cooled slowly. For slow cooling, which is very essential, the heated steel is taken out of the furnace and embedded in sand, ash, lime or some other non-conducting material.

Normalizing is another heat treatment process. This treatment is done to refine the structure and to remove strains that might have been caused by cold working. When steel is cold worked its crystalline structure may get upset and the metal may become brittle and unreliable. Also when the metal is heated to very high temperatures as for forging then it may lose its toughness. To remedy these effects steel is slowly heated to about 1000°C and allowed to cool in air.

Hardening or quenching of steel consists of heating the steel to above the transformation temperature and then suddenly cooling it by dipping it in a bath of cold water or oil. This way of cooling of hot steel is known as quenching or hardening. The steel after quenching is known as quenched steel. This type of steel is hard and brittle because of martensitic crystal structure. The hardness of quenched steel depends upon the medium used for quenching and the rate of cooling.

When steel is heated to or above its critical temperature (transformation temperature range the value of which is dependent upon the alloy percentages) and held at this temperature for some period of time carbon unites in solid solution with iron in the gamma or face centred cubic lattice form. In this phase, as much as 2% carbon can dissolve at the eutectic temperature of 1,148°C at which the widest range of gamma composition exists. This is called the process of austentization.

Tempering involves heating of hardened steel to a suitable temperature between 230°C and 600°C. This causes a particle transformation of the martensitic back to pearlite again thereby taking away some of the hardness of the steel to make it tougher.

Minimum hardness and maximum ductility of steel can be produced by a process called spheroidizing, which causes the iron carbide to form in small spheres or nodules in a ferrite matrix. In order to start with small grains that spheroids more readily, the process is usually performed on normalized steel. Several variations of processing are used, but all require the holding of the steel near the A1 temperature (usually slightly below) for a number of hours to allow the iron carbide to form in its more stable and lower energy state of small, rounded globules.

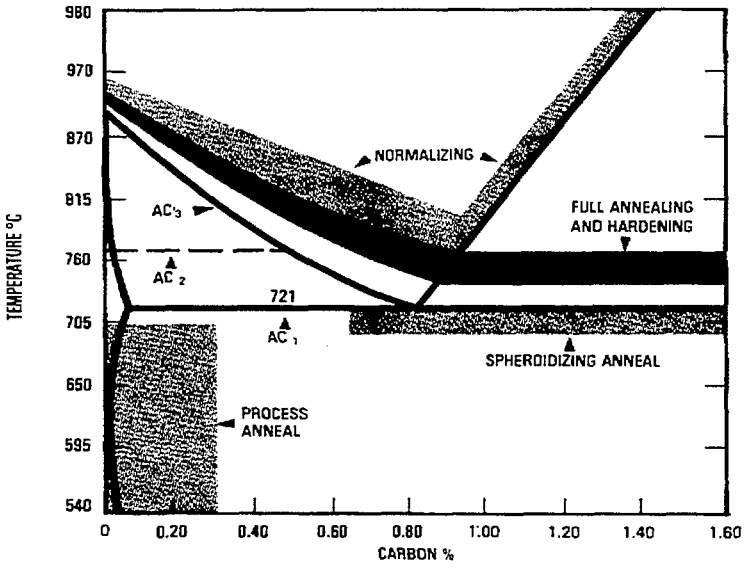


Figure 1.63 : Temperature ranges for various heat treating processes.

Heat treating cracks are often caused by stresses built up during heating and cooling. Unequal cooling between light and heavy sections may cause heat treatment cracks. Heat treatment cracks have no specific direction and usually start at sharp corners which act as stress concentration points (stress raisers).

Surface finishing

Products that have been completed to their proper shape and size frequently require some type of surface finishing to enable them to satisfactorily fulfil their function. In some cases, it is necessary to improve the physical properties of the surface material for resistance to penetration or abrasion. In many manufacturing processes, the product surface is left with dirt, metal chips, grease or other harmful material on it. Assemblies that are made of different materials or from the same materials processed in different manners, may require some special surface treatment to provide uniformity of appearance.

Surface finishing may sometimes become an intermediate step in processing. For instance, cleaning and polishing are usually essential before any kind of plating process. Some of the cleaning procedures are also used for improving surface smoothness on mating parts and for removing burrs and sharp corners, which might be harmful in later use. Another important need for surface finishing is for corrosion protection in variety of environments. The type of protection provided will depend largely upon the anticipated exposure, with due consideration to the material being protected and the economic factors involved.

Satisfying the above objectives necessitates the use of many surface finishing methods that involve chemical change of the surface, mechanical work affecting surface properties, cleaning by a variety of methods and the application of protective coatings, organic and metallic.

Case hardening of steels

Case hardening results in a hard, shell like surface. Some product applications require surface properties of hardness and strength to resist penetration under high pressure and to provide

maximum wear properties. Where through hardness and the maximum strength associated with it are not necessary, it may be more economical to gain the needed surface properties by a case hardening process. Case hardening involves a change of surface properties to produce a hard, wear resistant shell with a tough fracture resistant core. This is usually accomplished by a change of surface material chemistry. With some materials, a similar condition can be produced by a phase change of the material already present.

Case depth measurement is sometimes checked by destructive methods, cutting the object, etching the cut surface and checking the cut depth with a measuring microscope. A faster and more useable method when knowledge is needed directly for service parts, is to use eddy current tests.

Carburizing

Case hardening of steel may be accomplished by a number of methods. The choice between them is dependent on the material to be treated, the application and the desired properties. One of the more common methods is carburizing which consists of an increase or addition of carbon to the surface of the part. Carburizing is usually performed on a low alloy or plain low carbon steel. If an alloy steel is used, it usually contains small quantities of nickel or some other elements that act as grain growth retarder during the heating cycle. Low carbon steels are commonly used to minimize the effect of subsequent heat treatment on the core material. It is possible to carburize any steel containing less than the 0.7% to 1.2% carbon that is produced in the surface material.

The complete cycle for case hardening by carburizing is illustrated in Figure 1.64.

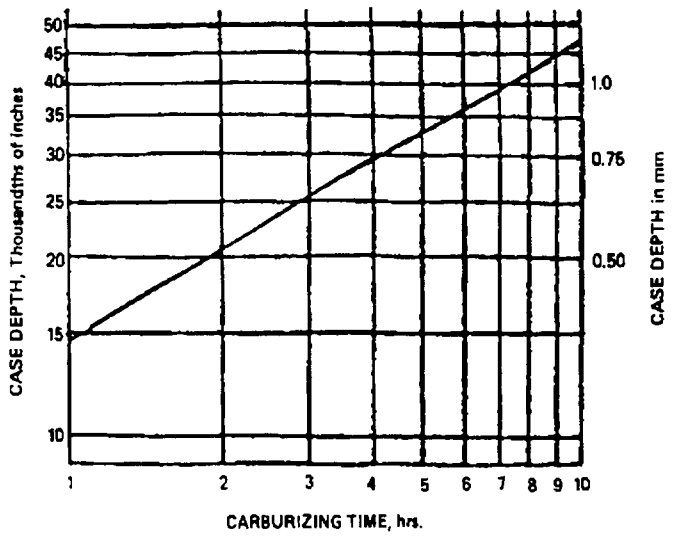


Figure 1.64 : Typical carburizing case depth-time relationship.

Flame hardening

Another case hardening process that does not require a change of composition in the surface material is flame hardening. This method can be used only on steels that contain sufficient

carbon to be hardenable by standard heat treating procedures. The case is produced by selectively heating part or all of the surface with special high capacity gas burners or oxy-acetylene torches at a rate sufficiently high that only a small depth from the surface goes above the critical temperature. Following immediately behind the torch is a water quenching head that floods the surface to reduce the temperature fast enough to produce a martensitic structure. As in the case of carburizing, the surface may be then reheated to temper it for toughness improvement. The depth of hardness is controlled by the temperature to which the metal is raised, by the rate of heating, and by the time that passes before quenching.

Cleaning

Few, if any, shaping and sizing processes produce products that are suitable without some type of cleaning unless special precautions are taken. Hot working, heat treating, and welding cause oxidation and scale formation in the presence of oxygen. For the same reason, castings are usually coated with oxide scale. If they are made in sand moulds they may have sand grains fused or adhering to the surface. Residue from coolants, lubricants and other processing materials is common on many manufactured parts. In addition to greasy films from processing, protective coatings of greases, oils, or waxes are frequently used intentionally to prevent rust or corrosion on parts that are stored for some period of time before being put to use. Even if parts are clean at the completion of manufacturing, they seldom remain that way for long. After only short storage periods, corrosion and dust from atmospheric exposure necessitate cleaning particularly if further processing is required.

When using NDT methods such as penetrant testing and ultrasonic testing good precleaning may be necessary to get accurate results and postcleaning is often needed to leave the surface in a suitable condition. In some applications such as on stainless steels and nickel based alloys, ultrasonic couplants and penetrant materials must be made of only certain materials so that they do not cause stress-corrosion failure.

Cleaning sometimes has finish improvement associated with it. Some shape producing methods produce unsatisfactory surface characteristics such as sharp corners, burrs and tool marks which may affect the function, handling ease, and appearance of the product. Some cleaning processes at least partially blend together surface irregularities to produce uniform light reflection. Improvement of surface qualities may be accomplished by removal of high spots by cutting or by plastic flow as cleaning is performed.

Many different cleaning methods are available. The most commonly used ones are briefly mentioned here: the most widely used cleaning methods use a cleaning medium in liquid form, which are applied to the object to be cleaned in different ways such as spraying, brushing or dipping the object in a bath of the cleaning liquid. Cleaning may be carried out through the process of blasting wherein the cleaning medium which may be a liquid or a solid (e.g. sand, glass or steel beads, etc.) is accelerated to high velocity and impinged against the surface to be cleaned. A number of cleaning operations can be quickly and easily performed by use of wire brushes either manually or by rotating them at high speeds. The cleaned surface may be given a final polishing touch using a flexible abrasive wheel. Buffing is a kind of polishing process.

Coatings

Many products, in particular those exposed to view and those subject to change by the environment with which they are in contact, need some type of coating for improved appearance or for protecting from chemical attack. All newly created surfaces are subject to corrosion,

although the rate of occurrence varies greatly with the material, the environment, and the conditions. For all practical purposes, some materials are highly corrosion resistant because the products of corrosion resist further corrosion. For example, a newly machined surface on an aluminium alloy will immediately be attacked by oxygen in the air. The initial aluminium oxide coating protects the remaining metal and practically stops corrosion unless an environmental change occurs. Corrosion rates are closely dependent on environment. Rates increase with rise of temperature and greater concentration of the attacking chemical. The need for corrosion protection for maintenance of appearance is obvious. Unless protected, an object made of bright steel will begin to show rust in a few hours of exposure to ordinary atmosphere. In addition to change of appearance, loss of actual material, change of dimensions, and decrease of strength, corrosion may be the cause of eventual loss of service or failure of a product.

Hardness and wear resistance can, however, be provided on a surface by plating with hard metals. Chromium plating of gauges subject to abrasion is frequently used to increase their wear life. Coatings of plastic materials and asphaltic mixture are sometimes placed on surfaces to provide sound deadening. The additional benefit of protection from corrosion is usually acquired at the same time.

Metallizing

Metal spraying, or metallizing, is a process in which metal wire or powder is fed into an oxy-acetylene heating flame and the same after melting, is carried by high velocity air to be impinged against the work surface. The small droplets adhere to the surface and bond together to build up a coating. The nature of the bond is dependent largely on the materials. The droplets are relatively cool when they make contact and in fact can be sprayed on wood, leather, and other flammable materials. Little, if any, liquid flow aids the bonding action. If, however, sufficient affinity exists between the metals, a type of weld involving atomic bonds may be established. The bond is largely mechanical in most cases and metal spraying is usually done on surfaces that have been intentionally roughened to aid the mechanical attachment. Zinc, aluminium, and cadmium, which are anodic to steel and therefore provide preferential corrosion protection, are usually sprayed in thin layers, averaging about 0.25 millimetre (0.010 inch) in thickness, as protective coatings. Because sprayed coatings tend to be porous, coatings of two or more times this thickness are used for cathodic materials such as tin, lead, and nickel. The cathodic materials protect only by isolating the base material from its environment.

Several metals, mainly zinc, tin, and lead, are applied to steel for corrosion protection by a hot dip process. Steel in sheet, rod, pipe, or fabricated form, properly cleansed and fluxed, is immersed in molten plating metal. As the work is withdrawn the molten metal that adheres solidifies to form a protective coat.

Coating of many metals can be deposited on other metals, and on non-metals by electroplating, when suitably prepared. This is based on the principle that when direct current power of high enough voltage is applied to two electrodes immersed in a water solution of metallic salt, current will flow through the circuit causing changes at the electrodes (Figure 1.65). At the negative electrode, or cathode (the work), excess electrons supplied from the power source neutralize positively charged metallic ions in the salt solution to cause dissolved metal to be deposited in the solid state. At the positive electrode, or anode (plating metal), metal goes into solution to replace that removed at the other electrode. The rate of deposition and the properties of the plated material are dependent on the metals being worked with, the current density, the solution temperature, and other factors.

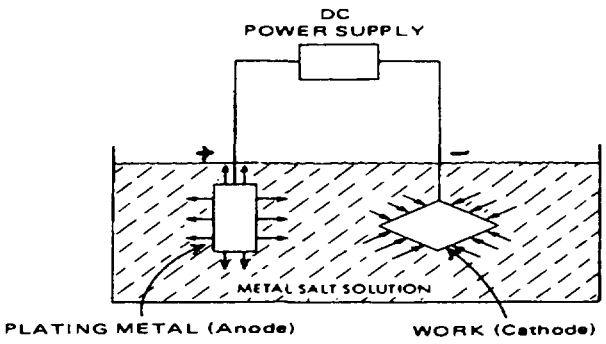


Figure 1.65 : Electroplating.

Chemical treatment

A relatively simple and often fully satisfactory method for protection from corrosion is by conversion of some of the surface material to a chemical composition that resists attack from the environment. These converted metal surfaces consist of relatively thin (seldom more than 0.025 millimetre, or 0.001 inch thick) inorganic films that are formed by chemical reaction with the base material. One important feature of the conversion process is that the coatings have little effect on the product dimensions. However, when severe conditions are to be encountered , the converted surface may give only partial protection, and coatings of entirely different types may be applied over them.

Aluminium, magnesium, and zinc can be treated electrically in a suitable electrolyte to produce a corrosion-resistant oxide coating. The metal being treated is connected to the anode in the circuit, which provides the name anodizing for the process.

Phosphate coatings, used mostly on steel, result from a chemical reaction of phosphoric acid with the metal to form a non-metallic coating that is essentially phosphate salts. The coating is produced by immersing small items or spraying large items with the phosphating solution.

A number of proprietary blackening processes, used mainly on steel, produce attractive black oxide coatings. Most of the processes involve the immersing of steel in a caustic soda solution heated to about 150°C (300°F) and made strongly oxidizing by the addition of nitrites or nitrates. Corrosion resistance is rather poor unless improved by application of oil, lacquer, or wax. As in the case of most of the other chemical conversion procedures this procedure also finds use as a base for paint finishes.

1. 4 MATERIALS IN SERVICE

1.4.1 Behaviour of materials in service

Materials have to operate and perform in widely varied environments and situations. The requirements of safety and reliability demand that the materials and components should perform well in their environments and situations without premature failure. There are a number of factors and processes which can cause the failure of materials. As premature failure of critical components can be disastrous in many situations apart from being a cause for lost production and bad reputation, it is essential to understand and control these causes of failure.

1.4.2 Conditions leading to defects and failures

Due to advances in technology and the understanding of materials and their design, and due to sophisticated inspection and testing methods, such as the non-destructive testing methods, metal failures occur only in an extremely low percentage of the millions of tons of metals fabricated every year. Those that do occur fall mainly into three categories. Operational failures can be caused by overload, wear, corrosion and stress-corrosion, brittle fracture and metal fatigue. In the second category fall the failures due to improper design. In this it is necessary to consider whether sharp corners or high-stress areas exist in the design, has sufficient safety stress factor been considered and whether the material selected is suitable for particular application. The third type of failure is caused by thermal treatments such as forging, hardening, tempering and welding, and by surface cracks caused by the heat of grinding. These aspects and especially those related to operational or in-service conditions will be described here in more detail.

1.4.2.1 Corrosion

With the exception of some noble metals, all metals are subject to the deterioration caused by ordinary corrosion. Iron, for example, tends to revert back to its natural state of iron oxide. Other metals revert to sulphides and oxides or carbonates. Buildings, ships, machines and automobiles are all subject to attack by the environment. The corrosion that results often renders them useless and they have to be scrapped. Billions of dollars a year are lost as a result of corrosion. Corrosion can also cause dangerous conditions to prevail, such as on bridges, where the supporting structures have been eaten away, or in aircraft in which an insidious corrosion called intergranular corrosion can weaken the structural members of the aircraft and cause a sudden failure.

Corrosion in metals is the result of their desire to unite with oxygen in the atmosphere or in other environments to return to a more stable compound, usually called ore. Iron ore, for example, is in some cases simply iron rust. Corrosion may be classified by the two different processes by which it can take place; direct oxidation corrosion, which usually happens at high temperature, and galvanic corrosion, which takes place at normal temperatures in the presence of moisture or an electrolyte. Direct oxidation corrosion is often seen in the scaling that takes place when a piece of metal is left in a furnace for a length of time. The black scale is actually a form of iron oxide, called magnetite (Fe_3O_4). Galvanic corrosion is essentially an electrochemical process that causes a deterioration of metals by a very slow but persistent action. In this process, part or all of the metal becomes transformed from the metallic state to the ionic state and often forms a chemical compound in the electrolyte. On the surface of some metals such as copper or aluminium, the corrosion product sometimes exists as a thin film that resists further corrosion. In other metals such as iron, the film of oxide that forms is so porous that it does not resist further corrosive action, and corrosion continues until the whole piece has been converted to the oxide.

Corrosion requires the presence of an electrolyte to allow metal ions to go into solution. The electrolyte may be fresh or salt water and acid or alkaline solutions of any concentration. Even a finger print on metal can form an electrolyte and produce corrosion. When corrosion of a metal occurs, positively charged atoms are released or detached from the solid surface and enter into solution as metallic ions while the corresponding negative charges in the form of electrons are left behind in the metal. The detached positive ions bear one or more positive charges. In the corrosion of iron, each iron atom releases two electrons and then becomes a ferrous iron carrying two positive charges. Two electrons must then pass through a conductor to the cathode area. The electrons reach the surface of the cathode material and neutralize positively charged hydrogen ions that have become attached to the cathode surface. Two of these ions will now become

neutral atoms, and are released generally in the form of hydrogen gas. This release of the positively charged hydrogen ions leaves an accumulation and a concentration of OH negative ions that increases the alkalinity at the cathode.

When this process is taking place, it can be observed that hydrogen bubbles are forming at the cathode only. When cathodes and anodes are formed on a single piece of metal, their particular locations are determined by, for example, the lack of homogeneity in the metal, surface imperfections, stresses, inclusions in the metal, or any thing that can form a crevice such as a washer.

Corrosion can also take the form of erosion in which the protective film, usually an oxide film, is removed by a rapidly moving atmosphere or medium. Depolarization can also take place, for example, on the propellers of ships because of the movement through the water, which is the electrolyte. This causes an increased corrosion rate of the anodic steel ship's hull. Impellers of pumps are often corroded by this form of erosion corrosion in which metal ions are rapidly removed at the periphery of the impeller but are concentrated near the centre where the velocity is lower. Another form of corrosion is intergranular corrosion. This takes place internally. Often the grain boundaries form anodes and the grains themselves form cathodes, causing a complete deterioration of the metal in which it simply crumbles when it fails. This often occurs in stainless steels in which chromium carbides precipitate at the grain boundaries. This lowers the chromium content adjacent to the grain boundaries, thus creating a galvanic cell. Differences in environment can cause a high concentration of oxygen ions. This is called cell concentration corrosion. Pitting corrosion is localized and results in small holes on the surface of a metal caused by a concentration cell at that point. When high stresses are applied to metals in a corrosive environment, cracking can also be accelerated in the form of stress-corrosion failure. It is a very localized phenomenon and results in a cracking type of failure.

Cathodic protection is often used to protect steel ships hulls and buried steel pipelines. This is done by using zinc and magnesium sacrificial anodes that are bolted to the ship's hull or buried in the ground at intervals and electrically connected to the metal to be protected. In the case of the ship, the bronze propeller acts as a cathode, the steel hull as an anode and the seawater as an electrolyte. Severe corrosion can occur on the hull as a result of galvanic action. The sacrificial anodes are very near the anodic end of the galvanic series and have a large potential differences between both the steel hull of the ship and the bronze propeller. Both the hull and propeller become cathodic and consequently do not deteriorate. The zinc or magnesium anodes are replaced from time to time.

Selection of materials is of foremost importance. Even though a material may be normally resistant to corrosion, it may fail in a particular environment or if coupled with a more cathodic metal. Coatings are extensively used to prevent corrosion. There are different types of such coatings, for example; anodic coatings, cathodic coatings, organic and inorganic coatings, inhibitive coatings, etc.

1.4.2.2 Fatigue

When metal parts are subjected to repeated loading and unloading over prolonged periods they may fail at stresses far below their yield strength with no sign of plastic deformation. This is called a fatigue failure. When designing machine parts that are subject to vibration or cyclic loads, fatigue strength may be more important than ultimate tensile or yield strength. Fatigue is a universal phenomenon observed in most solids. Cyclic loading leads to a continuous accumulation of damage which, as in the case of static fracture, eventually results in rupture.

Fatigue limit, or endurance limit, is the maximum load that can be applied an infinite number of times without causing failure (Figure 1.66). But 10 million loading cycles are usually considered enough to establish fatigue limits. The number of cycles leading to fracture at a given stress is often referred to as the fatigue strength or endurance. This phenomenon of failure of a material when subjected to a number of varying stress cycles is known as fatigue since it was once thought that fracture occurred due to the metal weakening or becoming tired.

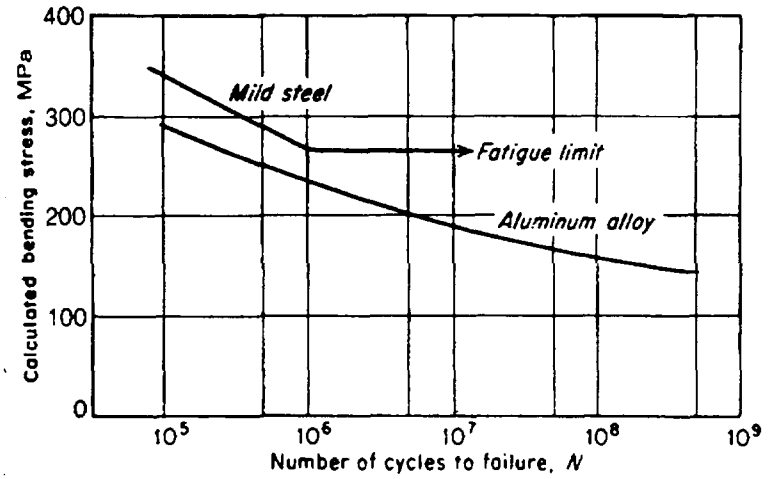


Figure 1.66 : Typical fatigue curves for ferrous and non-ferrous metals.

Failures caused by fatigue are found in many of the materials of industry. Some plastics and most metals are subject to fatigue in varying degrees as these are widely used in dynamically loaded structures and machines. It has been estimated that at least 75% of all machine and structure failures have been caused by some form of fatigue. Fatigue failure is caused by a crack that is initiated by a notch, bend, or scratch that continues to grow gradually as a result of stress reversals on the part. The crack growth continues until the cross-sectional area of the part is reduced sufficiently to weaken the part to the point of failure. In welding, even spatter on a sensitive surface such as a steel spring can initiate fatigue failure. Fatigue is greatly influenced by the kind of material, grain structure and the kind of loading. Some metals are more sensitive to sharp changes in section (notch sensitive) than others.

There are various types of fatigue failure. In the case of one-way bending load a small elliptically shaped fatigue crack usually starts at a surface flaw such as a scratch or tool mark. The crack tends to flatten out as it grows. It is caused by the stress at the base of the crack being lower because of the decrease in distance from the edge of the crack to the neutral axis. If a distinct stress raiser such as a notch is present, the stress at the base of the crack would be high, causing the crack to progress rapidly near the surface, and the crack tends to flatten out sooner. In a two-way bending load cracks start almost simultaneously at opposite surfaces when the surfaces are equally stressed. The cracks proceed toward the centre at similar rates and result in a fracture that is rather symmetrical.

In the early stages of fatigue testing, specimens will generally evolve an appreciable amount of heat. Later fissures develop at the surface eventually leading to failure. The surface of the specimen is a preferential seat of damage initiation. Corrosive effects may also assist in degradation of the structure at the surface. Corrosion is essentially a process of oxidation and under static conditions a protective oxide film is formed which tends to retard further corrosion attack. In the presence of cyclic stress the situation is quite different, since the partly protective oxide film is ruptured in every cycle allowing further attack. It is a rather simplified explanation

that the microstructure at the surface of the metal is attacked by the corrosive environment causing, an easier and more rapid initiation of cracks. One of the important aspects of corrosion fatigue is that a metal having a fatigue limit in air no longer possesses one in the corrosive environment and therefore fracture can occur at relatively very low stress levels.

In commercial alloys the technical fatigue limit generally lies between 0.3 and 0.5 of the ultimate tensile stress. The fatigue strength of metals can often be enhanced by treatments which render the surface more resistant to deformation. Fracture then tends to start at the interface between the hard surface layer and the softer core. Stress raisers, such as sharp notches, corners, key ways, rivet holes and scratches can lead to an appreciable lowering of the fatigue strength of metal components. Good surface finish and corrosion protection are desirable to enhance fatigue resistance. Fatigue is basically a low temperature problem and at temperatures relatively high with respect to the melting point, fracture and hence specimen life are governed by creep.

Fractured surfaces of fatigued metals generally show a smooth and lustrous region due to the polishing effects arising from attrition at fissures. The remaining parts of the fracture surface, over which failure occurred through weakening of the specimen by the reduction of its load bearing cross-section by surface cracks and fissures, may look duller and coarser, as it is essentially caused by static fracture.

Fatigue cracks are service type discontinuities that are usually open to the surface where they start from stress concentration points(Figure 1.67).

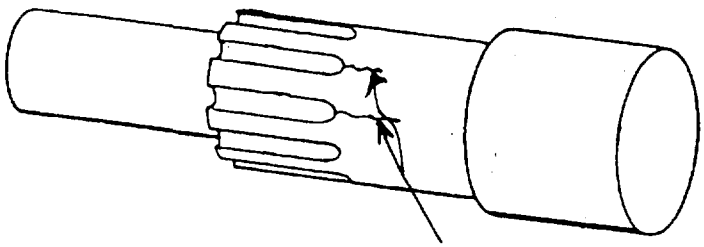


Figure 1.67 : Fatigue cracks.

1.4.2.3 Creep

The progressive deformation of a material at constant stress is called creep. To determine the engineering creep curve of a metal, a constant load is applied to a tensile specimen maintained at a constant temperature, and the strain (extension) of the specimen is determined as a function of time. Although the measurement of creep resistance is quite simple in principle, in practice it requires considerable laboratory equipment. The elapsed time of such tests may extend to several months, while some tests have been run for more than 10 years.

Curve A in Figure 1.68 illustrates the idealized shape of a creep curve. The slope of this curve ($d\varepsilon/dt$) is referred to as the creep rate. Following an initial rapid elongation of the specimen, ε_o, the creep rate decreases with time, then reaches essentially a steady state in which the creep rate changes little with time, and finally the creep rate increases rapidly with time until fracture occurs. Thus, it is natural to discuss the creep curve in terms of its three stages. It should be noted, however, that the degree to which these three stages are readily distinguishable depends strongly on the applied stress and temperature.

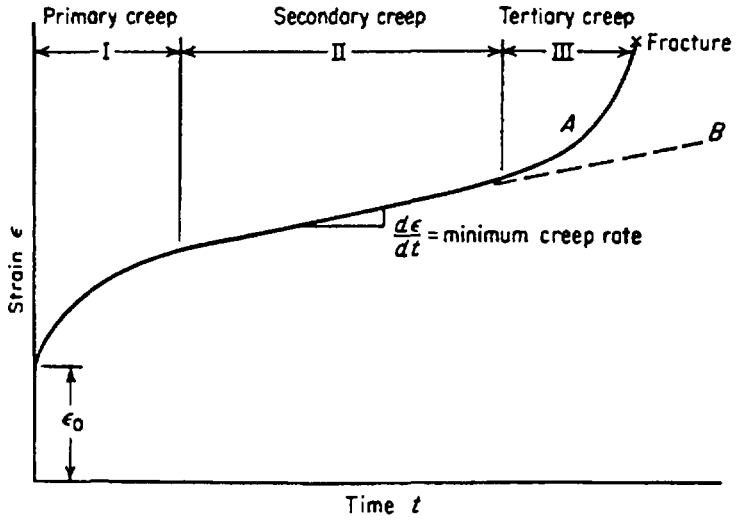


Figure 1.68 : Typical creep curve showing the three steps of creep curve A, constant-load test; curve B, constant-stress test.

In making an engineering creep test, it is usual practice to maintain the load constant throughout the test. Thus, as the specimen elongates and decreases in cross-sectional area, the axial stress increases. The initial stress which was applied to the specimen is usually the reported value of stress. Methods of compensating for the change in dimensions of the specimen so as to carry out the creep test under constant-stress conditions of the specimen have been developed. When constant-stress tests are made it is found that the onset of stage III is greatly delayed. The dashed line (curve B) shows the shape of a constant-stress creep curve. In engineering situations it is usually the load not the stress that is maintained constant, so a constant-load creep test is more important. However, fundamental studies of the mechanism of creep should be carried out under constant-stress conditions.

The first stage of creep, known as primary creep, represents a region of decreasing creep rate. Primary creep is a period of predominantly transient creep in which the creep resistance of the material increases by virtue of its own deformation. For low temperatures and stresses, as in the creep of lead at room temperature, primary creep is the predominant creep process. The second stage of creep, known also as secondary creep, is a period of nearly constant creep rate which results from a balance between the competing processes of strain hardening and recovery. For this reason, secondary creep is usually referred to as steady-state creep. The average value of the creep rate during secondary creep is called the minimum creep rate. Third-stage or tertiary creep mainly occurs in constant-load creep tests at high stresses at high temperatures. Tertiary creep occurs when there is an effective reduction in cross-sectional area either because of necking or internal void formation. Third-stage creep is often associated with metallurgical changes such as coarsening of precipitate particles, recrystallization, or diffusional changes in the phases that are present.

1.4.2.4 Wear

Wear may be defined as undesired removal of material from contacting surfaces by mechanical action. Excessive wear can be caused by continuous overload, but wear is ordinarily a slow process that is related to the friction between two surfaces. Rapid wear can often be attributed to lack of lubrication or the improper selection of material for the wear surface. Some wear is to be

expected, however, and could be called normal wear. Wear is one of the most frequent causes of failure. We find normal wear in machine tooling such as carbide and high-speed tools that wear and have to be replaced or resharpened. Parts of automobiles ultimately wear until an overhaul is required. Machines are regularly inspected for worn parts, which when found are replaced; this is called preventive maintenance. Often normal wear cannot be prevented; it is simply accepted, but it can be kept to a minimum by the proper use of lubricants. Rapid wear can occur if the load distribution is concentrated in a small area because of the part design or shape. This can be altered by redesign to offer more wear surface. Speeds that are too high can increase friction considerably and cause rapid wear.

Metallic wear is a surface phenomenon, which is caused by the displacement and detachment of surface particles. All surfaces subjected to either rolling or sliding contact show some wear. In some severe cases the wear surface can become cold welded to the other surface. In fact, some metals are pressure welded together in machines, taking advantage of their tendency to be cold welded. This happens when tiny projections of metal make a direct contact on the other surface and produce friction and heat, causing them to be welded to the opposite surface if the material is soft. Metal is torn off if the material is brittle. Insufficient lubrication is usually the cause of this problem. High pressure lubricants are often used while pressing two parts together in order to prevent this sort of welding. Two steel parts such as a steel shaft and a steel bore in a gear or sprocket, if pressed together dry, will virtually always seize or weld and cause the two parts to be ruined for further use. In general, soft metals, when forced together, have a greater tendency to "cold weld" than harder metals. Two extremely hard metals even when dry will have very little tendency to weld together . For this reason, hardened steel bushings and hardened pins, are often used in earth moving machinery to avoid wear. Some soft metals when used together for bearing surfaces (for example, aluminium to aluminium) have a very great tendency to weld or seize. Among these metals there are aluminium, copper and austenitic stainless steel.

Cast iron, when sliding on cast iron as is found in machine tools on the ways of lathes or milling machine tables, has less tendency than most metals to seize because the metal contains graphite flakes that provide some lubrication, although additional lubrication is still necessary. As a general rule, however, it is not good practice to use the same metal for two bearing surfaces that are in contact. However, if a soft steel pin is used in a soft steel link or arm, it should have a sufficiently loose fit to avoid seizing. In this application it is better practice to use a bronze bushing or other bearing material in the hole than a steel pin because the steel pin is harder than the bronze and when a heavy load is applied, the small projections of bronze are flattened instead of torn out. Also, the bronze will wear more than the steel and usually only the bushing will need replacing when a repair is needed.

Different types of wear include abrasive wear, erosive wear, corrosive wear and surface fatigue. In abrasive wear small particles are torn off the surfaces of the metal, creating friction. Friction involving abrasive wear is sometimes used or even required in a mechanism such as on the brakes of an automobile. The materials are designed to minimize wear with the greatest amount of friction in this case. Where friction is not desired, a lubricant is normally used to provide a barrier between the two surfaces. This can be done by heavy lubricating films or lighter boundary lubrication in which there is a residual film. Erosive wear is often found in areas that are subjected to a flow of particles or gases that impinge on the metal at high velocities. Sand blasting, which is sometimes used to clean parts, utilizes this principle. Corrosive wear takes place as a result of an acid, caustic, or other corrosive medium in contact with metal parts. When lubricants become contaminated with corrosive materials, pitting can occur in such areas as machine bearings. Surface fatigue is often found on roll or ball bearing or sleeve bearings where

excessive side thrust has been applied to the bearing. It is seen as a fine crack or as small pieces falling out of the surface.

Various methods are used to limit the amount of wear in the part. One of the most commonly used methods is simply to harden the part. Also, the part can be surface hardened by diffusion of a material, such as carbon or chrome, into the surface of the part. Parts can also be metallized, hard faced, or heat treated. Other methods of limiting wear are electroplating (especially the use of hard industrial chromium) and anodizing of aluminium. Some nickel plate is used, as well as rhodium, which is very hard and has high heat resistance. The oxide coating that is formed by anodizing on certain metal such as magnesium, zinc, aluminium, and their alloys is very hard and wear resistant. These oxides are porous enough to form a base for paint or stain to give it further resistance to corrosion. Some of the types of diffusion surfacing are carburizing, carbo-nitriding, cyaniding, nitriding, chromizing, and siliconizing. Chromizing consists of the introduction of chromium into the surface layers of the base metal. This is sometimes done by the use of chromium powder and lead baths in which the part is immersed at a relatively high temperature. This, of course, produces a stainless steel on the surface of low carbon steel or an iron base metal, but it may also be applied to non-ferrous material such as tungsten, molybdenum, cobalt, or nickel to improve corrosion and wear resistance. The fusion of silicon consists of impregnating an iron base material with silicon. This also greatly increases wear resistance.

Hard facing is put on a metal by the use of several types of welding operations, and it is simply a hard type of metal alloy such as alloying cobalt and tungsten or tungsten carbide that produces an extremely hard surface that is very wear resistant. Metal spraying is used for the purpose of making hard wear resistant surfaces and for repairing worn surfaces.

1.4.2.5 Overload

Overload failures are usually attributed to faulty design, extra loads applied, or an unforeseen machine movement. Shock loads or loads applied above the design limit are quite often the cause of the breakdown of machinery. Although mechanical engineers always plan for a high safety factor in designs (for instance the 10 to 1 safety factor above the yield strength that is sometimes used in fasteners), the operators of machinery often tend to use machines above their design limit. Of course, this kind of overstress is due to operator error. Inadequate design can sometimes play a part in overload failures. Improper material selection in the design of the part or improper heat treatment can cause some failures when overload is a factor. Often a machinist or welder will select a metal bar or piece for a job based upon its ultimate tensile strength rather than upon its yield point. In effect this is a design error and can ultimately result in breakdown.

Basically there are only two modes or ways in which metals can fracture under single or monotonic loads. These two modes are shear and cleavage and they differ primarily in the way the basic metal crystal structure behaves under load. Almost all commercial solid metals are polycrystalline. Each individual crystal or grain is a structure composed of a very large number of atoms of the constituent elements. These atoms are arranged in cells within each crystal in a regular, repetitive three-dimensional pattern. Adjacent cells share the corner atoms and their positions are balanced by electrical forces of attraction and repulsion. Applied forces can cause distortion of the cells. Shear deformation represents a sliding action on planes of atoms in crystals. In a polycrystalline metal slight deformation causes no permanent change in shape, it is called elastic deformation. That is, the metal returns to its original size and shape, like a spring, after being unloaded. If a greater load is imposed, permanent or plastic deformation occurs

because of irreversible slip between certain planes of atoms that make up the crystal structure. If the applied load or force is continued, the shear deformation causes tiny microvoids to form in the most highly stressed region. These tiny voids soon interconnect and form fracture surfaces. The cleavage mode of separation of the cell is different. In this case separation occurs suddenly between one face of the cell and the mating face of the adjacent cell without any deformation being present.

Fracture will originate whenever the local stress, i.e. load per unit cross-sectional area, first exceeds the local strength. This location will vary depending upon the strength of the metal and the applied stress. When a shaft or similar shape is pulled by tensile force it becomes longer and narrower. For ductile metals the shear strength is the weak link and these metals fail through the shear mode. These metals fail when shear stress exceeds the shear strength. In the case of brittle metals, these fail because the tensile stress exceeds the tensile strength. Brittle metals always have a fracture that is perpendicular to the tensile stress and little or no deformation because fracture takes place before the metal can deform plastically as ductile metals do.

When a cylinder is loaded in axial compression, a ductile metal becomes shorter and thicker. In short it bulges when squeezed by the compressive force and there is no fracture. A brittle metal in pure compression will fracture parallel to the length of the cylinder.

1.4.2.6 Brittle and ductile fracture

Fracture preceded by a significant amount of plastic deformation is known as ductile fracture, otherwise it is brittle fracture. Brittle fracture occurs, when plastic flow is inhibited either by the effective locking of atomic dislocations by precipitates or elements or by the pre-existence or formation of cracks and imperfections acting as local stress raisers in the material. All materials can be embrittled if the temperature is lowered sufficiently. Glass, sealing wax, germanium, silicon and other materials though ductile at temperatures close to their melting point are brittle at ordinary temperatures. In most materials the brittle strength, defined as the maximum tensile stress withstood without the occurrence of brittle fracture, is low compared with the ideal strength the fault-free material would be expected to exhibit. The source of brittle fracture is therefore to be sought in the presence of structural defects.

As has already been mentioned brittle metals always have a fracture that is perpendicular to the tensile stress and have little or no deformation because fracture takes place before the metal can deform plastically. Thus a tensile fracture of a brittle metal has a fracture plane that is essentially straight across. It also usually has a characteristic bright sparkling appearance when freshly fractured.

The pattern of a break can often reveal how the failure was precipitated. For example, if the break was caused by a sudden shock load such as an explosion, there are usually chevron-shaped formations present that point to the origin of fracture. When a stress concentration is present, such as a weld on a structure that is subject to a sudden overload, the fracture is usually brittle across the entire break, showing crystals, striations, and wave fronts. Brittle fractures are often intergranular (along the grain boundaries); this gives the fracture surface a rock candy appearance at high magnification. When grain boundaries are weakened by corrosion, hydrogen, heat damage, or impurities, the brittle fracture may be intergranular. Brittle failures can also be transgranular (through the grains): this is called cleavage.

Cleavage fracture is confined to certain crystallographic planes that are found in body centred cubic or hexagonal close-packed crystal structures. For the most part, metals having other

crystalline unit structures do not fail by cleavage unless it is by stress-corrosion cracking or by corrosion fatigue. Cleavage should normally have a flat, smooth surface; however, because metals are polycrystalline with the fracture path randomly oriented through the grains and because of certain imperfections, certain patterns are formed on the surface.

Small quantities of hydrogen have a great effect on the ductility of some metals. Hydrogen can get into steels when they are heated in an atmosphere or a material containing hydrogen, such as during pickling or cleaning operations, electroplating, cold working, welding in the presence of hydrogen-bearing compounds, or the steel-making process itself. There is a noticeable embrittling effect in steels containing hydrogen. This can be detected in tensile tests and seen in the plastic region of the stress- strain diagram showing a loss in ductility. Electroplating of many parts is required because of their service environment to prevent corrosion failure. Steel may be contaminated by electroplating materials that are commonly used for cleaning or pickling operations. These materials cause hydrogen embrittlement by charging the material with hydrogen. Mono-atomic hydrogen is produced by most pickling or plating operations at the metal-liquid interface, and it seems that single hydrogen atoms can readily diffuse into the metal. Preventive measures can be taken to reduce this accumulation of hydrogen gas on the surface of the metal.

A frequent source of hydrogen embrittlement is found in the welding process. Welding operations in which hydrogen-bearing compounds such as oil, grease, paint, or water are present, are capable of infusing hydrogen into the molten metal, thus embrittling the weld zone. Special shielding methods are often used that help to reduce the amount of hydrogen absorption. One effective method of removing hydrogen is a 'baking' treatment in which the part, or in some cases the welding rod, is heated for long periods of time at temperatures of 121 to 204°C. This treatment promotes the escape of hydrogen from the metal and restores the ductility.

Stress raisers such as notches on the surface of a material have a weakening effect and cause embrittlement. A classical example is provided by the internal notches due to graphite flakes in cast irons. The flakes embrittle the irons in tension. Therefore in structural applications cast irons are most usefully employed under compressive loads. Their brittle strength and toughness can, however, be increased appreciably if the graphite is allowed to form in spheroidal rather than flaky form. This can be done by alloying the melt, for example, with magnesium.

1.4.3 Concepts of rupture development in metals

Most of the ideas related to the development of defects in materials have already been discussed in Section 1.4.2. Rupture occurs when the size of these defects, especially cracks, reaches a certain critical size. These concepts related to rupture and critical size of cracks are usually studied under fracture mechanics.

1.5 QUALITY AND STANDARDIZATION

1.5.1 Need for quality control and assurance

In any manufacturing, fabrication or production process, the quality of the structure or component produced (or service provided) is a key factor in the long term economic and engineering success of that process. Increasing awareness of the importance of quality in every area of technology has resulted from sensitivity to growing pressure of international

competition, more discriminating demands from the marketplace and stricter consumer protection and product liability legislation. Part of this awareness is that consistent quality requires much more than product testing. The need to identify and correct inadequacies well before the final product is ready for shipping or handover has become an economic priority in many industries. Quality Control is required because of changing buyer-producer relationships and major marketplace demands for quality.

The social and economic demands for effective use of materials and production processes to turn out higher technology based products assure the need for quality assurance. Similarly the changing work practices in factories and offices and the need to compete in international markets require total quality control of all products and services.

Because the human factor is of great importance in the quality control operation, special attention must be paid to the personnel in the organization. They need to be educated to the benefits of quality control, they need to feel involved in the quality control process and they must be able to communicate with other personnel on quality control. This allows them to develop a quality control spirit and improved morale necessary to the success of any quality control programme.

Quality circles have been developed in many factories to oversee the quality of products. These involve staff representatives at all levels who meet for short periods of time, e.g. an hour, every week, to discuss the quality control of their product and any changes necessary.

Quality control has its roots in the guilds of the Middle Ages where quality was assured by long periods of training. This training instilled in workers pride for the workmanship in their product. Specialization of jobs, as industry grew, meant workers no longer made the entire product. This resulted in a decline in workmanship and alienation of the work force. As products became more complicated it became necessary to inspect them after manufacture. In the 1920's statistics were applied, initially at the Bell Laboratories in the USA, in the development of acceptance sampling as a substitute for 100% inspection. General acceptance of the techniques occurred during World War 2 when the early Military Standards containing quality control clauses were developed. Subsequently Quality Control Institutes and Standards Associations were formed. The Institutes promoted the use of quality control techniques for production and service, through publications, conferences and training. Standards Associations have promoted the development of universal standards which may be adopted as part of the quality control process.

1.5.2 Basic definitions related to quality and standardization

1.5.2.1 Quality

Quality of an industrial product does not mean the best or excellent. On the other hand it is defined as the fitness of the product to do the job required of it by the user. It may also be said to be the ability of the product to meet the design specifications which usually are set keeping in view the purpose and the use to which the product is expected or intended to be put. As stated earlier it would be better to set or define an optimum quality level for a product rather than trying to make it of best possible quality which will unnecessarily make the product more expensive which may not be acceptable to the customer.

In a generalized way, the typical characteristics of industrial products which help in defining and fixing its specifications and quality are chemical composition, metallurgical structure, shape and design, physical properties of strength and toughness, appearance, environmental properties, i.e.

response to service conditions and presence or otherwise of internal defects. These requirements should be met within the specified tolerances. The cost, of course, is an important component. The ability of an organization to meet quality criteria in production of goods or services will ultimately bear on the profitability and survivability of that organization. If it cannot produce goods to the customer's requirements, it cannot compete except under very abnormal and short-term circumstances. However, if the customer's requirements are impossible to meet, or difficult to meet within the financial constraints imposed, the solution may very well be to redefine the requirement. Insistence on an unnecessarily high performance requirement may be completely impractical. In every industry, in every corner of the world, striving for quality has become a popular activity, applied with more or less success depending on the organization and its level of commitment. It should be recognized that quality is not an accident, rather, it should be planned. Quality cannot be inspected into a product after it is made. Instead, the inspection criteria are only to verify that quality criteria are being achieved. The complexity of management of quality within an organization depends on the complexity of the product and the process as well as on the performance criterion. Once a customer's requirement is accepted, quality is the producer's responsibility.

1.5.2.2 Quality control

Quality control can be defined as the controls applied at each manufacturing stage to consistently produce a quality product or in another way it is said to be the applications of operational techniques and activities which sustain quality of a product or service that will satisfy given needs, also the use of such techniques and activities. The concept of total quality control is defined as a system for defining, controlling and integrating all company activities which enable economic production of goods or services that will give full customer satisfaction. The word "control" represents a management tool with four basic steps, namely, setting quality standards, checking conformance with the standards, acting when the standards are not met and assessing the need for changes in the standards.

In brief the objective of quality control is to provide the customer with the best product at minimum cost. This can be achieved by improvements in product design, consistency in manufacture, reduction in costs and improved employee morale. The factors affecting product quality can be divided into two major groups. First one is the technological which includes machines, materials and processes and second the human which includes operators, foremen and other personnel. The latter is the more important.

1.5.2.3 Quality assurance

As the name suggests quality assurance is the taking of all those planned and systematic actions necessary to assure that the item is being produced to optimum quality level and it will, with adequate confidence, perform satisfactorily in service.

Quality assurance is aimed at doing things right the first time and involves a continuing evaluation of the adequacy and effectiveness of the overall quality control programme with a view to having corrective measures initiated where necessary. For a specific product or service this involves verification audits and evaluation of quality factors that affect the production or use of the product or service.

Quality assurance is quality control of the quality control system.

1.5.2.4 Examination and testing

Examination and testing are those quality control functions which are carried out, during the fabrication of an industrial product, by quality persons who are employees of the manufacturer. Testing may also be defined as the physical performance of operations (tests) to determine quantitative measures of certain properties. Most of the non-destructive testing is performed under this heading.

1.5.2.5 Inspection

Inspections are the quality control functions which are carried out, during the fabrication of an industrial product by an authorized inspector. They include measuring, examining, testing, gauging or otherwise comparing the findings with applicable requirements. An authorized inspector is a person who is not the employee of the manufacturer of an industrial product but who is properly qualified and has the authority to verify to his satisfaction that all examinations specified in the construction code of the product have been made to the requirements of the referencing section of the construction code.

1.5.2.6 Process of standardization

The objective of most non-destructive testing methods is to detect internal defects with respect to their nature, size and location. This is done by different methods depending upon their inherent capability or sensitivity to flaw detection. A method is said to have a good or high sensitivity of flaw detection when it can detect relatively smaller flaws and vice versa. The sensitivity of flaw detection for different NDT methods depends upon a number of variable factors. Now imagine that someone is to perform, say, ultrasonic testing of circumferential welds in steel pipes of 50 cm diameter having a 10 cm wall thickness. He will undertake extensive experimentation to establish the values of different variable factors to evolve a method which gives reliable and reproducible results of desired sensitivity. This person is wise enough to carefully write down his procedure for testing of pipe welds. If someone else anywhere had a problem of ultrasonically inspecting pipe welds of similar specifications, there would be two options open to him. First he could undertake all the extensive experimentation involving lot of time, effort and money, and second he could request the first person and use his procedure which was known to be giving reliable and reproducible results of desired sensitivity. Many persons in one city, country or different countries could use this method as a guide or recommended procedure or practice. These many persons might sometimes get together in a meeting, conference or a committee to exchange their views and experience related to this procedure. They might mutually agree on a standard procedure for ultrasonic testing of circumferential welds in steel pipes of 50 cm diameter and 10 cm wall thickness and recommend it to the standard issuing authority of their country to issue this as a national standard. Some such standards issued by the standard issuing authority of the country could be taken up by the legislature or parliament of the country and their use made obligatory by law. This briefly explains in very simple terms the otherwise complex and time consuming process of formulation and issuance of codes and standards.

1.5.2.7 Guides and recommended practices

Guides and recommended practices are standards that are offered primarily as aids to the user. They use verbs such as "should" and "may" because their use is usually optional. However, if these documents are referenced by codes or contractual agreements, their use may become

mandatory. If the codes or agreements contain non-mandatory sections or appendices, the use of referenced guides and recommended practices by them, are at the user's discretion.

1.5.2.8 Standards

Standards are documents that govern and guide the various activities occurring during the production of an industrial product. Standards describe the technical requirements for a material, process, product, system or service. They also indicate as appropriate, the procedures, methods, equipment or tests to determine that the requirements have been met.

1.5.2.9 Codes and specifications

Codes and specifications are similar types of standards that use the verbs "shall" or "will" to indicate the mandatory use of certain materials or actions or both. Codes differ from specifications in that their use is mandated with the force of law by governmental jurisdiction. The use of specifications becomes mandatory only when they are referenced by codes or contractual documents. A prime example of codes is the ASME boiler and pressure vessel code which is a set of standards that assure the safe design, construction and testing of boilers and pressure vessels.

1.5.2.10 Procedure

In non-destructive testing, a procedure is an orderly sequence of rules or instructions which describe in detailed terms where, how and in which sequence an NDT method should be applied to a production.

1.5.2.11 Technique

A technique is a specific way of utilizing a particular non-destructive testing method. Each technique is identified by at least one particular important variable from another technique within the method (Example: RT method; X-ray/Gamma ray Techniques)

1.5.2.12 Report

A report of a non-destructive examination or of testing is a document which includes all the necessary information required to be able to:

(i) Take decisions on the acceptance of the defects by the examination.

(ii) Facilitate repairs of unacceptable defects.

(iii) Permit the examination or testing to be repeated.

1.5.2.13 Records

Records are documents which will give, at any time in the future, the following information about a non-destructive testing examination, (i) the procedure used to carry out the examination, (ii) the data recording and data analyzing techniques used, and (iii) the results of the examination.

1.5.3 Responsibility for quality

The departments responsible for quality are listed in Figure 1.69. Quality is not the responsibility of any one person or department; it is everyone's job. It includes the assembly line worker, the typist, the purchasing officer and the managing director.

The responsibility for quality begins when marketing department determines the customer quality requirements and continues through to the satisfied customer.

As can be seen from Figure 1.69 the responsibility for quality is delegated to all departments. Each has the authority to make quality decisions. The figure also shows the ideal place for an effective Quality Control department; it is independent, reporting directly to upper level management.

1.5.3.1 Inspection and test department

Inspection and test department has the responsibility to appraise the quality of purchased and manufactured items and to report the results. These results can be returned to other departments so that corrective action can be taken when necessary.

In order to perform inspection, accurate equipment is necessary. This means it must be maintained and regularly calibrated.

It is necessary to continually monitor the performance of inspectors. Some defects are more difficult to find and require more patience. Inspectors vary in ability and the defect level affects the number of defects reported. Samples with known defects should be used to evaluate and improve the inspectors' performance. The reliability of inspection can usually be quantified and is most often affected by the operator and not the possible defects in the component presented for inspection. Education (training) is the most effective way of improving reliability.

1.5.3.2 Quality control department

The quality control department does not have direct responsibility for quality. It assists or supports the other departments as they carry out their responsibilities. The relationship between the departments and quality control is similar to a line-staff organizational relationship.

Quality control appraises the current quality, determines quality problem areas and assists in the correction or minimization of these problem areas. The overall objective is the improvement of the product quality in co-operation with the responsible departments.

1.5.4 Quality control applications of NDT

Quality control of manufactured goods is accomplished by measuring dimensions, properties or other characteristics, comparing the measurements with predetermined standards and varying the manufacturing process as necessary to control these characteristics. Often direct measurements of characteristics can be accomplished only by destroying the parts. Obviously a product that has been destroyed cannot be sold. The commercial impact of this fact is two fold; costs were incurred to make the product, yet no profit can be made from its sale. However, if the same information can be obtained without destroying the part, even if only as indirect measurement, then the part can be sold for a profit after it has been tested. The commercial incentive to test non-destructively is large when small quantities and large profit margins are involved and is crucial with one of a kind products.

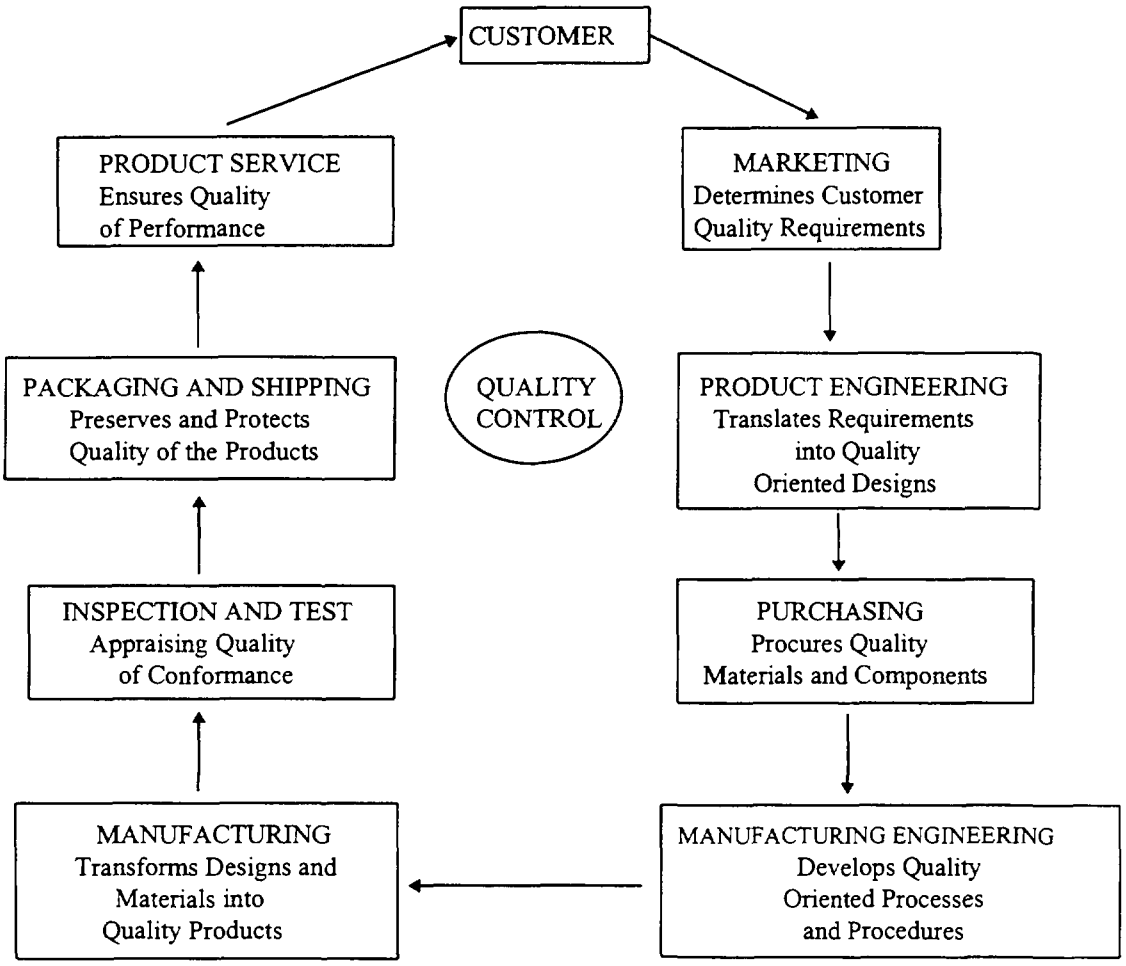


Figure 1.69 : Departments responsible for quality.

Various methods have been developed for accurately and reliably measuring characteristics of parts without affecting their commercial value. Many of these are indirect methods, but they have gained wide acceptance as tools that can aid both management and production personnel in reducing costs and improving product quality. Also use of non-destructive inspection has become necessary as a means of meeting certain legal and contractual requirements affecting the production and sale of a wide variety of manufactured products.

Factors that contribute to the reliable application of several of the major processes of non-destructive inspection are considered later.

1.5.4.1 Quality of inspection

As with all production processes many quality considerations must be applied to the control of non-destructive inspection processes to ensure that the information being supplied from them is accurate, timely and germane (i.e. relevant). One of the greatest problems of non-destructive inspection has been misapplication which usually meant that the wrong information was supplied. Thus non-destructive inspection sometimes has had only limited usefulness as a production or technical tool. Also only when the capability of a non-destructive process is known in quantitative terms can the inspection results be considered a measure of true product quality.

Successful application of non-destructive methods to the inspection of manufactured goods requires that:

(i) The test system and procedure be suited to both inspection objectives and types of flaws to be detected.

(ii) The operators have sufficient training and experience.

(iii) The standard for acceptance appropriately defines the undesirable characteristics of a non-conforming part.

If any of these pre-requisites is not met, there is a potential for error in meeting quality objectives. For instance, with inappropriate equipment or with a poorly trained operator, gross errors are possible in detecting and characterizing flaws. This is of particular concern if it means chronic failures to detect flaws that seriously impair service performance. With inadequate standards, flaws having little or no bearing on product performance may be deemed serious, or significant flaws may be deemed unimportant.

It is necessary that the types of flaws that can be induced by each manufacturing operation are understood, only then is it practical to define the non-destructive inspection that should be used. For instance, if a forging is inspected for internal forging cracks by radiography it is important to determine the direction of grain flow (and hence the most probable direction of cracking) because any cracks that are not aligned with the radiation beam will usually not be detected. Even when the direction of grain flow is known it may be difficult to orient the radiation beam properly but it is usually easy and effective to inspect the part ultrasonically.

As used in non-destructive testing and quality control, the term 'defect' means a detectable lack of continuity or a detectable imperfection in a physical or dimensional attribute of a part. The fact that a part contains one or more flaws does not necessarily imply that the part is non-conforming to specification or is unfit for use. Similarly the term 'non-conforming' means only that a part is deficient in one or more specialized characteristics. It should not be automatically assumed that a non-conforming part is unfit for use. In many instances a non-conforming part is entirely capable of performing its intended function even in its non-conforming condition. In other instances a non-conforming part can be reworked to make it conform to specifications. Of course sometimes a non-conforming part can neither be used nor reworked and must be scrapped.

1.5.4.2 Human factors

Education of all levels of personnel engaged in non-destructive inspection, including formal training, and certification in accordance with government, technical society or industry standards, is probably the greatest single factor affecting the quality of non-destructive inspection. All methods of non-destructive inspection are highly dependent on operators for obtaining and interpreting data. Inadequate education of personnel jeopardizes the reliability of inspection. This applies even to automated inspection which is controlled by the accept-reject criteria programmed into the process. Automatic data analysis techniques must be established, proven and monitored by competent non-destructive inspection personnel. In general, inspection should be performed by personnel who are trained to the national equivalent of ISO 9712 Level 2 in the particular method being used. Supervisory personnel should have skill equivalent to ISO 9712 Level 3.

The effects of human factors on the non-destructive inspection process must also be considered. It has been found through independent statistical studies that different people have widely differing abilities to find all the flaws in a part, even when the same non-destructive process and specific inspection procedure is used. This variability is usually more pronounced with small flaws. There is also a pronounced variation in the effect of factors such as heat, lighting, ventilation, fatigue and attitude on the performance of properly trained and qualified operators. As a result of these studies, confidence curves have been established showing the probability of detection versus defect size for each of the major non-destructive inspection processes. Human factors should always be considered by the design and quality control engineers when setting maximum allowable defect sizes or while setting accept-reject criteria.

1.5.4.3 Acceptance limits

The setting of accept-reject criteria is important to the quality of non-destructive inspection. Limits that are too strict unnecessarily increase both manufacturing and inspection costs, and often require special manufacturing techniques to meet the strict acceptability limits. Acceptance limits are usually indicated on the design drawing or specification. Often, however, these limits have been selected arbitrarily. It is a function of quality engineering to review acceptance criteria, ascertain that they are appropriate and can be met in production, and then approve them. It is often necessary, after production, to see if changes are needed. An acceptance limit that is too strict increases cost, but one that is too lax can contribute to failure to meet service requirements.

Fracture mechanics can be used to establish acceptance limits for critical parts, because it describes product performance in terms of the size of any flaw that might be present and can aid in establishing whether in-service inspection is necessary. Fracture mechanics studies usually are undertaken only for critical parts because such studies are exacting and expensive. Inspection criteria should include probability/confidence limits for the inspection procedure because it is not the smallest defect that must be detected, but the largest defect that might be missed that ultimately determines the reliability of a part (also see Sections 8.2.1 to 8.2.3).

1.5.4.4 Inspection standards

Inspection standards should be established so that decisions to accept/rework or scrap parts are based on the probable effect that a given defect will have on the service life or product safety. Once such standards are established non-destructive inspection can characterize flaws in terms of a real effect rather than on an arbitrary basis that may impose useless or redundant quality requirements.

Most non-destructive inspection methods rely on a reference standard to define acceptance limits or to estimate defect sizes. However, there often is no recognized universal standard that can be used on diverse products or to satisfy varying inspection requirements of individual users. For instance ultrasonic inspection is widely used to inspect adhesive bonded structures, yet the variety of designs, materials and adhesives that are used do not permit a standard reference panel that is universally acceptable to be produced. Under normal circumstances, producer and consumer agree in advance as to the design of the reference standard and to the procedure for using it.

1.5.4.5 Effect of manufacturing operations

It is difficult to define the best point in a sequence of manufacturing operation at which inspection should be performed. Obviously, there should be some type of final inspection after all manufacturing operations have been completed. However, final inspection is often far from optimal as regards either quality of inspection or overall economy of manufacture. In many instances it is easier, more reliable and more economical to perform limited inspection at each of several points in the manufacturing sequence rather than performing all inspections at the end of the sequence. In general, the principles listed below should be followed when choosing the point of inspection:

(i) Inspect raw material for flaw that may have been missed by the supplier's inspection and that can interfere with manufacturing operations or will reduce performance of the finished part.

(ii) Perform intermediate inspection following each operation or series of operations that have a significant probability of introducing serious flaws.

(iii) Perform intermediate inspection when the part shape affords easiest access to the region to be examined.

(iv) Limit the extent of non-destructive inspection to detection of flaw having a size, type and location that will significantly affect subsequent manufacturing operations or service performance.

(v) Use different inspection methods to detect different types of flaws particularly when no single method yields an optimal balance between inspection cost and sensitivity to the various types of flaws.

(vi) Perform final non-destructive inspection only to detect those flaws that could have been introduced after the last previous inspection or to serve as a check (audit) of intermediate inspection.

Characteristically, non-destructive tests are easiest to perform and most effective when applied to incoming stock or at intermediate points in the manufacturing process rather than at final inspection. From the standpoint of manufacturing economy it is foolish to spend time and effort processing parts that already contain flaws that exceed allowable limits. Consequently it is desirable to find non-conforming parts and remove them from the normal process flow as soon as possible after the non-conformance is introduced. Of course, each set of operations will be different from all others and each situation should be studied to determine where in the manufacturing sequence non-conformance can be detected with greatest effectiveness and least cost. Point of greatest effectiveness may not coincide with points of least cost so trade-offs to achieve optimal balance may have to be made. In some instances, a highly sensitive non-destructive test method cannot be economically justified. Usually a less costly method can be substituted but with an accompanying reduction in sensitivity.

1.5.5 Quality manuals

A quality manual is a document which lays down the basic policies and principles on which the inspection group functions and provides the co-ordination links with the others. More detailed collections of operating procedures, resource information and data upon which the inspection group's quality depends are also included. It is a working document describing the reality of the group's operations for use by both management and staff.

Typical elements of a quality manual are:

(i) Table of contents
(ii) Amendment of records
(iii) Introduction
(iv) Management of quality system
(v) Description of group and its function
(vi) Staff
(vii) Equipment
(viii) Testing environment
(ix) Test methods
(x) Operational procedure
(xi) Control of test items
(xii) Test records
(xiii) Diagnostic and corrective actions
(xiv) Test reports
(xv) Subcontracting
(xvi) Occupational health and safety
(xvii) Proprietary rights and confidentiality
(xviii) Accreditations held

1.5.6 Quality system

Quality system, also called quality assurance system, has already been defined in Section 1.5.2.3. It is an effective method of attaining and maintaining the desired quality standards. It is based on the fact that quality is the responsibility of the entire organization and that inspection alone does not assure quality or more precisely, does not assure conformance to requirements of the control or customer order. This applies not only to complex products such as satellites or nuclear submarines, but also to simple products such as nails or pipe fittings. Regardless of the product or service involved, the essentials of an effective quality assurance system include:

(i) Independence of the quality assurance department from the design and production departments.

(ii) Standards of quality that reflect both the needs of the customer and the characteristics of the manufacturing process.

(iii) Written procedures that cover all phases of design, production, inspection, installation and service, with a programme for continuous review and update of these procedures.

(iv) Control of the flow of documents such as order entry, order changes, specifications, drawings, route slips, inspection tickets and shipping papers.

(v) Methods for maintenance of part identity which must establish traceability through the process.

(vi) Methods for timely detection and segregation of non-conforming material which must also include programmes for corrective action.

(vii) Schedules for periodic calibration of inspection equipment.

(viii) Schedules for retaining important records.

(ix) Programmes for training and qualification of key production and inspection personnel.

(x) Systems for control of specifications incorporated into purchase order; for control of the quality of purchased goods and for appropriate inspection of purchased goods.

(xi) Systems for control of manufacturing, assembly and packaging processes, including inspection at key points in the process flow.

(xii) A system for periodic audit of any or all of the above by persons having no direct responsibility in the area being audited.

The quality assurance system is an evaluation or audit of each one of these subsystems to determine how effectively the functions are being performed. Evaluations are usually conducted each year to determine which elements and subsystems need improvement. The overall rating provides a comparison with past performance or with other plants of a multiplant corporation. These subsystems are briefly described in the following sections.

1.5.6.1 Independence of quality assurance department

Responsibility for the development, operation and monitoring of an effective quality assurance programme in a plan usually rests with the quality assurance manager. Companies having several plants may have a corporate quality assurance department that reviews and co-ordinates the system for the entire organization. To be effective this should be an independently staffed department that reports directly to an upper level manager such as general manager, vice president or president. The quality assurance department should be free to devise and recommend specific systems and procedures and require corrective action at their discretion.

1.5.6.2 Establishment of quality standards

No single quality level is necessary or economically desirable for universal use; the quality requirements of a paper clip are obviously quite different from those of a nuclear reactor. Many professional groups, trade associations and government agencies have established national codes and standards. However these codes and standards generally cover broad requirements, whereas a set of detailed rules for each product or class of products is required for the control of quality.

In most plants it is the responsibility of the quality assurance manager to interpret national codes and standards in terms of the purchase order and from these to devise process rules uniquely suited to the specific products and manufacturing methods used in that particular plant. The set of process rules thus devised may be known by various names: in these training notes it will be called an 'operating practice description'. There may be thousands of operating plant descriptions in plant files, each varying from the others as dictated by code or customer requirements, limits on chemical composition or mechanical properties, or other special

characteristics. Large plants may have computerized storage systems permitting immediate retrieval of part or all of the operating practice descriptions at key locations throughout the plant.

1.5.6.3 Written procedures

Written procedures are of prime importance in quality assurance. Oral instructions can be inadequately or incorrectly given and thus misunderstood and incorrectly followed. Clear and concise written instructions minimize the likelihood of misinterpretation. Vague generalizations that do neither assign specific responsibilities nor determine accountability in case of error must be avoided. For instance, procedures should be specific regarding the type and form of inspection records, the identity of the individual who keeps the records and where the records are kept. Similarly, a calibration procedure should not call for calibration at `periodic intervals' but should specify maximum intervals between calibrations. Depending on the type of equipment, calibration may be performed at intervals ranging from a few hours to a year or more.

1.5.6.4 Control of document flow

The original purchase order, which is often less than one page in length, may generate hundreds of other working papers before the ordered material or part is shipped. All paperwork must be accurate and must reach each work station on time. In some industries where there may be an average of two or more specifications or drawing changes per order, an effective system of material tracking that is separate and distinct from material identification is necessary.

Control of document flow places direct responsibility on departments not usually associated with quality control. The sales office (which is responsible for entry of the customer order), the production planning group (which is responsible for scheduling work and tracking material) and the accounting department (which is responsible for billing and shipping) are all involved. Many large plants have computerized order systems, the heart of which is an `active order file'. This computer file receives periodic inputs to update information on specifications, drawings, material sizes, shop operations, shipping and routing. In turn this file may be accessible from various terminals in the sales office, home office or plant, when information is needed on material location, order status and the like.

1.5.6.5 Maintaining identity and traceability of materials

In high speed manufacturing operations, particularly those involving hot work, identity markings on the raw material (such as paint mark, stencils or stamps) are usually destroyed during processing. In such instances, procedures must be devised for maintaining identity not by marking alone but also by location and count. These procedures sometimes must provide for traceability of individual units of products by a method suitable for the product and process and must include any additional identity that the customer may require. Ultimately both producer and customer must be confidant that the goods actually delivered are described accurately in the shipping papers, test reports and certificates of compliance. This confidence is of great importance in certain applications in the aerospace and nuclear industries.

1.5.6.6 Non-conforming material and corrective action

A system for detection and segregation of non-conforming material requires:

(i) Written inspection instructions that can be clearly understood.

(ii) Identified, segregated holding areas for parts that have been rejected.

(iii) A structured group (sometimes called a materials review board) to evaluate rejected material, make final judgement on its fitness for use, decide what is to be done with non-conforming material and prescribe action for the cause of rejection.

In many instances rejected parts are only slightly out of tolerance and their usefulness is not impaired. Even so, all decisions of a materials review board to accept non-conforming material must be unanimous. In the absence of unanimity, the problem may be referred to top management for a decision based on overall business judgement. In some companies, the authority of the materials review board is limited to merely deciding whether or not non-conforming material is fit for use. However, in many companies the board also determines what is to be done with non-conforming lots; whether they are to be shipped `as is', sorted, repaired or scrapped, and fixes the accountability for incurred losses. When corrective action is recommended by a materials review board, it is usually systems oriented, that is, intended to prevent recurrence of the non-conformity by avoiding its cause. In instances where a lot has been rejected because the acceptance number for a sampling plan has been exceeded, decisions concerning disposition of the lot often are made on the basis of costs, the solution that results in the least total cost to both producer and customer is adopted. Sometimes, material that is slightly out of tolerance and therefore not fit for use by one customer may meet the specifications of another customer.

1.5.6.7 Calibration of equipment

The quality assurance system must recognize that the accuracy and repeatability of measuring and testing equipment may be affected by continued use; maximum intervals between calibrations should be specified in the written quality assurance procedures. Except perhaps for small hand instruments such as micrometers, each testing machine or instrument should be plainly labelled with the last date of calibration. Calibration standards should be traceable to recognized industry or national standards of measurement. It is also desirable to maintain a central file of calibration records for each plant or department.

1.5.6.8 Retention of records

A quality assurance system must designate which records are to be retained and must set down minimum time periods for retention of such records. It is usual for important documents to be retained for 25 years or more; the nuclear industry is required to maintain records for 40 years. Retention time, however, should be consistent with real needs as dictated by projected lifetime of products or by legal requirements. Besides satisfying certain contractual or other legal requirements, retained records can provide important cost benefits to both producer and customer. In one instance, extensive and costly testing of a 50 years old structure prior to repair was avoided when the fabricator was able to produce original drawing and material test reports.

1.5.6.9 Personnel training and qualification

National codes exist for the qualification of certain specialized workers, for instance welders and inspectors. When applicable, codes should be incorporated as minimum requirements for training and qualification of key personnel. All of these, however, must be supplemented by local written procedures for both on-the-job and classroom training. Quality assurance management must reduce complex procedures to the simplest form that will permit a trainee to understand exactly what the job is and how it is to be performed.

1.5.6.10 Control of purchased material

All specifications and orders for outside purchases of material whose performance may affect product quality should be subject to approval by quality assurance management. Inspection of incoming material should be subject to approval by quality assurance management. Inspection of incoming material should be incorporated into the quality assurance programme. The main purpose of receiving inspection is to check for failures of vendor quality programmes, but receiving inspection should not be expected to compensate for poor quality control by vendors. The purchaser should evaluate and periodically audit the quality assurance system of each major supplier to make sure that the purchased material can be expected to have the specified level of quality.

1.5.6.11 Manufacturing, assembly and packaging

All manufacturing, assembly and packaging processes should be controlled to ensure attainment of the finished product of the right quality at the time of its reaching the customer. Design drawings and the processes of manufacturing and assembly should be assessed whether appropriate methods of adequate capability and sensitivity are being applied and whether the results being obtained are reliable and reproducible or not. The tests should be applied at appropriate stages during manufacture and all test reports should be properly signed by authorized persons. All manufacturing, testing, assembly and packing should be done according to verifiable written procedures.

1.5.6.12 Quality audit

Quality audit is an independent evaluation of various aspects of quality performance to provide information with respect to that performance. Quality audits are usually made by companies to evaluate their own quality performance, by buyers to evaluate the performance of their vendors, by regulatory agencies to evaluate the performance of organizations which they are assigned to regulate.

Purpose of audit is to provide assurance that:

- procedures for attaining quality are such that, if followed, the intended quality will be obtained;
- products are fit for use and safe for the user;
- laws and regulations are being followed;
- there is conformance to specifications;
- written procedures are adequate and being followed;
- the data system is able to provide adequate information on quality;
- corrective action is being taken with respect to deficiencies; and
- opportunities for improvements are identified.

For an internal quality audit typically the organization is divided up into its component parts and each area is audited. The time taken depends on the size of the organization. For a small NDT organization one could audit the following :

- documentation of NDT procedures
- control of stores

- receipt of job instructions
- purchasing of equipment and accessories
- maintenance of equipment and accessories
- calibration of equipment
- contract administration
- safety
- accounting
- office administration, e.g. wages, leave, superannuation
- organizational structure
- research and development
- reports and records

A periodic audit of quality of the system performance against written standard is needed to detect corner-cutting, non-compliance and intentional violations of established quality procedures. To be as unbiased as possible, such audits should be performed by persons not having responsibility in the area being audited. In companies having multiple plants, each individual plant may conduct its own internal audit, but in addition should be subject to audit by corporate staff personnel. The most important activities of corporate staff aside from auditing are review of the quality system with the highest level of plant management and follow up to approve corrective action for any discrepancies found during an audit.

Periodic review of the quality assurance system and reaffirmation of quality objectives by top management should be part of company policy. This will in part ensure long range viability of the business enterprise.

2. TERMINOLOGY, PHYSICAL PRINCIPLES AND FUNDAMENTALS OF ULTRASONICS

2.1 THE NATURE OF ULTRASONIC WAVES

Ultrasonics is the study of sound propagated at frequencies beyond the range audible to people (20 kHz). It was first discovered by Galton in 1883. Rapid development of the subject, however, took place during the two world wars. The use of pulse methods derived from radar techniques enhanced the scope of ultrasonics considerably and it became widely applied in non-destructive testing of materials, besides many other areas of applications such as medical diagnosis, instrumentation and control, cleaning, emulsification, drilling and various methods of processing materials. Ultrasonic is used in preference to audible sound in many applications for one or more of the following reasons:

(i) It has directional properties – the higher the frequency, the greater the directivity. This is the main consideration in, for example, flaw detection and under-water signalling.

(ii) At the higher frequencies the wavelengths become correspondingly shorter and are comparable with, or even much less than, the dimensions of the samples of the material

through which propagation takes place. This is important for the measurement of small thicknesses or for high-resolution flaw detection.

(iii) It is silent, which is advantageous for high intensity applications. These applications can often be carried out more efficiently at audible frequencies, but the resulting noise may be intolerable and possibly injurious.

Utrasound as we know is a form of mechanical vibration. To understand how ultrasonic motion occurs in a medium it is necessary to understand the mechanism which transfers the energy between two points in a medium. This can be understood by studying the vibration of a weight attached to a spring (Figure 2.1a).

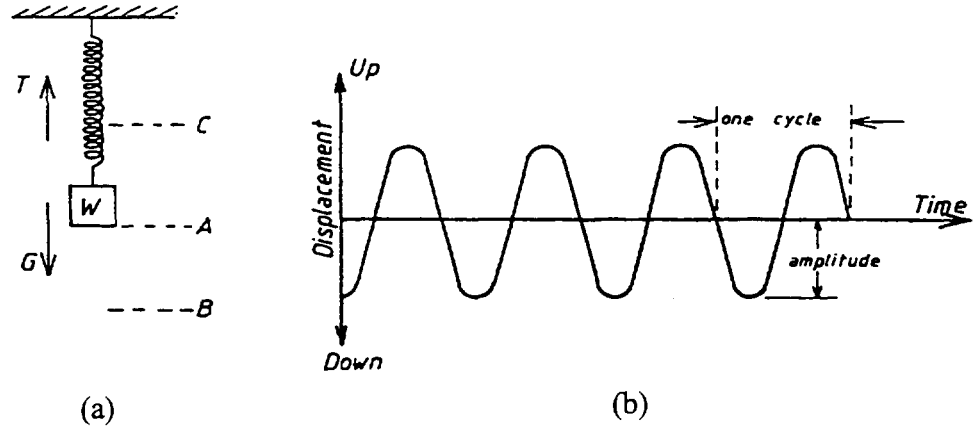


Figure 2.1 : (a) Weight attached to a spring, (b) Plot of displacement of W with time w.r.t. position A.

The two forces acting on W, while it is at rest, are force of gravity G and tension T in the spring. Now if W is moved from its equilibrium position A to position B, tension T increases. If it is now released at position B, W would accelerate towards position A under the influence of this increase in tension. At A the gravity G and tension T will again be equal, but as now W is moving with a certain velocity, it will overshoot A. As it moves towards position C, tension T decreases and the relative increase in gravity G tends to decelerate W until it has used up all its kinetic energy and stops at C. At C, G is greater than T and so W falls towards A again. At A it possesses kinetic energy and once more overshoots. As W travels between A and B, T gradually increases and slows down W until it comes to rest at B. At B, T is greater than G, and the whole thing starts again. The sequence of displacements of W from position A to B, B to A, A to C and C to A, is termed a cycle. The number of such cycles per second is defined as the frequency of vibration. The time taken to complete one cycle is known as the time period T of the vibration, where $T = 1/f$.

The maximum displacement of W from A to B or A to C is called the amplitude of vibration. All these concepts are illustrated in Figure 2.1(b).

All materials are made of atoms (or molecules) which are connected to each other by interatomic forces. These atomic forces are elastic, i.e. the atoms can be considered to be connected to each other as if by means of springs. A simplified model of such a material is shown in Figure 2.2.

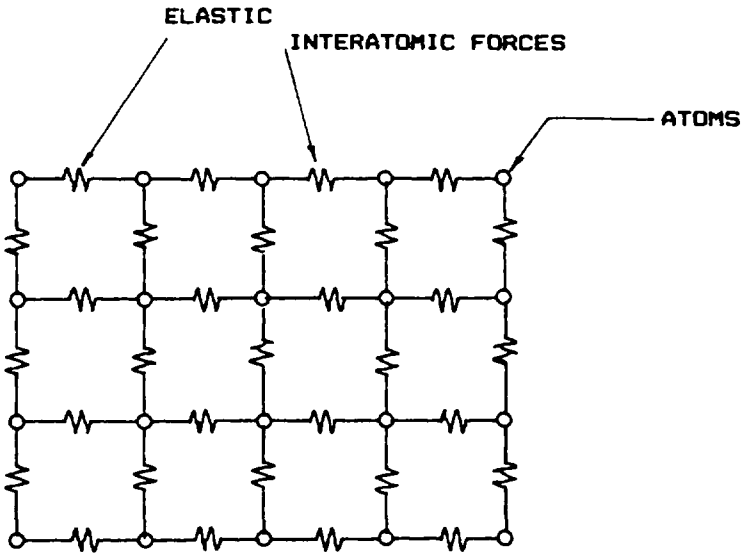


Figure 2.2 : Model of an elastic body.

Now if an atom of the material is displaced from its original position by an applied stress, it would start to vibrate like the weight W of Figure 2.1(a). Because of the interatomic coupling, vibration of this atom will also cause the adjacent atoms to vibrate. When the adjacent atoms have started to vibrate, the vibratory movement is transmitted to their neighbouring atoms and so forth. If all the atoms were interconnected rigidly, they would all start their movement simultaneously and remain constantly in the same state of motion, i.e. in the same phase. But since the atoms of a material are connected to each other by elastic forces instead, the vibration requires a certain time to be transmitted and the atoms reached later lag in phase behind those first excited.

When a mechanical wave traverses a medium, the displacement of a particle of the medium from its equilibrium position at any time 't' is given by:

$$a = a_0 \sin 2\pi ft \qquad (2.1)$$

where

a = displacement of the particle at time 't'
a_0 = amplitude of vibration of the particle &
f = frequency of vibration of the particle.

A graphical representation of Equation 2.1 is given in Figure 2.3.

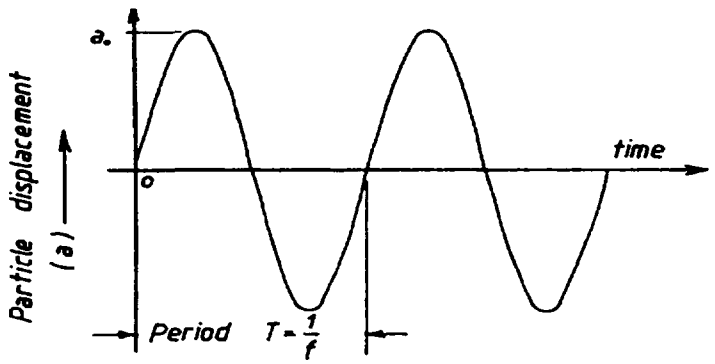


Figure 2.3 : Graphical representation of Equation 2.1 showing variation of particle displacement with time.

Equation 2.2 is the equation of motion of a mechanical wave through a medium. It gives the state of the particles (i.e. the phase) at various distances from the particle first excited at a certain time 't'.

$$a = a_0 \sin 2\pi f (t - x/v) \quad \text{----------} \quad (2.2)$$

where

a = displacement (at a time 't' and distance 'x' from the first excited particle) of a particle of the medium in which mechanical wave is travelling

a_0 = amplitude of the wave which is the same as that of the amplitude of vibration of the particles of the medium

v = velocity of propagation of the wave &

f = frequency of the wave.

Figure 2.4 below gives the graphical representation of Equation 2.2.

Since in the time period T, a mechanical wave of velocity 'v' travels a distance 'λ' in a medium, therefore we have:

$$\lambda = vT$$

or $$v = \lambda/T \quad \text{----------} \quad (2.3)$$

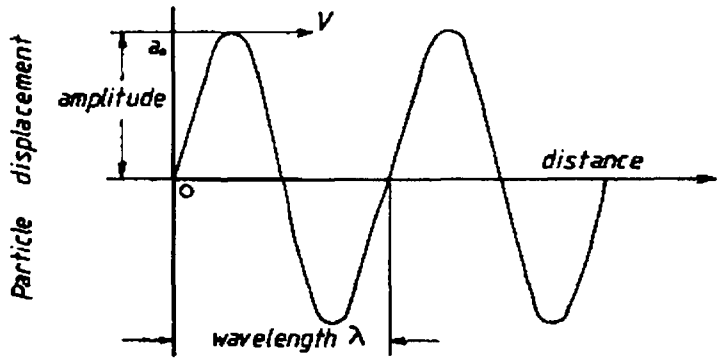


Figure 2.4 : Graphical representation of Equation 2.2.

But the time period 'T' is related to the frequency 'f' by:

$$f = 1 / T \quad \text{----------} \quad (2.4)$$

Combining Equations 2.3 and 2.4 we have the fundamental equation of all wave motion, i.e.

$$v = \lambda f \quad \text{----------} \quad (2.5)$$

In Equation 2.5 if 'f' is in Hz, 'λ' in mm then 'v' is in mm/sec. Alternatively if 'f' is in MHz, 'λ' in mm then 'v' is in kms^{-1}.

2.2 CHARACTERISTICS OF WAVE PROPAGATION

2.2.1 Frequency

The frequency of a wave is the same as that of the vibration or oscillation of the atoms of the medium in which the wave is travelling. It is usually denoted by the letter 'f ' and until recently was expressed as the number of cycles per second. The international term for a cycle per second is named after the physicist H. Hertz and is abbreviated as Hz.

1 Hz = 1 cycle per second
1 kHz = 1,000 Hz = 1,000 cycles per second
1 MHz= 1,000,000 Hz = 1,000,000 cycles per second
1 GHz = 1,000,000,000 Hz= 1,000,000,000 cycles per second

With the modern equipment, frequencies in the range of GHz can be generated. However, in general ultrasonic waves of frequency range 0.5 MHz to 20 MHz are used for the testing of materials. The most common range for testing metals is from 2 MHz to 20 MHz. Frequency plays an important role in the detection and evaluation of defects.

2.2.2 Amplitude

The displacement of the weight from its position of rest in Figure 2.1 and that of the particles of a medium in Figures 2.3 and 2.4 is called the amplitude. In Equation 2.2 'a' is the amplitude at any time 't' while 'a_o' is the maximum amplitude. (Also see Section 4.3.1.)

2.2.3 Wavelength

During the time period of vibration T, a wave travels a certain distance in the medium. This distance is defined as the wavelength of the wave and is denoted by the Greek letter λ. Atoms in a medium, separated by distance 'λ' will be in the same sate of motion (i.e. in the same phase) when a wave passes through the medium.

The relationship between 'λ' 'f ' and 'v' is given in Equation 2.5 which shows that in a particular medium the wavelength is the reciprocal of frequency. Therefore higher the frequency shorter the wavelength and vice versa. In practical testing usually flaws of the order of $\lambda/2$ or $\lambda/3$ can be detected. Therefore smaller the wavelength, smaller are the detectable defects. Thus smaller wavelength or higher frequency ultrasound waves provide a better flaw sensitivity. This is further elaborated by the following example.

Example : Compare the flaw sensitivities for probes of frequencies 1 MHz and 6 MHz in steel.

Let us assume that flaw sensitivity is of the order of $\lambda/3$. Then for a 1 MHz frequency we have

λ = v/f
= 5940 (for steel) x 1000/1 x 1000000 mm
= 5.94 mm
Flaw sensitivity = $\lambda/3$
= 1.98 mm

For the 6 MHz frequency we have

λ = 5940 x 1000 / 6 x 1000000 mm
= 0.99 mm

Flaw sensitivity = $\lambda/3$
= 0.33 mm

2.2.4 Velocity

The speed with which energy is transported between two points in a medium by the motion of waves is known as the velocity of the waves. It is usually denoted by the letter 'v'.

The velocity of propagation of longitudinal, transverse, and surface waves (Section 2.3) depends on the elastic modulus and the density of the material, and in the same material it is independent of the frequency of the waves and the material dimensions.

Velocities of longitudinal, transverse and surface waves are given by the following equations.

$$v_l = \sqrt{\frac{E}{\rho}} \quad \text{----------} \quad (2.6)$$

$$v_t = \sqrt{\frac{G}{\rho}} \quad \text{----------} \quad (2.7)$$

$$v_s = 0.9 \times v_t \quad \text{----------} \quad (2.8)$$

where

v_l = velocity of longitudinal waves
v_t = velocity of transverse waves
v_s = velocity of surface waves
E = Young's modulus of elasticity
G = modulus of rigidity
ρ = density of the material

For steel

$$v_t / v_l = 0.55 \quad \text{----------} \quad (2.9)$$

The velocity of propagation of Lamb waves depends not only on the material density but also on the type of wave itself and on the frequency of the wave.

Equation 2.6 also explains why the velocity is lesser in water than in steel, because although the density for steel is higher than that of water, the elasticity of steel is much higher than that of water and this outclasses the density factor.

Table 2.1 gives the velocities of longitudinal and transverse waves in some common materials.

2.2.5 Acoustic impedance

The resistance offered to the propagation of an ultrasonic wave by a material is known as the acoustic impedance. It is denoted by the letter Z and is determined by multiplying the density of the material by the velocity 'v' of the ultrasonic wave in the material, i.e.

$$Z = \rho v \quad \text{----------} \quad (2.10)$$

The value of the acoustic impedance for a given material can be seen to depend only on its physical properties and thus to be independent of the wave characteristics and the frequency. Values of acoustic impedances for a number of familiar materials are given in Table 2.1.

2.2.6 Acoustic pressure

Acoustic pressure is the term most often used to denote the amplitude of alternating stresses on a material by a propagating ultrasonic wave. Acoustic pressure P is related to the acoustic impedance Z and the amplitude of particle vibration `a' as:

$$P = Z.a \quad \text{----------} \quad (2.11)$$

where

P = acoustic pressure
Z = acoustic impedance
a = amplitude of particle vibration

Because it takes a small but finite time for the energy to pass from one layer to the next, the phase of the vibration of each layer differs from that of its neighbour by a small but finite amount. The sound energy thus takes a given time to pass from the source to the receiver (Equation 2.2).

2.2.7 Acoustic energy

Imagine a circular disc which vibrates and generates sound waves. If the material of propagation is imagined to be divided into very large number of thin layers then when the disc vibrates, the layer nearest to it is pushed into the direction of propagation. The next layer is then displaced in turn and the displacements are progressively transmitted from each layer to its neighbour until the final layer is reached, the displacement of which is suffered by the receiver.

It is the energy of the vibrations or waves and not the particles themselves in the material which move from the source to the receiver. The particles themselves only vibrate about their mean positions with minute displacement amplitudes, typically of a small fraction of a millimetre.

2.2.8 Acoustic intensity

The transmission of mechanical energy by ultrasonic waves through a unit cross-section area, which is perpendicular to the direction of propagation of the waves, is called the intensity of the ultrasonic waves. Intensity of the ultrasonic waves is commonly denoted by the letter I.

Table 2.1 : DENSITIES, SOUND VELOCITIES AND ACOUSTIC IMPEDANCES OF SOME COMMON MATERIALS

Material	Density Kg/m^3	v_t m/s	v_l m/s	Z $x\ 10^3 Kg\ m^{-2}\ s^{-1}$
air	1.3	-	330	430
aluminium	2700	3130	6320	17064
aluminium oxide	3600	5500	9000	32400
barium titanate	5400	-	5000	27000
brass	8100	2120	4430	35883
cast iron	6900	2200	5300	24150
concrete	2000	-	4600	9200
copper	8900	2260	4700	41830
epoxy resin	1170	1100	2650	3150
glass	3600	2560	4260	15336
glycerine	1300	-	1920	2496
grey casting	7200	2650	4600	33120
lead	11400	700	2660	24624
magnesium	1700	3050	5770	9809
motor oil	870	-	1740	1514
nickel	8800	2960	5630	49544
nylon	1140	-	2700	3000
olive oil	900	-	1400	1300
teflon	2200	550	1350	3000
perspex	1180	1430	2730	3221
polyamide (nylon)	1100	1080	2620	2882
polyethylene	940	925	2340	2200
polystyrol	1060	1150	2380	2523
polyvinylchloride (pvc hard)	1400	1060	2395	3353
quartz	2650	-	5760	15264
quartz glass	2600	3515	5570	14482
rubber vulcanized	1200	-	2300	2800
silver	10500	1590	3600	37800
steel (low alloy)	7850	3250	5940	46620
steel (calibration block)	7850	3250	5920	46472
steel (stainless)	7800	3130	5740	44800
titanium	4500	3120	5990	27000
tungsten	19300	2880	5170	100000
tungsten avaldite	10500	-	2060	21650
uranium	18700	2020	3370	63000
water	1000	-	1480	1480
zirconium	6400	2300	4650	29800

Intensity I of ultrasonic waves is related to the acoustic pressure P, acoustic impedance Z and the amplitude of vibration of the particles as:

$$I = P^2/2Z \quad \text{----------} \quad (2.12)$$

and

$$I = P.a / 2 \quad \text{----------} \quad (2.13)$$

where

I = intensity
P = acoustic pressure
Z = acoustic impedance
a = amplitude of vibration of the particles

2.2.8.1 The decibel (dB) scale

In the study of ultrasonics, the variations of intensity and acoustic pressure often take place in a logarithmic manner and measurements are made in comparison with some fixed standard.

The decibel unit is 1/10 of a bel which is a unit based on logarithms to the base 10. If there are two ultrasonic signals which have to be compared and they have intensities I_o and I_1 then these signals will vibrate the transducer and produce electrical signals whose power will be P_o and P_1 respectively. The ratio of these signals I_o/I_1 will equal the electrical power ratio. Thus

$$I_o/I_1 = P_o/P_1 \quad \text{----------} \quad (2.14)$$

It is usual to employ an a.c voltmeter or a cathode ray oscilloscope for detection. These instruments measure a voltage which is proportional to the square root of the pressure, i.e. $P\alpha V^2$. Substituting this in Equation 2.14 we get:

$$I_o/I_1 = P_o/P_1 = (V_o/V_1)^2 \quad \text{----------} \quad (2.15)$$

Since these are likely to be rather large ratios the logarithm to the base 10 of both sides of the Equation 2.15 gives.

$$\log (I_o/I_1) = \log (V_o/V_1)^2 = 2 \log (V_o/V_1) \text{ bels}$$

Since a decibel is 1/10 bel we get

$$\text{Intensity level in decibels} = 10 \log (I_o / I_1) = 10 \log (P_o /P_1)$$

$$= 20 \log (V_o/V_1) \quad \text{----------} \quad (2.16)$$

It will be shown in Section 4.3.1, how the use is made of the decibel scale in practical ultrasonic testing.

2.3 TYPES OF ULTRASONIC WAVES AND THEIR APPLICATIONS

Ultrasonic waves are classified on the basis of the mode of vibration of the particles of the medium with respect to the direction of propagation of the waves, namely longitudinal, transverse, surface and Lamb waves. The major differences of these four types of waves are discussed below:

2.3.1 *Longitudinal or compressional waves*

In this type of ultrasonic wave alternate compression and rarefaction zones are produced by the vibration of the particles parallel to the direction of propagation of the wave. Figure 2.5 represents schematically a longitudinal ultrasonic wave.

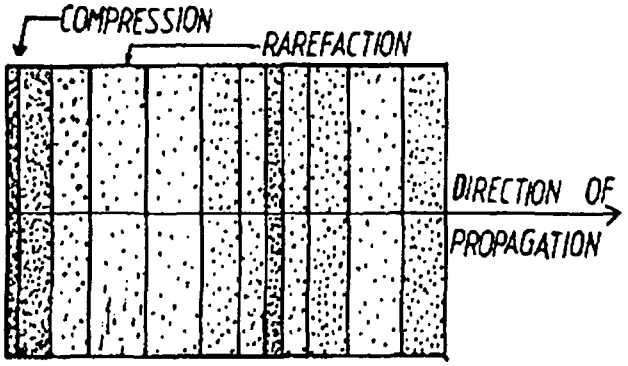


Figure 2.5 : Longitudinal wave consisting of alternate rarefactions and compressions along the direction of propagation.

For a longitudinal ultrasonic wave, the plot of particle displacement versus distance of wave travel along with the resultant compression crest and rarefaction trough is shown in Figure 2.6.

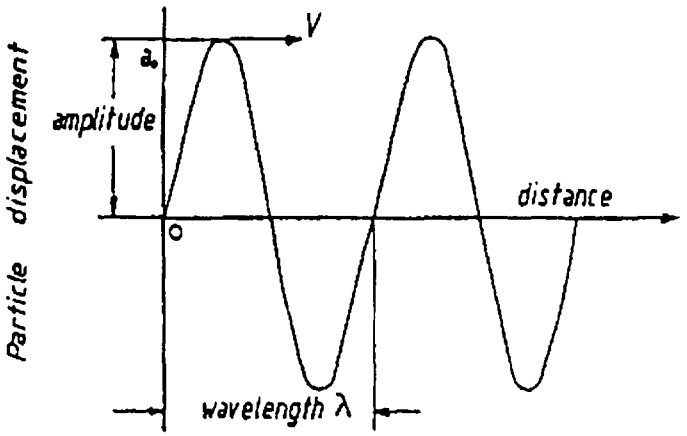


Figure 2.6 : Plot of particle displacement versus distance of wave travel.

Because of its easy generation and detection, this type of ultrasonic wave is most widely used in ultrasonic testing. Almost all of the ultrasonic energy used for the testing of materials originates in this mode and is then converted to other modes for special test applications. This type of wave can propagate in solids, liquids and gases.

2.3.2 *Transverse or shear waves*

This type of ultrasonic wave is called a transverse or shear wave because the direction of particle displacement is at right angles or transverse to the direction of propagation. It is schematically represented in Figure 2.7.

For such a wave to travel through a material it is necessary that each particle of material is strongly bound to its neighbours so that as one particle moves it pulls its neighbour with it, thus causing the ultrasound energy to propagate through the material with a velocity which is about 50 percent that of the longitudinal velocity.

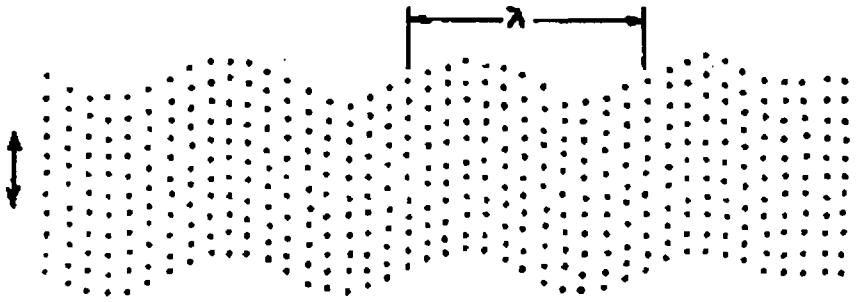


Figure 2.7 : Schematic representation of a transverse wave.

For all practical purposes, transverse waves can only propagate in solids. This is because the distance between molecules or atoms, the mean free path, is so great in liquids and gases that the attraction between them is not sufficient to allow one of them to move the other more than a fraction of its own movement and so the waves are rapidly attenuated.

The transmission of this wave type through a material is most easily illustrated by the motion of a rope as it is shaken. Each particle of the rope moves only up and down, yet the wave moves along the rope from the excitation point.

2.3.3 Surface or Rayleigh waves

Surface waves were first described by Lord Rayleigh and that is why they are also called Rayleigh waves. These type of waves can only travel along a surface bounded on one side by the strong elastic forces of the solid and on the other side by the nearly non-existent elastic forces between gas molecules. Surface waves, therefore, are essentially non-existent in a solid immersed in a liquid, unless the liquid covers the solid surface only as a very thin layer. The waves have a velocity of approximately 90 percent that of an equivalent shear wave in the same material and they can only propagate in a region no thicker than about one wavelength beneath the surface of the material. At this depth, the wave energy is about 4 percent of the energy at the surface and the amplitude of vibration decreases sharply to a negligible value at greater depths.

In surface waves, particle vibrations generally follow an elliptical orbit, as shown schematically in Figure 2.8.

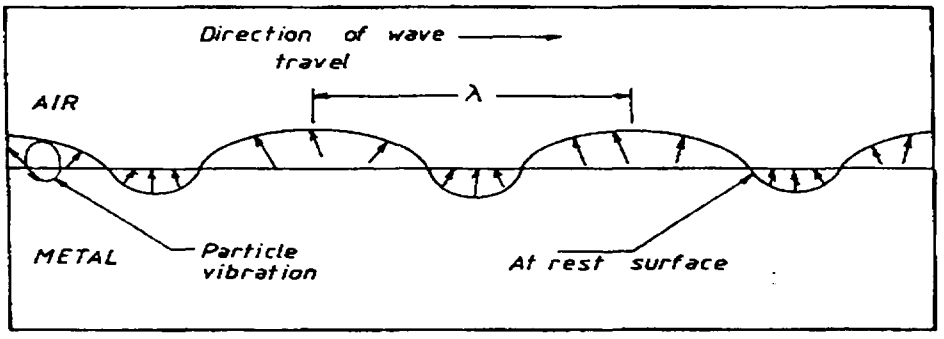


Figure 2.8 : Diagram of surface wave propagating at the surface of a metal along a metal-air interface. Small arrows indicate directions of particle displacement.

The major axis of the ellipse is perpendicular to the surface along which the waves are travelling. The minor axis is parallel to the direction of propagation. A practical method of generating surface waves is given in Section 2.4.2.3.

Surface waves are useful for testing purposes because the attenuation they suffer for a given material is lower than for an equivalent shear or longitudinal waves and because they can travel around corners and thus be used for testing quite complicated shapes. Only surface or near surface cracks or defects can be detected, of course.

2.3.4 Lamb or plate waves

If a surface wave is introduced into a material that has a thickness equal to three wavelengths, or less, of the wave then a different kind of wave, known as a plate wave, results. The material begins to vibrate as a plate, i.e. the wave encompasses the entire thickness of the material. These waves are also called Lamb waves because the theory describing them was developed by Horace Lamb in 1916. Unlike longitudinal, shear or surface waves, the velocities of these waves through a material are dependent not only on the type of material but also on the material thickness, the frequency and the type of wave.

Plate or Lamb waves exist in may complex modes of particle movement. The two basic forms of Lamb waves are (a) symmetrical or dilatational and (b) asymmetrical or bending. The form of the wave is determined by whether the particle motion is symmetrical or asymmetrical with respect to the neutral axis of the test piece. In symmetrical Lamb (dilatational) waves, there is a longitudinal particle displacement along neutral axis of the plate and an elliptical particle displacement on each surface (Figure 2.9 a).

This mode consists of the successive thickening and thinning in the plate itself as would be noted in a soft rubber hose if steel balls, larger than its diameter, were forced through it. In asymmetrical (bending) Lamb waves, there is a shear particle displacement along the neutral axis of the plate and an elliptical particle displacement on each surface (Figure 2.9 b). The ratio of the major to minor axes of the ellipse is a function of the material in which the wave is being propagated. The asymmetrical mode of Lamb waves can be visualized by relating the action to a rug being whipped up and down so that a ripple progresses across it.

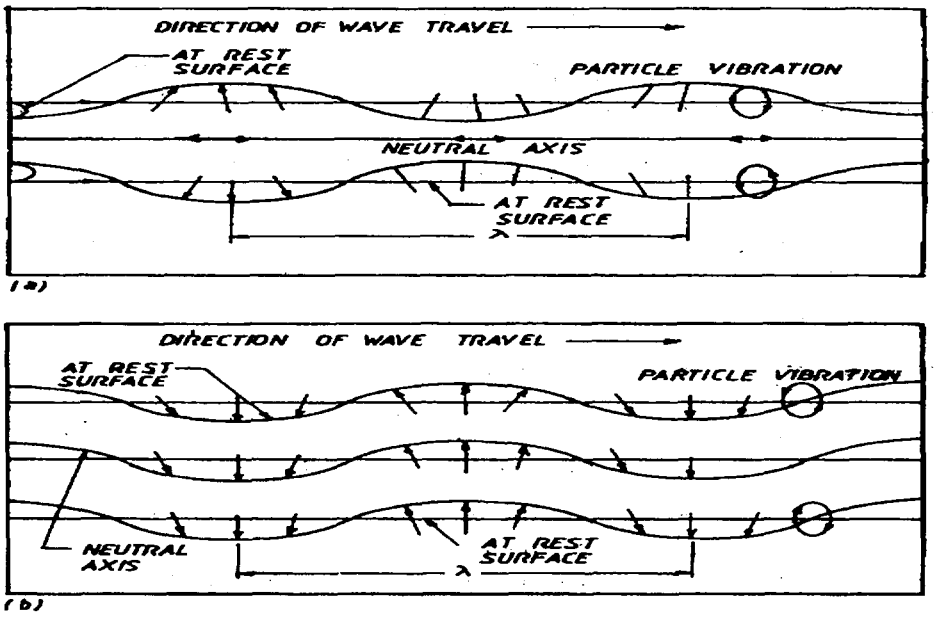


Figure 2.9 : Diagrams of the basic patterns of (a) symmetrical (dilatational) and (b) asymmetrical (bending) Lamb waves.

2.4 BEHAVIOUR OF ULTRASONIC WAVES

2.4.1 Reflection and transmission at normal incidence

2.4.1.1 Reflected and transmitted intensities

When ultrasonic waves are incident at right angles to the boundary (i.e. normal incidence) of two media of different acoustic impedances, then some of the waves are reflected and some are transmitted across the boundary. The surface at which this reflection occurs is also called an interface. The amount of ultrasonic energy that is reflected or transmitted depends on the difference between the acoustic impedances of the two media. If this difference is large then most of the energy is reflected and only a small portion is transmitted across the boundary. While for a small difference in the acoustic impedances most of the ultrasonic energy is transmitted and only a small portion is reflected back.

Quantitatively the amount of ultrasonic energy which is reflected when ultrasonic waves are incident at the boundary of two media of different acoustic impedances (Figure 2.10), is given by:

$$\text{Reflection coefficient} = \frac{\text{Intensity of reflected waves at the boundary}}{\text{Intensity of incident waves at the boundary}}$$

or $$R = I_r/I_i = (Z_2-Z_1)^2 / (Z_1+Z_2)^2 \quad \text{----------} \quad (2.17)$$

where

R = reflection coefficient
Z_1 = acoustic impedance of medium 1
Z_2 = acoustic impedance of medium 2
I_r = reflected ultrasonic intensity
I_i = incident ultrasonic intensity

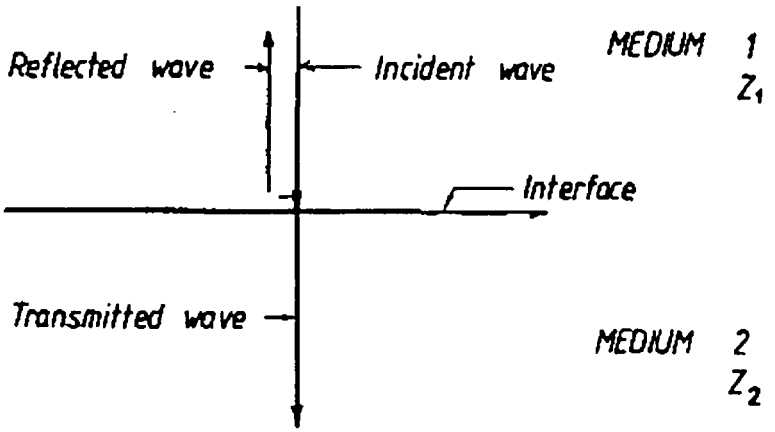


Figure 2.10 : Reflection and transmission at normal incidence.

The amount of energy that is transmitted across the boundary is given by the relation:

$$\text{Transmission coefficient} = \frac{\text{Intensity of transmitted waves at the boundary}}{\text{Intensity of incident waves at the boundary}}$$

or $$T = I_t/I_i = 4Z_1Z_2/(Z_1+Z_2)^2 \text{ ----------} \quad (2.18)$$

where

T = transmission coefficient
Z_1 = acoustic impedance of medium 1
Z_2 = acoustic impedance of medium 2
I_t = transmitted ultrasonic intensity
I_i = incident ultrasonic intensity.

The transmission coefficient T can also be determined from the relation:

$$T = 1 - R \quad \text{----------} \quad (2.19)$$

where

T = transmission coefficient
R = reflection coefficient

Using the values of the characteristic impedances given in Table 2.1 reflection and transmission coefficients can be calculated for pairs of different materials. The equations show that the transmission coefficient approaches unity and the reflection coefficient tends to zero when Z_1 and Z_2 have approximately similar values. The materials are then said to be well matched or coupled. On the other hand, when the two materials have substantially dissimilar characteristic impedances, e.g. for a solid or liquid in contact with a gas, the transmission and reflection coefficients tend to zero and 100 percent, respectively. The materials are then said to be mismatched or poorly coupled. A difficulty may arise when both the materials are solids. Unless their surfaces are ground flat to optical precision, contact occurs only in a few places and there is, effectively, a thin layer of fluid between them. If the fluid is a liquid for which the characteristic impedance is not too far removed from those of the solids and the thickness of the layer is much less than a wavelength, the value of the transmission coefficient is the same as if the two solids were in perfect contact. On the other hand, if the layer of fluid were a gas, as would be the case if the two materials were in air, the transmission coefficient is reduced almost to zero. Substitution of values of acoustic impedances, shown in Table 2.1, into Equation 2.18 gives 75 percent for the transmission coefficient when a quartz crystal is placed in perfect contact with a steel block. In practice, however, there is a gap of an effective width of 1 μm when the surface of steel is machined to a tolerance of this magnitude. At a frequency of 1 MHz, there is a reduction of transmission coefficient by only one or two per cent when the gap is filled with a liquid. On the other hand, if the gap were to contain air, the transmission coefficient would be reduced to about 4×10^{-9}, a decrease of more than 80 dB. This illustrates the importance of the use of a coupling fluid when transmitting or receiving sound waves in solids.

2.4.1.2 Reflected and transmitted pressures

The relationships which determine the amount of reflected and transmitted acoustic pressures at a boundary for normal incidence are:

$$P_r = (Z_2 - Z_1)/(Z_2 + Z_1) \quad \text{----------} \quad (2.20)$$

and

$$P_t = (2Z_2)/(Z_1 + Z_2) \quad \text{----------} \quad (2.21)$$

where

P_r = amount of reflected acoustic pressure
P_t = amount of transmitted acoustic pressure
Z_1 = acoustic impedance of material from which the waves are incident
Z_2 = acoustic impedance of material in which the waves are transmitted.

As is clear from Equations 2.20 & 2.21, P_r may be positive or negative and P_t may be greater than or less than unity, depending on whether Z_2 is greater or less than Z_1. When $Z_2 > Z_1$, e.g. water - steel boundary then P_r is positive and $P_t > 1$. This means that the reflected pressure has the same phase as that of the incident pressure and the transmitted pressure is greater than that of the incident pressure (Figure 2.11 b). The fact that the transmitted pressure is greater than the incident pressure is not a contradiction to the energy law because it is the intensity and not the pressure that is partitioned at the interface and as shown by Equations 2.20 & 2.21 the incident intensity is always equal to the sum of the reflected and transmitted intensities irrespective of whether $Z_1 > Z_2$ or $Z_2 > Z_1$. The reason for a higher transmitted acoustic pressure in steel is that the acoustic pressure is proportional to the product of intensity and acoustic impedance although the transmitted intensity in steel is low, the transmitted acoustic pressure is high because of the high acoustic impedance of steel. When $Z_1 > Z_2$, e.g. steel - water interface, then P_r is negative which means that the reflected pressure is reversed as shown in (Figure 2.11 a).

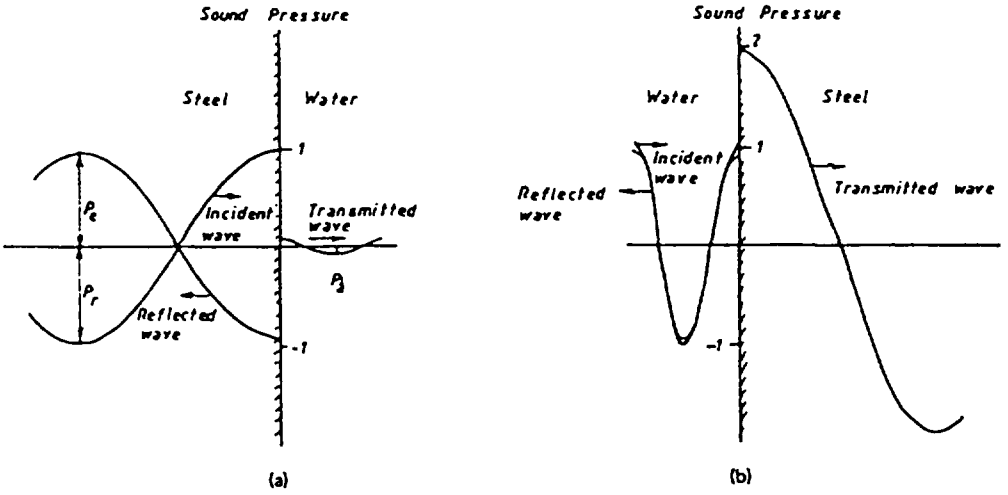


Figure 2.11 : Acoustic pressure values in the case of reflection on the interface steel-water, incident wave in steel (a) or in water (b).

Example: What would be the percentage of acoustic energy reflected and transmitted at the interface between water and steel ?

From Table 2.1 we have the following data:

$Z_{water} = Z_1 = 1480 \times 10^3 \text{ kg m}^{-2}\text{s}^{-1}$

$Z_{steel} = Z_2 = 46629 \times 10^3 \text{ kg m}^{-2}\text{ s}^{-1}$

Reflection coefficient (R) $= (Z_2-Z_1)^2 / (Z_1+Z_2)^2$
$= (46629-1480)^2 / (1480 + 46629)^2$
$= (45149)^2 / (48109)^2$
$= 2.0384322/2.3144759$
$= 0.88$

% reflection $= 0.88 \times 100$
$= 88\%$

Transmission coefficient (T) $= (4Z_1 Z_2) / (Z_1 + Z_2)^2$
$= 4 \times 1480 \times 46629 / (48109)^2$
$= 2.7604368 \times 10^8 / 23.144759 \times 10^8$
$= 0.119 = 0.12$

% transmission $= 0.12 \times 100$
$= 12\%$

Example : What percentages of the original sound energy will be reflected and transmitted at the water to aluminium interface as shown in the diagram (Figure 2.12) ? Also calculate the percentage of the original sound energy that will finally enter the water on its way back to the transducer from the back surface of the aluminium part.

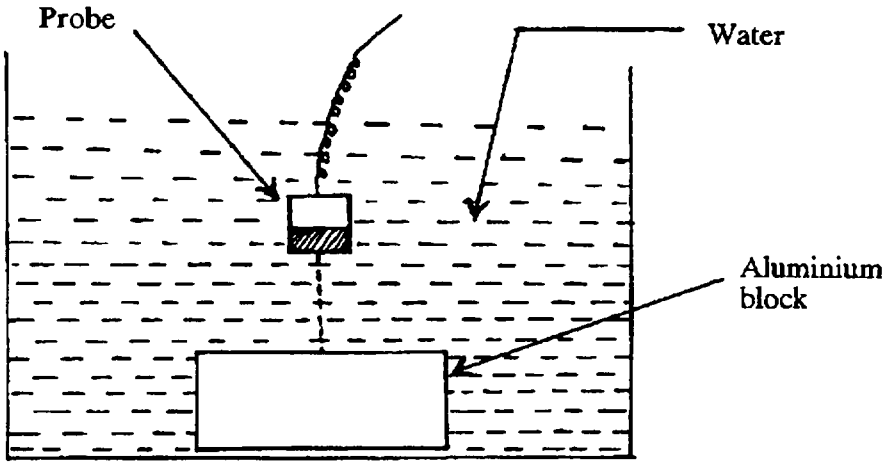


Figure 2.12 : Arrangement of probe and aluminium block.

Using Table 2.1 we have the following data:

$Z_{water} = Z_1 = 1480 \times 10^3 \text{ kg m}^{-2} \text{ s}^{-1}$

$Z_{aluminium} = Z_2 = 17064 \times 10^3 \text{ kg m}^{-2} \text{ s}^{-1}$

Reflection coefficient (R) $= (1.48 - 17.06)^2 / (1.48 + 17.06)^2$
$= 242.73 / 343.73$
$= 0.71$
% reflection $= 71\%$

Transmission coefficient (T) $= (4Z_1 Z_2) / Z_1+Z_2)^2$
$= (4 \times 1.48 \times 17.06) / (1.48+17.06)^2$
$= (100.99) / (343.73)$
$= 0.29$
% transmission $= 29\%$

Therefore 29% of the energy is transmitted into the aluminium test piece. At the back it faces an aluminium water interface. 71% of this 29% is reflected back from the backwall. This comes to 20.6% which comes up and encounters the aluminium water boundary once again. At this 71% of 20.6% is reflected back into the test specimen. This comes out to 14.6%. The remaining (20.6 - 14.6) which comes to about 6% finally enters the water.

Example : A clad material is to be tested for bond defects. One material has a thickness of 7.5 mm and an acoustic impedance of 5.0×10^3 kg m^{-2} s^{-1} and the other material is 100 mm thick and has an acoustic impedance of 4.5×10^3 kg m^{-2} s^{-1}. If the bond is perfect and acceptable what percentage of sound is expected to be reflected from the interface.

The bond being perfect the reflection will be only as a consequence of differences in the acoustic impedances. It may be mentioned that because of the near zone problems the testing will be done from the side of the larger thickness.

Reflection coefficient (R) $= (Z_1 - Z_2)^2 / (Z_1 + Z_2)^2$
$= (5 - 4.5)^2 / (5 + 4.5)^2$
$= (0.25) / (90.25)$
$= 0.0027$
% reflection $= 0.0027 \times 100$
$= 0.27\ \%$

2.4.2 Reflection and transmission at oblique incidence

2.4.2.1 Refraction and mode conversion

If ultrasonic waves strike a boundary at an oblique angle, then the reflection and transmission of the waves become more complicated than that with normal incidence. At oblique incidence the phenomena of mode conversion (i.e. a change in the nature of the wave motion) and refraction (a change in the direction of wave propagation) occur. Figure 2.13 shows what happens when a longitudinal wave strikes obliquely a boundary between two media. The incident longitudinal wave splits up into two components, one longitudinal and the other transverse and this happens for both the reflected as well as refracted parts. L_1 and S_1 denote respectively longitudinal and shear waves in medium 1 while L_2 and S_2 denote these waves in medium 2. Of course there will be no reflected transverse component or refracted transverse component if either medium 1 or medium 2 is not solid. Figure 2.13 gives all the reflected and transmitted waves when a longitudinal ultrasonic wave strikes a boundary between two media. The refracted transverse component in medium 2 will disappear if medium 2 is not a solid.

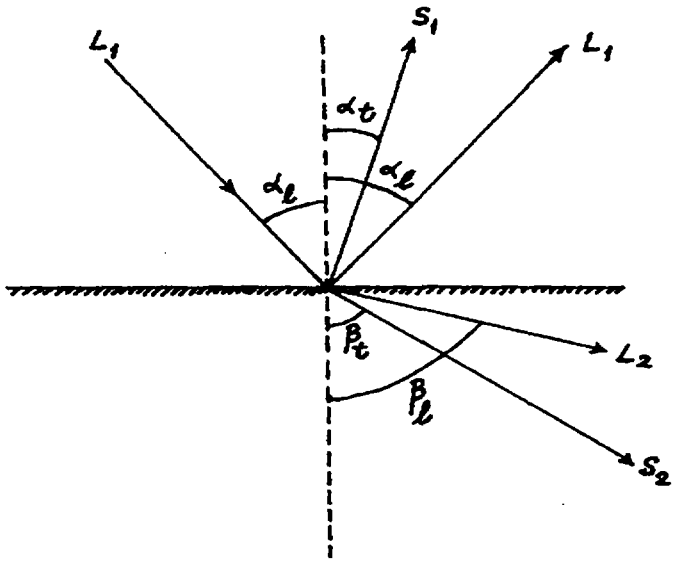


Figure 2.13 : Refraction and mode conversion for an incident longitudinal wave.

α_l = angle of incidence of longitudinal wave
α_t = angle of reflection of transverse wave
β_l = angle of refraction of longitudinal wave
β_t = angle of refraction of transverse wave

2.4.2.2 Snell's law

The general law that, for a certain incident ultrasonic wave on a boundary, determines the directions of the reflected and refracted waves is known as Snell's Law. According to this law the ratio of the sine of the angle of incidence to the sine of the angle of reflection or refraction equals the ratio of the corresponding velocities of the incident, and reflected or refracted waves. Mathematically Snell's Law is expressed as:

$$\text{Sin}\,\alpha / \text{Sin}\,\beta = v_1/v_2 \qquad (2.22)$$

where

α = the angle of incidence
β = the angle of reflection or refraction
v_1 = velocity of incident wave
v_2 = velocity of reflected or refracted waves

Both α and β are measured from a line normal to the boundary.

2.4.2.3 First and second critical angles

Applying Snell's Law to Figure 2.13 we can write

$\text{Sin}\,\alpha_l / \text{Sin}\,\beta_t = v_{l1} / v_{t2}$
$\text{Sin}\,\beta_l / \text{Sin}\,\beta_t = v_{l2} / v_{t2}$
$\text{Sin}\,\alpha_t / \text{Sin}\,\beta_l = v_{t1} / v_{l2}$
$\text{Sin}\,\beta_t / \text{Sin}\,\beta_l = v_{t2} / v_{l2}$

These equations can be combined to give

$$\text{Sin}\,\alpha_l / v_{l1} = \text{Sin}\,\beta_l / v_{l2} = \text{Sin}\,\beta_t / v_{t2} = \text{Sin}\,\alpha_t / v_{t1} \text{ ----------} \quad (2.23)$$

where α_l, α_t, β_l and β_t have already been defined and

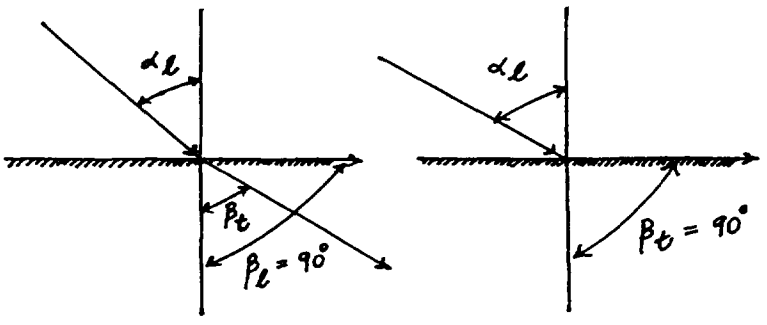
v_{l1} = velocity of longitudinal waves in medium 1
v_{l2} = velocity of longitudinal waves in medium 2
v_{t1} = velocity of transverse waves in medium 1
v_{t2} = velocity of transverse waves in medium 2

Consider now the relation $\text{Sin}\,\alpha_l / \text{Sin}\,\beta_l = v_{l1} / v_{l2}$. If the angle of incidence α_l is small ultrasonic waves travelling in a medium undergo the phenomena of mode conversion and refraction upon encountering a boundary with another medium. This results in the simultaneous propagation of longitudinal and transverse waves at different angles of refraction in the second medium. As the velocity of transverse waves for a given solid is always less than that of longitudinal waves, the angle of refraction β_l for longitudinal waves is always greater than the angle of refraction β_t for transverse waves. As the angle of incidence is increased, the angle of refraction also increases. For a certain value of the angle of incidence α_l the refraction angle β_l reaches 90°. The longitudinal wave then emerges from the second medium and travels parallel to the boundary. The angle of incidence at which the refracted longitudinal wave emerges is called the first critical angle. It is given by

$\alpha_l = \text{Sin}^{-1}(v_{l1} / v_{l2})$ (Figure 2.14 a).

Now consider the relationship $\text{Sin}\,\alpha_l / \text{Sin}\,\beta_t = v_{l1} / v_{t2}$. If the angle of incidence α_l is further increased the angle of refraction for transverse wave β_t also approaches 90°. This value of α_l for which the angle of refraction of the transverse wave is exactly 90° is called the second critical angle. At the second critical angle the refracted transverse wave emerges from the medium and travels parallel to the boundary. The transverse wave, has become a surface or Rayleigh wave. The value of second critical angle is given by $\alpha_l = \text{Sin}^{-1}(v_{l1} / v_{t2})$. Schematically, the critical angles are shown in Figure 2.14 b. For propagation from water to steel, the values of first and second critical angles come out to be 14° and 30° respectively. With plastic to steel boundary these angles have values of 28° and 58°.

α_l = angle of incidence of longitudinal wave
α_t = angle of reflection of transverse wave
β_l = angle of refraction of longitudinal wave
β_t = angle of refraction of transverse wave



(a) (b)

Figure 2.14 : (a) First critical angle, (b) Second critical angle.

2.4.2.4 Reflected acoustic pressure at angular incidence

Figure 2.15 gives the acoustic pressure reflection factors for reflected transverse and longitudinal waves at a steel - air boundary.

The angle of incidence of longitudinal waves is shown by lower horizontal scale and the angle of incidence of shear waves by the upper horizontal scale. The vertical scale shows the reflection factor in percentages. It can be noted from Figure 2.15 that:

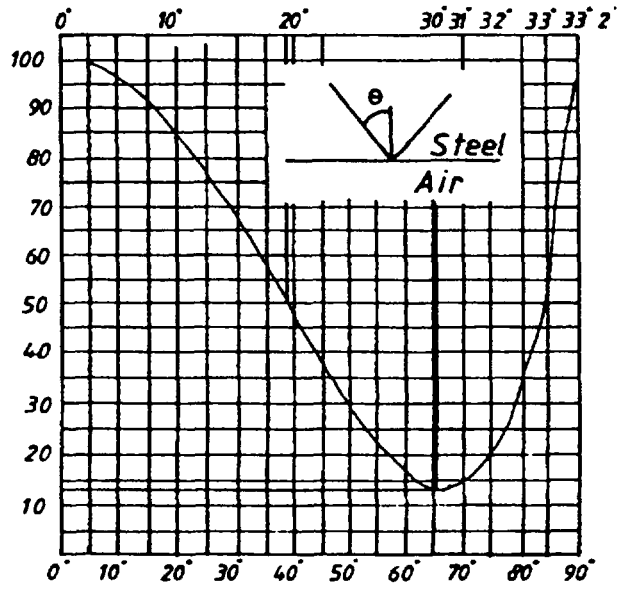


Figure 2.15 : Acoustic pressure of reflected waves vs angle of incidence.

(i) The reflected acoustic pressure of longitudinal waves is at a minimum of 13% at 68° angle of incidence. This means the other portion of the waves is mode converted to transverse waves.

(ii) For an angle of incidence of about 30° for incident transverse waves, only 13% of the reflected acoustic pressure is in the transverse mode. The remainder is mode converted into longitudinal waves.

(iii) For incident shear waves if the angle of incidence is larger than 33.2°, the shear waves are totally reflected and no mode conversion occurs.

Example: If it is desired that a shear wave travels into steel at 60 degrees, what would be the incident angle on the lucite (perspex) wedge ?

It is required to find the angle α_l in the following sketch (Figure 2.16) while the angle β_t is given to be 60 degrees.

From Table 2.1 the velocity of longitudinal waves in perspex is v_{l1} = 2730 ms^{-1} and velocity of shear waves in steel is v_{t2} =3250 ms^{-1}. Applying Snell's Law: Sin α_l / Sin β_{t2} = v_{l1}/v_{t2}, we know β_{t2} = 60° and from the Table 2.2 Sin 60 = 0.8660. Putting this value we get sin α_{l1} = 0.8660x2730/3250 = 0.7274. Therefore α_{l1} = Sin^{-1} (.7274) = 47 degrees.

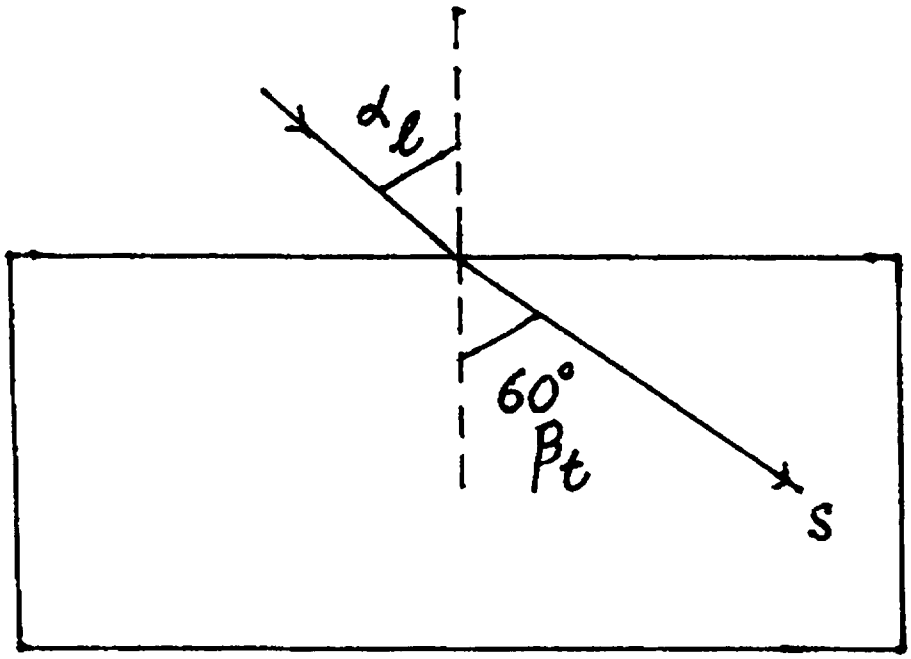


Figure 2.16.

Example : What would be the refracted longitudinal wave if the angle of incidence through a water to steel interface is 12 degrees ?

It is required to find the angle β_{l2} in the following sketch (Figure 2.17) while the angle of incidence,α_{l1} is given to be 12 degrees.

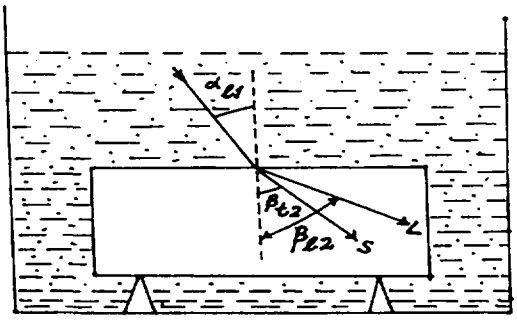


Figure 2.17.

Using Table 2.1 and applying Snell's Law we get:

$$\begin{aligned}
\text{Sin } \alpha_{l1} / \text{Sin } \beta_{l2} &= v_{l1} / v_{l2} \text{ or} \\
\text{Sin } \beta_{l2} &= \text{Sin } \alpha_{l2} \times v_{l2} / v_{l1} \\
&= 0.2079 \times 5940 / 1480 \\
&= 0.8344 \text{ or} \\
\beta_{l2} &= \text{Sin}^{-1}(0.8344) \\
&= 57 \text{ degrees}
\end{aligned}$$

Example: If the angle of incidence through perspex is 36°, is it possible to have a refracted longitudinal wave? If yes, what is it ? If no, why not ?

It is required to find the value of angle β_{l2} in the Figure 2.17 while the value of α_{l1} is given to be 36°.

Using Tables 2.1 and applying Snell's Law we get:

$$\begin{aligned} \text{Sin } \beta_{l2} &= \text{Sin } 36 \times v_{l2} \text{ (steel)} / v_{l1} \text{ (perspex)} \\ &= 0.5878 \times 5940/2730 \\ &= 1.2789 \end{aligned}$$

This indicates that angle β_{l2}, i.e. refracted angle for longitudinal waves is greater than 90°. Therefore there will be no refracted longitudinal wave in steel in this case.

Example: An angle probe gives a beam angle of 55° in steel. What is its beam angle when used to inspect aluminium ?

Take velocities :	shear waves, steel	= 3250 m/s
	shear waves, A1	= 3130 m/s
	compressional waves, steel	= 5940 m/s
	compressional waves, A1	= 6320 m/s

As we are considering angle probes, we are generating shear waves, so we use Snell's Law.

$\text{Sin}\alpha / \text{Sin}\beta = v_1 / v_2$

where v_2 is the shear wave velocity

α is the incident beam angle

β is the refracted beam angle

and we wish to calculate angle α in the angle probe, knowing that in steel, $\beta_{steel} = 55°$

$\text{Sin}\alpha / v_1 = \text{Sin}\beta_{steel} / V_2 \text{ (steel)} = \text{Sin}55 / 3250$

where v_1 is the compressional wave velocity in the material of the probe shoe. In the aluminium case,

Also $\text{Sin}\beta_{Al} / v_2 \text{ (Al)} = \text{Sin}\alpha / v_1$ or $\text{Sin}\beta_{Al} = v_2 \text{ (Al)} \times \text{Sin}\alpha / v_1$

But from previous equation we have

$\text{Sin}\alpha / v_1 = \text{Sin}55 / 3250$ and therefore

$\text{Sin}\beta_{Al} = 3130 \times \text{Sin}55 / 3250 = 3130 \times 0.8192 / 3250$

Using log tables or a calculator

$\sin \beta_{Al} = 0.7892$, so $\beta_{Al} = 52$ degrees approx. which is the beam angle in aluminium.

Example : A 150 mm OD, 80 mm ID, steel tube is to be examined ultrasonically by rotating it under water, under an angle probe, to generate shear waves in the steel. Calculate the angle of incidence, neglecting beam spread, to ensure full coverage of the metal.

Vel. of compressional waves in water = 1500 m/s

Vel. of shear waves in steel = 3250 m/s

Sketch out the tube showing OD and ID and the sound beam such that it touches the internal surface of the tube. If we draw the inner radius to touch this point and the outer radius to the point of beam entry into steel, then we get a right angled triangle. If β is the required probe angle then from the triangle it is given by

$$\sin\beta = \frac{ID/2}{OD/2} = \frac{40}{75}$$

Also by Snell's law $\sin\alpha / \sin\beta = v_1 / v_2$ where v_1 is the longitudinal wave velocity in water and v_2 is the shear wave velocity in steel. Values of v_1 and v_2 from Table 2.1 are respectively 1500 m/s and 3250 m/s. Therefore $\text{Sin}\alpha = \text{Sin}\,\beta\,(v_1 / v_2) = (40/75)\,(1500/3250)$. Therefore $\alpha = 14°\text{-}\,15'$ which is the angle required.

2.5 TRANSFER OF ENERGY FROM ONE MEDIUM TO ANOTHER

2.5.1 Generation of ultrasonic waves

Generation of sound is a phenomenon wherein different forms of energy are converted into sound energy which in turn is the energy of mechanical vibrations. For example, in the case of piezoelectric transducers electrical energy is converted to sound energy (section 2.6.1). In magnetostrictive transducers it is the effect of magnetic field which is utilized to induce mechanical vibrations in some special materials (section 2.6.2). In mechanical transducers it is the shock or friction which generates ultrasound. The electromagnetic generation of sound is by the use of the fact that if a magnetic alternating field acts upon an electrically conductive body eddy currents are induced in it. Due to the interaction between eddy currents and the external magnetic field a force called Loretz force is produced in the test piece which generates the sound (section 9.1.8). In the electrostatic process a force acts between the plates of a capacitor. If one plate of the capacitor is movable then sound can be generated by an alternating voltage. Use can also be made to convert thermal energy into sound energy. A sudden heating up of a solid surface causes a sudden local extension of the material. The mechanical tensions produced by this process excite sound waves with a wide frequency spectrum. Laser lights and electron beams are usually used for very rapid and strong heating (section 9.1.7).

2.5.2 Energy losses in various media

In sections 2.2.4 and 2.2.5 it has been said that the velocities of sound are different in different media and therefore different media have different acoustic impedances, i.e. they offer differing degrees of resistance to the passage of sound energy through them. This indicates that some part of the sound energy must be lost during its passage through materials such as air, water, oil, steel, perspex, etc.

In section 2.4 it has been shown how the ultrasound behaves at the interfaces of different media. In case of normal incidence a portion of the sound energy is reflected back into the first medium while the remaining portion is transmitted into the second medium. The percentage of these portions of sound energy depends upon the differences or mismatch between the acoustic

impedances of the two media. At oblique incidence, apart from the usual reflection and transmission, the phenomenon of mode conversion is encountered which converts a part of the longitudinal sound waves into transverse mode. The latter have much lower velocity of propagation into the second medium.

The ultrasonic beam from the probe is divergent (Section 2.7.2). With increase of distance from the transducer the beam intensity is distributed over an increasing cross section and is consequently decreased throughout space.

The ultrasonic energy undergoes interaction with the medium through which it travels and is consequently attenuated (Section 2.8). Such attenuation or decrease falls under two headings:

(i) The true absorption which occurs in every medium, and by which is meant the conversion into other forms of energy, notably into heat.

(ii) The scatter of ultrasonic energy which occurs mainly in inhomogeneous poly-crystalline media (i.e. notably in metals). This comprises the deflection of a part of the energy from the original beam direction owing to diffraction, reflection and refraction at anisotropic single crystallites.

Various other factors which contribute to the loss of sound energy in a beam are given in Sections 2.7.3 and 2.7.4.

2.6 PIEZOELECTRIC AND MAGNETOSTRICTIVE EFFECT ON THE CRYSTAL

2.6.1 Piezoelectric effect

A transducer is a device which converts one form of energy into another. Ultrasonic transducers convert electrical energy into ultrasonic energy and vice versa by utilizing a phenomenon known as the piezoelectric effect. The materials which exhibit this property are known as piezoelectric materials.

In the direct piezoelectric effect, first discovered by the Curie brothers in 1880, a piezoelectric material when subjected to mechanical pressure will develop an electrical potential across it (Figure 2.18 a). In the inverse piezoelectric effect, first predicted by Lippman in 1881 and later confirmed experimentally by the Curie brothers in the same year, mechanical deformation and thus vibration in piezoelectric materials is produced whenever an electrical potential is applied to them (Figure 2.18 b). The direct piezoelectric effect is used in detecting and the inverse piezoelectric effect in the generation of ultrasonic waves.

2.6.1.1 Types of piezoelectric transducers

Piezoelectric transducers can be classified into two groups. The classification is made based on the type of piezoelectric material which is used in the manufacture of the transducer. If the transducers are made from single crystal materials in which the piezoelectric effect occurs naturally, they are classified as piezoelectric crystal transducers. On the other hand the transducers which are made from polycrystalline materials in which the piezoelectric effect has to be induced by polarization, are termed as polarized ceramic transducers.

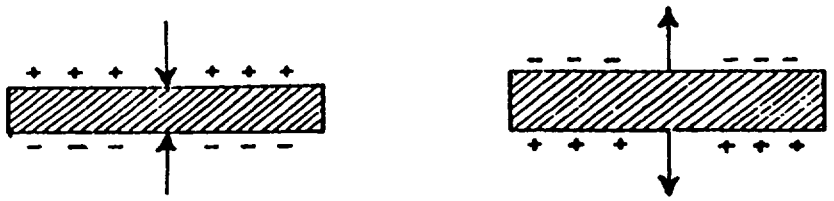


Figure 2.18 (a) : Direct piezoelectric effect.

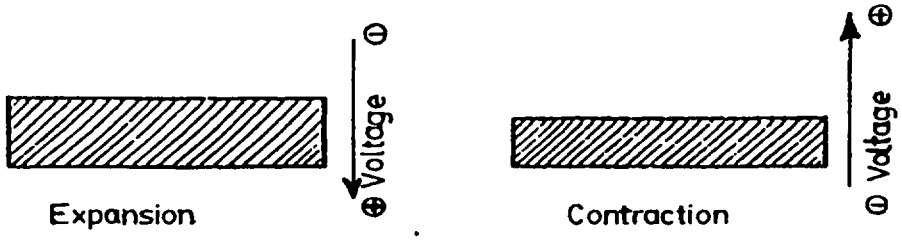


Figure 2.18 (b) : Inverse piezoelectric effect.

Piezoelectric crystal transducers

Some of the single crystal materials in which the piezoelectric effect occurs naturally are quartz, tourmaline, lithium sulphate, cadmium sulphide and zinc oxide. Among these quartz and lithium sulphate are the most commonly used in the manufacture of ultrasonic transducers.

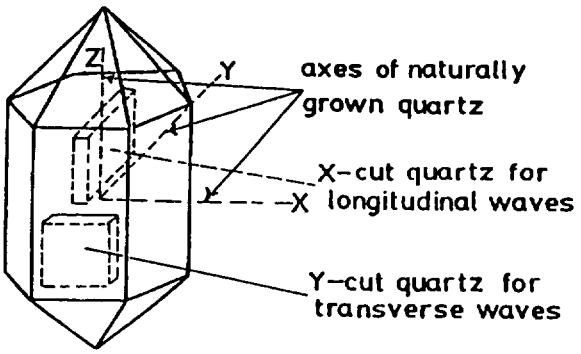


Figure 2.19 : System co-ordinates in a quartz crystal (simplified) and positions at X and Y-cut crystals.

(a) Quartz

Naturally or artificially grown quartz crystals have a certain definite shape which is described by crystallographic axes, consisting of an X-, Y- and Z-axis.

The piezoelectric effect in quartz can only be achieved when small plates perpendicular either to the X-axis or Y- axis are cut out of the quartz crystal. These are called X-cut or Y-cut quartz crystals or transducers. X-cut crystals are used for the production and detection of longitudinal ultrasonic waves (Figure 2.20) while Y-cut crystals are used for the generation and reception of transverse ultrasonic waves (Figure 2.21). Transverse and surface waves can be produced from an X-cut crystal by taking advantage of the phenomenon of mode conversion which occurs at an interface of two media of different acoustic impedances when a longitudinal ultrasonic wave strikes the interface at an angle. When an alternating voltage is applied across its electrodes, a piezoelectric transducer oscillates at the applied frequency with an amplitude of the order of 10

times its thickness. If, however, the transducer is excited at one of its resonance frequencies the amplitude is considerably increased, e.g. to about 10 times the thickness at the fundamental frequency.

Some of the advantages and limitations of quartz when used as an ultrasonic transducer, are given below :

Advantages:

(i) It is highly resistant to wear.

(ii) It is insoluble in water.

(iii) It has high mechanical and electrical stability.

(iv) It can be operated at high temperatures.

Limitations:

(i) It is comparatively expensive.

(ii) It is the least efficient generator of ultrasonic energy.

(iii) It suffers from mode conversion – when an X- cut quartz is used besides generating longitudinal waves it also generates transverse waves. Transverse waves are generated because an X-cut crystal when compressed, elongates in the Y-direction also. Production of transverse waves gives rise to spurious signals after the main pulse.

(iv) It requires an high voltage for its operation.

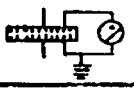
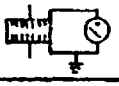
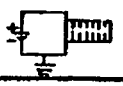
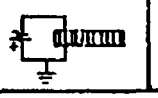
	CAUSE	SCHEDULE	EFFECT
direct piezo–electric effect	crystal being compressed		positive voltage on faces
	crystal being expanded		negative voltage on faces
inverse piezo–electric effect	positive voltage on faces		expansion of crystal
	negative voltage on faces		contraction of crystal

Figure 2.20 : The piezoelectric effect of quartz (X-cut schematic).

(b) Lithium sulphate

Lithium sulphate is another piezoelectric crystal which is commonly used for the manufacture of ultrasonic transducers. Some of the advantages and limitations of a lithium sulphate transducer are as follows:

Advantages:

(i) It is the most efficient receiver of ultrasonic energy.

(ii) It can be easily damped because of its low acoustic impedance.

(iii) It does not age.

(iv) It is affected very little from mode conversion.

Limitations:

(i) It is very fragile.

(ii) It is soluble in water.

(iii) It is limited in use to temperatures below 75°C.

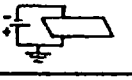
	CAUSE	SCHEDULE	EFFECT
direct piezo-electric effect	shearing strain deforms crystal to the left		positive voltage on faces
	shearing strain deforms crystal to the right		negative voltage on faces
inverse piezo-electric effect	positive voltage on faces		shearing motion of crystal to the right
	negative voltage on faces		shearing motion of crystal to the left

Figure 2.21 : The piezoelectric effect of quartz (Y-cut schematic).

Polarized ceramic transducers

Polarized ceramic transducers have nearly completely replaced quartz and are on their way to replacing artificially grown crystals as transducer elements. Polarized ceramic transducer materials are ferroelectric in nature. Ferroelectric materials consist of many "domains" each of which includes large number of molecules, and each of which has a net electric charge. When no voltage gradient exists in the material these domains are randomly oriented (Figure 2.22). If a voltage is applied, the domains tend to line up in the direction of the field. Since a domain's shape is longer in its direction of polarization than in its thickness the material as a whole expands. If the voltage is reversed in direction the domains also reverse direction and the material again expands. This is in contrast to the piezoelectric crystal materials which contract for a voltage in one direction and expand for a voltage in the opposite direction.

The ferroelectric mode (i.e. expansion for both positive and negative voltage) can be easily changed to piezoelectric mode by heating the ferroelectric material to its Curie point (the temperature above which a ferroelectric material loses its ferroelectric properties) and then cooling it under the influence of a bias voltage of approximately 1000 V per mm thickness. In

this way the ferroelectric domains are effectively frozen in their bias field orientations and the polarized material may then be treated as piezoelectric.

Polarized ceramic transducers, as the name implies, are produced like ceramic dishes, etc. They are made from powders mixed together and then fired or heated to a solid. The characteristic properties required of a transducer for certain applications are controlled by adding various chemical compounds in different proportions. Because, prior to polarization, these ceramic transducers are isotropic, they do not require to be cut with reference to any particular axis. Thus it is possible to shape them in any convenient form, e.g. a concave transducer capable of focusing ultrasound can be produced without difficulty. Some of the advantages and limitations of ceramic transducers are:

Advantages:

(i) They are efficient generators of ultrasonic energy.

(ii) They operate at low voltages.

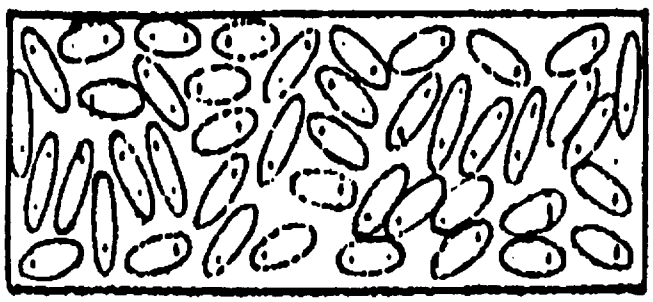
(iii) Some can be used for high temperature applications, e.g. lead metaniobate Curie point is 550°C.

Limitations:

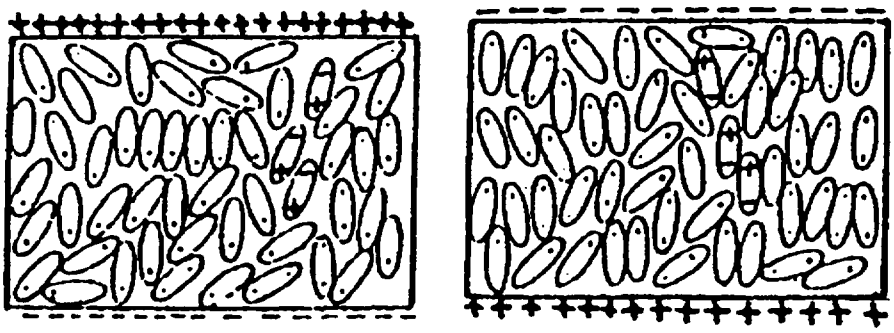
(i) Piezoelectric property may decrease with age.

(ii) They have low resistance to wear.

(iii) They suffer from mode conversion.



No potential applied



Potential applied

Figure 2.22 : Domains in ferroelectric material.

Comparison of piezoelectric transducers

The piezoelectric deformation constant 'H' is a measure of the ability of a transducer to act as an ultrasonic receiver. High H values show the greater ability of the transducer as a receiver. From Table 2.2, it is evident that lithium sulphate is the best receiver of ultrasonic energy. The electromechanical coupling factor 'K' shows the efficiency of a transducer for the conversion of electric voltage into mechanical displacement and vice versa. This value is important for pulse echo operation as the transducer acts both as a transmitter and receiver. Higher values of K mean that the overall efficiency of the transducer as a transmitter and receiver is better. The values for lead metaniobate, lead zirconate-titanate and barium-titanate lie in a comparable order. A satisfactory resolution power requires that the coupling factor for radial oscillation K_p is as low as possible. K_p is a measure for the appearance of disturbing radial oscillations which widen the signals. These radial oscillations are because of the mode conversion disturbances of the transducers. From this point of view lithium sulphate and lead metaniobate are the best transducer materials. Since in the case of contact as well as immersion testing a liquid couplant with a low acoustic impedance Z is required, the transducer material should have an acoustic impedance of the same order to give a better transmission of ultrasonic energy into the test object. In this respect the best choices are lithium sulphate or lead metaniobate or quartz as all of them have low acoustic impedances.

Table 2.2 : SOME CHARACTERISTICS OF COMMON PIEZOELECTRIC TRANSDUCERS

	Lead zirconate titanate	Barium titanate	Lead metaniobate	Lithium sulphate	Quartz	Lithium niobate
Sound velocity 'v' m/s	4000	5100	3300	5460	5740	7320
Acoustic impedance 'Z' 10^6 kg/m^2s	30	27	20.5	11.2	15.2	34
Electromechanical coupling factor 'K'	0.6 - 0.7	0.45	0.4	0.38	0.1	0.2
Piezoelectric modulus 'd'	150 - 591	125 - 190	85	15	2.3	6
Piezoelectric deformation constant 'H'	1.8 - 4.6	1.1 - 1.6	1.9	8.2	4.9	6.7
Coupling factor for radial oscillations 'K_p'	0.5 - 0.6	0.8	0.07	0	0.1	-

2.6.2 Magnetostrictive effect and transducers

Magnetostrictive transducers are generally made of ferromagnetic materials, i.e. certain metals, such as nickel, cobalt, and iron, which can easily be magnetised and which display magnetostriction or the Joule effect. When a bar or rod of one of these materials is placed in a magnetic field, it suffers a change in length, either an increase or decrease, depending on the nature of the material and the strength of the field. Whether the strain is a positive or negative one is independent of the sense of the field. Thus, when the magnetic field is reversed in direction, there is no change in the sense of the strain, i.e. an increase in length remains an increase.

The magnetostrictive effect can also be observed in certain non-metals known as ferrites. They have the advantage that, being poor electrical conductors, they are not overheated by eddy currents which are induced by the alternating currents exciting the periodic magnetic field.

However, because of their poor mechanical properties, they are not often used in the design of ultrasonic transducers.

Magnetostrictive transducers are often made in the form of rods surrounded by coil windings (Figure 2.23). An alternating current through the coil induces an alternating magnetic field of the same frequency; this gives rise to longitudinal oscillations of the rod.

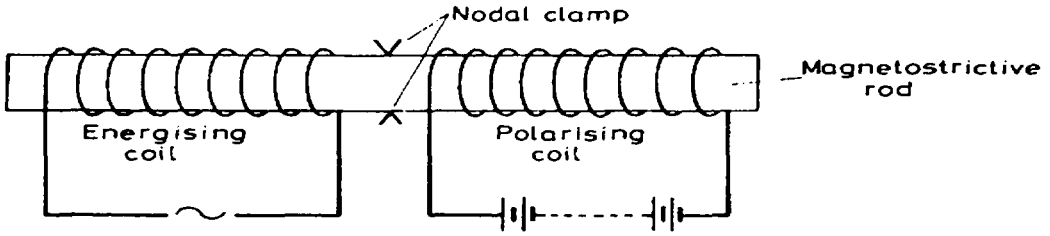


Figure 2.23 : Schematic diagram showing the method of exciting a magnetostrictive transducer in the form of a rod.

Because the value of the strain in the rod depends only on the magnitude of the applied magnetic field and is independent of its sense, these oscillations take place at a frequency twice that of the field and take on the form of an unsmoothed rectified alternating current, i.e. the vibrations are of low amplitude and contain many unwanted frequencies. As in the case of ceramic transducers, this disadvantage is overcome by polarisation. Similarly, as with piezoelectric transducers maximum efficiency of the oscillations is obtained at the fundamental resonance frequency. The effects of harmonics are minimised by nodal mounting.

Magnetostrictive transducers are seldom used in non-destructive testing except for Lamb wave testing of wire specimens. However, the applications of ultrasound for the purposes of drilling and cleaning are based on the magnetostrictive phenomenon.

2.7 THE CHARACTERISTICS OF THE ULTRASONIC BEAM

2.7.1 The ultrasonic beam

The region in which ultrasonic waves are propagated from an ultrasonic transducer is known as the ultrasonic beam. For the purpose of ultrasonic testing of materials, the greatly simplified shape of an ultrasonic beam for a circular transducer is as shown in Figure 2.24. This could be imagined like a cone as is the light coming out of a torch. Two distinct regions of the beam exist and are classified as near field (Freznel zone) and far field (Fraunhofer zone).

The intensity variation along the axial distance for a typical transducer is shown in Figure 2.25. The intensity passes through a number of maxima and minima. The last minima occurs at N/2 while the last maxima occurs at N where N denotes the near field length. After one near field length the intensity decreases continuously. From a distance of approximately three near field lengths the sound pressure on the central axis of the beam is reduced proportional to the inverse distance and the sound beam diverges with a constant angle of divergence. We call this area the far field or the Fraunhofer zone. The area from 1 N to approximately 3 N is referred to as the transition zone where the divergence angle still changes and is not constant and the decrease of the sound pressure is not yet proportional to the inverse distance.

Figure 2.26 shows the radial distribution of acoustic intensity from a typical disc type circular transducer. Such a diagram in practice can be drawn using reflections from a small round ball in

water or a small flat bottom or side drilled hole. The ball or holes are scanned at a distance. The echo is maximized which shows the position of the central beam axis. Then the reflector is moved perpendicularly to the axis and the positions are noted when the echo amplitude falls to 50% and 10% of its maximum. Such points, no doubt, exist on both the sides of the central beam axis. This is schematically presented in Figure 2.26 (also see Section 2.7.1.3).

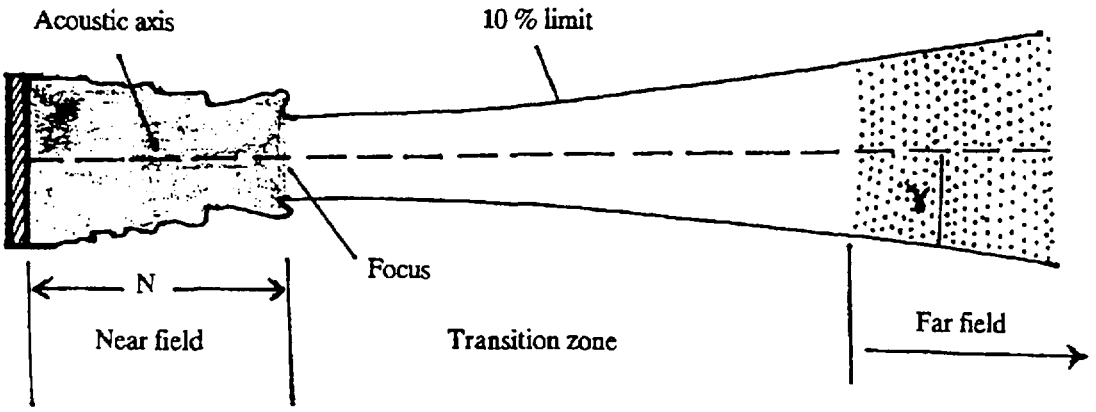


Figure 2.24 : Shape of a typical sound beam from a circular transducer.

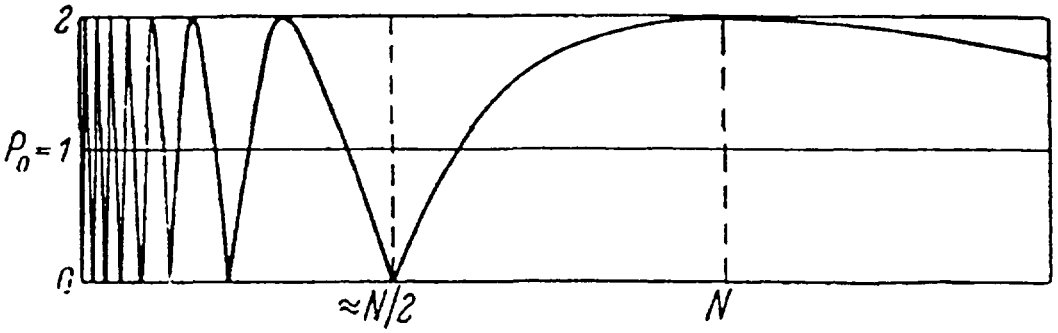


Figure 2.25: Distribution of intensity along the axial distance.

The quantities describing the shape of the sound field in a useful practical approximation are the near field length N and the divergence angle γ (gamma). These two values are functions of the crystal diameter 'D', the frequency 'f 'and the sound velocity 'v' in the medium in which the sound beam develops. Some formulae that apply are explained in the following sections. Summarizing the results concerning the sound field we can say that:

(i) The character of sound field is determined by the ratio of the dimensions of the crystal to the wavelength. A large value furnishes a sharp, far-reaching beam with a long near zone.

(ii) The intensity of the sound pressure at a given distance is determined by the ratio of surface area to wavelength.

(iii) At sufficient distance, a sound field follows the law that the sound pressure decreases inversely with the distance.

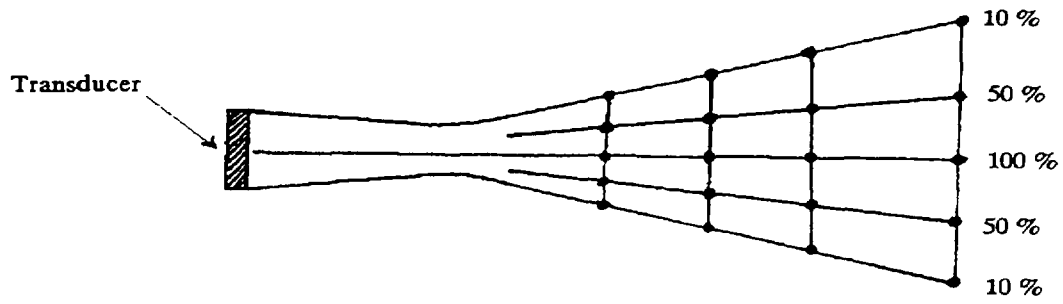


Figure 2.26 : Schematic presentation of the radial distribution of intensity in a sound beam.

2.7.1.1 Near field

A piezoelectric transducer can be considered to be a collection of point sources, each of which is emitting spherical ultrasonic waves to the surrounding medium (Figure 2.27).

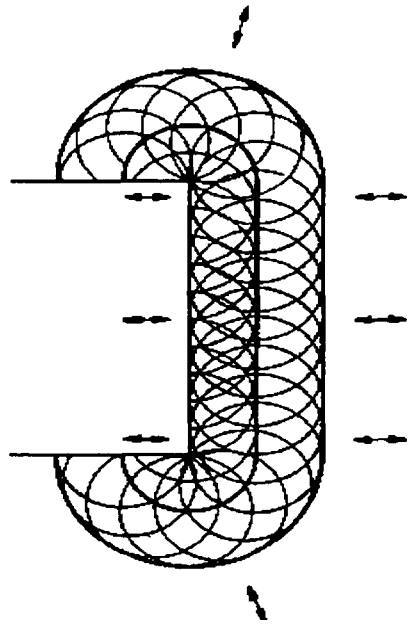


Figure 2.27 : Shape of the wave front in the near field.

The spherical waves interfere with each other and result in a system of maxima and minima in intensity in the region close to the transducer. This region is known as the near field region or Freznel zone. The near field shows a beam having a width approximating the diameter of the crystal. However, it is reduced up to the end of the near field which is called the focus.

Flaws appearing in the near field must be carefully interpreted because a flaw occurring in this region can produce multiple indications and the amplitude of the reflected signal from the flaw can vary considerably if the effective distance from the probe varies. This is specially true in the case of smaller defects with which there are greater difficulties of interpretation in the near zone as compared to larger defects (comparable with crystal diameter). The near field problem can be reduced or even completely overcome by the use of plastic shoes in front of the crystals generating ultrasound.

2.7.1.2 Calculation of near field length

The length N of the near field depends upon the diameter of the transducer and the wavelength of the ultrasonic waves in the particular medium. The near field length for a probe increases with increase in its diameter and frequency and can be calculated approximately from:

$$N = D^2/4\lambda \quad \text{----------} \quad (2.24\ a)$$

$$= D^2 f/4v \quad \text{----------} \quad (2.24\ b)$$

where

N = near field length
D = diameter of transducer
v = velocity of sound in material
f = frequency

2.7.1.3 Far field

The region beyond the near field is known as the far field. The wave front of ultrasonic waves in the far field beyond a distance of three near field lengths from the transducer is spherical as compared to the wave front in the near field which is planar. The region in the far field between one near field length and three near field lengths is known as the transition region because transition in shape of the wave front from planar to spherical occurs in this region.

The intensity in the far field along the axial distance from the transducer beyond three near field lengths falls off with distance in accordance with the inverse square law, i.e. the intensity decreases inversely with the square of the distance (Figure 2.24). The intensity in the transition region of the far field varies exponentially with distance with an exponent of distance between 1 and 2.

The reflected intensity of ultrasonic waves from flaws occurring in the far field depends upon the size of the flaw with respect to the beam dimensions. If the flaw is larger than the beam then the reflected intensity follows the inverse proportional law, i.e. intensity of reflection α 1/distance. On the other hand if the size of the flaw is smaller than the beam dimensions then the reflected intensity varies inversely as the square of the distance, i.e. Intensity α 1/(distance)^2.

2.7.2 Field divergence or beam spread

It has already been mentioned in Section 2.7.1 that there is always some spreading of the ultrasonic beam in the far field as the waves travel from the transducer. It is important to understand the beam spread as it helps to point out the importance of selecting the proper frequency and size of the transducer. The length of the ultrasonic wave and the diameter of the transducer are often critical in the determination of flaw size and location. The intensity of the beam is a maximum on the central axis and decreases in proportion to the distance from the centre. The angle of beam spread or divergence angle $\Theta/2$ can be calculated from the following equation:

$$\Theta_n/2 = \text{Sin}^{-1} K_n \lambda /D = \text{Sin}^{-1} (K_n v/Df) \quad \text{----------} \quad (2.25)$$

where λ is the wavelength of the ultrasonic waves, D is the diameter in case of a circular transducer and K is a constant which depends :

(i) On the edge of the beam which is considered. Usually the value of K is determined with respect to the reduction of the beam intensity to 50% (6 dB), 10% (20 dB) and 0% (extreme edge) of the maximum amplitude. The subscript "n" in θ_n and K_n denotes the respective edge, e.g. θ_6 is the divergence angle for 6 dB edge and θ_{20} is the divergence angle for 20 dB edge.

(ii) The method which is used to determine beam spread. In one method the through transmission technique is used. In this case a very small diameter probe is moved over the backwall surface of several plane parallel specimens of different thicknesses and a record is made of the amplitudes of the CRT screen indications. The beam spread is then plotted by joining together those points which have the same indications amplitude. The sound beam thus obtained is also referred to as the free field.

In the second method the beam spread is measured by making use of the pulse echo technique. In this method small reflectors of constant size at different depths are used to plot the beam. The plot of the beam made by this method is known as the "echo field".

(iii) The shape of the transducer, i.e. whether circular or rectangular.

Values of K for circular and rectangular transducers determined by the first method are given in Table 2.3 while Table 2.4. gives different values of K determined by the second method for both circular and rectangular transducers.

Table 2.3 : VALUES OF K FOR CIRCULAR AND RECTANGULAR TRANSDUCERS AS DETERMINED BY THROUGH TRANSMISSION TECHNIQUE

Edge % (dB)	K circular	K rectangular
0 %	1.22	1.00
10 % (20 dB)	1.08	0.60
50 % (6 dB)	0.54	0.91

Table 2.4 : VALUES OF K FOR CIRCULAR AND RECTANGULAR TRANSDUCERS AS DETERMINED BY PULSE ECHO TECHNIQUE

Edge % (dB)	K circular	K rectangular
0 %	1.22	1.00
10 % (20 dB)	0.87	0.74
50 % (6 dB)	0.51	0.44

2.7.3 *Influence of sound velocity and transducer size*

Referring to Section 2.7.1.2, the near field length of an ultrasonic field is given by $D^2/4\lambda$ or $D^2f/4v$. Larger values of this factor furnish a sharp, far-reaching beam with a long near zone. These large values mean that larger the transducer size, longer the near field length in a given material for a given frequency. Larger diameter gives greater output of sound energy which acts like a big bang and pushes more and further in front of it. This results in longer near field length on the one hand and greater depth of penetration into material under test on the other. Therefore if, for example, we are testing steel with a 4 MHz probe, the near field length will be about 17 mm for a 1 cm diameter probe while it will be 421 mm for a 5 cm diameter probe. Similarly if we are testing steel with a 4 MHz probe having crystal diameter of 1 cm then the near field length will be 17 mm as before. Now if the same probe is used for testing of perspex then the near field length will be about 36 mm. This difference is because of the difference in sound velocities in steel and perspex. Next let us see the effect of sound velocity and the transducer size on the beam divergence. Equation 2.25 gives the beam divergence angle $\theta/2$ to be $Sin^{-1}(K\lambda/D)$ or $Sin^{-1}(Kv/Df)$ which shows that the transducer diameter has a definite influence on the sound beam for a given frequency, a smaller transducer has a greater beam spread angle than a larger diameter transducer as shown in Figure 2.28.

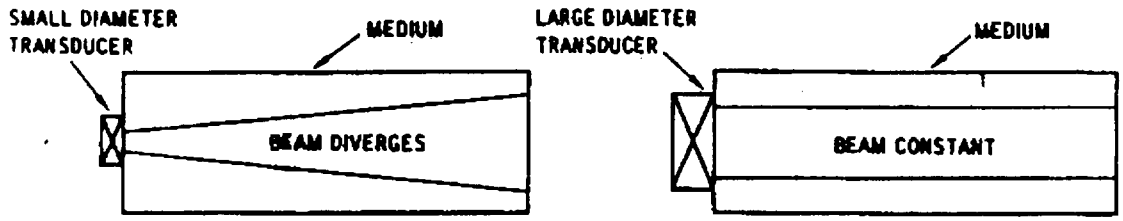


Figure 2.28 : Influence of transducer size on the beam divergence.

Changing the transducer's vibrating frequency will also change the beam spread. Beam divergence is inversely proportional to frequency. Therefore a high frequency transducer has a more constant (less divergent) sound beam than a low frequency transducer.

Example : What would be the beam spread (divergence angle) when testing steel using a 5 MHz transducer having a diameter of 25 mm ?

$\gamma = Sin^{-1}(K\lambda/D) = Sin^{-1} 1.22\,\lambda/D$

$\lambda = v/f = 5940x1000 / 5 \times 1000000 = 1.18$ mm.

Then

$\gamma = Sin^{-1}(1.22 \times 1.18/25) = Sin^{-1}(0.0575) = 3$ degrees

Example: What would be the beam spread using a 25.4 mm diameter, 2.25 MHz transducer on an aluminium test piece ?

$\lambda = v/f = 6320x1000/2.25x1000000 = 2.8$ mm

$\gamma = Sin^{-1} 1.22\,\lambda/D = Sin^{-1}(1.22 \times 2.8 / 25.4)$

$= Sin^{-1}(0.1344) = 8$ degrees

2.8 ATTENUATION OF SOUND

2.8.1 Cause and effect

The intensity of an ultrasonic beam that is sensed by a receiving transducer is considerably less than the intensity of the initial transmission. Attenuation is the term used to describe this condition of energy loss. Attenuation means the process of lessening the amount. With sound attenuation the echo amplitudes of any reflectors are additionally reduced proportional to their distance. This additional reduction per unit distance is called the sound attenuation coefficient. Assuming that there are no major discontinuities producing regular reflections, for example, cracks, etc. various causes of attenuation exist namely scattering, absorption, surface roughness and diffraction, etc. These causes will be described in the following sections. The general equation describing attenuation is :

where

P_o = initial pressure at distance 'd' = o

P = final pressure at a distance 'd' in the medium

α = attenuation coefficient which is measured in nepers or dB mm^{-1} or dB m^{-1} depending upon units of 'd' (1 neper = 8.686 dB).

Table 2.5 : FLAW DETECTABILITY IN DIFFERENT REGIONS OF A SONOGRAM

Region/Colour	Flaw detectability
Scarlet red	This is the region of dead zone where testing is not possible.
Deep red	In this area a discontinuity can be detected if it corresponds to a disc reflector which is at least 8 mm in diameter.
Light red	Flaws corresponding to 4 mm diameter discs can be detected.
Orange	Flaw detectability corresponds to 2 mm diameter disc reflector.
Light orange	Flaw detectability corresponds to 1 mm diameter disc reflector.
Yellow	This is the area of best detectability where flaws corresponding to 0.5 mm diameter disc reflector can be detected.
Greenish yellow	Flaw detectability corresponds to 1 mm diameter disc reflector. Reduction in flaw detectability occurs due to divergence of the sound beam and attenuation.
Light Green	Flaw detectability corresponds to 2 mm diameter disc reflector.
Dark Green	In the portion of the region closer to the probe the flaw detectability corresponds to 4 mm diameter disc reflector while beyond that it corresponds to 8 mm diameter disc reflector.

2.8.1.1 Scattering of ultrasonic waves

The scattering of ultrasonic waves is due to the fact that the material in which the ultrasonic wave is travelling is not absolutely homogeneous. The inhomogeneities can be anything that will present a boundary between two materials of different acoustic impedance such as an inclusion

or pores and possibly grain boundaries containing contaminants. Certain materials are inherently inhomogeneous, such as cast iron which is composed of a matrix of grains and graphite particles which differ greatly in density and elasticity. Each grain in the agglomeration produces severe scattering. It is possible to encounter scattering in a material of just one crystal type if the crystals exhibit velocities of different values when measured along axes in different directions. A material of this type is said to be anisotropic. If individual grains are randomly oriented throughout a material, scattering will occur as if the material is composed of different types of crystals or phases. Materials exhibiting these qualities not only decrease the returned ultrasonic signal because of scattering, but also often produce numerous small echoes which may mask or "camouflage" real indications. A condition for scattering not to occur is that the dimensions of the particles must be small compared with wavelength, i.e. the particle dimensions must be less than 0.1 times the wavelength. The attenuation coefficient, is related to the mean particle diameter `$\phi$' and the frequency `f' as follows :

$$\alpha = Kf^{4}\phi^{-3} \quad \text{----------} \quad (2.26)$$

Where K is a constant for a particular material. Scattering increases rapidly with increasing grain size or decreasing wavelength when the grain size is about 0.1 to 1.0 times the wavelength.

2.8.1.2 Absorption of ultrasonic waves

Absorption of ultrasonic waves is the result of the conversion of a portion of the sound energy into heat. In any material not at absolute zero temperature the particles are in random motion as a result of the heat content of the material. As the temperature increases, there will be an increase in particle activity. As an ultrasound wave propagates through the material it excites the particles. When these particles collide with unexcited particles, energy is transmitted causing them to oscillate faster and through larger distances. This motion persists after the sound wave has passed on, so energy of the passing wave has been converted to heat in the material. Absorption can roughly be visualized as a sort of braking effect of the oscillations of the particles, which also make it clear why a rapid oscillation loses more energy than a slow oscillation. The absorption usually increases proportional to frequency at a rate much slower than the scattering.

2.8.1.3 Loss due to coupling and surface roughness

A third cause of attenuation is transmission loss due to the coupling medium and the surface roughness. When a transducer is placed on a very smooth surface of a specimen using a couplant, the amplitude of signal from the back surface varies with the thickness as well as the type of the couplant.

2.8.1.4 Diffraction

An important property of ultrasonic waves is their ability, or tendency, to bend around, and pass obstacles which are comparable in size to their wave length. This wave interference or diffraction occurs if the wave impinges upon a small inclusion or pore in the metal. A portion of the energy bends around the defect and reflection is much reduced (Figure 2.29 a). A second example of this phenomenon is the bending of ultrasonic waves near the edge of a specimen (Figure 2.29 b). This bending may divert the ultrasonic wave from where it would normally be received, to some other point.

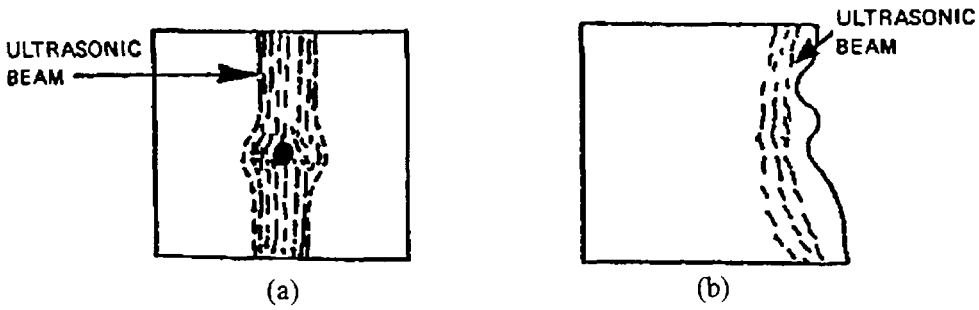


Figure. 2.29 : Diffraction of ultrasound in solids;
(a) Around the defect, (b) Near the irregular edge.

2.8.1.5 Overall effect of attenuation

In addition to the amount of sound lost due to the above causes, there are other factors to consider, such as losses in scattering due to surface roughness of a reflector and spreading of the sound beam. In this instance, attenuation is considered as the sum of all these factors since they all affect the amount of sound transmitted to and returned from an area of interest in the test material. The attenuation losses during propagation in a material are shown in Figure 2.30.

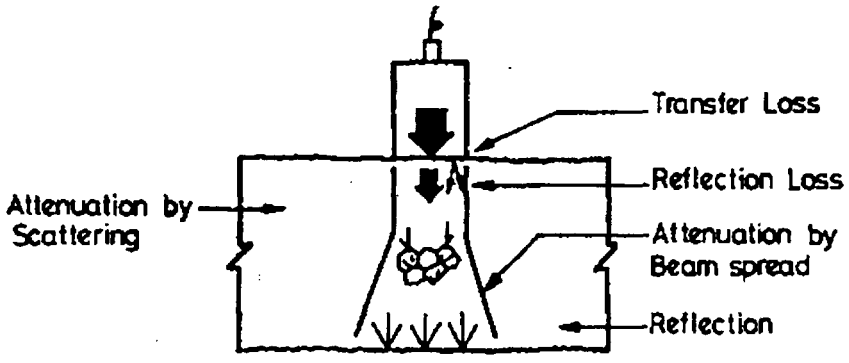


Figure 2.30 : Attenuation losses during transmission.

The variation of acoustic pressure with distance due to divergence, attenuation and beam spread is shown in Figure 2.31.

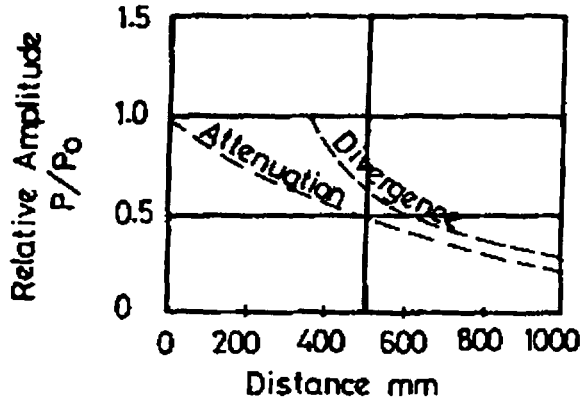


Figure 2.31 : Variation of signal amplitude with distance due to divergence and attenuation losses (linear representation).

The sound pressure which decreases as a result of attenuation by scattering and absorption can be written in the form of an exponential function:

$$P = P_o \exp(-\alpha d) \quad \text{----------} \quad (2.27)$$

The natural logarithm of this equation gives

$$\alpha d = \ln(P_o / P) \quad \text{----------} \quad (2.28)$$

This is the attenuation proper, which is expressed in nepers. However, following the practice in electrical measurement, the decibel measure is given preference. This is obtained when the common logarithm with base 10 is used and multiplied by 20.

Hence

$$\alpha d = 20 \log (P_o / P) \text{ dB}$$

$$\alpha = 20/d \log (P_o / P) \text{ dB/mm or dB/m} \quad \text{----------} \quad (2.29)$$

(depending upon the units of 'd')

As mentioned earlier in Section 2.8.1, α is measured either in nepers per mm or in dB per mm. The decibel unit is more convenient to use. Thus an attenuation of 20 dB is equivalent to a reduction of 1/10, 40 dB equivalent to reduction of 1/100 and 60 dB equivalent to a reduction of 1/1000. Conversely an increase by 20 dB means a ten-fold increase and so forth. Further, 1 dB means a change of approximately 10% and 0.1 dB means a change of 1%. If the attenuation coefficient of a given material is 1 dB /mm the wave is attenuated by a layer of 1 mm thickness by approximately 10% and by a 20 mm layer by approximately 90%. At 100 mm the attenuation is of the order of $(10)^5$ and the sound pressure is $(10)^{-5}$. This would already be a very severe attenuation. Scattering increases rapidly with increasing grain size of the material. Absorption is reduced with decreasing frequency. When absorption and scattering act together one has to compromise in order to find the ideal test frequency. As long as the minimum equivalent reflector size to be recorded is large compared to the average grain size, a frequency reduction may lead to an improved flaw detectability. As a thumb rule a flaw can be regarded as being detectable if its size is bigger or equal to 1/5 of the wavelength in a fine grain material.

With most frequencies up to 5 MHz and with longitudinal waves (straight beam probes and longitudinal angle beam probes) sound attenuation can normally be neglected in all low alloy, forged steel, in low alloy cast aluminium and magnesium, worked steel nickel, etc. These are termed as materials of low attenuation. The attenuation coefficient for these stays below 10 dB/m. The materials of medium attenuation include high alloy and cast steel, deformed copper, zinc, brass, bronze, lead, hard metals and sintered metals. Attenuation coefficients of up to 100 dB/m occur in these materials. Lastly attenuation coefficients greater than 100 dB/m occur in materials with high attenuation. To this category belong materials such as all kinds of plastics, rubber, concrete, ceramics and wood, as well as high alloy cast steel, high alloy cast aluminium and magnesium, cast copper, zinc, brass, bronze, porous ceramics and rocks, etc. Ultrasonic testing of these materials turns out to be very difficult, although in practical applications many problems have already been solved. If testing is possible then, due to the high loss of sound

energy, this would only be for quite thin workpieces. If the pulse echo technique fails in these cases the through transmission technique may still be applicable.

The discussion of attenuation made so far is applicable to the longitudinal waves. For transverse waves the attenuation is generally much stronger, particularly in plastics. Similarly attenuation usually increases with the temperature of the test specimen. For steel a maximum of the attenuation of sound appears at the transition point from body-centred to face-centred iron (approx. 721°C).

2.8.2 Principles of measurement of attenuation

Evaluation of the flaw sizes in ultrasonic testing is made on the basis of the sound reflected from these flaws and the echoes which this reflected sound produces on the oscilloscope screen. Since the sound pressure is proportional to the oscilloscope echo height (H), the Equation 2.29 can be rewritten as:

$$\alpha = 20/d \log (H_o/H) \text{ dB/m (if 'd' is in metres)} \text{ ---------- } (2.30)$$

But from the knowledge of attenuation we know that the echo height as seen on the screen is not due entirely to the flaw but also includes an element of attenuation in it. A compensation of attenuation losses with the echo amplitude evaluation of flaws is only possible if the attenuation coefficient of the workpiece and, if applicable, of the reference block, are known. Absolute measurements of the attenuation are very difficult because the echo amplitude depends not only on the attenuation but also on a number of other influencing factors. Relative measurements are easier and can be made experimentally for each test. For this purpose the shape of the specimens, the probe and the coupling are kept constant while the amplitudes of the backwall echoes are compared. When a plate material is examined the amplitude difference, ΔH, between the first back reflection, H_{B1}, and the second back reflection, H_{B2}, is due to attenuation by beam spread and scattering, assuming no contact surface losses, as shown in Figure 2.32. Curve A is due to beam spread while B is due to scattering and T is the specimen thickness.

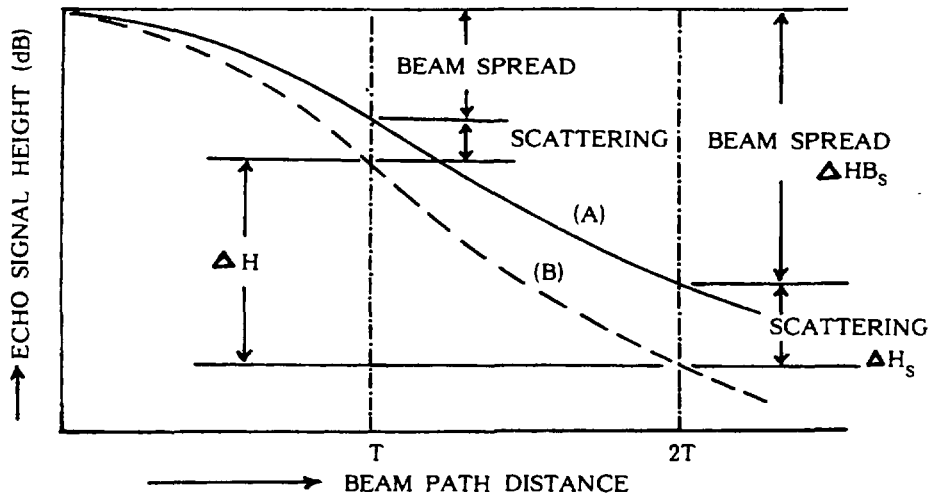


Figure 2.32 : Attenuation by beam spread and scattering.

Thus $\Delta H = H_{B1} - H_{B2}$ ---------- (2.31)

and also $\Delta H = HB_s + \Delta H_s$ ---------- (2.32)

The amplitude difference, ΔH between the multiple back reflections can be read out on the equipment gain (or attenuator). The attenuation difference, ΔHB_s by the beam spread is possible to obtain from the DGS diagram. Hence, the attenuation difference, by scattering and absorption is expressed as follows:

$$\Delta H_s = \Delta H - \Delta HB_s \quad \text{----------} \quad (2.33)$$

If ΔHs is divided by the total distance travelled, the result is called the attenuation coefficient, Thus,

$$\alpha = \Delta H_s / 2T = (\Delta H - \Delta HB_s) / 2T \text{ (dB/m)} \quad \text{----------} \quad (2.34)$$

When the distance, T, is at least 3N, the beam spread law for large reflectors can be utilised. The amplitude is inversely proportional to the distance, so that if the distance is doubled, the amplitude is halved, i.e. a 6 dB reduction. This law provides a simple method of measuring the attenuation coefficient since ΔHB_s = 6 dB and the attenuation coefficient α is calculated, as follows:

$$\alpha = (\Delta H - 6) / 2T \text{ (dB/m)} \quad \text{----------} \quad (2.35)$$

for $(T \geq 3\,N)$

A typical example is as follows:

Plate thickness = 30 mm

Probe frequency = 4 MHz

Probe diameter = 10 mm

Near field length = 17 mm

The second back echo at 60 mm distance is greater than 3 N (51 mm); therefore the second and fourth echoes are on the 6 dB slope.

Suppose the difference in echo amplitude measured between second and fourth echo is 10 dB. Total beam distance between second and fourth echo is 120 mm. Therefore, the attenuation coefficient of the plate material at 4 MHz is

$$\alpha = (10 - 6)/120 = 1/30 \text{ (dB/mm)} = 33 \text{ dB/m.}$$

TABLE 2.6 : TRIGNOMETRIC FUNCTIONS OF ANGLES

Angle	Sin	Cos	Tan	Angle	Sin	Cos	Tan
1°	.0175	.9998	.0175	46°	.7193	.6947	1.0355
2°	.0349	.9994	.0349	47°	.7314	.6820	1.0724
3°	.0523	.9986	.0524	48°	.7431	.6691	1.1108
4°	.0698	.9976	.0699	49°	.7547	.6561	1.1504
5°	.0872	.9962	.0875	50°	.7660	.6428	1.1918
6°	.1045	.9945	.1051	51°	.7771	.6293	1.2349
7°	.1219	.9925	.1228	52°	.7880	.6157	1.2799
8°	.1392	.9903	.1405	53°	.7986	6018	1.3270
9°	.1564	.9877	.1584	54°	.8090	.5878	1.3764
10°	.1736	.9848	.1763	55°	.8192	.5736	1.4281
11°	.1908	.9816	.1944	56°	.8290	.5592	1.4826
12°	.2079	.9781	.2126	57°	.8387	.5446	1.5399
13°	.2250	.9744	.2309	58°	.8480	.5299	1.6013
14°	.2419	.9703	.2493	59°	.8572	.5150	1.6643
15°	.2588	.9659	.2679	60°	.8660	.5000	1.7321
16°	.2756	.9613	.2867	61°	.8746	.4848	1.8040
17°	.2924	.9563	.3057	62°	.8829	.4695	1.8807
18°	.3090	.9511	.3249	63°	.8910	.4540	1.9626
19°	.3256	.9455	.3443	64°	.8988	.4384	2.0503
20°	.3420	.9397	.3640	65°	.9063	.4226	2.1445
21°	.3584	.9336	.3839	66°	.9135	.4067	2.2460
22°	.3746	.9273	.4040	67°	.9205	.3907	2.3559
23°	.3907	.9205	.4245	68°	.9272	.3746	2.4751
24°	.4067	.9135	.4452	69°	.9336	.3584	2.6051
25°	.4226	.9063	.4663	70°	.9397	.3420	2.7475
26°	.4384	.8988	.4877	71°	.9455	.3256	2.9042
27°	.4540	.8910	.5095	72°	.9511	.3090	3.0777
28°	.4695	.8829	.5317	73°	.9563	.2924	3.2709
29°	.4848	.8746	.5543	74°	.9613	.2757	3.4874
30°	.5000	.8660	.5774	75°	.9659	.2588	3.7321
31°	.5150	.8572	.6009	76°	.9703	.2419	4.0108
32°	.5299	.8480	.6249	77°	.9744	.2250	4.3315
33°	.5446	.8387	.6494	78°	.9781	.2079	4.7046
34°	.5592	.8290	.6745	79°	.9816	.1908	5.1446
35°	.5736	.8192	.7002	80°	.9848	.1736	5.6713
36°	.5878	.8090	.7265	81°	.9877	.1564	6.3138
37°	.6018	.7986	.7536	82°	.9903	.1392	7.1154
38°	.6157	.7880	.7813	83°	.9925	.1219	8.1443
39°	.6293	.7771	.8098	84°	.9945	.1045	9.5144
40°	.6428	.7660	.8391	85°	.9962	.0872	11.4301
41°	.6561	.7547	.8693	86°	.9976	.0698	14.3007
42°	.6691	.7431	.9004	87°	.9986	.0523	19.0811
43°	.6820	.7314	.9325	88°	.9994	.0349	28.6363
44°	.6947	.7193	.9657	89°	.9998	.0175	57.2900
45°	.7071	.7071	1.0000	90°	1.000	.0000	

3. TESTING TECHNIQUES AND THEIR LIMITATIONS

3.1 BASIC ULTRASONIC TEST METHODS

Ultrasonic waves arriving at an interface between two media are partially reflected into the medium from which they are incident and partially transmitted into the other medium. The method of ultrasonic testing which utilizes the transmitted part of the ultrasonic waves is the through transmission method while that which makes use of the reflected portion of the waves is classified as the pulse echo test method. Another method which is used for the ultrasonic testing of materials is the resonance method.

3.1.1 Through transmission method

In this method two ultrasonic probes are used. One is the transmitter probe and the other is the receiver probe. These probes are situated on opposite sides of the specimen as shown in Figure 3.1.

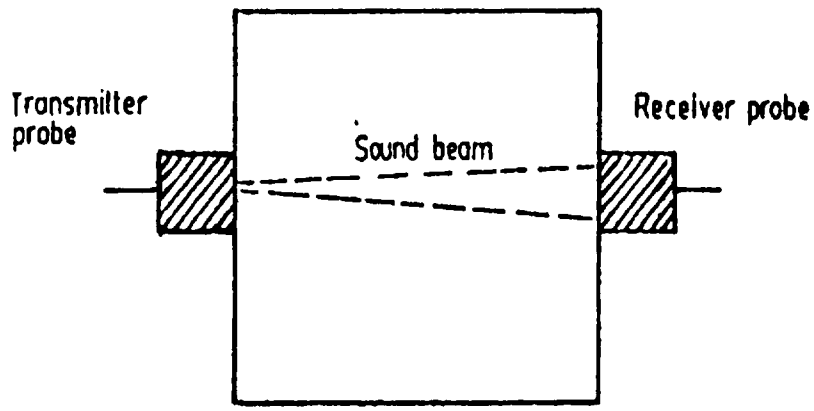


Figure 3.1 : Position of transmitter and receiver probes in the through transmission method of ultrasonic testing.

In this method the presence of an internal defect is indicated by a reduction in signal amplitude, or in the case of gross defects, complete loss of the transmitted signal. The appearance of the CRT screen is as illustrated in Figure 3.2 (a, b & c).

This method is used for the inspection of large ingots and castings particularly when the attenuation is high and gross defects are present. The method does not give the size and location of the defect. In addition good mechanical coupling and alignment of the two probes is essential.

3.1.2 Pulse echo method

This is the method most commonly utilized in the ultrasonic testing of materials. The transmitter and receiver probes are on the same side of the specimen and the presence of a defect is indicated by the reception of an echo before that of the backwall echo. Mostly the same probe acts as the transmitter as well as the receiver. The CRT screen is calibrated to show the separation in distance between the time of arrival of a defect echo as against that of the backwall echo of the specimen, therefore, the location of a defect can be assessed accurately. The principle of the pulse echo method is illustrated in Figure 3.3 (a, b & c).

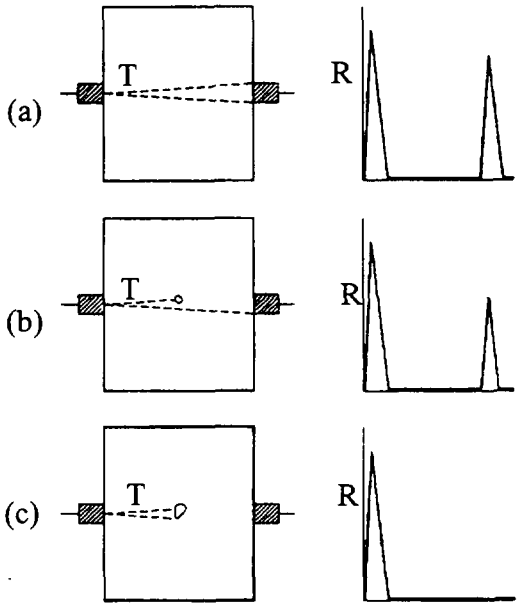


Figure 3.2 : CRT screen appearance for defects of varying sizes in the through transmission method; (a) Defect free specimen, (b) Specimen with a small defect, (c) Specimen with a large defect.

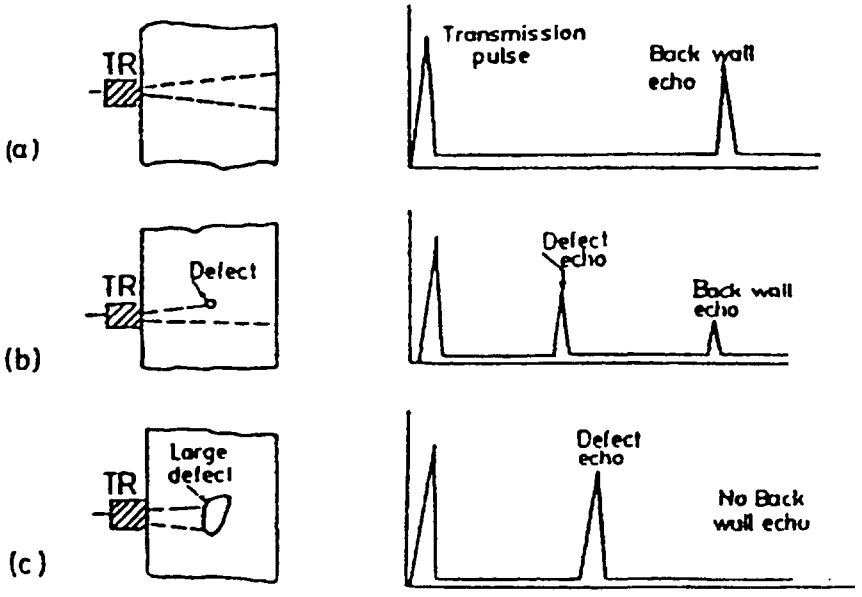


Figure 3.3 : Principle of pulse echo method of ultrasonic testing; (a) Defect free specimen, (b) Specimen with small defect, (c) Specimen with large defect.

A specimen with parallel boundaries (Figure 3.3 a) yields not only single backwall echo but a sequence of multiple echoes spaced evenly, provided the measuring range of the viewing screen is large enough (Figure 3.4). These multiple echoes are obtained because the first wave reflected at the backwall transmits only a small portion of its energy to the probe when it arrives at the front wall. It is therefore only attenuated slightly when reflected from the front wall and it passes through the specimen a second time and so forth. The height of the multiple echoes decreases because, in addition to the slight energy loss in the probe, the wave is attenuated in the material and because the propagation of sound beam follows the laws of beam spread and diffraction, etc.

There are two ways to transmit ultrasonic waves into the test specimen in pulse echo testing; one is the normal beam or straight beam technique and the other is the angle beam technique. Similarly tandem testing technique as well as immersion testing are also different forms of pulse echo testing.

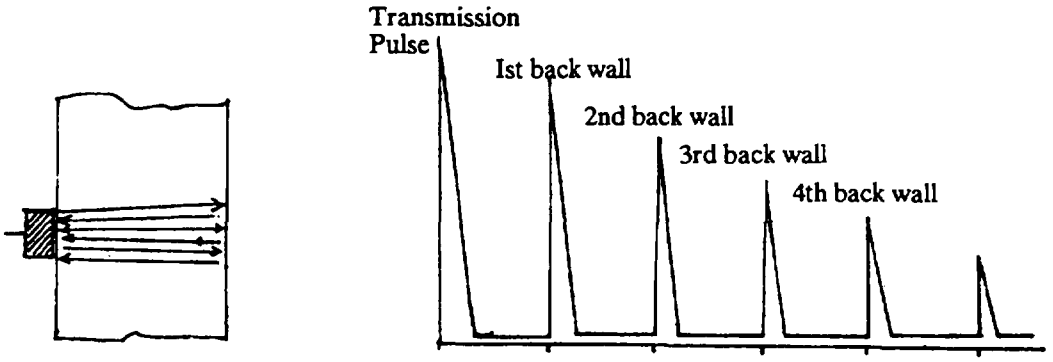


Figure 3.4 : Multiple echoes in case of a pulse echo method.

As the name suggests, pulse echo method utilizes short pulses of sound instead of continuous waves. A wave train refers to the short group of waves, before or after which there are no waves. This formation is generally referred to as a pulse. A pulse may take several forms. It may start and drop rapidly. It may build and decay gradually. It may build up rapidly and decay exponentially.

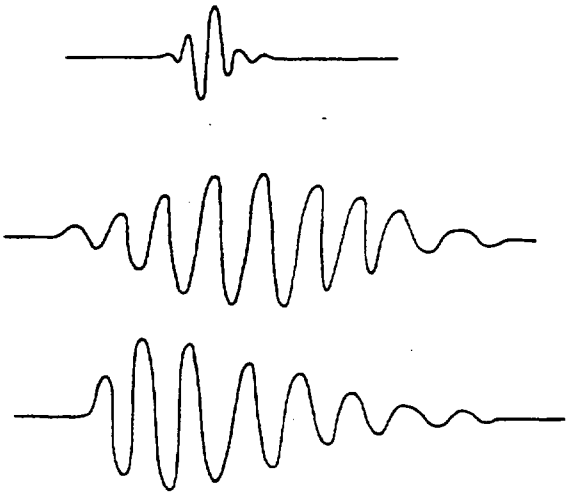


Figure 3.5 : Ultrasonic pulses of different lengths and shapes.

The type of wave illustrated in Figure 3.5 is referred to as a decayed or damped train and this is probably the most commonly used type of pulse in ultrasonics.

Almost all probes incorporate assisted damping to the crystal, in the form of backing. This backing medium must have a higher acoustic impedance than the crystal. The reason for the damping in a single probe is the very fact that the crystal has to produce short and above all sharp bursts of pulsed energy. Ideally the crystal motion must end abruptly from its previous pulse so that the reflected energy excites a relatively inactive crystal and not one that is already in a stage of oscillation (Figure 3.6 a & b).

What type of pulse width can we expect to be displayed on the cathode ray tube time base? Pulse width will depend on the frequency of the probe used and is also a function of pulse energy. In other words one must apply an electrical pulse to the crystal that is wide enough to cause the transducer to reach maximum oscillations at the same time remembering that an increase in pulse width will reduce resolution.

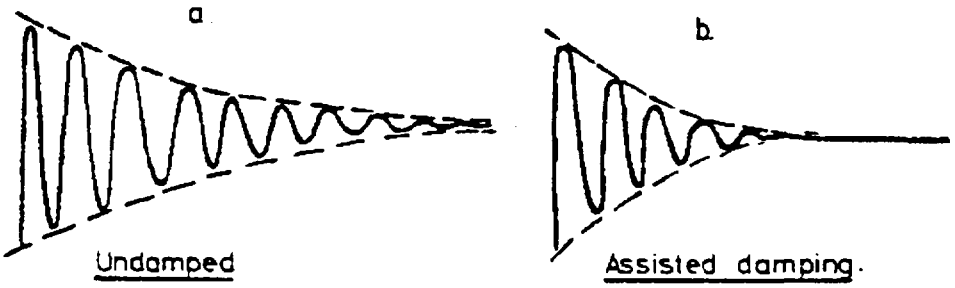


Figure 3.6 : Effect of damping on probe ringing.

The effect of pulse width with regards to resolution will now be discussed. First of all it is necessary to emphasize the fact that a pulse of energy is made up of several waves produced from oscillations of the crystal during a given number of microseconds (Figure 3.7).

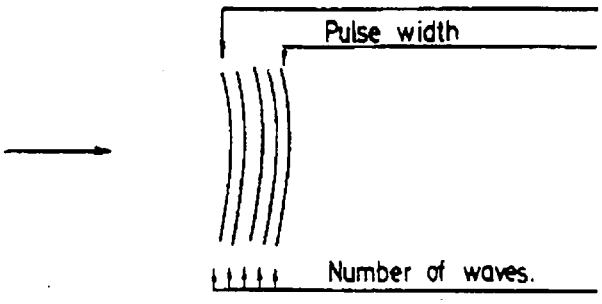


Figure 3.7 : The case of larger pulse width.

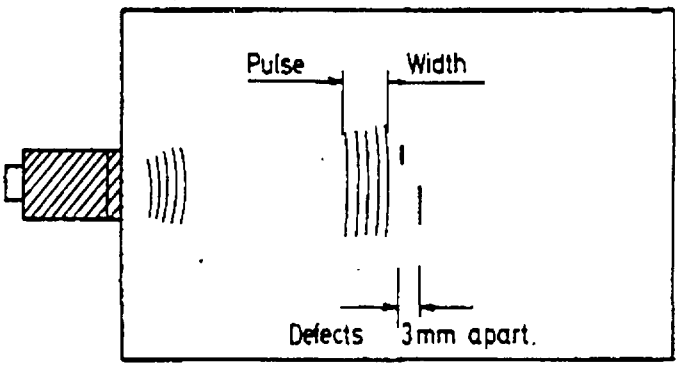


Figure 3.8 : The case of smaller pulse width.

We will now consider the pulse width in steel for a crystal that has produced a pulse of energy for a period of 2 microseconds. The width of the pulse will be approximately 12 mm. Figure 3.8

shows two defects separated by 3 mm. This pulse width of 12 mm would not be able to resolve these two defects because their echoes would overlap. Therefore this pulse width would not satisfactorily resolve defects closer than approximately 6 mm together. Defects around this 6 mm separation band would give an indication on the back edge of the main signal on the cathode ray tube. Defects below this value would be lost in the main signal envelope. Figure 3.9 (a & b) shows the pulse from the 3 mm separation and the 6 mm separation.

To determine the pulse width, multiply the number of waves in the pulse by the wavelength or Pulse length = (velocity/frequency) × number of waves.

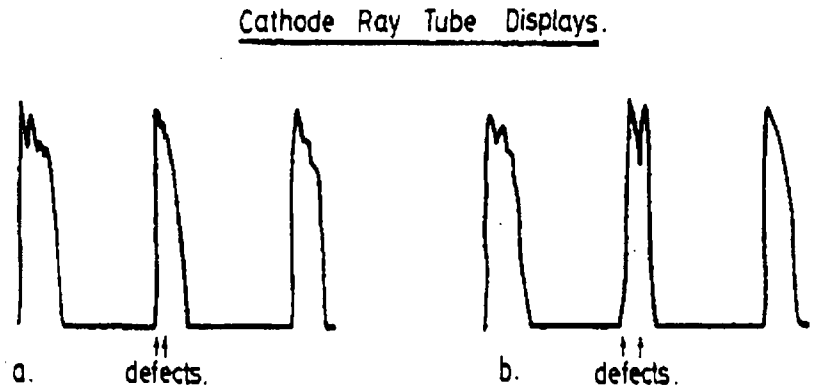


Figure 3.9 : Effect of pulse width on resolution of defects;
(a) Lesser resolution because of larger pulse width,
(b) Better resolution with smaller pulse width.

On summarizing, good resolution demands a very short pulse so that the reflection from one defect lying close to another is not lost in the received signal of the first. Good and poor resolutions are shown in Figure 3.10. It should be further noted that the higher the frequency the shorter the pulse width. Also the higher the frequency the shorter the wavelength thereby giving greater sensitivity to small defects. The two combinations give good defect detectability and good resolution.

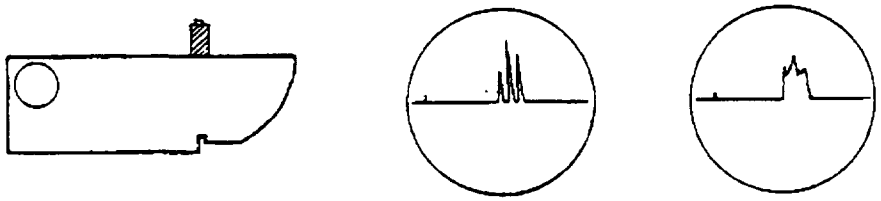


Figure 3.10 : Example of good and poor resolution.

3.1.3 Resonance method

A condition of resonance exists whenever the thickness of a material equals half the wavelength of sound or any multiple thereof in that material. Control of wavelength in ultrasonics is achieved by control of frequency. If we have a transmitter with variable frequency control, it can be tuned to create a condition of resonance for the thickness of plate under test. This condition of resonance is easily recognized by the marked increase of received pulse amplitude. Knowing the

resonance or fundamental frequency 'f' and velocity 'v' of ultrasound in the specimen, the thickness 't' of the specimen under test can be calculated from the equation:

$$t = v / 2f \quad \text{----------} \quad (3.1)$$

Since it is difficult to recognize the fundamental mode of vibration, the fundamental frequency is usually calculated from the difference of two adjacent harmonics which are depicted by two adjacent rises in the pulse amplitude.

Therefore,

$$t = v / 2 (f_n - f_{n-1}) \quad \text{----------} \quad (3.2)$$

where

f_n = frequency at nth harmonic

f_{n-1} = frequency at (n-1)th harmonic.

The resonance method of ultrasonics was at one time specially suited to the measurement of thickness of thin specimens such as the cladding tubes for reactor fuel elements. The method has now been largely superseded by the pulse echo method because of improved transducer design. Figure 3.11 shows the basic elements of a resonance testing equipment.

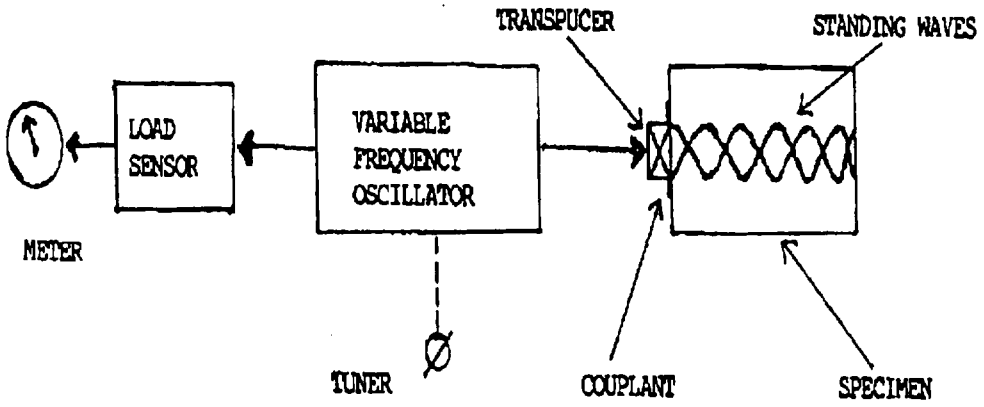


Figure 3.11 : Basic components of a resonance testing equipment.

3.1.4 Automatic and semi-automatic methods

The semi and fully automatic and remote control systems of the ultrasonic examination are rapidly improving in these days covering very wide range of industries with much varieties in applications. Salient features of such a system and the objectives and the benefits which it is aimed at achieving will be described here while the detailed methods and applications will be dealt with in Section 9.2 as well as in various sections of Chapter 6.

The purpose to employ the automatic and remote control ultrasonic examination may be summarized as follows:

(i) Elimination of operational variations and personal errors caused by examination.

(ii) Manual operation of the equipment is difficult or impossible to perform.

(iii) Saving manpower or reduction of working time through increased speed of inspection.

(iv) Accuracy of records, and enlarging capacity of data processing.

(v) Automatic analysis and evaluation of the results by computerized system.

The automatic system of the ultrasonic examination is, herein, defined as a system of the ultrasonic examination capable of mechanical operation of the probes, automatic records of the test results and data processing. The system essentially consists of one or several probes which are coupled to the test specimen by a control unit and are moved across the test object according to a predetermined scanning pattern. The ultrasonic signals are processed by the evaluation unit (e.g. an ultrasonic flaw detector) and displayed on a CRT screen if available. All measured data along with the information about the probe position are fed to a computer where they are further processed and evaluated. The evaluation device, based on a more or less complex programme of data processing, can make provision for signalisation of flaw, identification of defective specimens or documentation of test results. The test report is produced by means of a printer. The computer also controls the marking and sorting device which marks the flaw locations on test objects. Test objects which have unacceptable flaws are rejected. A further task of the computer is to control the transport of the work piece and to signal defined test conditions. Figure 3.12 shows block diagram of a typical automatic ultrasonic testing system. The detailed components of the system are given below:

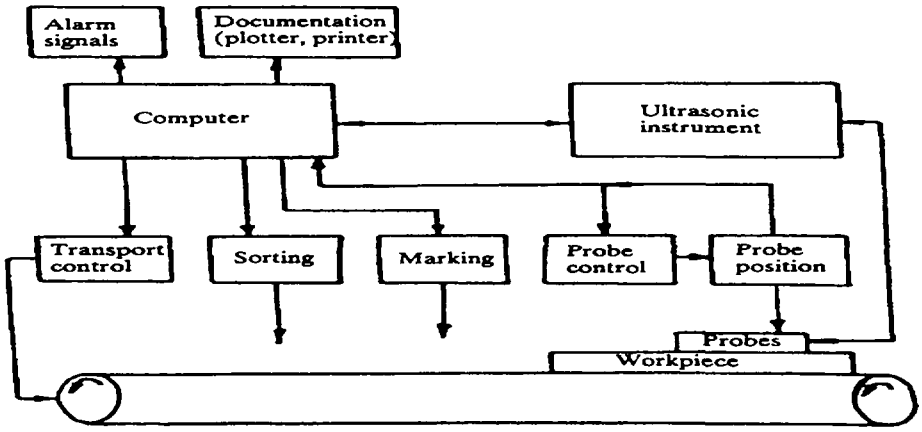


Figure 3.12 : Block diagram of a typical automatic ultrasonic testing system.

(i) Mechanical operation of the probe or probes and remote control.

(ii) Capability of the probes or transducers adequate to the automation.

(iii) Automatic supply of the couplant.

(iv) Automatic gain control.

(v) Automatic adjustment of the equipment gain for specified working sensitivity (automatic distance-amplitude correction).

(vi) Self-checking or monitoring system.

(vii) Ultrasonic data processing system.

(viii) Applications of B-scope, C-scope, Quasi-three dimensional display system (acoustic holography, frequency analysis, etc.).

Presentation and documentation of results in automatic testing needs special attention. It can be realized in many different ways. Apart from recording the test data by direct recorders, either by amplitude or by areas, use is made in some instances also of recording by film. To an increasing extent the test information (flaw echoes, backwall echoes or reference echoes, acoustic

transmission readings and transit-time data) is being made available in digital form. Consequently, increasingly greater use is made of printers. So far punched tape stores are little used. The complete storage of the test on magnetic tape has been realized.

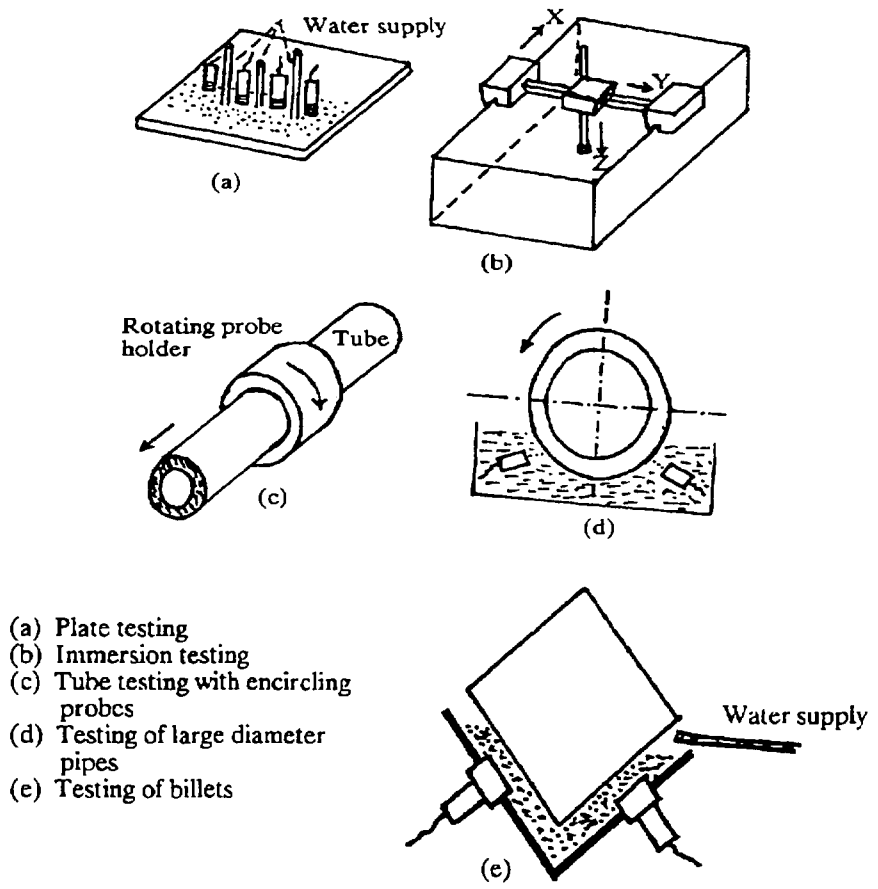


Figure 3.13 : Different arrangements with automatic testing.

Semi and fully automated methods of ultrasonic testing are generally useful for testing of specimens of uniform and regular shapes. To this category belong plates of all sizes and thicknesses, uniform shaped castings, forgings and welds, pipes and tubes, rods and cylinders, small and large pressure vessels, rotor shafts, etc. (also see Chapters 6 and 9). Figure 3.13 shows the different arrangements with automatic testing.

3.2 SENSORS

The term sensor in ultrasonic testing is used for the device used for transmission and receipt of ultrasound. It is also called a transducer or a probe. An ultrasonic probe (Figure 3.14) consists of:

(i) A piezoelectric crystal or transducer.

(ii) A backing material.

(iii) A matching transformer which matches the piezoelectric transducer's electrical impedance to that of the cable to the flaw detector in order to transfer maximum energy from the cable to the transducer and vice versa.

(iv) A case which is simply a holder of suitable dimensions and construction.

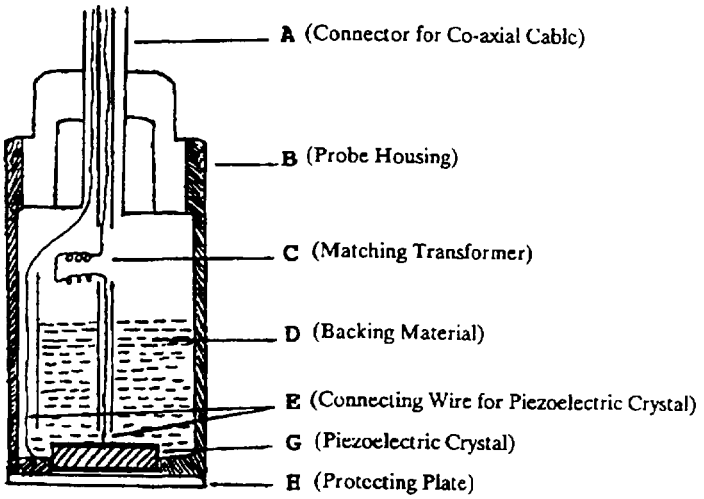


Figure 3.14 : A typical ultrasonic probe.

(a) Piezoelectric transducers

Piezoelectric transducers are already discussed in detail in Section 2.6. An ultrasonic probe is generally excited by a voltage pulse of less than 10 micro second duration. A short voltage pulse consists of a band of frequencies. Among these frequencies, the transducer vibrates with maximum amplitude at the frequency known as the resonance frequency of the transducer, which is related to its thickness as follows:

$$f_r = v / 2t \qquad (3.3)$$

where

f_r = resonance frequency of the transducer.
t = thickness of the transducer.
v = longitudinal wave velocity of ultrasound in the transducer material.

Equation 3.3 is used to determine the thickness of the transducer required to construct an ultrasonic probe of a particular frequency. For example to make a probe of 1 MHz frequency the thickness of a quartz crystal will be 2.98 mm. The thickness for 10 MHz frequency comes out to be 0.298 mm while for a frequency of 20 MHz it will be 0.14 mm. It will be appreciated that although flaw sensitivity will be much improved with a 20 MHz probe (at this frequency the wavelength = 0.298 mm and flaw sensitivity being of the order of $\lambda/3$ is 0.1 mm) the crystal in this case will be extremely thin and consequently quite fragile and difficult to handle. Therefore in practice a compromise has to be made between the crystal thickness that can be conveniently managed and the flaw sensitivity to be achieved. In cases where high sensitivity is essentially required the probes are immersed in a liquid and most testing is done with the probe receiving minimum possible disturbance. For quartz the upper practicable fundamental frequency is in the region of 20 MHz while for most ceramic transducers the upper frequency limit is only about 10 MHz.

The other important parameter of the crystal which affects the ultrasonic beam produced by it is its diameter, D (Section 2.7.3). On crystal diameter depend the near field length, the beam divergence and the width of the beam at a given point.

Most probes have circular radiating surfaces with diameters of approximately 5 to 40 mm. Diameters larger than 40 mm are unsuitable for most test problems because a corresponding flat contact surface is not available. The disadvantage of smaller diameters, particularly in the case of low frequencies, is the greater radiation of lateral transverse waves and surface waves. Another difficulty arising from the use of probes with small diameters is their greatly reduced sensitivity.

For providing the electrical pulses to the crystal, its faces need to be electrically connected with the help of wires. For this purpose the faces of the crystal are electroplated with silver and contacts are then provided by soldering the connecting wires to this layer of electroplated silver. In case of quartz and ceramic piezoelectric materials the most durable electrodes are obtained by spraying on liquid conducting silver, burned in at temperatures from 500 to 700°C. The wires can then be soldered on with soft silver solder. In the case of barium titanate the soldering on of wires can be done after polarization if done carefully. Lithium sulphate can be metalized by evaporating silver on its surface in vacuum, by painting the surface with cold drying conducting silver or by cementing on thin metal foils. The wires should be glued on by means of a conducting cement.

If the front of the plate has to be used for direct contact, silver plating would not prove sufficiently resistant to the wear on surfaces to which the piezoelectric plate must be applied, which in practice are usually contaminated with very hard scale particles and impurities such as sand, resulting in excessive wear, particularly if the probe is applied by a sliding action, which can never be avoided completely. It is then preferable either to use a completely unprotected quartz plate whose gradual wearing off will have to be accepted, or the silver layer must be strengthened by applying layer of copper and hard chrome with an overall thickness of a few tenths of a millimetre. This layer should be connected to the earth probe because wires or strips soldered to the front may interfere. Such probes can also be used on non-metallic test pieces, e.g. porcelain, or test pieces with non-conducting coatings. In the case of unprotected probes it may be necessary to interpose thin metal foils or electrically conducting coupling liquids, e.g. water, if necessary with additives to increase both the viscosity and the conductivity.

Satisfactory wear resistance combined with high resolution and sensitivity is realized by thin protective layers of aluminium oxide, sapphire, boron carbide or quartz cemented to the front of the transducer. Of course, in consequence of the high impedance of these materials, the testing sensitivity of these probes varies considerably with varying degrees of coupling and in addition, the protective layers, particularly in high frequency probes, are sensitive to shock. These shortcomings can be avoided by using layers of synthetic resins which contain, for instance, an admixture of corundum powder. However, such material is less resistant to wear.

Where high resolution is not essential, as usually in routine tests under rough operating conditions, the contact face is protected preferably by an exchangeable plastic film a few tenth mm thick stretched over the transducer and coupled by applying oil or grease. Particularly suitable for this purpose are plastics with high resistance to wear and high absorption. Because of the thinness of the layer the high absorption has little influence on the sensitivity but it reduces multiple reflections in the layer, which could broaden the pulse.

(b) Backing material

The backing material in a probe is used to control the two basic performance characteristics of the probe, namely, resolution and sensitivity. Resolution of a probe is its ability to separate the echoes from two flaws which are close together in depth. Sensitivity of a probe is defined as the

ability of the probe to detect echoes from small flaws. To have a high resolution probe, the vibration of the transducer of the probe should be damped as quickly as possible to produce short pulses. But to have a high sensitivity probe, the damping of the transducer vibration should be as low as possible. The two requirements are contradictory to each other and therefore a compromise has to be made.

The maximum damping of the transducer's vibrations is achieved when the backing material has the same acoustic impedance as that of the transducer. It could consist of solid and hard materials such as metal or porcelain. This matching of the acoustic impedance of transducer and backing material allows the ultrasound to pass easily from the transducer into the backing material. In the case of thin crystal plates, the damping body gives the necessary mechanical support and it should therefore not be deformed when pressed upon. Materials such as vulcanized rubber and moulded fire plastics are satisfactory for moderate demands at higher frequencies. Preferable are composite materials based on curable synthetic resins or rubber in which other powdery admixtures have been incorporated. Natural and synthetic rubber have higher intrinsic absorption than moulded resins.

The backing material should also provide high degrees of attenuation and absorption to dissipate the transmitted ultrasound so that it will not reflect from the back of the backing material to create spurious signals. To have sufficient sensitivity with high resolution the mismatch of acoustic impedances of the transducer and backing material is usually approximately 5 to 1 for quartz transducers and 1.1 to 1 for lithium sulphate transducers. The acoustic impedance can be increased by admixing metal powder, and the absorption can be increased by adding finely ground materials, which combine high absorption with usually low mechanical strength. Attempts have also been made to scatter the waves by using saw dust or cellular structures. Such means, as well as disturbances of the plane reflection on the end of the damping body by oblique or sawtooth shaped end faces, can be applied successfully only in combination with an already intrinsically effective absorption. Otherwise the various interfering echoes will be replaced by a background of grass behind the transmitting pulse. Attenuation can be controlled by the grain size of the powder and the impedance by the proportions of metal powder and plastic.

Backing materials for pulse echo probes are often made of fibrous plastics or metal powders combined with various plastic materials. If the content of admixed metal powder is high, the damping can attain sufficiently high electrical conductivity for the high frequency pulse. In the case of quartz the electrode can then be omitted but the damping body must be mounted insulated. However, barium titanate, with its high dielectric constant, definitely requires a metallic electrode directly on the piezoelectric plate.

The cementing layer between piezoelectric plate and damping body might again reduce the actual damping considerably, even in the case of a material of suitable properties. This layer should therefore be as thin as possible, or better still, eliminated completely by vulcanizing to the surfaces a rubber material or by applying to them portable mixtures which are then cured.

A damping body attached to the back of the transducer damps mainly the thickness oscillation of the piezoelectric plate. However, interfering radial oscillations may also be present which are difficult to suppress, particularly in the case of barium titanate. They can be reduced by embedding the edge of the plate in a damping compound. Alternatively a transducer with small coupling factor for radial oscillations can be chosen. The whole oscillator could of course also be constructed in the form of a mosaic with intermediate layers consisting of a damping compound.

(c) Matching transformer

All types of probes also contain electrical matching elements (capacitors and inductors) in order to maximize the electrical coupling of the probe to the input of the amplifier. In other words the transformer matches the piezoelectric transducer electrical impedance to that of the cable to the flaw detector in order to transfer maximum energy from the cable to the transducer and vice versa.

(d) Protective face and housing

As shown in Figure 3.14, the essential elements of an ultrasonic probe are encased in a metallic housing and usually provided with a protective face or cover. The protective face of a probe does not only protect the sensitive transducer from direct contact with the test piece surface but also improves the acoustical matching to the test piece.

(e) Maintenance of Probes

The probes during use may experience certain damages. The user should therefore be well aware of the possible causes and effects of these damages. These are briefly described here.

(i) The probe may be mechanically damaged because of dropping down, fixing the probe too firmly or by the application of too much load on the coupling surface. This can result in changing of the sound field and reduction or loss of sensitivity.

(ii) The crystal may be loosened from the protective face or delay block because of penetration of liquids into the probe or because of the probe temperatures being too high. This can also affect the sound field and sensitivity of the probes.

(iii) Natural wear of the protective face and the perspex delay blocks may take place in case of direct contact type probes. This may result in an increase of the probe index and a change in the probe angle. In case of TR probes a change in the sound field, increase of cross talk and reduction in sensitivity can take place.

(iv) Extremely high voltages (transmission pulse) at the probe can lead to a dielectric break down resulting in complete destruction of the crystal. Standard probes normally withstand such high voltages. Special probes designed for working at low voltages (e.g. probes for digital thickness gauges) may be affected when connected to an instrument with a high power transmitter.

3.2.1 Normal incidence sensors

These sensors send a sound beam, usually longitudinal, into the test specimen at right angle to the surface of the test specimen. Figure 3.14 shows the design of a typical probe of this kind. The crystal should have its surface precisely parallel to the surface of the test specimen to achieve an exact normal incidence. This consideration is usually made at the design stage when the crystal is being fixed in its housing as well as when the protective face is being applied.

The normal incidence probes are either used in direct contact with the test specimen or without such contact. The former are termed as contact type probes while the latter are said to be non-contact type. In the normal probes of direct contact type a wear plate is often used to protect the transducer from wear. When using this protective plate a thin layer of an appropriate couplant usually light oil is always required between the transducer and the wear plate to obtain

transmission of ultrasound energy across the interface. There are probes which have only one transducer crystal while there are others in which two crystals are simultaneously mounted in the same housing. Some probes have specially ground plastic faces which are used for focusing the beam at a particular region or points. All these different types of normal incidence probes are described below.

3.2.1.1 Single transducer normal beam probes

These probes use a single transducer (Figure 3.14) as a transmitter and receiver of ultrasound. This transducer has a common connection to the transmitter and amplifier units of the flaw detector (Figure 3.15). Because of this common connection to the transmitter and receiver unit, the single transducer probes have a large initial or transmission pulse which results in a large dead zone for the probe generally making the probe useless for near surface flaw detection and thin wall thickness measurement. Short pulse length probes are now available which have shorter dead zones thus making them more useful for testing thin material. The dead zone is a zone where it is not possible to detect defects. The dead zone is shown as the transmission signal at the start of the time base. Its depth can be seen on a calibrated time base as the amount of time base, occupied by the transmission signal. The dead zone increases when the frequency is decreased, therefore a 5 MHz single probe will have a smaller dead zone than a 2.5 MHz probe.

Various characteristics of a single crystal normal beam probe have been explained in Section 2.7. These include frequency, crystal diameter, near field length, beam divergence angle. The manufacturers of probes usually supply probe data sheets and sonograms for different types of their probes.

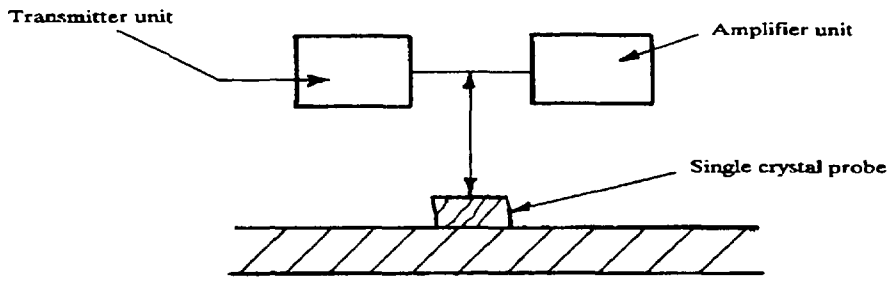


Figure 3.15 : Mode of operation of single crystal probes.

3.2.1.2 Single crystal focused normal beam probes

Occasionally focusing probes of special design are used to increase the sensitivity over a definite range for certain testing problems. For this purpose either a curved, ground, piezoelectric plate of ceramic material is used, or a curved layer with lens effects is cemented to the flat plate. The latter method greatly increases the sensitivity immediately below the surface in the case of probes used according to the immersion technique (Figure 3.16) where such a focusing layer is not subjected to wear. For testing by direct contact, curved transducer surfaces of barium titanate or quartz are suitably ground, or alternatively strips of quartz are assembled in the form of a cylinder for special testing purposes (round stock or forgings) such as testing from holes. In the case of concave test surfaces and direct contact the sound beam would open wide, resulting in low depth sensitivity. This can be improved by inserting between the transducer and the test surface a lens shaped body. This will produce a certain zone of disturbance which must be accepted, even if an absorbing material is used for the lens, such as vulcanized rubber which may contain fillers.

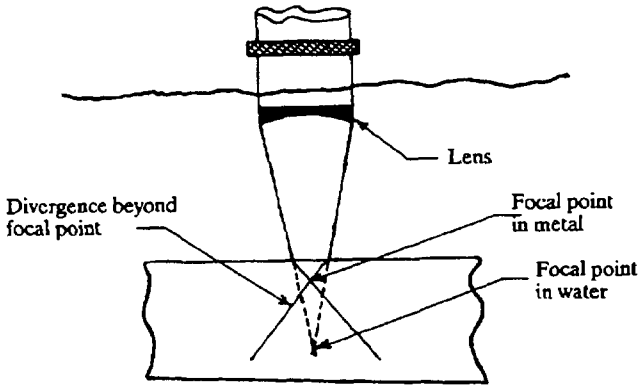


Figure 3.16 : Testing by the immersion technique with focused beam (schematic) showing the change of focal point of the beam in water compared with metal immersed in water.

3.2.1.3 Twin crystal normal beam probes (S.E. probes)

To avoid the limitations encountered in the use of single transducer normal beam probes for thin wall thickness measurements and near surface flaw detection, double transducer normal beam probes are used. These are also called twin-crystal or TR or S.E probes. These are probes which incorporate two transducers in a single case. These transducers are separated acoustically and electrically from each other by an acoustic barrier (Figure 3.17). One of the transducers is connected to the transmitter unit and the other to the receiver unit of the flaw detector, as shown in Figure 3.18, thus eliminating the transmission pulse.

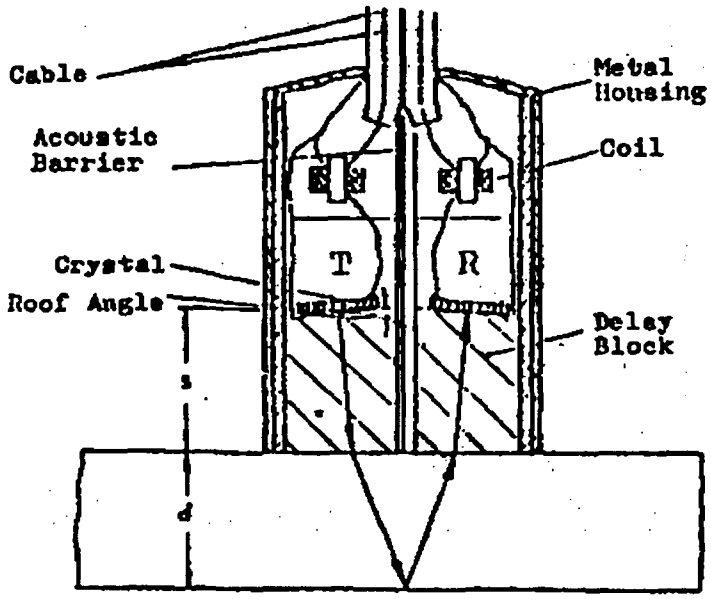


Figure 3.17 : Twin crystal contact type probe and its ultrasonic propagation.

The special features to note in the construction of a double transducer probe are the inclination of the transducers and the long delay blocks. The inclination of the transducers gives a focusing effect and maximum sensitivity can be obtained at a certain point in the specimen for a particular angle of inclination, i.e. "roof angle", (Figures 3.19 & 3.20).

The long delay blocks which are made of perspex or for hot surfaces, of a heat resistive ceramic material, allow the ultrasonic beam to enter the test specimen at its divergent part (i.e. in the far

zone). This eliminates the difficulties of evaluating a flaw occurring in the near field and also helps in producing a shorter dead zone for the probe for a larger roof angle.

The minimum distance at which echoes of flaws can be detected is given by the beginning of the region where the sound beam of the transmitter and the receiving characteristics of the receiver overlap. Due to this fact, with TR-probes, we can define a pipe shaped region of maximum sensitivity which is often dealt with in the data sheets of TR probes. The high sensitivity in the subsurface region is caused by the roof angle of the two crystals. On the other hand, with high gain settings, this leads to an interference echo, known as the cross talk echo which should not be misinterpreted as being a flaw.

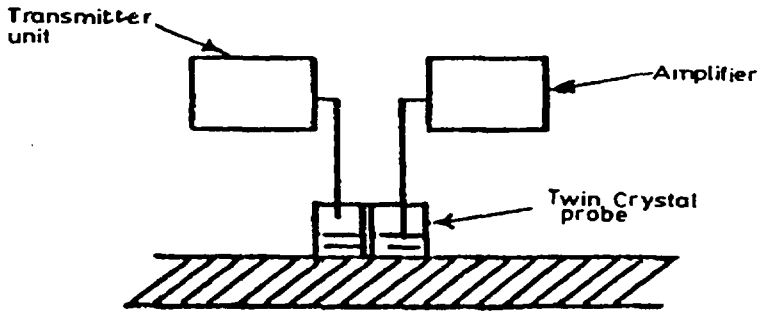


Figure 3.18 : Mode of operation of twin crystal probe.

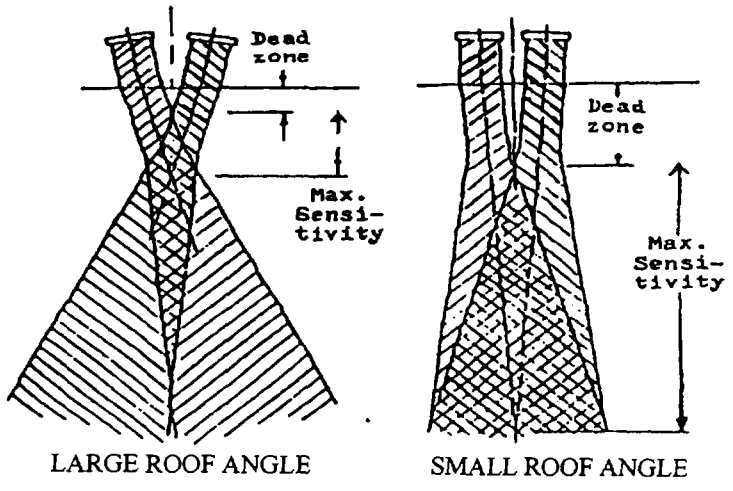


Figure 3.19 : Ultrasound propagation at large and small roof angles of a double crystal probe.

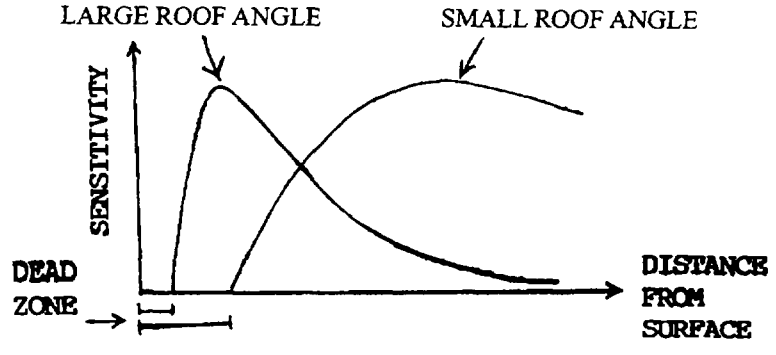


Figure 3.20 : Influence of roof angles over sensitivity of twin crystal probe.

Further attention must be paid to the fact that, with decreasing thickness of the work piece (plate) or flaw location, a big measuring error may occur, known as the V-path error (Figure 3.21). It never occurs with distances lying between the two steps used for calibration if the thickness ratio of the two steps does not exceed 2 : 1.

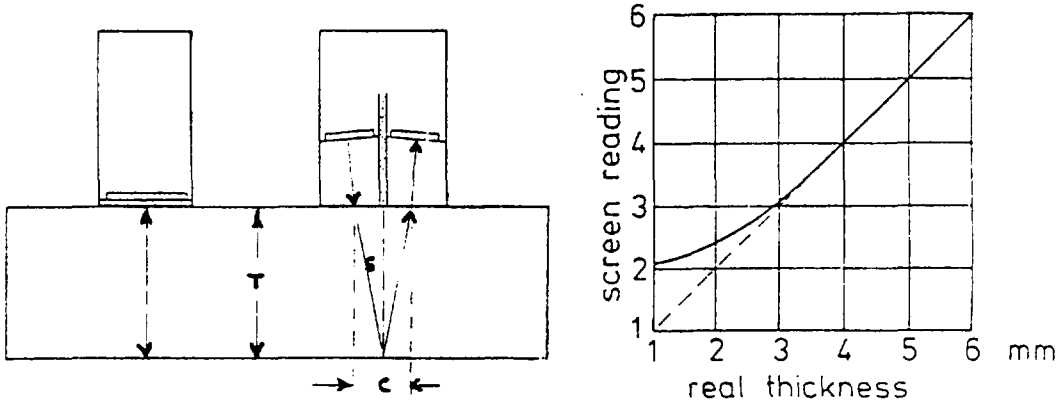


Figure 3.21 : V-path error with TR-probes.

The % error in measurement introduced due to this effect can be calculated from the formula:

$$\% \text{ error} = \frac{S-T}{T} \times 100 = \frac{\sqrt{T^2 - 0.25c^2}}{T} \times 100 \quad \text{----------} \quad (3.4)$$

where, T = Thickness of the specimen

S = Actual beam path length

c = Distance between the probe indices of ultrasound exit and ultrasound entrance

For c = 4 mm and wall thickness, T, from 9 mm to 1 mm the corresponding values of percentage errors are given in Table 3.1. The table shows that the deviations with large wall thickness are rather small. However, with small wall thicknesses the measuring thicknesses to be expected are of considerable size (100% or more).

TABLE 3.1 : PERCENT ERRORS FOR VARIOUS VALUES OF BEAM PATH LENGTH AND SPECIMEN THICKNESS

T	S	U = S - T	%
9.0	9.2	0.22	2
8.0	8.2	0.25	3
7.0	7.3	0.28	4
6.0	6.3	0.32	5
5.0	5.4	0.39	8
4.0	4.5	0.47	12
3.0	3.6	0.61	20
2.0	2.8	0.83	41
1.0	2.2	1.24	124

Defect location and evaluation can only be performed up to the backwall echo because after the backwall echo numerous interference echoes occur due to the splitting off of transverse wave. TR-probes are very often used in ultrasonic testing for:

(a) Checking the dimensions of work pieces (e.g. plates).

(b) Remaining wall thickness measurements.

(c) Detection, location and evaluation of subsurface flaws.

(d) Scanning large defects (lamination) using the half value method.

3.2.1.4 Normal beam immersion type probes

The construction of an immersion type probe is essentially the same as that of the contact type normal beam probe. Since, however, immersion type probes are always in contact with water they need to be water proofed and also do not need to have a wear protective plate in front. Figure 3.22 shows the construction of an immersion type probe.

Special care should be taken in the use of immersion type probes. Wear should not occur since the coupling surface should never get in contact with the surface of the test specimen. In case of direct coupling immersion probe wear results in a quick destruction of the probe because the protecting face is very thin and soft.

Leakage may take place by penetration of water at the cable connection caused by repeated probe movement, between housing and transducer due to chemical processes and due to swelling of the delay block. Any such leakage leads to a reduction of the sensitivity up to a total drop out of the probe due to a short circuit at the crystal connections.

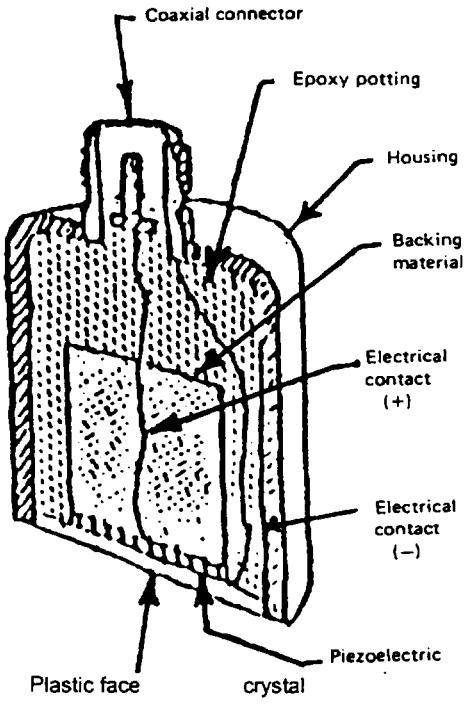


Figure 3.22 : Construction of an immersion type probe.

3.2.2 *Angular incidence sensors*

In angle probes, refraction and conversion of wave modes are used to transmit ultrasound into the test specimen at various angles to the surface. A typical construction of an angle beam contact type probe is shown in Figure 3.23.

An angle probe transmits longitudinal waves through a perspex delay block at a definite angle of incidence to the surface of the specimen. The angle of incidence chosen is greater than the first critical angle so that only transverse waves enter that specimen. The longitudinal portion is reflected back into the probe and is attenuated by the damping block and thus spurious indications that may arise due to the presence of the longitudinal waves are avoided. The angle of refraction for steel specimen and the beam exit point, generally known as the probe index, are marked on the metal case of the probe.

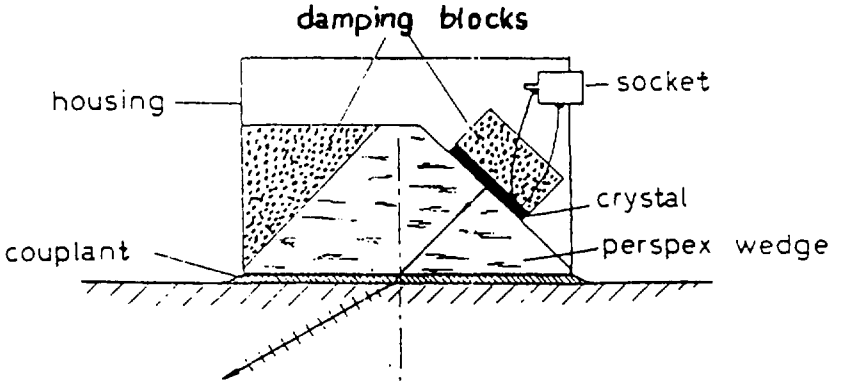


Figure 3.23 : Design of an angle beam probe.

A surface wave probe is an angle beam probe in so far as it uses a wedge to position the transducer at an angle to the surface of the specimen. The wedge angle is chosen so that the shear wave refraction angle is 90° and the wave resulting from mode conversion travels along the surface.

When an angle beam probe designed for steel is used for another material, the change in angle of refraction should be taken into account.

In the case of a 35° angle probe used on copper and gray cast iron, a longitudinal wave is also present at 57° and 55° respectively. With these materials it is therefore preferable to use larger angles. It is also required that the wedge is made of a material whose longitudinal wave velocity is smaller than the transverse wave velocity in the test piece such as to refract the incident beam away from perpendicular. In the case of aluminium and steel with v_t = 3.1 and 3.2 km/s respectively, suitable plastics are available, such as perspex (v_l = 2.7 km/s) or polystyrene (2.4 km/s), which are therefore usually used. In the case of copper, however, with v_t = 2.3 km/s the full angular range up to 90° could no longer be covered nor in the case of gray cast iron with v_l = 2.2 km/s. Lead with v_l = 2.2 km/s would be suitable for the purpose but certain nylon grades with v_l from 1.69 km/s to 2.60 km/s and teflon and soft rubber are commonly used.

Some testing problems require that the beam angle be adjusted continuously. Figure 3.24 shows various possible solutions. In the case of the first design two plastic wedges are rotated against each other, one of which mounts the transducer. With equal wedge angles , any angle between zero and double the wedge angle can be obtained. The rotation changes the plane of incidence. The second design makes use of a plastic semi-cylinder with a cemented-on transducer mounted

in a plastic block. In this design the plane of incidence remains constant but the beam exit point is shifted. In the third design, also the beam exit point remains practically constant. These adjustable angle probes are used for testing of uniform thickness plates wherein they generate the plate waves.

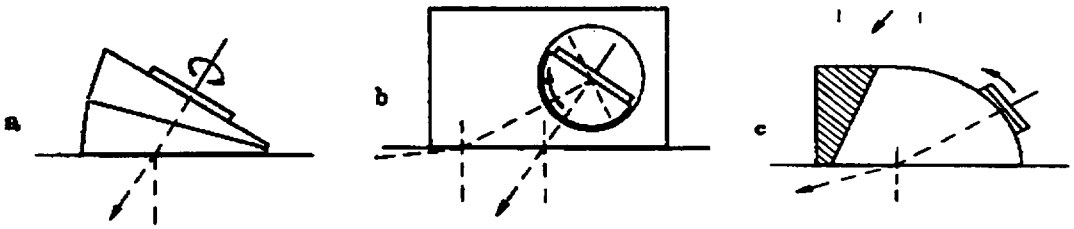


Figure 3.24 : Different designs of angle probes with continuously adjustable beam angle.

3.2.3 Special sensors

3.2.3.1 Need for special sensors

There is a large variation in the nature of test problems in industry. Therefore there cannot be a set of general purpose probes which can be universally used for the solution of these varied problems. Each type in principle requires a special probe for its testing and solution. There is a large variety of components, machines and structures of varying designs, geometry and shapes that need to be tested. There is therefore a corresponding need for having special ultrasonic probes to cater for specific inspection requirements. Materials may vastly differ in their composition and grain size and therefore have different degrees of attenuation of sound in them. Special probes may thus be needed for inspection of different types of materials. The permissible flaw sizes and therefore the flaw detection sensitivity as well as the resolution requirements may be different for different materials and applications. In many situations the application of couplant may present serious problems or the couplant may have to be supplied continuously to improve the speed of inspection. Ultrasonic testing in some situations may have to be carried out in unfriendly environments as, for example, hot and rough surfaces, corrosive environment, areas having high nuclear radiation levels, under-water inspection as well as in difficult-to-reach locations such as engines and complicated assemblies. There may be a demand for high speed inspection as in the case of automatic testing of rails, tubes, plates and other regularly shaped objects. All these situations require specific and special sensors.

Selection of a transducer for a given application is done on the basis of crystal size, frequency, frequency bandwidth and type of the flaw detector. Different materials exhibit different electrical impedance characteristics. Tuning coils or matching transformers may be needed. Both the amount of sound energy transmitted into the material being inspected and beam divergence are directly related to the size of the transducer element. Thus, it is sometimes advisable to use a larger search unit to obtain greater depth of penetration or greater sound beam area.

Narrow-bandwidth transducers exhibit good penetrating capability and sensitivity, but relatively poor resolution. (Sensitivity is the ability to detect small flaws; resolution is the ability to separate echoes from two or more reflectors that are close together in depth.) Broad-bandwidth transducers exhibit greater resolution, but lower sensitivity and penetrating capability, than narrow-bandwidth transducers. Operating frequency, bandwidth, and active element size must all be selected on the basis of inspection objectives. For example, high penetrating power may

be most important in the axial examination of long shafts. It may be best to select a large-diameter, narrow-bandwidth, low-frequency transducer for this application, even though such a transducer will have both low sensitivity (because of low frequency and large size) and low resolution (because of narrow-bandwidth).

When resolution is important, such as in the inspection for near-surface discontinuities, use of a broad-bandwidth transducer is essential. Penetrating capability probably would not be very important, so the relatively low penetrating power accompanying the broad-bandwidth would not be a disadvantage. If necessary, high sensitivity could be achieved by using a small, high-frequency, broad-bandwidth transducer; an increase in both sensitivity and penetrating power would require the use of a large, high-frequency transducer, which would emit a more directive ultrasonic beam. Resolution can also be improved by using a very short pulse length, an immersion technique, or delay-tip or dual-element contact-type search units.

3.2.3.2 Some special sensors

Phased array transducers

In recent years there has been a growing need to increase the speed of ultrasonic inspections. The fastest means of scanning is the use of an array of transducers that are scanned electronically by triggering each of the transducers sequentially. Such transducers consist of several crystals placed in a certain pattern and triggered one at a time either manually or by a multiplexer. A typical multiplexer and array circuit is shown in Figure 3.25. In this case, each circuit A through J consists of a separate pulser and transducer. Each probe element is assumed to be a point, or very small, source and the firing sequence of the pulsers is controlled through other circuitry.

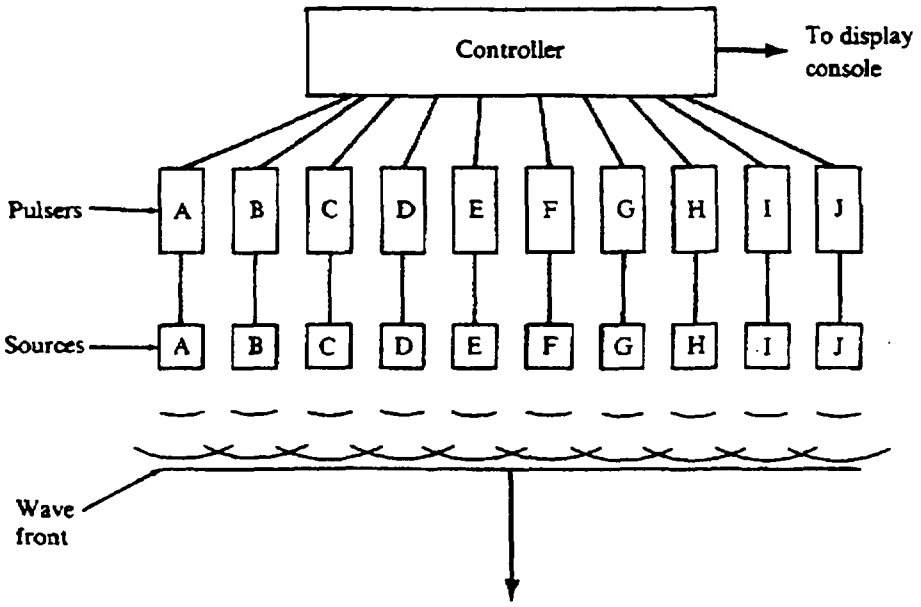


Figure 3.25 : Multiplexer arrangement for array transducers. Normally refracted, longitudinal wave shown.

Pulsing the probes in phased sequences can create a variety of beam patterns, including angle-beam and focus configurations. For example, the angle-beam shown in Figure 3.26 results when the firing sequence is evenly phased from A through J. The inclination angle θ is given by:

$$\theta = \sin^{-1}\frac{C\Delta t}{w} \qquad \text{----------} \qquad (3.5)$$

where C = phase speed in the material
Δt = phase delay in pulsing each probe
w = probe centre-line spacing

Varying the delay Δt between pulses would change the angle θ. Firing the pulsers in the reverse order, J through A, would result in an angle beam with the opposite orientation. Further, firing from the outside to the inside, i.e. A and J simultaneously, then B and I, etc., will create a focused beam.

A wide variety of sources may be used to construct an array transducer, including piezoelectric elements as well as EMAT and laser sources. The expense of the system is significantly increased since each circuit is essentially a separate ultrasonic system controlled by the multiplexer. The increased speed and versatility of inspection that the array transducers permit, however, may offer advantages that counter the added expense of the system.

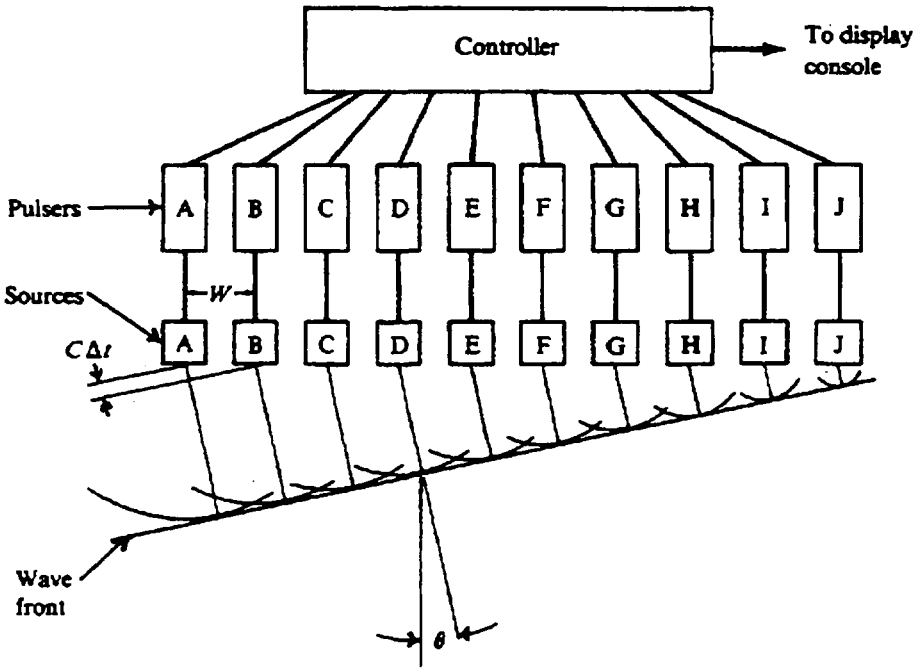


Figure 3.26 : Angle-beam multiple probe array transducer.

Electromagnetic acoustic transducers (EMAT)

Electromagnetic acoustic transducers are based on the principle that an electromagnetic wave incident on the surface of an electrical conductor induces eddy currents within the skin of the conductor. In the presence of a static magnetic field and in the region where the eddy current density is non-vanishing, ions are subjected to oscillatory forces. It is these oscillatory forces (the Lorentz mechanism) generated within the skin depth that are the sources of electromagnetically induced acoustic waves (Section 9.1.8).

The electromagnetic-acoustic transducers offer the potential advantage of performing ultrasonic inspection without the need for a physical couplant or other contact media between the probe and the test piece. This would facilitate automated inspection of linear items such as pipe, pipelines, railroad rail, etc., where there is relative motion between the probe and the test item. Further, the need for increased speed in inspection creates an additional advantage for these probes since the dynamic effects from higher speeds are minimal. EMAT probes may also be used to inspect metals covered with a protective coating.

Laser based ultrasonic transducers

Ultrasonic waves may be excited in materials when the surface is struck by laser pulses. The heating of the impulse creates expansions at the localized region where the laser strikes the surface. Ultrasonic waves are generated with these expansions and subsequent contractions.

The reception of ultrasound with laser technology is not done with the same system that is used to excite the signal. Generally, reception is accomplished with an optical beam which is capable of measuring small surface displacements.

The ability to perform high-power, non-contact ultrasonic inspection is a very important advantage for laser ultrasonics (also see Sections 9.1.2 and 9.1.7).

Paintbrush transducers

Paintbrush transducers are usually constructed of a mosaic or series of matched crystal elements. The primary requirement of a paintbrush transducer is that the intensity of the beam pattern not vary greatly over the entire length of the transducer. The paintbrush transducers are designed to be survey devices; their primary function being to reduce inspection time while still giving full coverage. This is a big advantage as the inspection of large areas with a small single-element transducer is a long and tedious process. After a scan with paintbrush transducers has indicated the presence of discontinuities, these can be further investigated for their size and location using standard probes.

Miscellaneous special sensors

Some of the ultrasonic test probes which have been described elsewhere may also belong to the category of special sensors. For example, these could be magnetostriction transducers (Section 2.6.2), focused transducers (Section 3.2.1.2), immersion testing probes (Section 3.2.1.4), variable angle probes (Section 3.2.2), probes for automatic testing (Section 9.2.4), surface wave probes (Section 3.3.4) and probes for in-service inspection specially of nuclear power plants (Section 9.1.5). It may be seen that in all these cases the probes have to be specially designed for specific application purposes.

3.3 TECHNIQUES

Techniques of ultrasonic testing are either of the contact type or the non-contact type. In the contact type, the probe is placed in direct contact with the test specimen with a thin liquid film used as a couplant for better transmission of ultrasonic waves into the test specimen. In the non-contact type, either a waterproof probe is used at some distance from the test specimen and the

ultrasonic beam is transmitted into the material through a water path or water column or the transducer is coupled to the test specimen simply through air.

Contact techniques are divided into three types. These are normal beam techniques, angle beam techniques and surface wave techniques. To the second category may belong the immersion techniques and the air-coupled techniques. Some of these techniques as these are applied in practical ultrasonic testing are described below.

3.3.1 Tandem techniques

In some cases it is necessary to conduct angle beam contact testing using two probes. One probe acts as a transmitter and the other as a receiver. The transmitting transducer pitches a sound beam that skips in the material and is caught by a receiving transducer. This two probe method is therefore also called "pitch and catch" or tandem method. The principle of the method is illustrated in Figure 3.27.

The usual objective with tandem technique is discontinuity location and characterization. The method can also characterize material properties. Suppose if a welded joint contains large, flat crack faces or bonding defects normal to the surface of the plate in the centre of the joint, testing with a single probe is no longer satisfactory for reliable detection of defects. The sound pulse is deflected away from direction of incident beam and it can be received satisfactorily only by a second probe. The position of both probes on the plate depends on the plate thickness and the location of defects. The pair of probes are displaced from each other by a fixed distance and this distance can be calibrated to maximize the received signal amplitude. The distance between the probes is determined by the relation:

$$S = 2 (t - d) \tan \phi \qquad \text{----------} \qquad (3.6)$$

where

ϕ= probe angle
t = specimen thickness, and
d = depth of the aiming point

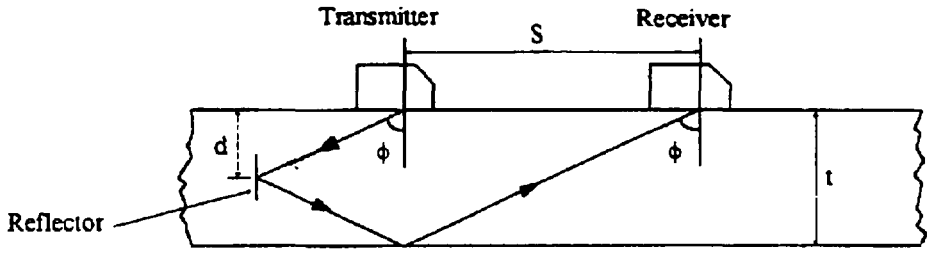


Figure 3.27 : Tandem technique arrangement.

Economic manual testing in accordance with this method requires that both probes are interconnected by a suitable guiding device. This would maintain the required constant distance between probes and ensures the correct angle relative to the joint and probes all the time.

The surface preparedness for tandem method is similar to other contact methods. The corroded or painted surfaces will be necessary to clean by grinding or sand-blasting. A new surface

requires only cleaning with a steel wire brush. On a horizontal surface it is best to use water for coupling and oil or grease on vertical walls and overhead.

The tandem method is most commonly used method for testing the welded joints in thick walled vessels, specifically in pressure vessels for reactors. Most of the test is carried out using an array of probes. Another application of tandem technique is in the examination of the root in double vee welds (Section 6.1.2.6).

3.3.2 Focused sensor technique

These techniques employ the focused probes which concentrate on focusing the ultrasonic beam at a certain pre-determined point or region within the test specimen. The focusing effect is obtained through the use of acoustic lenses which work in a manner similar to that in which the light is focused by optic lenses (Section 3.2.1.2). For optimum sound transmission the acoustic lens is usually bonded to the transducer face. Typical desired characteristics for the suitability of any material to act as an acoustic lens include a large index of refraction in water, acoustic impedance close to that of water at the probe crystal, low internal sound attenuation and the ease of fabrication. Some of the materials which meet these criteria are methyl methacrylate, polystyrene, epoxy resin, aluminium and magnesium. The shapes of acoustic lenses can be either cylindrical or spherical. Former produce a line focus beam while the latter produce spot focus. The sound beam from a cylindrical probe has a rectangular shape having a length and a breadth. Such probes are mainly used for the inspection of thin wall tubing and round bars. These are specially sensitive to fine surface and sub-surface cracks. The sound beam from a spherical probe illuminates a small circular spot. These have the greatest sensitivity and resolution but the area covered as well as the depth range are small.

Focusing can also be achieved by shaping the transducer element. The front surface of quartz crystal can be ground to a cylindrical or spherical radius. Barium titanate can be formed into a curved shape before it is polarized. A small piezoelectric element can be mounted on a curved backing member to achieve the same result. The method of focusing the beams from multiple phased array transducers has also been mentioned in Section 3.2.3.2.

Focused transducers are described by their focal length, that is, short medium, long, or extra-long. Short focal lengths are best for the inspection of regions of the testpiece that are close to the front surface. The medium, long, and extra-long focal lengths are for increasingly deeper regions. Frequently, focused transducers are specially designed for a specific application. The longer the focal length of the transducer, the deeper into the testpiece the point of high sensitivity will be.

The focal length of a lens in water has little relation to its focal depth in metal, and changing the length of the water path in immersion inspection produces little change in focal depth in a testpiece. The large differences in sonic velocity between water and metals cause sound to bend at a sharp angle when entering a metal surface at any oblique angle. Therefore, the metal surface acts as a second lens that is much more powerful than the acoustic lens at the transducer, as shown in Figure 3.16. This effect moves the focal spot very close to the front surface, as compared to the focal point of the same sound beam in water. This effect also causes the transducer to act as a notably directional and distance-sensitive receiver, sharpens the beam, and increases sensitivity to small reflectors in the focal zone. Thus, flaws that produce very low amplitude echoes can be examined in greater detail than is possible with standard probes.

The useful range of focused transducers extends from about 0.25 to 250 mm below the front surface. In this range the focused transducers have some distinct advantages over the standard non-focused probes. These include high sensitivity to small flaws, high resolution power, low effects of surface roughness, low effects of front-surface contour and low background noise. The limitation of the focused probes is the small region in the test specimen which is examined at a time.

Focused sensor techniques are usually employed for precise thickness measurements, detection of laminations, discontinuities in the thin sheets. Measurement of internal corrosion in pipes and vessels is also done on the same principle of thickness measurement whereby the remaining wall thickness in a corroded object is measured. Thin wall tubing and small diameter rods and forgings are also inspected for internal defects using focused probes. Use of the focusing of ultrasound beam is made for the testing of specimens with curved surfaces.

3.3.3 Double-crystal sensor techniques

These techniques are based on the use of two probes. One probe transmits the ultrasonic beam into the specimen and the other receives the echoes from the flaws and backwall (Figure 3.28). Generally the two crystals are housed in the same casing. Such transducers are called twin-crystal, TR or SE probes (Section 3.2.1.3). The crystals are usually mounted with a roof angle and therefore the overall result is that a beam focusing effect is obtained.

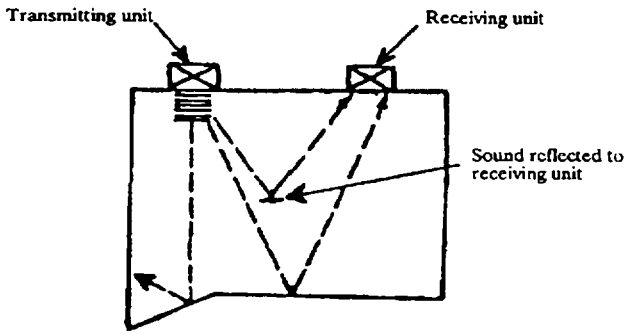


Figure 3.28 : Double transducer normal beam technique.

As the TR probes give a focusing effect the applications of double sensor techniques employing such probes are similar to those for focused probes and these include:

(a) Checking the dimensions of work pieces, e.g. plates;

(b) Remaining wall thickness measurements such as for corrosion and wear testing;

(c) Detection, location and evaluation of near-to-surface flaws;

(d) Scanning for large defects such as laminations using a half value method.

3.3.4 Surface wave sensor techniques

The nature of surface waves and the concepts for their generation have been explained respectively in Sections 2.3.3 and 2.4.2.2. The main advantage of surface waves is that they follow gentle contours and are reflected sharply only by sudden changes in contour thus making a very useful tool for the examination of complex shaped components. Their energy is concentrated in a relatively small region about one wavelength deep near the surface. For

example surface waves travelling on the top surface of a metal block are reflected from a sharp edge. But if the edge is rounded off, the waves continue down the side face and are reflected at the lower edge returning to the sending point. In this way surface waves could travel completely around a cube if all edges of the cube are rounded off.

Surface wave techniques have been used very successfully in the aircraft industry. Figure 3.29 shows an aircraft component having a complex shape. Application of compression or shear waves with this may be impossible or difficult. Development of cracks can be expected along the edge of the blade out to about 2/3 of the blade length or in the root area. A surface wave probe placed at the end of the blade and directed towards the root will send a beam along the surface, around the radius and reflect from the edge of the root as shown. Cracks in the suspect areas will give reflections at an earlier time than the root. The blade shown also has cooling ducts which might create problems, if a shear wave technique were chosen. However, surface waves only penetrate to a depth of about one wave length and if the correct frequency is chosen the cooling ducts will not interfere with the surface waves.

The penetration depth of surface waves can be used to advantage when testing relatively thin wall sections. Figure 3.30 shows a pipe with a change of section. If a surface wave at a frequency for which the wavelength is approximately equal to the wall thickness, then the surface wave will fill the wall thickness and follow the section change reflecting for a defect breaking either surface. Thus sub-surface flaws can also be detected easily by this technique.

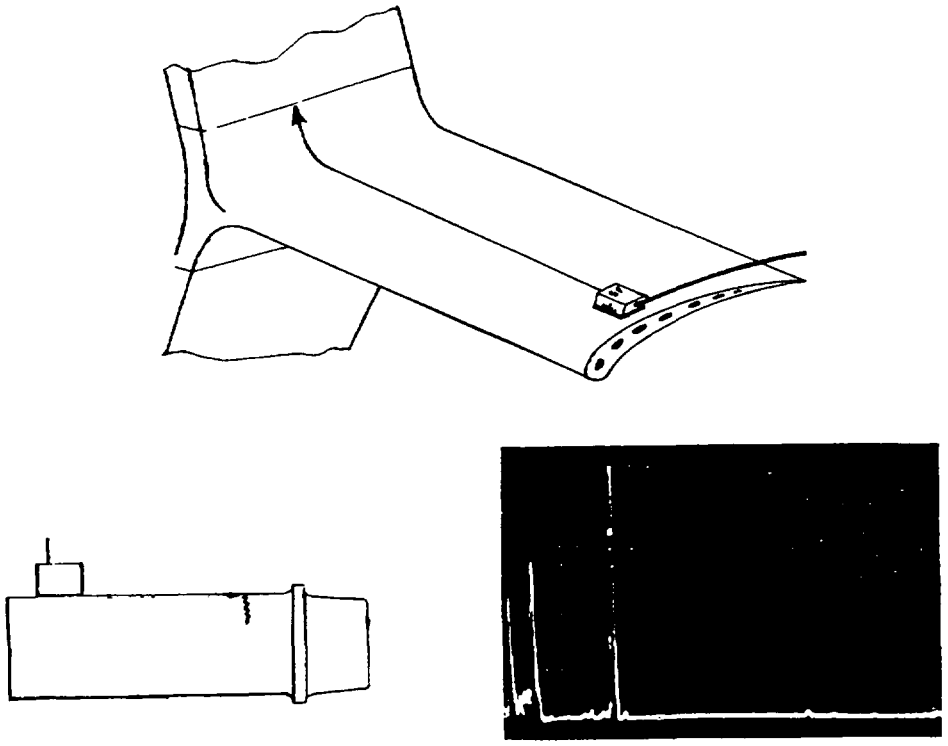


Figure 3.29 : Testing of blades for surface cracks using surface waves

The main limitation of surface wave techniques is that they are almost immediately attenuated if the surface finish is improper or if the surface is covered with scale or a liquid (such as the couplant) or if any pressure is applied by another object or even the hand of the operator. Therefore the coupling liquid should be limited to the contact point as far as possible. Misleading indications may even be produced by unsmoothly applied couplant such as grease.

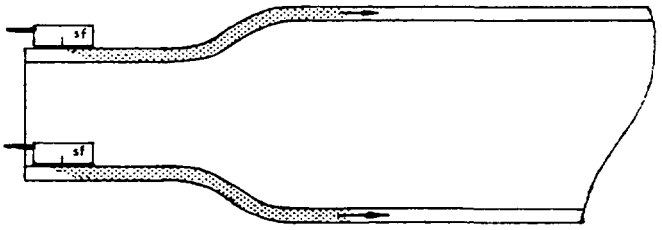


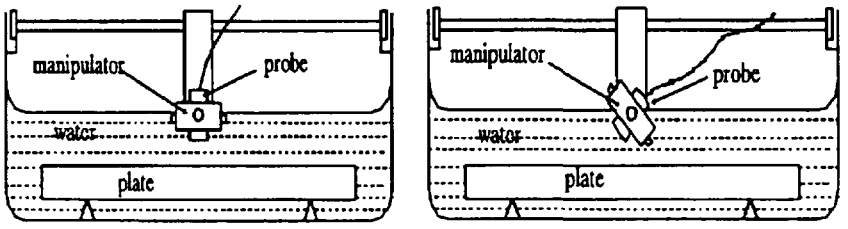
Figure 3.30 : Testing of multi-diameter pipe for wall defects using surface waves.

3.3.5 Immersion testing techniques

Immersion testing techniques are mainly used in the laboratory and for large installations doing automatic ultrasonic testing. It has the advantage that uniform couplant conditions are obtained and longitudinal and transverse waves can be generated with the same probe simply by changing the incident beam angle.

The three basic techniques used in immersion testing are the immersion technique, the bubbler technique and the wheel transducer technique.

In the immersion technique both the probe and the test specimen are immersed in water. The ultrasonic beam is directed through water into the test specimen, using either a normal beam technique (Figure 3.31 a) for generating longitudinal waves or an angle beam technique (Figure 3.31 b) for generating transverse waves.



(a) (b)

Figure 3.31 (a & b) : Immersion testing techniques.

When the normal beam technique is being used, the water path distance must always be longer than the distance S in Equation 3.7 below:

$$S = \frac{\text{Thickness of the specimen} \times \text{sound velocity in water}}{\text{Sound velocity in the specimen}} \quad \text{---------} \quad (3.7)$$

When the specimen is steel, the water path distance must be longer than 1/4 steel thickness otherwise the 1st backwall echo overlaps the 2nd surface echo and defects near the backwall may not be seen.

In the bubbler or squirter technique, the ultrasonic beam is directed through a water column into the test specimen (Figure 3.32). This technique is usually used with an automated system for high speed scanning of plate, sheet, strip, cylindrical forms and other regularly shaped forms. The ultrasonic beam is either directed in a perpendicular direction (i.e. normal direction) to the test specimen to produce longitudinal waves or is adjusted at an angle to the surface of the test specimen for the production of transverse waves.

In the wheel transducer technique the ultrasonic beam is projected through a water-filled tire into the test specimen. The probe, mounted on the wheel axle, is held in a fixed position while the

wheel and tire rotate freely. The wheel may be mounted on a mobile apparatus that runs across the specimen, or it may be mounted on a stationary fixture, where the specimen is moved past it (Figure 3.33 a & b). The position and angle of the probe mounted on the wheel axle may be constructed to project normal beams, as shown in Figure 3.33 (a & b) or to project angled beams as shown in Figure 3.34.

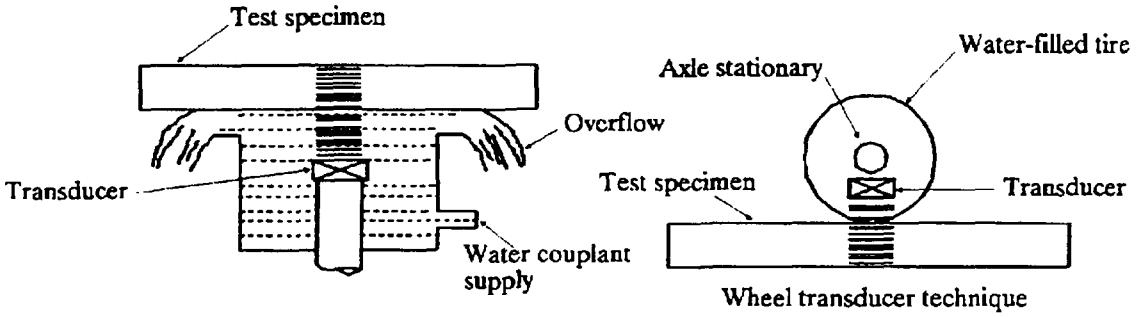


Figure 3.32 : Bubbler and wheel transducer techniques.

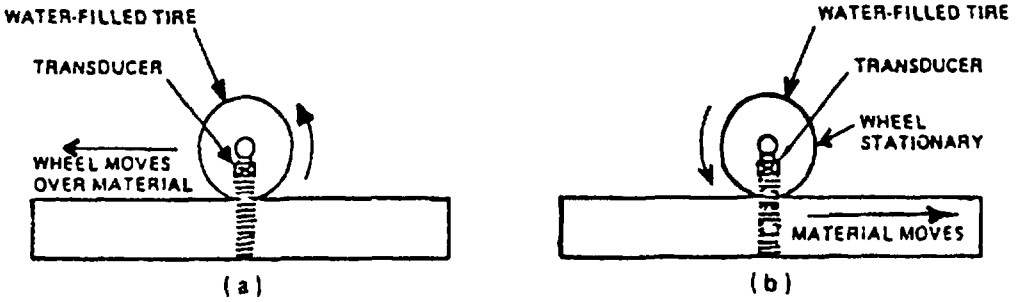


Figure 3.33 : Stationary and moving wheel transducers.

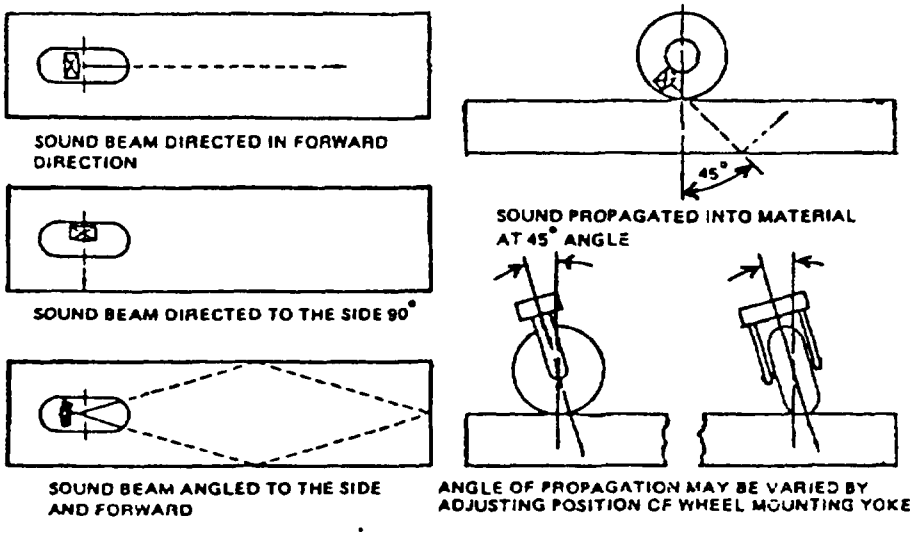


Figure 3.34 : Wheel transducer angular capabilities.

3.4 LIMITATIONS IN THE APPLICATION OF THE ULTRASONIC TEST METHOD

See Section 1.1.8.

4. ULTRASONIC EQUIPMENT AND ACCESSORIES

4.1 CONSTRUCTION AND MODE OF OPERATION OF ULTRASONIC EQUIPMENT

The ultrasonic equipment and accessories include, in principle, the ultrasonic flaw detector, transducers and connecting cables, calibration blocks, data presentation and recording systems, immersion tanks and handling systems for probes and the test specimen. The salient features of the flaw detector and data presentation systems are described in this chapter while the other topics have been dealt with elsewhere at appropriate places in the book.

Figure 4.1 shows the components of an ultrasonic flaw detection system. The simultaneous triggering of the time-base generator and transmitter by the clock, initiates the transmission of ultrasonic pulse from the probe at the same time as the electron beam spot starts to move across the cathode ray tube. When a single crystal probe is used, the electrical voltage pulse supplied by the transmitter to the probe is also fed to the receiver unit and is thus amplified and displayed as indication 'a' on the CRT screen (Figure 4.1). The indication 'a' is known as the transmission echo, 'transmission pulse', the 'initial pulse', the 'main bang' or the 'front surface reflection'.

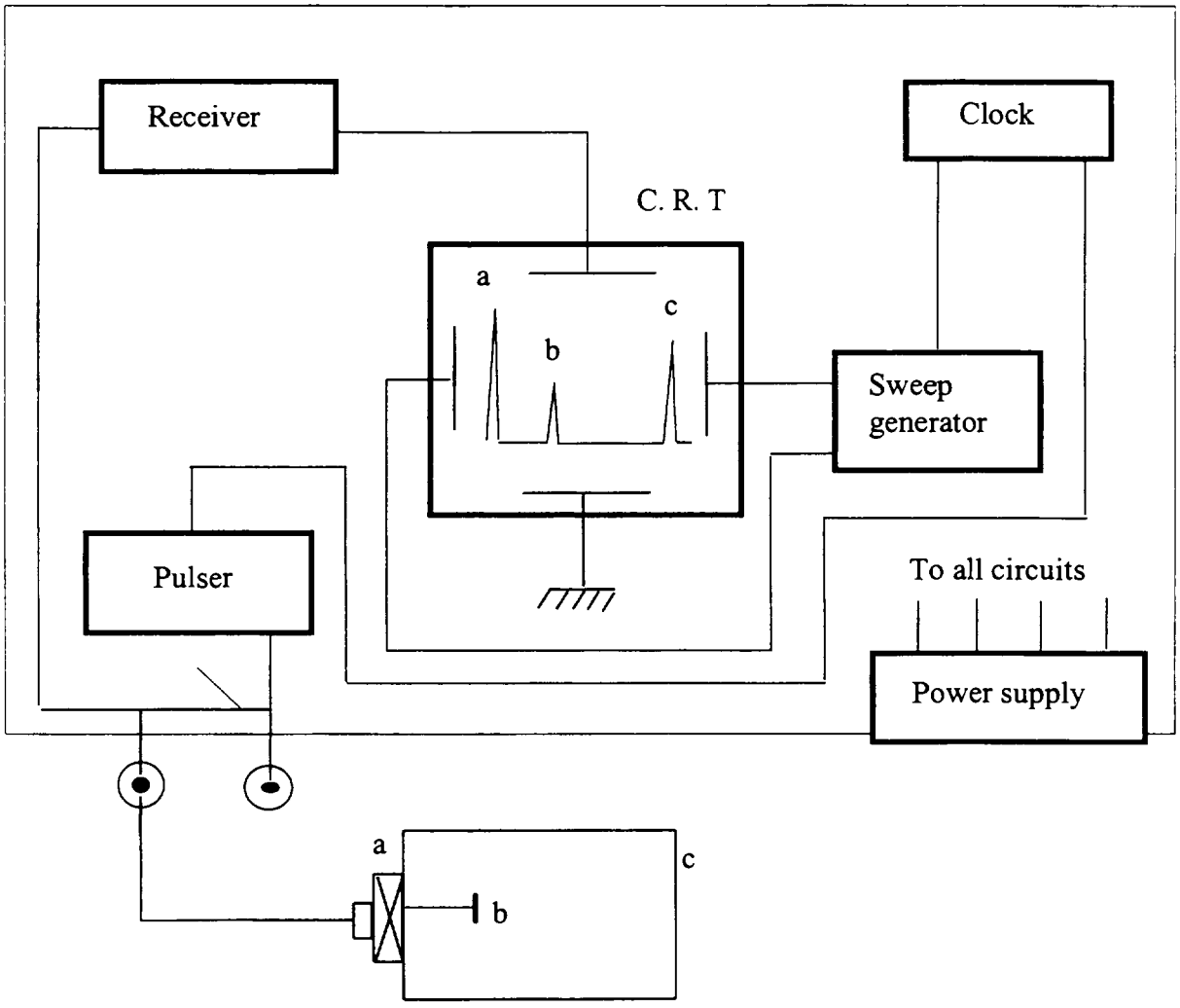


Figure 4.1 : Basic components of an ultrasonic flaw detection system.

The electron beam spot continues to move across the CRT screen as the ultrasound from the probe moves through the specimen. When the ultrasound reaches the reflecting surface b, a part of it is reflected via a probe and receiver unit to register an indication 'b' on the CRT screen. The other part which is carried to the far surface 'c' of the test specimen is reflected by it to be displayed as indication 'c' on the CRT screen. The indications from the reflecting surface 'b' and the far surface or backwall 'c' of the specimen are known as the 'defect echo' and 'back-wall echo' or 'bottom echo' respectively.

If the specimen of Figure 4.1 is a 25 mm thick steel plate, the above operation would have taken about 8 millionth of a second (8 μs) to complete. The pulse repetition frequency (PRF) should, therefore, be high enough to make the pattern to be bright enough to be visible to the human eye. On the other hand for a 500 mm thick specimen, the time required for the whole operation to complete is about 160 μs. If a high repetition frequency is used in this case, confusion would arise because the probe will send a second ultrasonic pulse before the first one is received. Depending upon the thickness of the test specimen, in most of the instruments, the PRF can be varied between 50 pulses per second (PPS) to 1250 PPS. This is done automatically in modern instruments with the setting of the 'test range' control. It alters the velocity of the electron beam spot across the CRT screen for different test ranges.

In twin crystal and transverse wave probes there is a perspex delay block, fitted between the piezoelectric transducer and the surface of the specimen. The ultrasonic waves travel for sometime before entering the test specimen. To prevent the electron beam spot to travel a distance proportional to this travelling time in perspex delay block, the 'delay' control is used. The 'delay' control makes the time base generator to wait for a period equal to the perspex travelling time, before making the spot to start from the zero position.

4.1.1 Functions of the electronic components in a typical instrument

The essential components of a typical ultrasonic flaw detector are as shown in Figure 4.1. The functions of these components are explained in the following sections.

4.1.1.1 Cathode ray tube

The cathode ray tube or CRT (Figure 4.2) contains a heater coil H which heats the cathode C to make it emit electrons. These electrons are accelerated by a voltage applied across the cathode C and anode A. The resultant electron beam is focused by the focusing cylinder F to make it appear on the fluorescent screen S as a spot. As the electrons travel toward the CRT screen S they pass two pairs of deflecting plates X and Y. A voltage applied to the X plates would deflect the electron beam horizontally while a voltage applied to the Y-plates would deflect the beam vertically.

The focusing of the spot is indicated as 'focus', on the CRT controls. The 'astigmation' or 'auxiliary focus' are the controls to correct the unsharpness induced in the CRT trace by the changing transit time of the electron beam spot when it is deflected by a voltage applied to the vertical plates. The brightness of the CRT trace can be varied through a control knob marked as 'brightness'. Similarly the control knobs for horizontal and vertical movement of the CRT trace are respectively marked as 'horizontal shift', 'set zero', 'X-shift' or 'delay' and 'vertical shift' or 'Y-shift'.

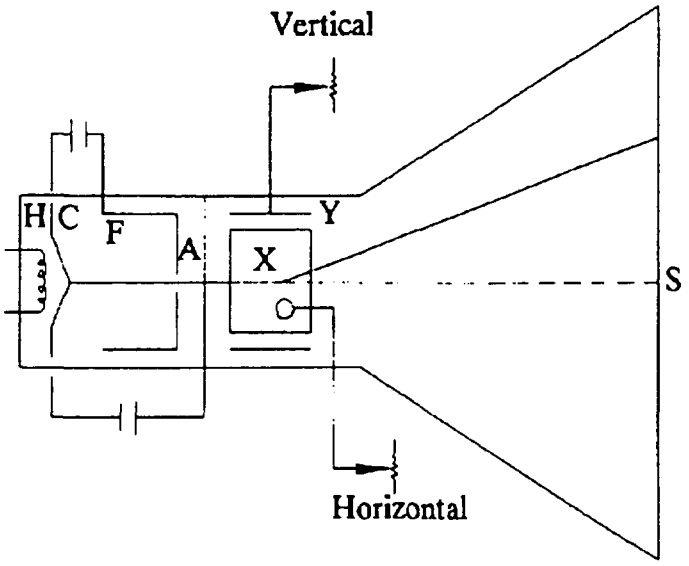


Figure 4.2 : Construction of a cathode ray tube (CRT).

4.1.1.2 Time base generator

The time-base generator provides a sawtooth voltage to the X-plates of CRT to move the electron beam spot from left to right across the CRT screen with a uniform speed. The speed of the spot depends on the rise time of the sawtooth voltage, i.e. the time in which the sawtooth voltage rises from zero to its maximum value (Figure 4.3). The shorter the rise time the greater would be the speed of the spot. The practical implication of this is related to the thickness of the test specimen. If we want to display the full thickness of the specimen on the CRT, we need to ensure that the spot takes at least as long to sweep from left to right as it takes the sound to travel to the bottom of the specimen and back to the top. For thin specimens we can allow the spot to move quickly, whereas for thick specimens we must slow down the spot. Flaw detectors can display across the CRT anything from about 6 mm of steel to about 10 metres of steel. Therefore the range of control of speed for the spot needs to be very large (from about 2 μs to about 3500 μs). The control which is provided for the adjustment of the rise time of sawtooth voltage and hence the speed of the spot is termed as 'depth range' or 'test range'. To prevent the return of the electron beam spot to produce a trace on the screen, the time base generator simultaneously controls the brightness of the spot by means of a square wave voltage so that the spot remains bright only during the rise time of the sawtooth voltage (Figure 4.4).

Sometimes it is needed that the pulse which triggers the time base should be delayed as compared to the pulse which triggers the transmitter. For example, twin crystal and shear wave probes usually are fitted with a perspex shoe. As the transducer is energized, the sound takes some time to travel through the perspex before entering the test specimen. We do not want to display this perspex travel time on the time base. This is done through a control called 'delay' which makes the time base generator wait for a period equal to the sound travel time in perspex before making the spot travel from zero. The delay control can also allow to start the time base when the sound has travelled say 200 mm through a 225 mm thick section so that it is possible to look at just the last 25 mm of the specimen.

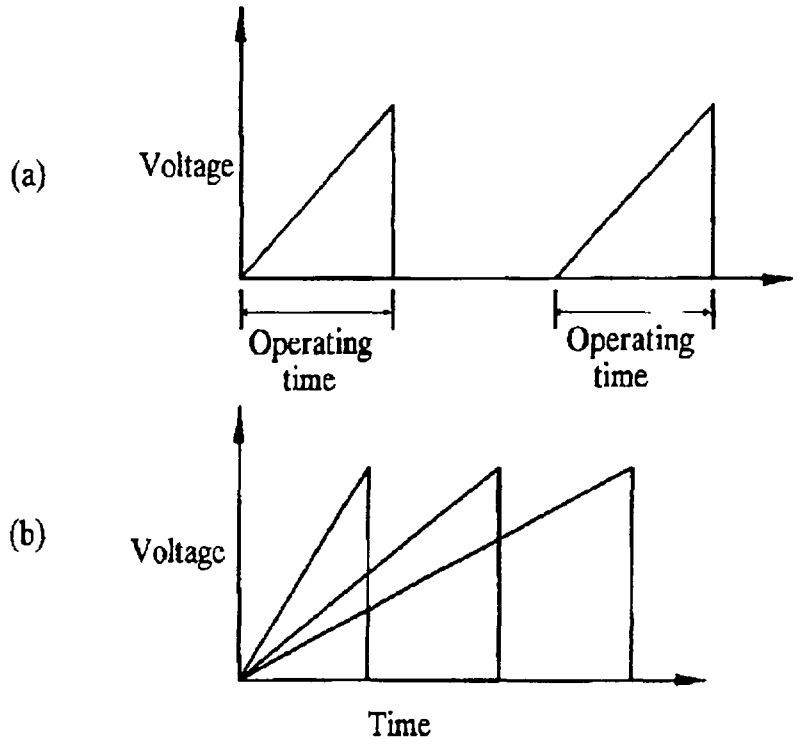


Figure 4.3 : *(a) Sawtooth voltage for time base, and (b) with different operating times.*

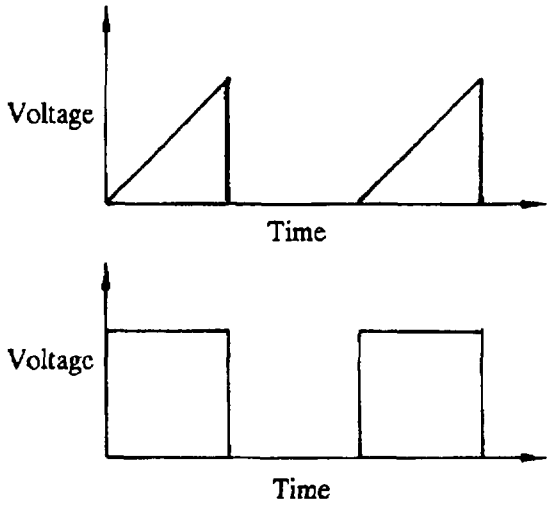


Figure 4.4 : Sawtooth voltage for time base with corresponding square wave voltage for control of brightness.

4.1.1.3 Transmitter

The transmitter, also called an oscillator, is basically a tuned electronic circuit comprising of a thyratron, capacitances and inductances (LC) as shown in Figure 4.5. The circuit receives a control pulse from the time base generator which also had triggered the time base. The control pulse is received slightly later than the start of rise of the deflecting voltage so that the rise of the transmitting pulse appears on the CRT slightly to the right from the beginning of the time base.

The rise of the transmitting pulse serves as zero of the time delay or the depth scale. The control pulse is fed to the thyratron which generates a voltage surge by the sudden discharge of the capacitor charged to several hundred, up to 1000 volts. This surge excites the tuned circuit to its own damped oscillation which becomes the electrical transmitting pulse.

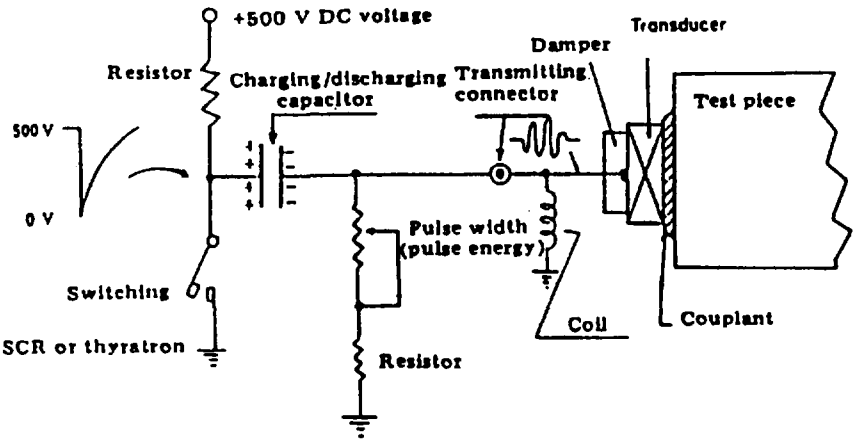


Figure 4.5 : Typical electronic circuit of the transmitter in an ultrasonic flaw detector.

Different modifications can be made to this basic circuit to get pulses of desired amplitude, shape and length. For example in the modern equipment thyratron is replaced by thyristors and sometimes by avalanche transistors. The damping can be increased by shunts parallel to the induction coil which permits a control of the pulse characteristics. The shape of the transmitted pulse is also determined by the connected probe. In some instruments the induction coils are not mounted in the instrument but in the probe so that the pulse oscillation can appear only after the probe has been connected. Without the probe the pulse is only a short voltage surge.

The transmitter supplies a short electrical voltage pulse of 300-1000 V to the piezoelectric transducer in the probe. The piezoelectric transducer, in turn, converts this electrical voltage pulse into an ultrasonic wave. In some instruments controls are provided to adjust the frequency and amplitude of the input electrical voltage pulse, while in others this adjustment is done automatically. The frequency and width of the ultrasonic wave pulse are controlled respectively by the thickness and degree of damping of the piezoelectric transducer in the probe.

4.1.1.4 Receiver unit

The ultrasonic transducer receives pulses from the transmitter and generates sound waves which travel within the test specimen and are reflected back from the boundaries as well as the discontinuities present within the test specimen. The reflected sound waves received by the probe are converted back into electrical voltage pulses. While the pulses fed to the probe are of the order of hundreds of volts, those produced by the sound waves returning from the test specimen are comparatively very weak, e.g. only of the order of 1/1000 to 1 volt. These weak pulses need to be amplified before being fed to the oscilloscope. This is done in the receiver unit which consists of a preamplifier, an amplifier, a rectifier and an attenuator. The purpose of the preamplifier is the amplification of small echo signals in order to lift them above the unavoidable noise level of the following circuit. The amplifier amplifies any voltage pulse supplied to it from the probe. The amplification is of the order of about 10^5. In most of the instruments the amplifier is of a wide band type with a frequency range of about 1 to 15 MHz and a control to tune the amplifier to the frequency of the probe is not needed. In some cases it is a narrow band type and a control is provided to tune it to the frequency of the probe. There are

two general types of the amplifiers from the amplification point of view. Firstly, the linear amplifiers in which the indication of the echo amplitude on the screen is proportional to the receiver voltage of the probe, and secondly, the logarithmic amplifiers in which the echo amplitude is proportional to the logarithm of the probe voltage. Since the echo amplitudes are usually quoted in decibels (dB) and since the latter is a logarithmic quantity the logarithmic amplifiers offer the advantage of being dB-proportional amplifiers (also see Sections 4.2.1 and 4.3.1).

The rectifier in the receiver unit rectifies the voltage signal for ease of observation. In some instruments a control is provided to observe the received signal either in the rectified or unrectified state. The attenuator in the receiver unit is used to vary the signal amplitude as needed. The control provided to do this is known as "gain control" and is calibrated in the decibels or dB. It controls the input from the probe to the main amplifier so that the operator can keep echo height from a reflector within the CRT screen for echo heights comparison and making the flaw sizing possible. Another control known as 'reject' or "suppression" control is provided in the receiver unit to remove the indications of random noise, known as grass, from the CRT display. Typical circuit of a receiver is shown in Figure 4.6.

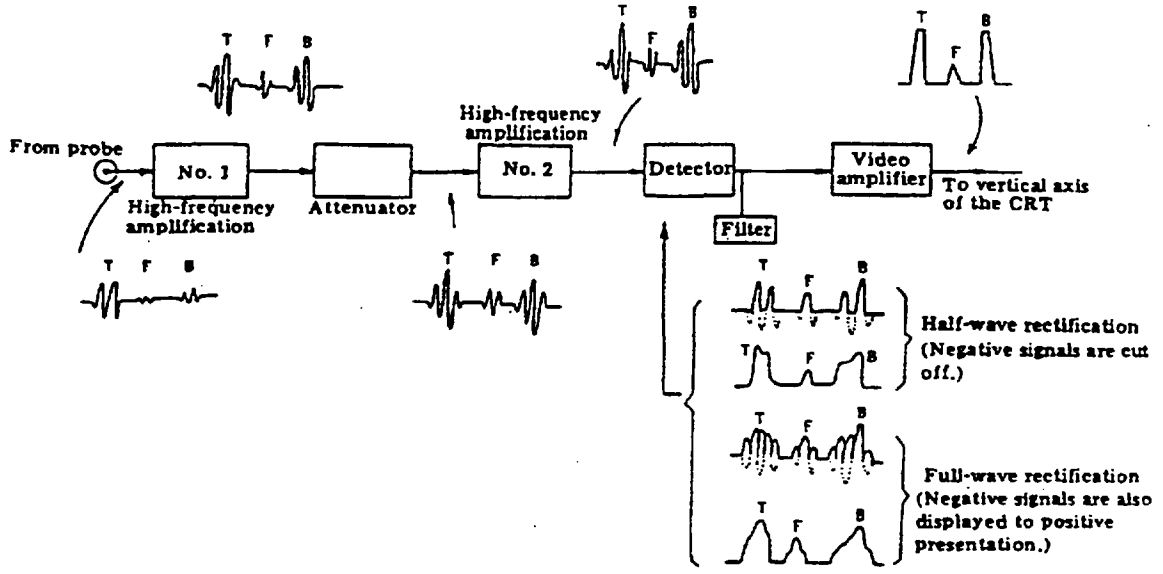


Figure 4.6 : Typical receiver circuit and waveforms.

4.1.1.5 Clock or timer

The clock or timer circuit generates electrical pulses which trigger the time base generator and transmitter at the same time. These pulses are generated repeatedly to make the trace on the CRT screen steady and bright. The frequency with which these pulses are generated is known as the pulse repetition frequency (PRF). In some instruments a control is provided for the adjustment of PRF while in others it is adjusted automatically with the alteration in setting of the 'test range' control.

4.1.1.6 Signal monitors and gates

Visual evaluation of the screen traces is often slow and not suitable for rapid and continuous testing. It is desirable that the test data such as the echo amplitude and echo transit time are converted to electrical values for purposes of quick recording. This is done with the help of

signal monitors which indicate the echo in the form of a signal as soon as the former appears in a pre-selected transit time zone, i.e. the gate, and exceeds a pre-selected amplitude reading. On the screen this gate is usually indicated by a step or by a brightness change of the base line. The position as well as the width of the gate is adjustable. The width can be varied from a few millimetres in steel upwards. The start of the gating is usually initiated by the transmitting pulse after a certain delay. Several gates can be used to monitor different ranges simultaneously.

Electronically the monitor consists of a gate amplifier receiving the same voltage pattern as the CRT which, however, transmits only the desired portion of this pattern through a transit time interval, i.e. the gate. The gating voltage is synchronized by the pulse repetition frequency (PRF) of the instrument.

The output signals of the monitor can be used for actuating any acoustical (horns or bells) or optical (lamps) signalling devices. Also switching operations can be initiated which, for instance, can stop the movement of the test piece in continuous testing or can actuate a marking device, such as a paint spraying gun, for flaw indication on the test specimen.

4.1.2 Types of instrumentation

4.1.2.1 Portable equipment

The portable instruments are manufactured for field operation and their design is, therefore, based on the following factors:

(i) Ease of operation,

(ii) smaller size and

(iii) lower weight.

These instruments are, thus, used only for special applications, for example, weld inspection, casting inspection and thickness gauges, etc. These instruments have only the essential controls. The inspection of castings is normally carried out at lower frequencies because castings have coarse grained structures. The instruments designed for the inspection of castings (and for coarse grained materials for that matter) have a lower frequency range.

The thickness meters are special ultrasonic instruments having either no controls or one or two controls. They have either an analogue (meter type) or a digital display. Modern thickness gauges are of the latter type. The number of controls in a thickness gauge depends upon its application. If it is to be used for the thickness measurement of a specific material then it usually has no control at all. A thickness meter used for thickness measurements of a number of materials with known acoustic properties usually have only one control known as the zero adjust (or delay) control. Such meter requires a single thickness step for its calibration. The thickness meter which is to be used for thickness measurements of materials with unknown acoustic characteristics has two controls, a zero adjust (delay) and a test range control. Such a gauge requires two steps with known thicknesses for its calibration. Apart from its versatility such a gauge renders the highest measuring accuracy if used properly. Such a gauge is, therefore, mostly used for precision measurements of machined components. Thickness meters of the latter type also have the highest cost.

All portable instruments are single channel, meaning that operation with either a single crystal probe or with twin crystals (in a single casing or in separate casing) is possible. These

instruments are usually employed for manual operation. Portable instruments are operated both from batteries and mains supply.

4.1.2.2 Laboratory type equipment

Laboratory type instruments are usually used for the development of ultrasonic inspection techniques. These instruments are versatile and have every possible control which enable the operator to develop an inspection technique which will render optimum results. Consequently these instruments are bulky, heavy and have higher cost. These are generally single channel instruments and can be used for both manual and mechanized inspection.

4.1.2.3 Digital instruments

The manual conventional ultrasonic flaw detectors incorporate an oscilloscope screen in order to display information generated by the instrument. Along the X-axis, the time scale, controlled by the sweep generator circuit, is displayed. Along the Y-axis, the amplitude of the probe response is displayed after passing through the receiver-amplifier circuitry. The combined effect of these two controlling circuits is a continuous, or analogue, trace on the screen.

In general, the conventional analogue instruments are quite good for defect detection and thickness determination. The use of these instruments for defect evaluation and sizing, however, has not been universally accepted for a number of reasons. Ultrasonics has suffered in comparison with radiography, for example, in that a permanent record of the examination is not easily made. In addition, the display format does not present an image of the internal defect, although the defect can be mapped out using simple geometric considerations and a knowledge of how the ultrasonic beam interacts with a defect. But this can be a time-consuming process subject to limited (although usually tolerable) accuracy. Defect mapping must be done manually since the instrument has a limited ability to manipulate signals beyond simple filtering and amplification.

In an attempt to overcome these limitations, ultrasonic instruments have recently been developed which produce a digital, rather than an analogue, response. In this case, the analogue electrical signal generated by the transducer is digitized by an analogue to digital converter (ADC) circuit inside the instrument. The digitized signals are in turn manipulated by an internal microprocessor which controls the display and storage of the data.

Depending on the complexity of the instrument, digital UT data can be displayed in different formats. The more sophisticated automated ultrasonic systems produce two and three dimensional displays of the recorded UT data. Although useful for critical applications, these systems are not cost effective for routine use. The digital flaw detectors, with a lower base price provide a display similar to their analogue counterparts but with some of the features of the more expensive C-scan instruments.

Some of the features common to digital flaw detectors are summarised below:

- Calibration memory: Instrument settings such as sound velocity, gain, range, delay, probe angle, frequency filtering, etc., are initially inputted to a status display screen. This information is held in memory until changed and can be displayed at any point during the inspection. In addition, the instruments can keep a number of calibrations in permanent memory for recall at a later time. This is a useful feature when a specific type of inspection is conducted routinely.

- Linear reject: The 'reject' function attempts to improve the signal to noise ratio by filtering out low amplitude signals and background noise ("grass"). In analogue instruments, the use of 'reject' tends to destroy the linear relationship between signal amplitudes. For this reason several codes do not allow the use of the 'reject' function. The digital flaw detectors, however, do maintain signal linearity when 'reject' is used.

- Distance-amplitude correction: Comparing indications at different depths in a component must take into account the attenuation of the ultrasonic beam. This is achieved by incorporating a distance-amplitude correction, or DAC. On many analogue instruments, a DAC curve must be manually drawn on the flaw detector screen. This is done electronically by the digital instruments. (Electronic DAC is also available on some analogue flaw detectors.)

- Peak/averaging functions: The memory capabilities of the digital instruments allow the flaw detector to hold a peak response on the display screen. It is also possible to apply a signal averaging function to the recorded data. Both functions are useful in improving the signal to noise ratio.

- Automatic reflector location: The location of an indication within the component relative to the position of the probe can be determined from simple geometric considerations by knowing the probe angle and the sound-path distance. When using an analogue instrument, this must be calculated manually. The digital instruments will perform this calculation automatically. This capability greatly facilitates the defect sizing techniques.

- Data record keeping functions: Screen images can be permanently recorded using a video or graphic character printer. It is also possible to record the entire examination on VCR. An RS232 port is also available for down loading the digital signal to computer.

4.1.2.4 Types of digital thickness meters

Compared to analogue thickness meters digital thickness meters are more widely used because of their very compact size, higher measurement accuracy and somewhat simpler operating procedures. The digital thickness meters that are commercially available nowadays can be classified into the following categories:

(a) Pre-calibrated thickness meters

These meters are ideal for quick routine thickness measurements of components of a known material. Because these meters have no operator controls, therefore, they can be used quickly and efficiently with complete confidence even by an untrained operator. These meters give an accuracy of about ±0.1 mm over their measuring range.

(b) Calibratable thickness meters

A calibratable thickness meter is required when one wants to measure the thickness of different materials and with higher measurement accuracy. In this category instruments are available either with a single calibrating control or with twin calibrating controls. Though the thickness meters with single calibrating control require simpler operating procedures and hence not highly skilled personnel, they have, nonetheless, the following two limitations:

(i) For their operation one needs to know the acoustic velocity in the material under test.

(ii) Since these instruments are calibrated with a single thickness, usually about 5 mm, their measuring accuracy decreases rapidly when the thickness measured departs from this value.

The above cited limitations of the single calibrating control thickness meters are overcome by using the twin controls calibrating thickness meters. These meters require two thickness steps containing the thickness or thickness range that is to be measured and a somewhat lengthy calibrating procedure. If proper calibrating thickness steps are available and the calibration is carried out with much care then measuring accuracy obtained with such type of thickness meters is of the order of ±0.001 mm. Some of the digital thickness meters can be used as single calibration control or a twin calibration controls instruments.

The situations in which an ultrasonic flaw detector is used instead of a thickness meter are:

(i) When the thickness is so large or the material of the test specimen is so attenuative (e.g. cast iron, plastics or rubber) that the backwall obtained is too weak to stop the counting circuit.

(ii) When one wishes to combine thickness measurements with flaw detection, as in the case of thickness measurements of corroded surfaces and detection of surface cracks due to corrosion.

4.1.2.5. Thickness meters with A-scan display

Ultrasonic equipment manufacturers have now incorporated both digital and echo displays on the same equipment. This would allow a technician to look at the reflected echoes and see if a weaker echo is coming from a deeper corrosion pit not readable by the electronic gate of the thickness meter. In order to be able to interpret such a phenomenon, a technician need to be trained and be familiar with behavioural pattern of ultrasonic waves reflected from uneven or corroded backwall. A 10 minutes training in the use of digital meters is definitely not sufficient to produce an ultrasonic corrosion-detection technician.

4.1.2.6. Automatic equipment

Automatic systems are used where large amounts of similar parts are to be tested. These systems essentially consist of one or several probes which are coupled to the test specimen by a control unit and are moved across the test object according to a predetermined scanning pattern (Figure 4.7). A simplified diagram of a four channel automatic flaw detection system is shown in Figure 4.8. The ultrasonic signals are processed by the evaluation unit (e.g. an ultrasonic flaw detector) and displayed on a CRT-screen, if available. All measured data along with the information about the probe position are fed to a computer where they are further processed and evaluated. The test report is produced by means of a printer. The computer also controls the marking and sorting device which marks the flaw locations on test objects. Test objects which have unacceptable flaws are rejected. A further task of the computer is to control the transport of the work piece and to signal defined test conditions.

In this system four probes along with their pulser are connected to a single main amplifier and four monitor gates in an automatic sequence. By using a selector switch the echo pattern of any of the four channels can be displayed on the CRT screen (also see Section 9.2).

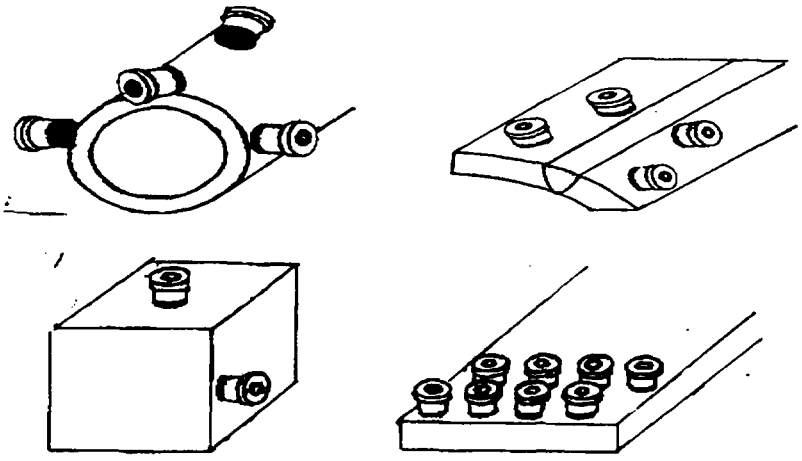


Figure 4.7 : Automatic scanning of pipe, billet, weld and plate with multiple probes.

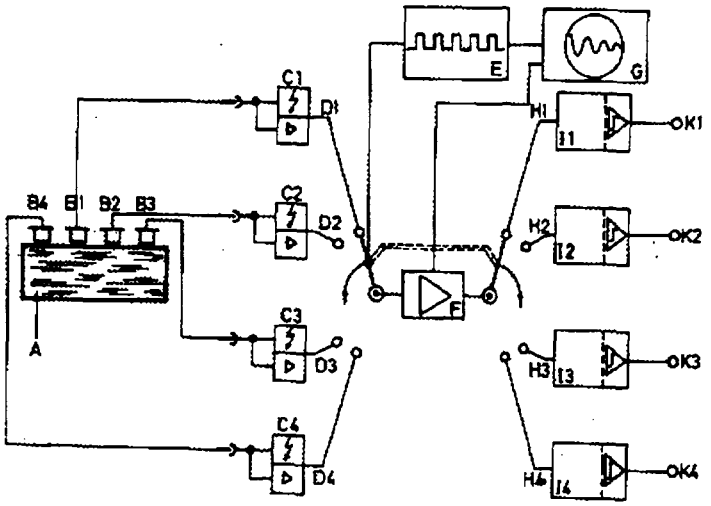


Figure 4.8 : Schematic diagram of a four channel flaw detection system.

A remote controlled ultrasonic inspection system for the pre-service and in-service inspection of reactor pressure vessel is shown in Figure 4.9.

4.2 CHARACTERISTICS OF EQUIPMENT AND SYSTEM CONTROLS

4.2.1 Properties of vertical and horizontal amplifiers

Since the signal coming from an ultrasonic probe is usually weak it has to be "amplified" before displaying it on the CRT screen. This amplification is done by the radio frequency (RF) amplifier. The two performance characteristics which are important are the dynamic range and frequency response of the amplifier.

4.2.1.1 Dynamic range

Dynamic range of the amplifier is the ratio of maximum and minimum inputs which it can amplify without distortion. A large dynamic range is required in ultrasonic flaw detection since flaw sizes are evaluated by comparing the height of the echoes from these flaws. The dynamic

range of a linear amplifier used in ultrasonic flaw detectors is usually 34 dB (50:1) while that of a logarithmic amplifier is 100 dB (10^5 : 1).

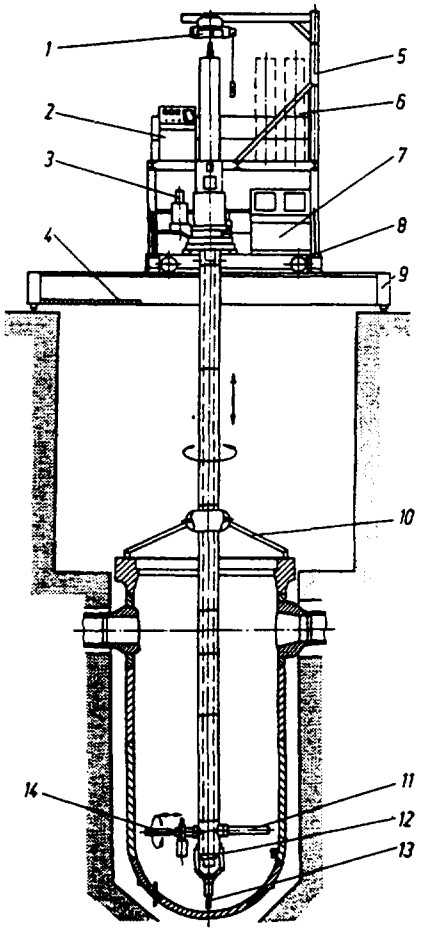


Figure 4.9 : Manipulator for internal tests on nuclear reactors, schematic (Design MAN-Krautkrämer): 1 Monorail hoist, 2 control panel 3, mast bearing, 4 maintenance platform, 5 slewing crane, 6 mast sections, 7 electronic panel, 8 cross-bridge, 9 manipulator bridge, 10 spider support, 11 telescopic tube, 12 swivel arm, 13 probe system mount for hemispherical bottom, 14 probe system mount for cylindrical wall and nozzles.

4.2.1.2 Frequency response

Frequency response of an amplifier determines the range of frequencies which an amplifier can amplify equally. A narrow band amplifier usually amplifies a narrow band of frequencies around the resonance frequency of the probe used. Narrow band amplifier improves the signal to noise ratio by amplifying the signal from an interface to a greater degree than that of noise signals thus improving flaw detection sensitivity. But an excessive narrow band width has the disadvantage that the pulses are broadened, resulting in reduced resolving power. To accommodate probes of different frequencies, the instrument using a narrow band amplifier is usually provided with a frequency selection switch. Wide band (WB) amplifiers can amplify a wide band of frequencies. This type of amplifier improves the resolution of the flaw detector though the signal to noise ratio (detection sensitivity) is usually lowered. This type of amplifier is usually used in portable

ultrasonic flaw detectors and with shock wave probes. Typical range of frequencies for a wide band amplifier is from 1 to 10 MHz.

4.2.2 Correlation between resolving power and frequency, transmitting power and damping

Resolving power of a flaw detection system is its ability to give separate echoes from two closely occurring flaws. The resolving power of a flaw detection system depends upon the ultrasonic pulse length generated by the probe. The pulse length is controlled by the frequency and damping of the crystal of the probe and the electrical power provided to the probe for generation of ultrasonic waves. The vibration of the crystals of the commercially available standard probes is so damped that the ultrasonic pulse generated by these probes consists of four to five cycles of vibration when the crystal is energised by a normal strength electrical pulse. It consists of more than five cycles when it is energised by a high strength electrical pulse. Shock wave probes on the other hand are highly damped probes and the ultrasonic pulse generated by such probes, at normal transmitting power, consists of half to one cycle of vibration. Since shorter pulse length (i.e. smaller number of cycles of vibration in the pulse) will occupy less space in the material it will therefore result in higher depth (or far) resolution. But since the energy in the pulse (i.e. the transmitting power) is less, the flaw detection sensitivity would be lowered. Another characteristic of a shorter pulse is its higher frequency band width. This frequency band consists of higher as well as lower frequencies around the resonance frequency of the probe. The higher frequencies give rise to sharp echoes therefore improving the resolution of the system. Increasing the transmitting power of the probe will increase the pulse length generated by the probe thus increasing the flaw detection sensitivity and reducing the resolution of the system.

Ultrasonic flaw detectors are usually provided with a two position transmitting power control. The first position of the control provides a low power electrical pulse to the probe. This position provides sufficient flaw detection sensitivity and higher resolution and most of the flaw detection is carried out with this position. However, when inspecting specimens with either large thicknesses or high attenuation characteristics, the transmitting power of position one may not be sufficient. In such cases position two of the control is used. In this position, a higher power electrical pulse is provided to the probe for generating a longer ultrasonic pulse (higher energy). This position therefore renders high flaw detection sensitivity and lower resolution.

4.2.3 Linearity

The amplifier should amplify small signals as much as the large signals. This is an essential requirement, since flaw size in ultrasonic detection is determined by comparing the echo heights. As already mentioned the range of inputs at which the amplifier exhibits this characteristic (known as the linearity) is called the dynamic range of the amplifier. In ultrasonic flaw detection this property of linearity has to be checked regularly as a part of the calibration process.

4.2.4 Saturation

Beyond a certain maximum input the amplifier will not amplify the signal in the same ratio as it does in the dynamic range. The amplification or the gain of the amplifier decreases for inputs with greater signal amplitude. This phenomenon is called the saturation of the amplifier. Since flaw sizing in the saturation region of the amplifier will not be accurate, therefore, an attenuator is provided to control the input to the amplifier; to keep it below the saturation limit. The

attenuator control enables the operator to determine accurate flaw size for inputs larger than the saturation limit as well.

4.3 SIGNAL PRESENTATION

4.3.1 Echo amplitude and its control

A convenient way of measuring changes in amplification or attenuation of ultrasonic waves is in terms of decibel (dB). A decibel is 1/10 th of a bel which is a unit based on logarithms to the base 10. In physics, the term "power" is used to mean the rate at which work is done. If two powers are taken as P_1 and P_2, they are said to differ by n bels when

$$P_1 / P_2 = 10^n$$

or $$n = \log P_1 / P_2 \text{ bels}$$

Hence, since 1 bel is equal to 10 decibels the above equation can be rewritten as:

$$n = 10 \log P_1 / P_2 \text{ decibels}$$

Acoustical power is proportional to the square of the amplitude and hence for comparison of amplitudes A_1 and A_2, we have :

$$n = 10 \log (A_1 / A_2)^2 \quad \text{----------} \quad (4.1)$$

As the amplitudes of the reflected ultrasonic waves are proportional to the heights of the echoes displayed on the CRT screen, therefore Equation 4.1 can be modified as:

$$n = 20 \log H_1 / H_2 \text{ dB} \quad \text{----------} \quad (4.2)$$

where,

H_1 = echo height proportional to ultrasonic wave amplitude A_1

H_2 = echo height proportional to ultrasonic wave amplitude A_2

The advantages of decibel unit are:

(a) large echo height ratios can be given in small figures, e.g.

1000 : 1 = 60 dB

1000,000 : 1 = 120 dB

(b) a reversal of the echo height ratios only requires a change of sign, e.g.

100,000 : 1 = +80 dB, and

1 : 100,000 = –80 dB

(c) multiplication of the echo height ratios corresponds to the simple addition of a dB value, e.g.

gain factor 2 +6 dB
gain factor 10 +20 dB
gain factor 100 +40 dB

Table 4.1 lists the dB values of some of the echo height ratios. To find echo height ratios corresponding to a dB value not included in Table 4.1, dB values from Table 4.1 are chosen whose sum is equal to the dB values for which the echo height is to be determined. And then the multiplication of the echo height ratios corresponding to these chosen dB values will give the required echo height ratio. For example, to find the echo height ratio corresponding to 30 dB, let the dB values whose sum is equal to 30 dB, be 16 dB and 14 dB. The echo height ratio for 16 dB is 6.31 and echo height ratio for 14 dB is 5 and hence 6.31 x 5 = 31.55 is echo height ratio corresponding to 30 dB. Alternately, the dB value of an echo height ratio, which is not given in Table 4.1, can be calculated by reducing this ratio to echo height ratios included in Table 4.1, and then adding their corresponding dB values. For example, the dB value of an echo height ratio of 625 can be determined as follows :

Reducing 625 to factors included in Table 4.1, we have 625 = 1.25 x 5 x 10 x 10 ; and the dB values corresponding to 1.25,5 and 10 are 2 dB, 14 dB and 20 dB respectively. Thus, the dB value corresponding to echo height ratio of 625 = 2+14+20+20 = 56 dB.

TABLE 4.1 : dB VALUES OF SOME OF THE ECHO HEIGHT RATIOS

dB value	Echo height ratio	dB value	Echo height ratio
1	1.12	14	5.00
2	1.26	15	5.62
3	1.41	16	6.31
4	1.59	17	7.8
5	1.78	18	7.94
6	2.00	19	8.91
7	2.24	20	10.00
8	2.51	21	11.2
9	2.82	22	12.59
10	3.16	23	14.13
11	3.55	24	15.85
12	3.98	25	17.78
13	4.47		

4.3.2 A-scan presentation

The most commonly used presentation is the A-scan presentation. In this presentation, the horizontal line on the screen indicates the elapsed time and the vertical deflection shows the echo amplitude. From the location and amplitude of the echo on the screen the depth of the flaw in the material and an estimate of the size of the flaw can be made. A typical A-scan system is shown in Figure 4.10.

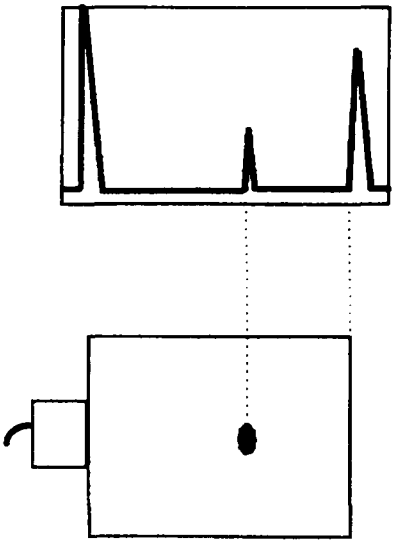


Figure 4.10 : A-scan presentation (Basic display).

4.3.3 B-scan presentation

This presentation gives a cross-sectional view of the material being tested and will show the length and depth of a flaw in the test material. The B-scan presentation shows the reflections from the front and back surfaces of the test material and the flaw. A typical B-scan system is shown in Figure 4.11. The system differs from the A-scan system in the following respects:

(i) The display is generated on CRT screen that is coated with a compound of a long persistence phosphor. This property of the CRT screen allows the imaginary cross-section to be viewed as a whole without having to resort to permanent imaging.

(ii) The CRT input for one axis of the display is provided by an electromechanical device that generates an electrical voltage proportional to the position of the transducer relative to a reference point on the surface of the test specimen. Most B-scans are generated by scanning the probe in a straight line across the surface of the test piece at a uniform rate. One axis of the display, usually the horizontal axis, represents the distance travelled along this line.

(iii) Echoes are indicated by bright spots on the screen rather than by deflections of the time trace. The position of a bright spot along the axis orthogonal to the probe position axis, usually measured top to bottom on the screen, indicates the depth of the echo within the test specimen.

(iv) To ensure that echoes are recorded as bright spots, the echo-intensity signal from the amplifier is connected to the trace brightness control of the cathode ray tube. In some systems, the brightness corresponding to different values of echo intensity may exhibit enough contrast to enable semiquantitative appraisal of echo intensity, which can be related to flaw size and shape.

The chief advantage of B-scan presentation is that it displays a cross-sectional view of the test specimen and the flaws within it. This retention of the image for a time long enough to evaluate the entire specimen, can avoid the need to photograph the CRT screen display for a permanent record.

The limitations of the B-scan systems are that:

(i) The areas behind a reflecting surface are in shadow, and no indication behind this surface can be obtained.

(ii) The flaw width in a direction mutually perpendicular to the ultrasonic beam and the direction of probe travel is not recorded except if the width affects the echo intensity and thus, echo image brightness.

(iii) Because the sound beam is slightly conical rather than cylindrical, flaws near the back surface of the specimen appear longer than those near the front surface.

Although B-scan systems are more widely used in medical applications, they can be used in industry for the rapid screening of specimens and for the selection of certain specimens or portions of certain specimens for more thorough inspection with A-scan techniques.

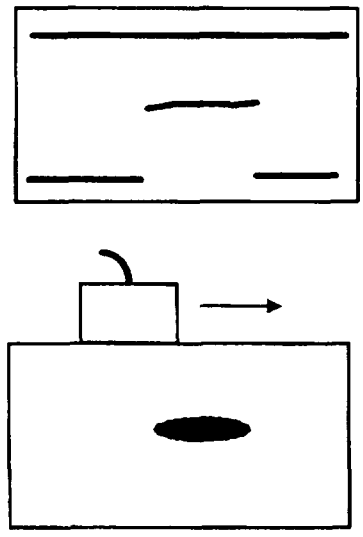


Figure 4.11 : B-scan presentation (Side view).

4.3.4 C-scan presentation

C-scan systems are designed to provide a permanent record of the test when high speed automatic scanning is used. A C-scan presentation displays the flaws in a plan view, but provides no depth or orientation information. A C-scan system is shown in Figure 4.12. Although a persistent phosphor oscilloscope could, in principle, be used for the C-scan presentation, in practice, other means of recording the presentation are superior. Usually, some form of electromechanical recorder producing a permanent paper record, is used.

For C-scan operation, the ultrasonic test unit must be equipped with an electronic gate which samples the received echoes for a selected elapsed time after the initial transmitted pulse. The elapsed time selected is proportional to the distance from the top to the bottom of the inspected slice. Usually, the depth gate is set so that front reflections and back reflections are just barely excluded from the display. Thus, only echoes from within the test specimen are recorded,

except for echoes from thin layers adjacent to both surfaces of the test specimen. As mentioned earlier, the outstanding disadvantage of C-scan presentation is that it does not provide information about the depth and orientation of flaws.

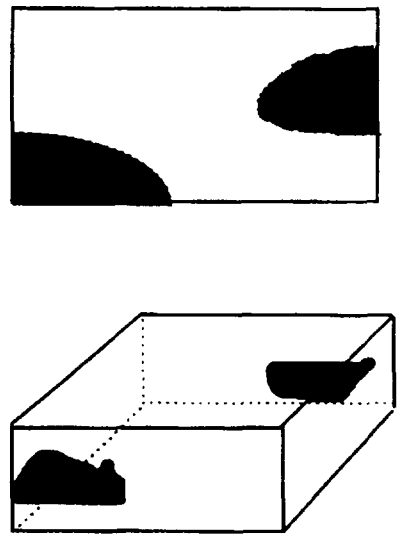


Figure 4.12 : C-scan presentation (Plane view).

4.3.5 Correlation of digital and analogue signals

To use computers for storing and processing of echo patterns (signals) from a conventional ultrasonic flaw detection system, the analogue signal has first to be digitized. An analogue signal varies continuously with time while the digitized signal takes only certain discrete values (Figure 4.13). The digitizing of the analogue signal is accomplished by first sampling it at regular intervals. If the sampling rate is fast enough, the digitized signal can still look very much like the original signal but not that smooth. If the digitized signal does not look like the original it would be because of the under sampling (i.e. the sampling rate is low). The low sampling rate of the signal gives rise to an effect known as aliasing. Due to this effect a high frequency signal is converted to a low frequency signal thus changing its appearance. To avoid aliasing there is a simple rule, known as the Nyguist's Law which says that the signal should be sampled at twice the highest frequency contained in the analogue signal. After sampling the signal, the sampled values are then converted to binary numbers. A binary number is the representation of a decimal number in a series of "0's" and "1's". Binary number system is the only number system which the computer understands. 0 and 1 are known as binary digits (or bits for short) and these two numbers represent two states, "On" or "Off" . A group of binary digits (or bits) is known as a word. A "word" can be of any number of bits but in ultrasonic testing words of 8 and 12 bits are most common. A 4-bit word will represent 2^4 (=16) levels of the signal amplitude values. An 8-bit and a 12-bit words would give 2^8 (=256) and 2^{12}(=2048) different levels of the signal voltage.

As an example suppose that a signal with a peak voltage of 15 volts is to be digitized. If a four bit word is used then 15 volts could be represented in 16 levels with a one volt difference between each level, i.e. up to 15 volts in a 1 volt step. If the same 15 volts are to be represented by an 8 bit word then there will be 256 different voltage levels with 0.059 volt difference between each level. If the same 15 volts is to be represented by a 12 bit word then there would be 2048 levels with 0.0073 volt difference between each level. It is clear from the above

example that the greater the word length used the greater would be the number of levels (or resolution) and the digital signal would be more like the original signal.

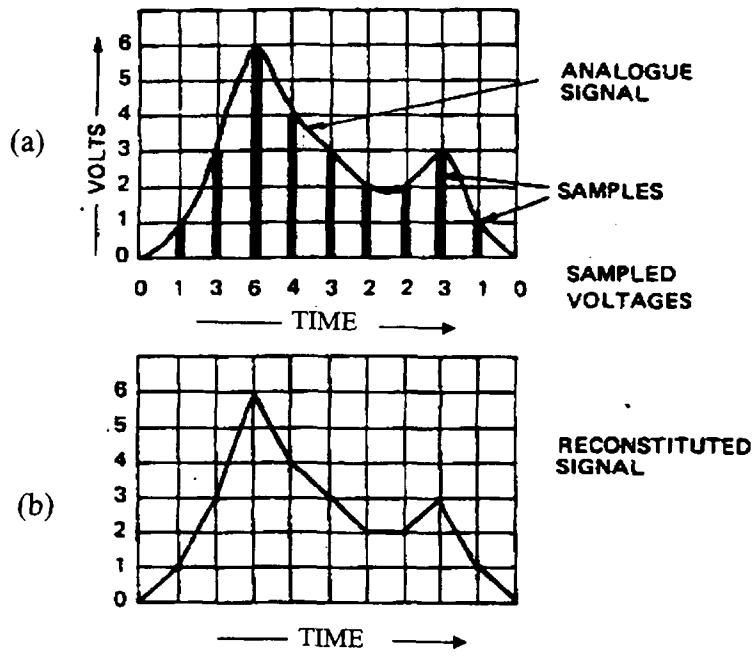


Figure 4.13 : Correlation of digital and Analogue signals; (a) analogue signal, (b) digital signal.

4.4 RECORDING INSTRUMENTS

4.4.1 Automatic monitor

Many instruments are equipped with a monitor function which facilitates observing the flaw in the expectancy range. The start and end of the flaw expectancy range can thereby be marked by means of a step on the base line of the screen or an additionally displayed bar on the screen. If now an echo appears within this range then this releases a visible and/or audible alarm signal. The response threshold of the monitor is also variable so that an echo indication only releases the alarm when it has reached a certain height. This mode of operation is called "coincidence" mode. Some systemse are fitted with monitor which can also operate in the "anticoincidence" mode, i.e. an echo indication only releases the alarm when it has fallen below a certain threshold value. The anticoincedence mode is usually used for monitoring the backwall echo height. This monitoring enables the operator to check whether sufficient ultrasonic energy is being transmitted into the test specimen or not.

In addition to the monitor function, most of these instruments have a control output which can be used to further process the information. As soon as an echo appears within the monitor threshold a voltage is fed to the control output which is proportional to the echo height and which can be immediately used for automatic recording. By means of this monitor function together with a path pick-up which is fixed into the probe, C-scans of workpieces can be easily printed on an X-Y recorder.

4.4.2 Computer interfacing

The signal acquired through a conventional ultrasonic flaw detection system can only be processed by a computer if it is first converted into a digital signal. The digitization of the

analogue signal is carried out in a special electronic circuit called the analogue-to-digital converter (ADC) which samples the incoming analogue signal at a fast rate of more than 20 MHz . This process of connecting the output of an ultrasonic flaw detector through an ADC to the computer is called as computer interfacing. The ADCs used in ultrasonic detection are either of successive approximation type or of flash type of 8 or 12 bit resolution and sample rate (or conversion rate) of 20 MHz or above.

ADCs of 8 to 12 bit resolution and a sampling rate of 200 MHz or more are available on boards which can be mounted into an empty slot provided in a personal computer. These boards will then digitize and store the output of the flaw detector which can then be processed by the computer using appropriate software packages.

4.4.3 Recorders, printers and colour markers

4.4.3.1 Recorders

Almost any type of recorder can be used in ultrasonic test systems. The type of recorder is usually related closely to the mechanical scanner used, since search unit position is often one or two of the variables to be recorded. Some of the pertinent advantages of various recorders follow.

Strip chart recorders

These recorders are usually the least expensive type. Chart paper flows through the recorder at a constant rate while a pen (or pens in a multi-channel recorder) moves back and forth across the paper. They are useful where the search unit is carried over the test piece at a constant rate so that its position can be determined easily from the chart.

The helix-drum type recorder is commonly used to make C-scan recordings. In this recorder a chemically treated paper is passed between a bar and a drum with a helix of wire wrapped around it. The printing bar has a narrow edge and is connected to the output of an alarm or proportional output gate. The other electrical terminal is the helix. As the drum rotates, the contact point between it and the bar scans across the paper. Electric current passing through the paper between the bar and the helix darkens the paper. The scanning of the probe over the workpiece can be directly coupled to the scan of the spot across the paper. At the end of each scan the search unit and the paper are both indexed along. C-scan recordings showing many shades of gray are possible, each shade representing a different amplitude.

X-Y recorders

In an X-Y recorder the pen moves in two orthogonal directions and the paper remains stationary. In many models the pen can be lifted from the paper automatically allowing its use as a C-scan recorder. Also in many models a constant scan speed along one axis can be chosen if desired.

Magnetic tape recorders

Tape recorders have been used for recording the A-scan display of the CRT screen directly, although the tape must be played back on another CRT device. However, this scheme does allow retention and re-examination of the signal pattern seen during an inspection.

4.4.3.2 Printers

Digital recorders are new to ultrasonic testing. They print rows of numbers on a paper tape rather than drawing lines. Each column or group of columns of numbers can record several different variables simultaneously. The numerical print out is often much easier to use than trying to read values from a scale on a strip chart. However, electrical data must be supplied to the recorder in a digital form. This means that analogue to digital converters must be used thus increasing the cost of the system, or the system must be designed to produce data in a digital form originally.

4.4.3.3 Colour markers

Colour markers are devices which are triggered by the monitor gates to mark the location of flaws on the test specimen surface. These devices are usually used in automatic inspection of plates, bars, billets, pipes, etc.

In immersion testing the location of flaws is either marked by using a pneumatically operated lipstick or by running a grinding belt which is pressed against the specimen at positions of the flaw.

5. CALIBRATION OF THE TESTING SYSTEM

5.1 PURPOSE OF CALIBRATION

Ultrasonic test equipment provides a number of basic functions. These include the generation of an elastic wave, the reception of ultrasonic signals, signal conditioning and processing, discontinuity signal, gating and signal presentation. Codes usually specify the required instrument capability. To ensure that this can be achieved, equipment shall always be properly calibrated. Calibration of equipment is most important if accurate testing and reliable results are to be obtained.

In ultrasonic testing calibration means the verification and adjusting of ultrasonic equipment characteristics so that reliable and reproducible test results are obtained. The calibration procedure used in ultrasonic testing can be classified into:

(i) Equipment characteristics verification.

(ii) Range calibration.

(iii) Reference level or sensitivity setting.

5.2 STANDARD TEST BLOCKS

5.2.1 Calibration and reference blocks

In ultrasonic pulse echo testing test blocks containing notches, slots or drilled holes are used to:

(i) Determine the operating characteristics of the flaw detector and probes.

(ii) Establish reproducible test conditions.

(iii) Compare the height or location of the echo from a flaw in the test specimen to that from an artificial flaw in the test block.

The blocks used for the first two purposes are termed calibration blocks, while test blocks used for the third purpose, are known as reference blocks. The same test block may be used as a calibration or reference block. Test blocks whose dimensions have been established and sanctioned by any of the various groups concerned with material testing standards are called standard test blocks. Some of the commonly used test blocks along with their uses are as follows:

5.2.2 I.I.W. calibration block

The most versatile calibration block is the block made from medium carbon ferritic and normalized steel described by the International Institute of Welding (I.I.W) and proposed by the International Standard Organization (I.S.O.). This block, called the I.I.W. V1 block, is as shown in Figure 5.1.

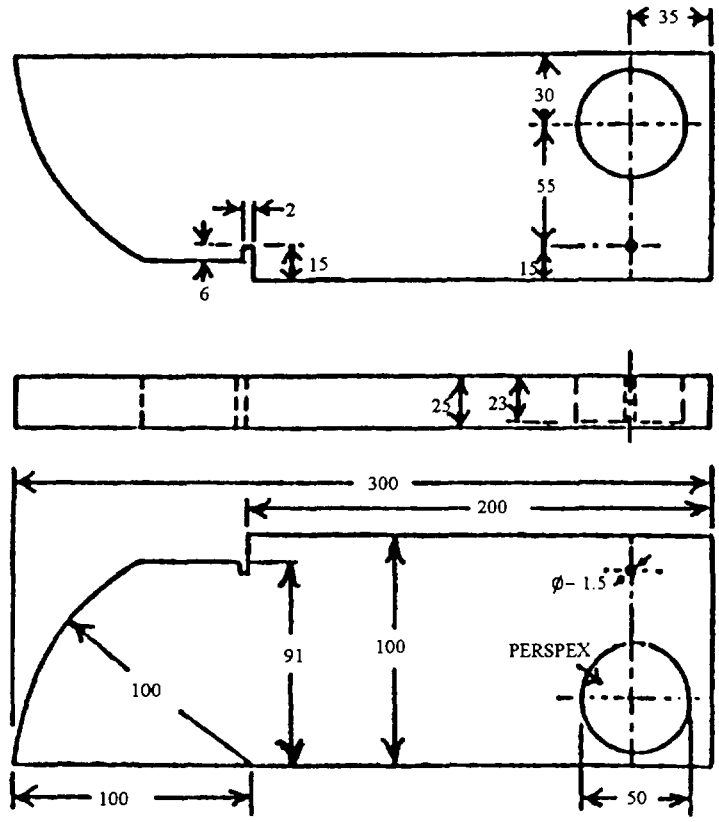


Figure 5.1 : Test block I.I.W. (V1) for calibration of an equipment with normal and angle probes (all dimensions are in millimetres).

This block is generally used for:

(i) The calibration of the time base using 25 mm, 100 mm and 200 mm thickness with the normal beam probes and 100 mm quadrant for angle beam probes.

(ii) The determination of probe index using 100 mm quadrant.

(iii) The determination of the probe angle using plastic wedge and degrees stamped on the side of the block. The angle beam transducer is subject to wear in normal use. This wear can change the probe index and the probe angle.

(iv) The checking of performance characteristics of the ultrasonic flaw detector such as:

- Time base linearity.
- Screen height linearity.
- Amplitude control linearity.
- Resolving power.
- Penetrative power.
- Dead zone check.
- Pulse length.

(v) The setting of sensitivity.

(vi) The calibration of time base and sensitivity setting for DGS method.

(vii) The comparison of various materials due to their different acoustic velocities.

5.2.3 V2 calibration block

This is a more compact form of the V1 block suitable for site use, although somewhat less versatile in its function. It is also described by International Institute of Welding (I.I.W). The latest version of this block is shown in Figure 5.2. It is particularly suitable for short near field lengths and the time base calibration of small diameter normal and angle probes.

This calibration block is made of steel with the dimensions in millimetres as shown in Figure 5.2. The tolerances are ±0.1 mm except on the length of the engraved scale where they are ±0.5 mm. This calibration block contains two quadrants having radii of 25 mm and 50 mm. Point 'A' is the common focal point for both quadrants. The uses of the block are as follows:

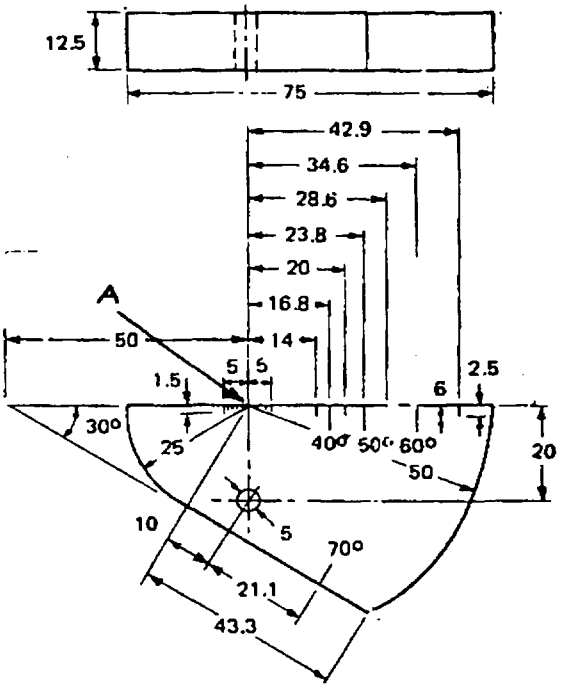


Figure 5.2 : I.I.W V2 calibration block.

5.2.4 *ASME reference block*

The block is used to construct a distance-amplitude-correction (DAC) curve on the CRT screen by noting the changes in echo amplitude from the hole with change in scanning distance (multiple skip). This block is made from the same material as that of the test specimen and contains side drilled holes. Thickness of the block and the diameter of the side drilled holes depend on the thickness of the test specimen. A typical ASME reference block called the basic calibration block (BCB) used for the inspection of welds is shown in Figure 5.3. Specified calibration reflectors for different weld thicknesses are as shown in Table 5.1.

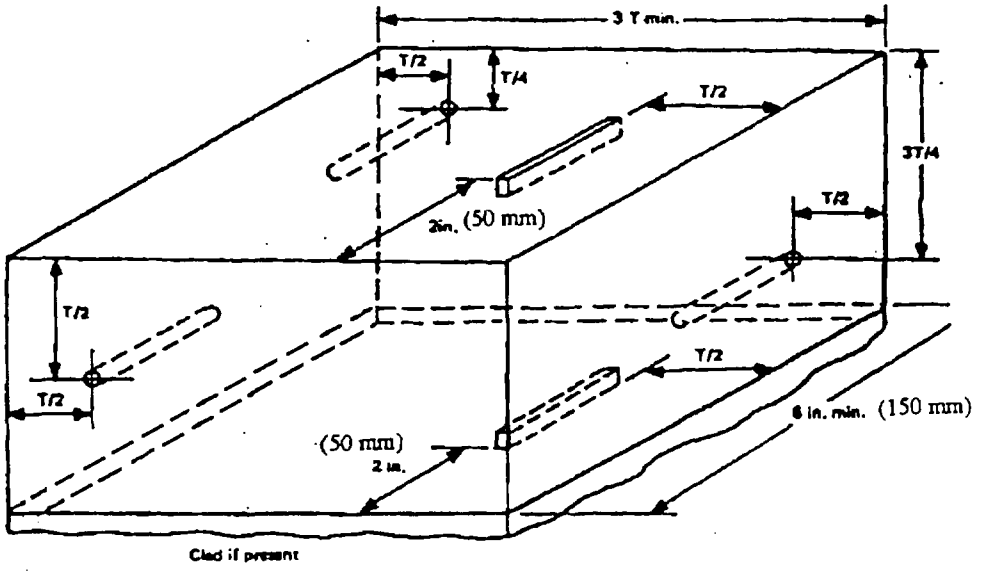


Figure 5.3 : ASME basic calibration block (BCB).

TABLE 5.1 : SPECIFIED CALIBRATION REFLECTORS

Weld thickness (t)	Basic calibration block thickness T	Hole diameter	Notch size
1 in (25.4 mm) or less	3/4 in (19.0 mm) or t	3/32 in (2.38 mm)	Width = 1/8 in (3.17 mm) to 1/4 in (6.35 mm)
Over 1 in (25.4 mm) through 2 in (50.8 mm)	1-1/2 in (38.1 mm) or t	1/8 in (3.17 mm)	--
Over 2 in (50.8 mm) through 4 in (101.6 mm)	3 in (76.2 mm) or t	3/16 in (4.76 mm)	Depth = 2 % T
Over 4 in (101.6 mm) through 6 in (152.4 mm)	5 in (127.0 mm) or t	1/4 in (6.35 mm)	--
Over 6 in (152.4 mm) through 8 in (203.2 mm)	7 in (177.8 mm) or t	5/16 in (7.94 mm)	Length = 2 in (50.8 mm)
Over 8 in (203.2 mm) through 10 in (254 mm)	9 in (228.6 mm) or t	3/8 in (9.52 mm)	--
Over 10 in (254.0 mm)	--	--	--

General notes:

(a) Holes shall be drilled and reamed a minimum of 1-1/2 in (38.1 mm) deep and essentially parallel to the examination surface.

(b) Notches may be provided as required.

(c) The tolerance for hole diameter shall be ±1/32 in (0.79 mm). The tolerance on notch depth shall be +10 and -20%. The tolerance on hole location through the thickness shall be ±1/8 in (3.17 mm).

(d) For each increase in thickness of 2 in (50.8 mm) or fraction thereof, the hole diameter shall increase 1/16 in (1.58 mm).

5.2.5 Area-amplitude blocks

Area-amplitude blocks provide artificial flaws of different sizes at the same depth. Eight blocks made from the same (50 mm) diameter round stock, each 3-3/4" (95.25 mm) in height, constitute a set of area-amplitude blocks. The block material must have the same acoustic properties as the test piece material. Each block has a 3/4" (19.6 mm) deep flat bottom hole drilled in the centre of the bottom surface (Figure 5.4). The hole diameters vary from 1/64" (0.4 mm) to 8/64" (3.17 mm). The blocks are numbered to correspond with the diameter of the holes, that is block No. 1 has a 1/64" (0.4 mm) diameter hole, and so on up to No. 8, which has an 8/64" (3.17 mm) diameter hole. Similar area-amplitude blocks made from 1-15/16" (49.2 mm) square stock are sometimes known as Alcoa series-A blocks.

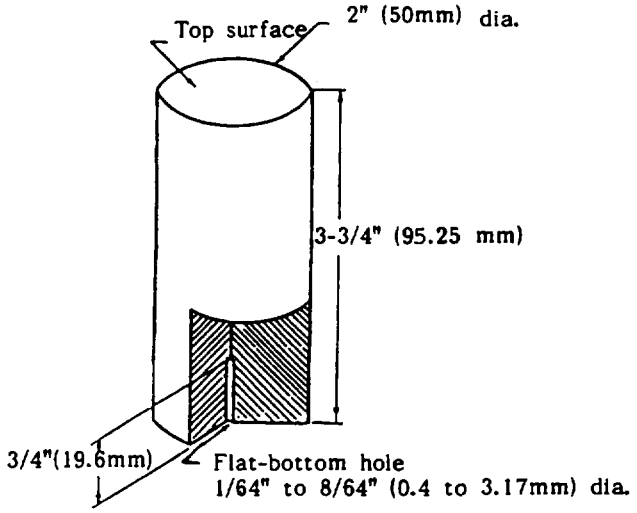


Figure 5.4 : Area-amplitude block.

The amplitude of the echo from a flat bottom hole in the far field of a normal beam probe is proportional to the area of the bottom of the hole. Therefore these blocks can be used to check linearity of a pulse echo inspection system and to relate echo amplitude to the area (or, in other words, the size of a flaw). Because a flat bottom hole is an ideal reflector and most natural flaws are less than ideal in reflective properties, an area-amplitude block defines a lower limit for the size of a flaw that yields a given height of indication on the CRT screen. For instance if the height of indication from a flaw in a test piece is six scale units and this is also the height of the indication from a 5/64" (1.98 mm) diameter flat bottom hole at the same depth as the flaw, it is not possible to determine accurately how much larger than the reference hole the flaw actually is. But the flaw is at least as large as the diameter of flat bottom hole.

5.2.6 *Distance-amplitude blocks*

Distance-amplitude blocks provide artificial flaws of a given size at various depths (metal distance). From ultrasonic wave theory it is known that the decrease in echo amplitude from a flat bottom hole using a circular probe is inversely proportional to the square of the distance to the hole bottom. Distance-amplitude blocks (also known as Alcoa series-B or Hitt blocks) can be used to check actual variations of amplitude with distance for normal beam inspection in a given material. They also serve as reference for setting or standardizing the sensitivity of the inspection system so that readable indications will be displayed on the CRT screen for flaws of a given size and larger, but the screen will not be flooded with indications of smaller discontinuities that are of no interest. On instruments so equipped, these blocks are used for distance-amplitude correction so that a flaw of a given size will produce an indication on the CRT screen that is of a predetermined height regardless of distance from the entry surface.

There are 19 blocks in an Alcoa series-B set. All are 2" (50 mm) diameter blocks of the same material as that being inspected, and all have a 3/4" (19.6 mm) deep flat bottom hole drilled in the centre of the bottom surface (Figure 5.5). The hole diameter is the same in all the blocks of a set. Sets can be made with hole diameters of 3/64" (1.19 mm), 5/64" (1.98 mm) and 8/64" (3.17 mm). The blocks vary in length to provide metal distances of 1/16" (1.59 mm), 1/8" through 1" (25.4 mm) in 1/8" (3.17 mm) increments and 1-1/4" (31.7 mm) through 5-3/4" (146 mm) in 1/2" (12.7 mm) increments (see Table 5.2).

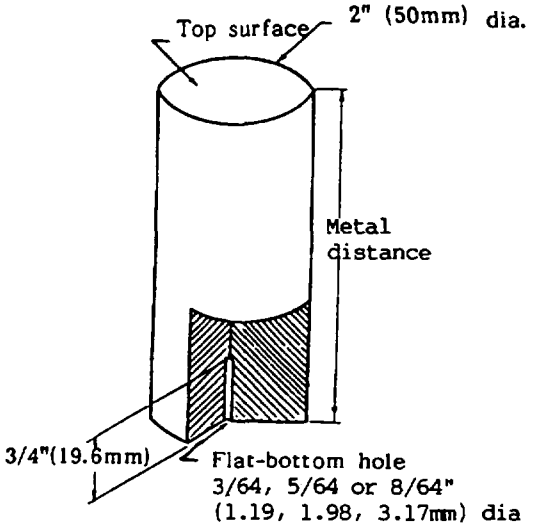


Figure 5.5 : Distance-amplitude block.

Each Alcoa series-B block is identified by a code number consisting of a digit, a dash and four more digits. The first digit is the diameter of the hole in one sixty fourths of an inch. The four other digits are the metal distance from the top surface to the hole bottom in one hundredth of an inch. For instance, as illustrated in the Table 5.2 a block marked 3-0075 has a 3/64" (1.19 mm) diameter hole and a 3/4" (19.6 mm) metal distance.

5.2.7 *ASTM blocks*

ASTM blocks can be combined into various sets of area-amplitude and distance-amplitude blocks. The ASTM basic set of distance-amplitude blocks consists of ten 2" (50 mm) diameter blocks, each with a 3/4" (19 mm) deep flat bottom hole drilled in the centre of the bottom surface. One block has a 3/64" (1.19 mm) diameter hole at a 3" (76.2 mm) metal distance. Seven

blocks have 5/64" (1.98 mm) diameter holes at metal distances of 1/8" (3.17 mm), 1/4" (6.35 mm), 1/2" (12.7 mm), 3/4" (19 mm), 1-1/2" (38.1 mm), 3" (76.2 mm) and 6" (152.4 mm). The remaining blocks have 8/64" (3.17 mm) diameter holes at 3" (76.2 mm) and 6" (152.4 mm) metal distances. The ASTM basic set of area-amplitude blocks consists of three blocks with a 3" (76.2 mm) metal distance and holes with diameter of 3/64" (1.19 mm), 5/64" (1.98 mm), and 8/64" (3.17 mm). The remaining amplitude blocks with the 3/64" (1.19 mm) diameter holes form the set of distance-amplitude blocks.

In addition to the basic set, ASTM lists five more area-amplitude standard reference blocks and 80 more distance-amplitude blocks. Each ASTM block is identified by a code number, using the same system as that used for the Alcoa series-B set.

TABLE 5.2 : DISTANCE-AMPLITUDE SET

Block identification number	Metal distance		Overall length	
	Inches	mm	Inches	mm
3-0006	0.062 (1/16)	1.57	0.875	22.2
3-0012	0.125 (1/8)	3.2	0.875	22.2
3-0025	0.250 (2/8)	6.4	1.000	25.4
3-0037	0.375 (3/8)	9.5	1.125	28.6
3-0050	0.500 (4/8)	12.7	1.250	31.8
3-0062	0.625 (5/8)	15.9	1.375	34.9
3-0075	0.750 (6/8)	19.1	1.500	36.1
3-0087	0.875 (7/8)	22.2	1.625	41.3
3-0100	1.000	25.4	1.750	44.5
3-0125	1.250 (1-1/4)	31.8	2.000	50.8
3-0175	1.750 (1-3/4)	44.5	2.500	63.5
3-0225	2.250 (2-1/4)	57.2	3.000	76.2
3-02753	2.750 (2-3/4)	69.9	3.500	88.9
3-0325	3.250 (3-1/4)	82.6	4.000	101.6
3-0375	3.750 (3-3/4)	95.3	4.500	114.3
3-0425	4.250 (4-1/4)	108.0	5.000	127.0
3-0475	4.750 (4-3/4)	120.7	5.500	139.7
3-0525	5.250 (5-1/4)	133.4	6.000	152.4
3-0575	5.750 (5-3/4)	146.1	6.500	165.1

5.3 EQUIPMENT CHARACTERISTICS

The most important equipment characteristics to be verified are horizontal linearity, screen height linearity, amplitude control linearity, resolution of equipment, dead zone estimation and penetrative power.

5.3.1 Horizontal linearity

The horizontal linearity or time base linearity is a measure of the degree of difference between an actual distance and a distance read out on the CRT. The I.I.W, DIN 54122 or any block of similar material and finish may be used to measure horizontal linearity. The choice of thickness is determined by the requirement that a longitudinal wave probe placed on the block produces several backwall echoes (usually four or five) within the chosen range. For checking the linearity two of the backwall echoes (say, the first and fourth in a five echo display) should be set to coincide with appropriate scale divisions. The position of each of the remaining echoes is then carefully noted. The maximum tolerance is 1% for the range chosen. Non-linearity of the time base is seldom a real problem with modern flaw detectors and the most common cause of apparent non-linearity is the poor calibration of time base zero by the operator.

An important precaution to take during the assessment of time base linearity is that time base readings are taken as each signal is brought to a common amplitude. This is usually about 1/2 screen height.

5.3.2 Screen height linearity

The screen height linearity or amplitude linearity is a measure of the degree of proportionality between an input to the amplifier and echo height displayed on the CRT.

To know whether the amplifier of the flaw detector amplifies a small signal in the same ratio as it amplifies a large signal, i.e. whether the amplifier is linear or not, the procedure used is as follows: the time base of the flaw detector is calibrated for a range of 250 mm and ten backwall echoes from 25 mm thick side of the V1 block are obtained (Section 5.2.2). The amplitude of the nth echo (usually the one which is just outside the near field length) is set to a particular amplitude (normally 4/5 the screen height). The amplitudes of the subsequent echoes (n+1, n+2, n+3 echoes, etc.) are noted. The amplitude of the nth echo is then reduced to half its original value and the reduction in amplitudes of the subsequent echoes are noted. If they are all reduced to half of their original values, then the amplifier is linear, otherwise it is not.

Deviation from linearity for any particular echo can be expressed as a percentage relative deviation from the following equation:

$$\text{Deviation} = \frac{\text{(original amplitude of echo) - (twice the reduced amplitude)}}{\text{(original amplitude of the echo)}} \times 100 \quad \text{-------} \quad (5.1)$$

5.3.3 Amplitude control linearity

For the checking of amplitude control linearity, the time base is calibrated for a desired range and an echo about midway along the time base is obtained. The echo amplitude is set to a desired height and the attenuator reading is noted. The attenuator setting is then reduced by 6 dB, four or five times in succession and the decrease in echo amplitude is noted every time. If it decreases to half the value of the previous setting then the gain control of the equipment is properly calibrated.

5.3.4 *Resolution*

The resolution of a flaw detector is the ability to resolve minor difference in distance and direction. To determine the resolution of a flaw detector I.I.W V1 block is used with normal beam probes. This block has three target reflectors at ranges of 85 mm, 91 mm and 100 mm. A probe is placed on the block as shown in Figure 5.6 (a) and echoes from the three reflectors are obtained. The separation of the echoes from each other indicates the degree of resolution of the flaw detector for that particular probe. Figures 5.6 (b) & (c) show the degree of resolution for a flaw detector using two different normal beam probes.

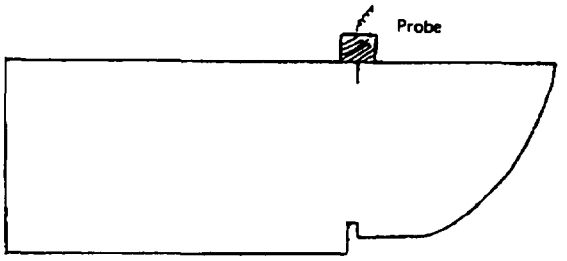
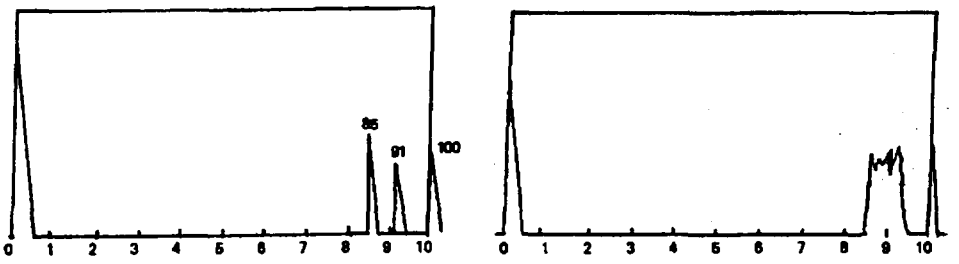


Figure 5.6 : (a) Placement of probe on I.I.W V1 block to determine the resolution of flaw detector and probe system.



(b) (c)

Figure 5.6 (b & c) : CRT display showing resolving power of the flaw detector using two different normal beam probes; (b) shows better resolution, while, (c) shows a poor resolution.

A rough estimate of the length of the dead zone beneath a compressional wave probe is obtainable using the 1.5 mm hole and the plastic insert of the V1 block. Any attempt to add holes would limit its usefulness, and the use of a special block of the kind shown in Figure 5.7 (described in BS 3923: Part 3 : 1972) is, therefore, recommended. With this block the resolution is determined by the minimum distance apart that flaws can be indicated clearly and separately. In use the probe is placed on the centre line of the block over the change in radius from one step to the next. Its position is adjusted so that echoes from the two radii are of the same height and approximately 1/2 full screen height. The steps are said to be resolved when their echoes are clearly separated at half maximum echo height or less.

5.3.5 *Maximum penetrative power*

This is the term used in British Standard BS 4331. It describes a check which is used to compare the energy output for a particular set and probe with its past performance or with similar equipment. The check is carried out as follows:

A longitudinal wave probe is placed on the plastic insert (methyl polymethacrylate cylinder) of the I.I.W V1 block (Figure 5.8) having a thickness of 23 mm which is equal to 50 mm of steel and the gain for the instrument is set to its maximum. The number of multiple echoes and the amplitude of the last echo are noted and are used to express the maximum penetrative power of the set and the probe.

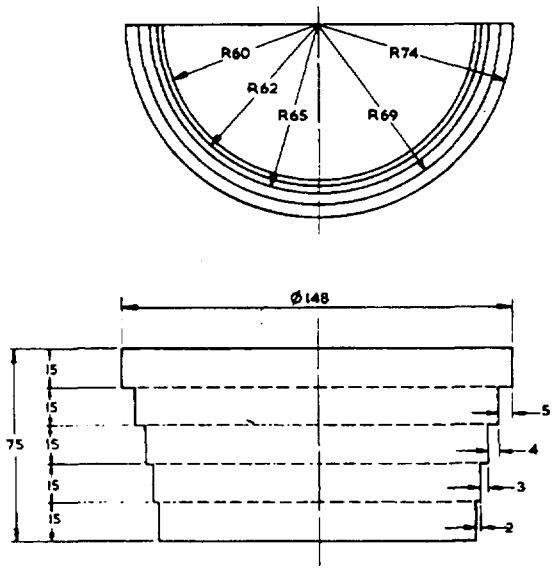


Figure 5.7 : British standard test block for measuring resolution of the probe and the flaw detector system.

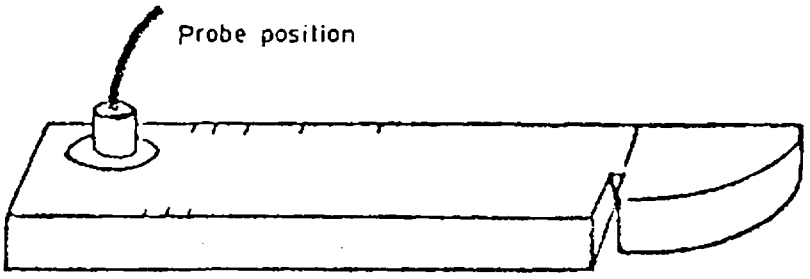


Figure 5.8 (a) : Placement of normal beam probe to determine penetrative power of the system.

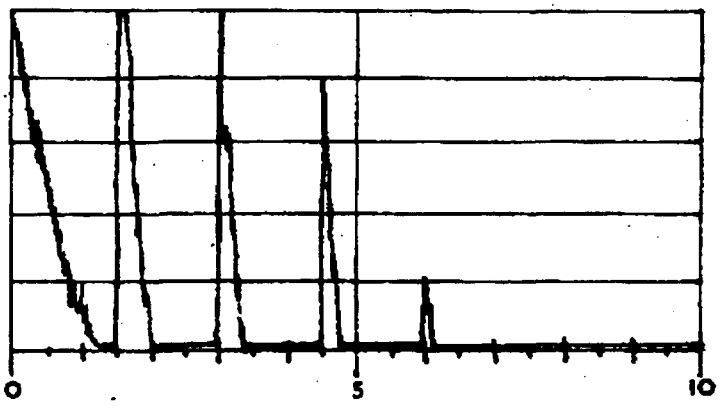


Figure 5.8 (b) : CRT display illustrating penetrative power of the system.

5.3.6 *Determining the pulse length*

5.3.6.1 *Normal probe*

On flaw detectors with a rectified display, place the probe at position L (Figure 5.9 a) and calibrate the test range using the 6 mm step (equivalent to 1 μs transit time in steel) to a short time range. Place the probe on a suitable surface of the block to produce a back echo and adjust the delay and amplification to display the back echo at 100% full screen height (FSH). Estimate the pulse length as the distance between the points on the rising and falling flanks of the displayed pulse which are at 10% of the peak amplitude. The pulse length is expressed in mm or as a time interval in microseconds.

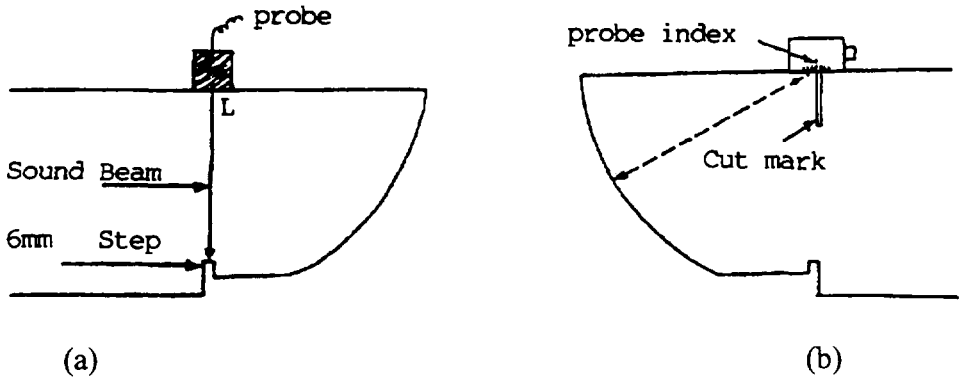


Figure 5.9 (a & b) : Probe position on V1 block with normal beam and angle beam probes for determination of pulse length.

5.3.6.2 *Angle probe*

Position the angle probe at position L (Figure 5.9 b) and obtain a back echo from the 100 mm radius after calibrating the time base to a short range. The delay is adjusted to bring the 100 mm back echo into the calibrated range. Set the backwall echo to 100% FSH. The pulse length can be estimated as the distance between the points on the rising and falling flanks of the displayed pulse which are at 10% of the peak amplitude (Figure 5.10).

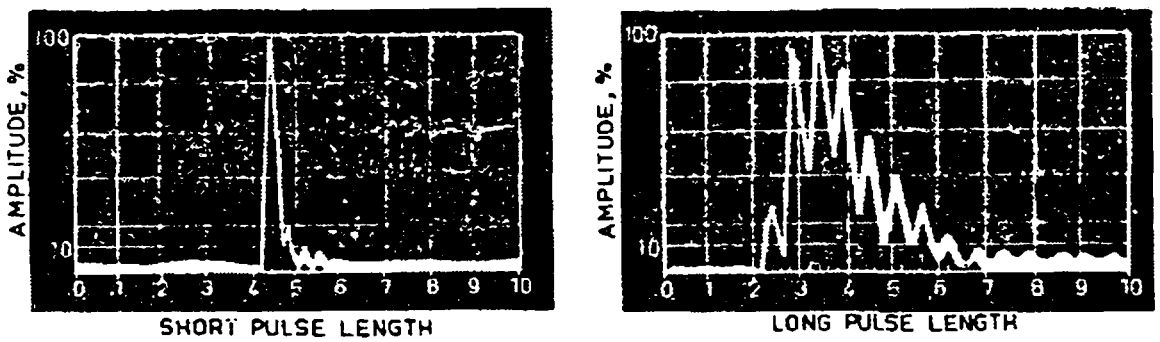


Figure 5.10 : Typical pulse length display.

5.4 CALIBRATION WITH NORMAL PROBES

5.4.1 Calibration of time base

5.4.1.1 Using V1 block

For calibration of the time base with a normal beam probe for a range of up to 250 mm, the probe is placed at position C (Figure 5.11) and multiple backwall echoes are obtained and adjusted to the appropriate scale division of the CRT screen using the delay and fine material testing range controls. Figure 5.12 shows the CRT screen display for an 100 mm calibrated CRT screen. The points where the rising backwall echoes leave the base line have been adjusted to the appropriate scale divisions to give the time base calibration.

For time base calibration of more than 250 mm with normal beam probe, the probe is placed at position A or B (Figure 5.11) and multiple backwall echoes are obtained and adjusted to the appropriate scale divisions. Figure 5.13 shows the CRT screen display for a one metre range. For time base calibration of 91, 182, 273, ... normal beam probe is placed at position D (Table 5.3).

Multiple backwall echoes are used for time base calibration because the distance between the transmission pulse and the first backwall echo is some what larger than the distance between two consecutive multiple echoes. This zero error is caused by the ultrasound travelling in the transducer, probe protective layer (if any) and the layer of the couplant before entering the specimen.

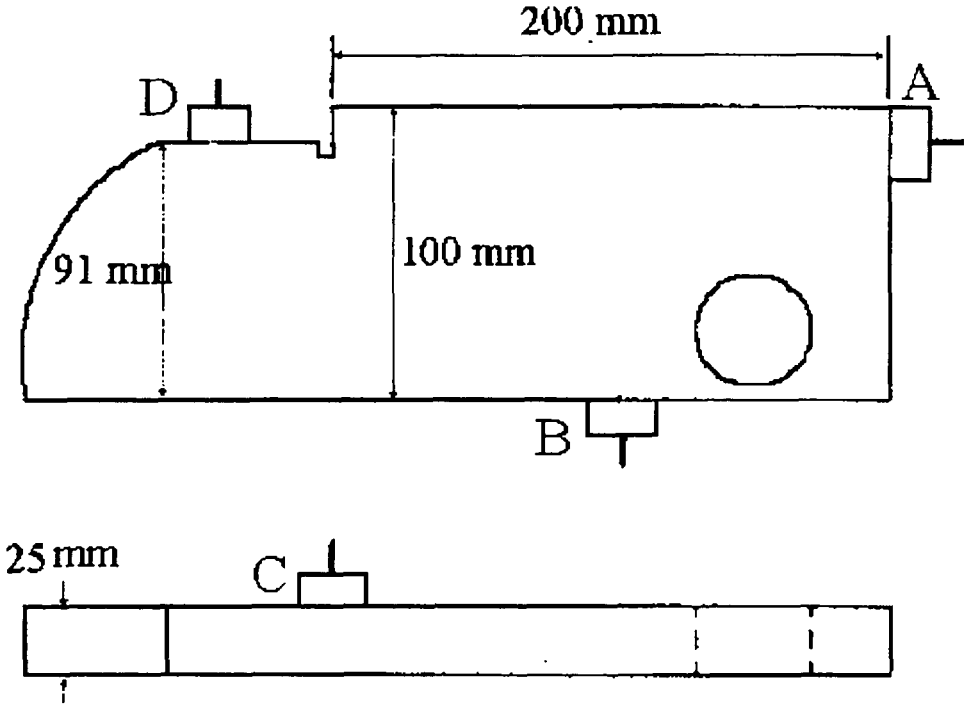


Figure 5.11 : Probe positions on I.I.W. (V1) calibration block for different thickness ranges.

TABLE 5.3 : RELATIONSHIP BETWEEN THE PROBE POSITIONS AND THE THICKNESS RANGES FOR CALIBRATION

Probe position on calibration block	Thickness ranges (mm)
A	200, 400, 600, ----------
B	100, 200, 300, 400, 500,----------
C	25, 50, 75, 100, 125, 150, 175, 200, 225, 250
D	91, 182, 273,----------

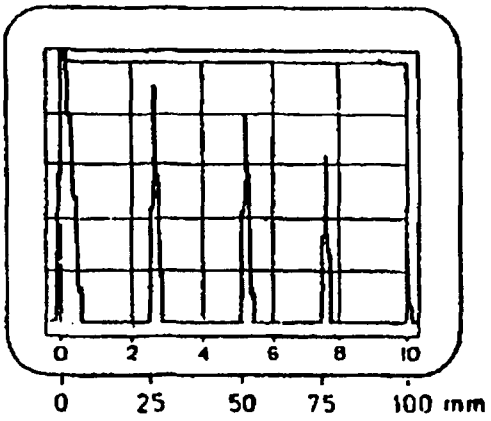


Figure 5.12 : CRT screen display for 100 mm test range calibration (when the probe is placed at position 'C').

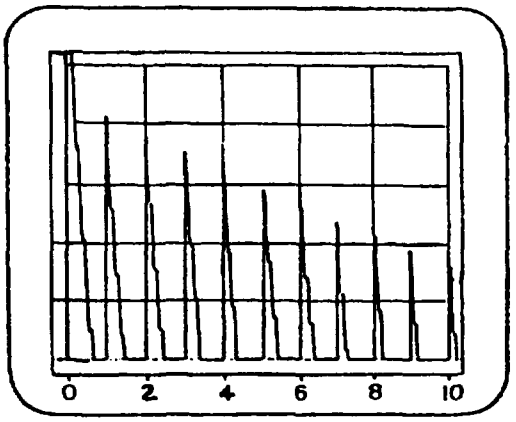


Figure 5.13 : CRT screen display for one metre test range calibration (when the probe is placed at position 'B').

5.4.1.2 Using V2 block

A normal probe is placed on the block as shown in Figure 5.14 (a) and multiple backwall echoes are obtained. These echoes are adjusted using the test range and delay controls. Figure 5.14 (b) shows the screen display for a 50 mm range calibration.

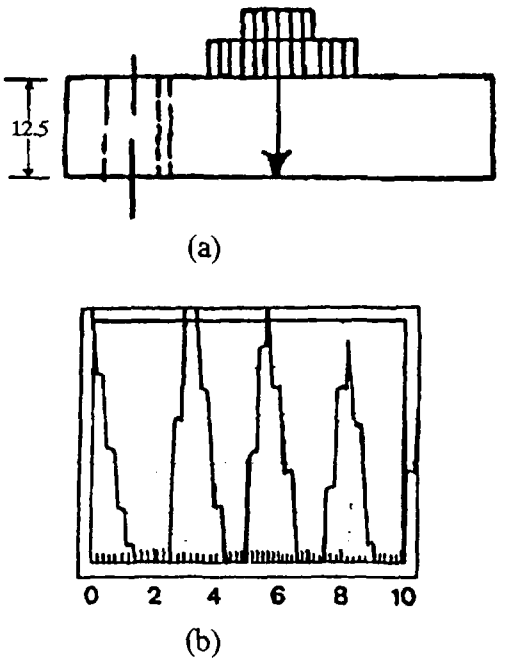


Figure 5.14 (a & b) : Probe position on I.I.W V2 calibration block for test range of 50 mm and CRT screen display.

5.5 CALIBRATION WITH ANGLE PROBES

5.5.1 Range calibration

5.5.1.1 Using V1 block

For a range of 100 mm or more the most direct method is to get multiple backwall echoes from the 100 mm quadrant by placing the probe at position 'E' (Figure 5.15 a). A CRT screen display for a range of 200 mm is shown in Figure 5.15 (b).

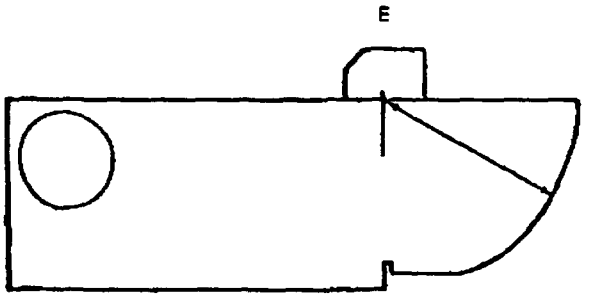


Figure 5.15 (a) : Probe position for the test range calibration of 100 mm and above with angle probes.

Figure 5.15 (b) : CRT screen display for 200 mm test range calibration (when the probe is positioned at 'E').

Another method of calibrating the time base for angle beam probes is to position a normal wave probe at 'D' in Figure 5.11 at which the distance of 91 mm for a longitudinal wave corresponds to 50 mm for shear waves. Figure 5.16 shows the CRT display for a range of 250 mm for an angle probe which has been calibrated with a normal probe and the 91 mm length of the calibration block.

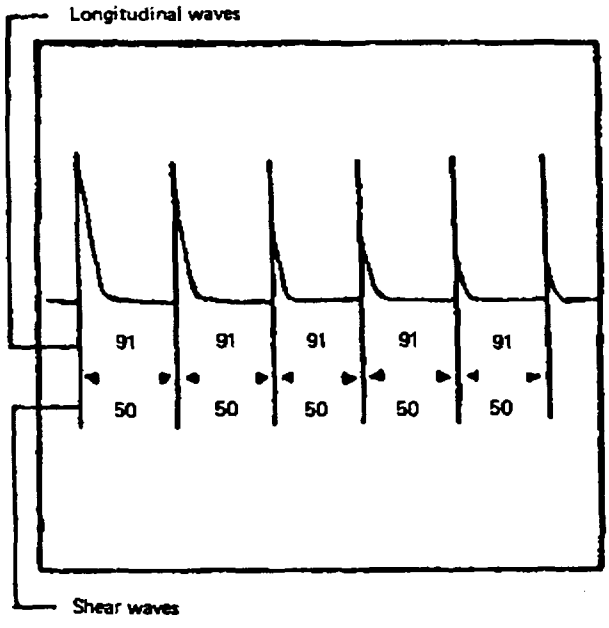


Figure 5.16 : CRT screen display for 250 mm test range for an angle beam probe which has been calibrated with a normal beam probe and the 91 mm length of the calibration block.

After calibrating with the normal probe replace the normal probe with an angle beam probe, position the probe at 'E' (Figure 5.15 a) so that a maximum response is obtained from the 100 mm radius face. This coincides with the 100 mm reflection previously obtained with the normal probe thereby correcting for the delay which occurs in the probe shoe.

To calibrate the time base for a 100 mm range with an angle beam probe, the procedure used is explained in Figure 5.17 a, b & c.

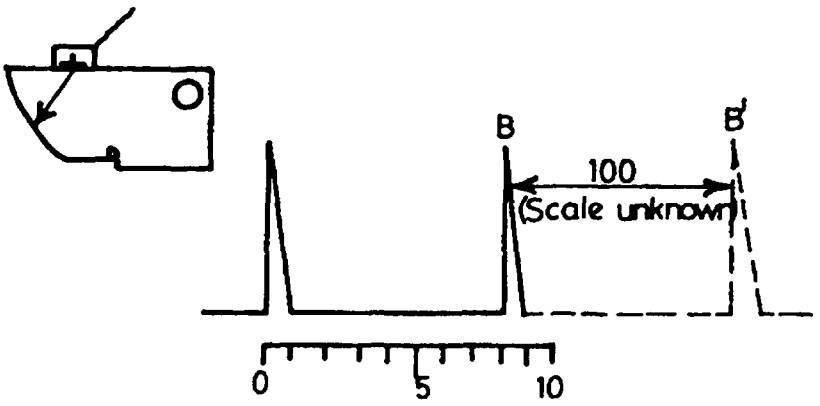


Figure 5.17 (a) : Peak B is set provisionally at or near 10 using the sweep length control.

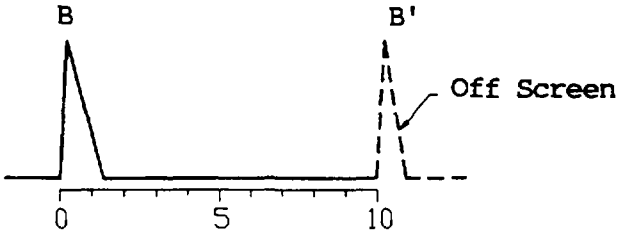


Figure 5.17 (b) : Peak B is set at 0 and 10 using the delay and sweep length controls respectively.

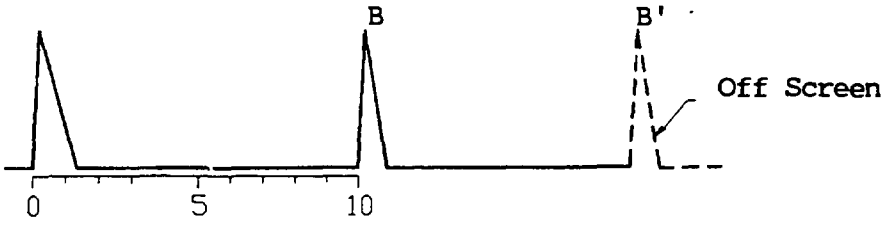


Figure 5.17 (c) : Set peak B to 10 using the delay control. The zero is automatically correct.

5.5.1.2 Using V2 block

The time base calibration for an angle beam probe for range up to 250 mm can be done by one of the following two methods. In both these methods, the probe is moved to and fro until a maximum echo is obtained.

In the first method the probe faces the 25 mm radius quadrant as shown in Figure 5.18 (a). By this method the screen can be calibrated for 100 mm, 175 mm, 200 mm and 250 mm ranges. For 100 mm test range calibration, facing the probe crystal to 25 mm quadrant of V2 block, first echo is obtained from 25 mm quadrant, the same wave is then reflected from probe index towards 50 mm quadrant. This wave is reflected back to the probe crystal which is not received by the crystal due to the orientation of the crystal as it is towards 25 mm quadrant. Again it is reflected to the 25 mm quadrant, this reflected wave from 25 mm quadrant is received by the crystal. The echo obtained now is at 100 mm on CRT, which means that after first echo obtained

at 25 mm on CRT the other multiple echoes will be obtained at an interval of 75 mm. The echo pattern for a 200 mm range is as shown in Figure 5.18 (b). The echoes appear at 25 mm, 100 mm, and 175 mm. For a 250 mm range the echoes appear at 25 mm, 100 mm, 175 mm and 250 mm.

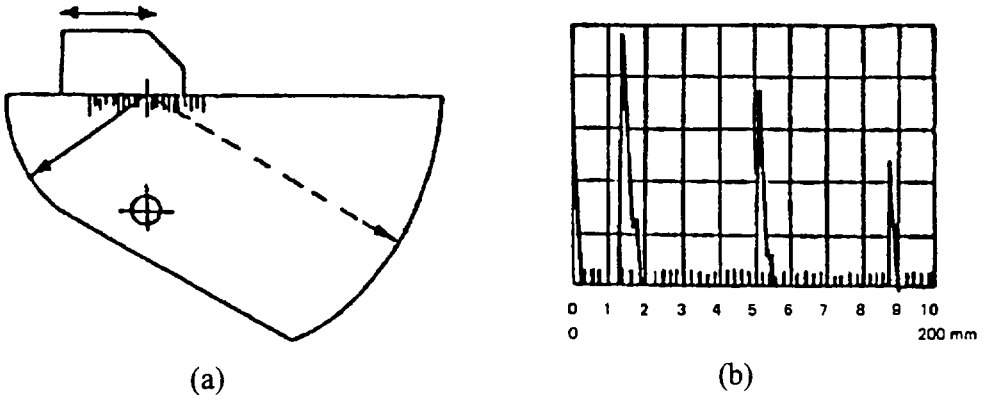


Figure 5.18 (a & b) : Calibration of time base up to 200 mm using V2 block and angle probe facing the 25 mm quadrant.

In the second method the probe faces the 50 mm radius quadrant as shown in Figure 5.19 (a). The CRT screen in this case can be calibrated for ranges of 125 mm and 200 mm. The CRT screen pattern for a 200 mm range is as illustrated in Figure 5.19 (b). The echoes appear at 50 mm, 125 mm and 200 mm.

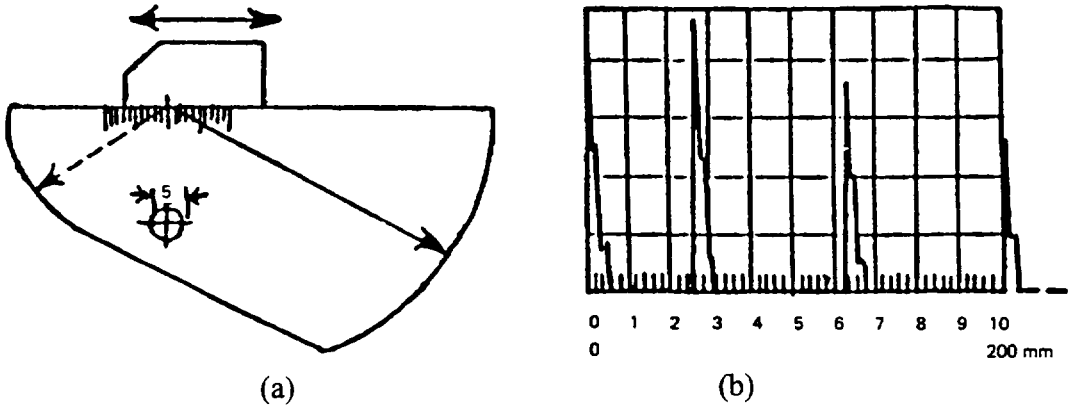


Figure 5.19 (a & b) : Calibration of time base up to 200 mm using V2 block and angle probe facing the 50 mm quadrant.

In this method the echo from the 50 mm quadrant is set at 10th scale division of CRT screen using the sweep control or range control. The probe is then reversed so that the echo from the 25 mm quadrant in obtained. This echo is set at 5th scale division of CRT screen using the delay control. The procedure is repeated until the echoes from 25 mm and 50 mm quadrants respectively coincide with 5 and 10 scale divisions of CRT. The calibration for 50 mm range is then said to have been achieved.

5.5.2 *Determination of the probe index*

5.5.2.1 *Using V1 block*

The probe is placed at position L on the calibration block (Figure 5.20) and a backwall echo from the 100 mm quadrant is obtained. The maximum amplitude of this backwall echo is determined by moving the probe to and fro about the position L. When the maximum amplitude is found then the point on the probe which coincides with the point 0 (or cut mark) on the block is the probe index.

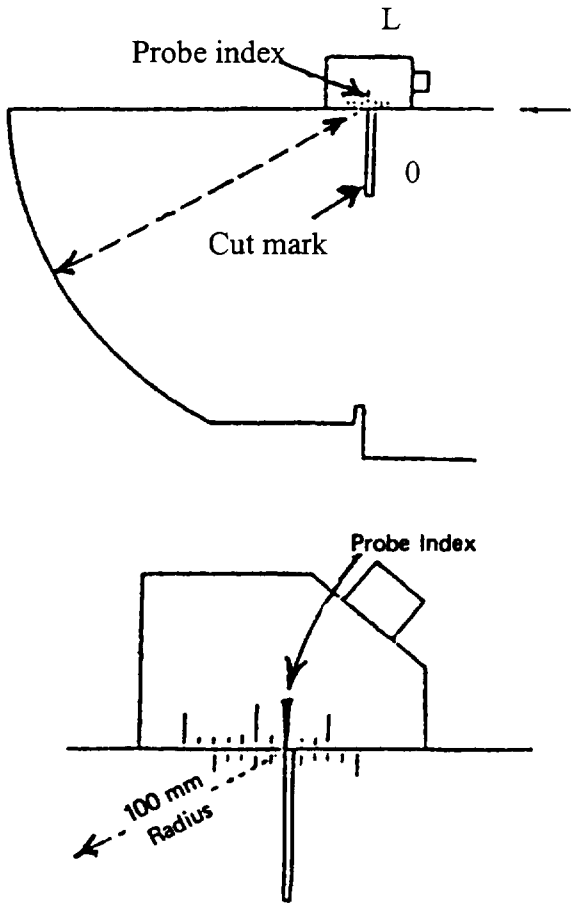


Figure 5.20 : Determination of probe index using V1 block.

5.5.2.2 *Using V2 block*

The probe is placed either facing the 25 mm quadrant or the 50 mm quadrant to obtain echoes at 25 mm or 50 mm on the CRT screen. The probe is moved to and fro to maximize the echo. When the echo amplitude is a maximum, the probe index is obtained by extending the centre mark of the millimetre scale on the block on to the probe.

5.5.3 *Determination and checking the probe angle*

5.5.3.1 *Using V1 block*

To determine the probe angle, the probe is moved to and fro according to its angle either at position "a" (35° to 60°), "b" (60° to 75°) or "c" (75 ° to 80°) as shown in Figure 5.21 until the

amplitude of the echo from the perspex insert or 1.5 mm diameter hole is maximum. The angle of the probe is the one at which the index of the probe meets the angle scale on the block when the echo amplitude is maximum.

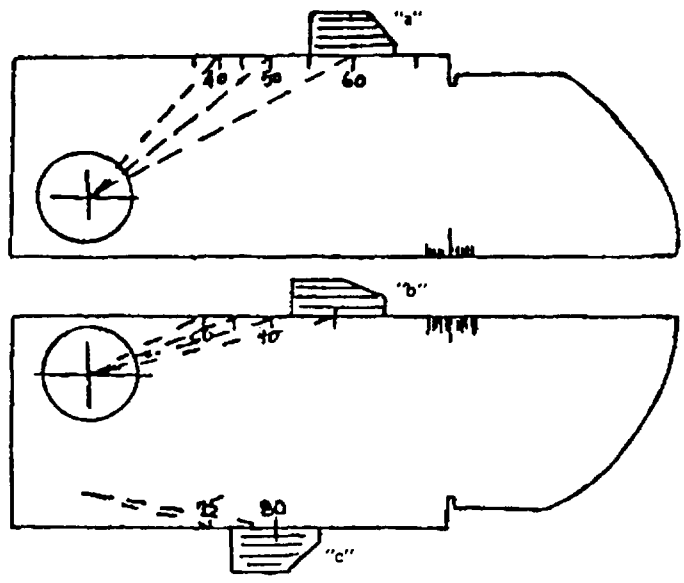


Figure 5.21 : Determination of probe angle using V1 block.

5.5.3.2 *Using V2 block*

To determine the actual probe angle, the probe index is placed against the appropriate probe angle inscribed on the block with the beam directed towards the 5 mm diameter hole (Figure 5.22). The probe is moved to and fro until the echo is a maximum. An estimate of the probe angle is then made by noting the probe index position with respect to the angles inscribed on the block.

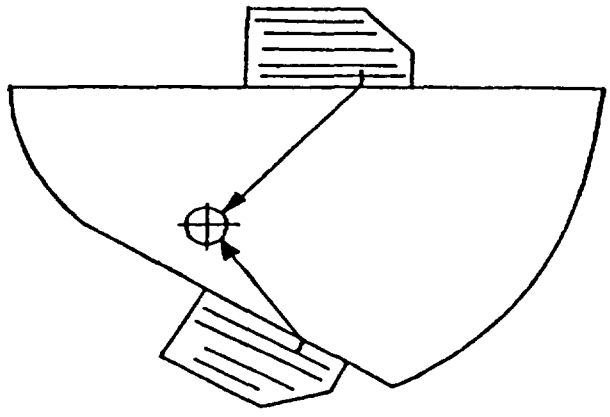


Figure 5.22 : Checking of probe angles using V2 block.

5.6 CALIBRATION IN CURVED WORK PIECES

5.6.1 ***Sensitivity***

Two factors contribute to the reduction in sensitivity when a test specimen with a curved surface is ultrasonically tested. One is the widening or divergence of the transmitted beam because of

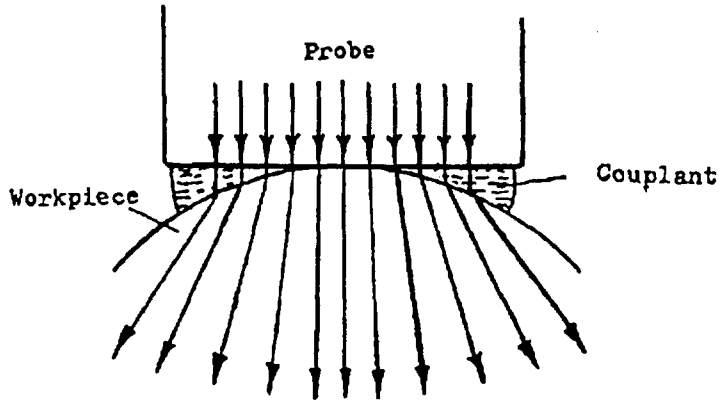


Figure 5.23 : Additional sound beam divergence caused by refraction between couplant and work piece surface.

refraction and the other is the reduction in the contact area between the probe and the test specimen. Both of these effects are shown in Figure 5.23.

The contact area can be increased, and thus the contribution of this factor in reducing sensitivity can be minimized, by the use of an adapter block or shoe. These blocks are made to fit the surface curvature of the test specimen.

5.6.2 Skip distance and beam path length correction

The range calibration for a test with angle probes is usually made with I.I.W V1 calibration block. The skip-distances and beam-path-length respectively are increased by factors 'f_p' and 'f_s', which depend on the probe angle θ and the ratio of wall thickness 'd' to the outside diameter 'D' (i.e. d/D) and can be obtained from Figures 5.24 & 5.25 respectively. The procedure is as follows:

(i) Determine the d/D ratio.

(ii) Draw a line perpendicular to the d/D axis at the value calculated in (i), and determine its point of intersection with the curve of the probe to be used.

(iii) Draw a line parallel to the d/D axis at this point and determine its point of intersection with f_p axis.

(iv) Read the values of factor f_p.

(v) Repeat the above steps for determination of the factor f_s.

(vi) Using the following formulae, calculate P_r and S_r.

$$P_r = f_p \times P_e \quad \text{----------} \quad (5.2)$$

and

$$S_r = f_s \times S_e \quad \text{----------} \quad (5.3)$$

Where P_r is the increased full skip distance for curved surface and it is determined by multiplying the full skip distance in a plate of same thickness, P_e ,with the factor f_p, and S_r is the increased beam path length, i.e. range due to surface curvature, and S_r is obtained by multiplying the beam path length, S_e, in a flat material of the same thickness with the factor f_s. Figure 5.26 illustrates the concepts.

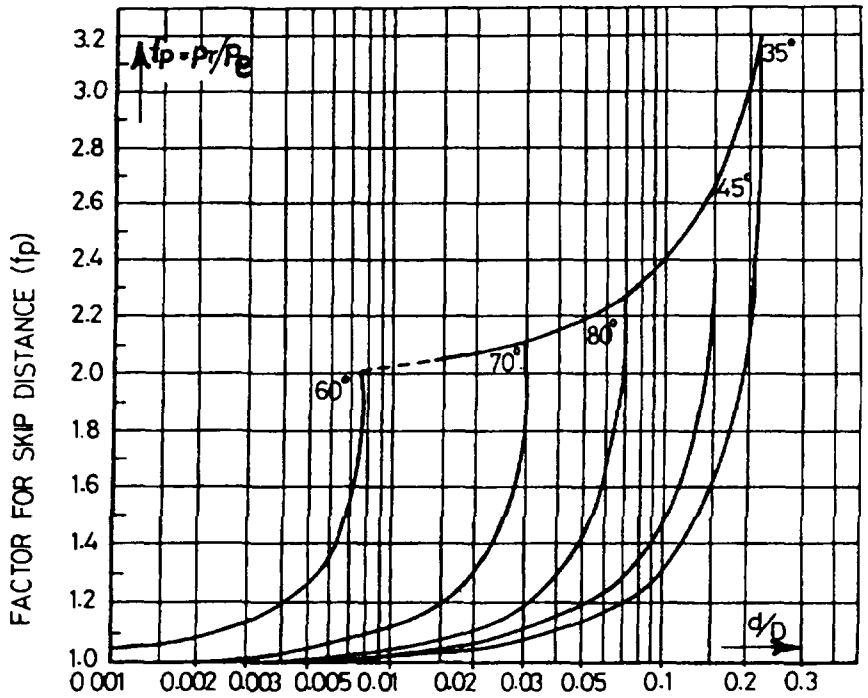


Figure 5.24 : Skip distance multiplying factor for pipes and curved surfaces.

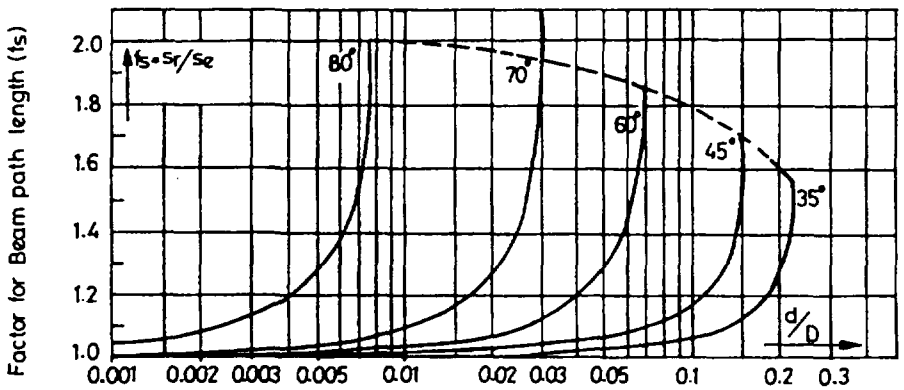


Figure 5.25 : Beam path multiplying factor for pipes and curved surfaces.

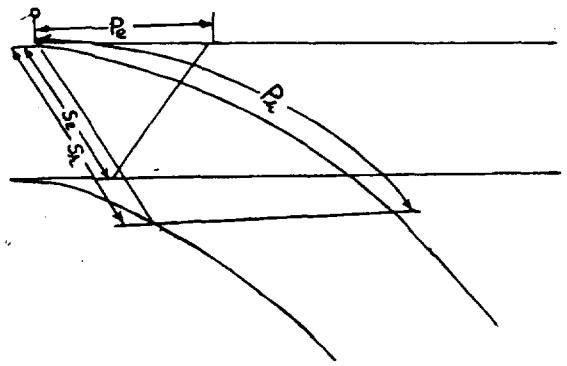


Figure 5.26 : Correction for curved surfaces.

5.7 CONSTRUCTION OF DAC USING REFERENCE BLOCKS

Distance Amplitude Correction (DAC) curves are produced using a reference block with a side drilled hole as a reference in the case of angle beam probes and flat bottom holes in series of blocks as references for normal probes. The ASME code uses this method to set PRE level sensitivity.

The primary reference is set for an angle probe by adjusting the signal from the drilled reference target, scanned from a beam path length just into the far field to an amplitude of 75% of full screen height and marking the position of the echo peak on the CRT screen. The probe position is as shown position 1 in Figure 5.27 and the screen presentation is as shown in Figure 5.28. The probe is then moved to other locations (positions 2, 3, and 4, in Figure 5.27) and the signal amplitude is marked on the CRT for each position (Figure 5.28). A curve is drawn joining these points. This is the Distance Amplitude Correction (DAC) curve. This line, represents the reference level at various depths in the specimen. Lines may also be drawn at 50% or 20% of this reference level. Transfer loss is then calculated between the reference block and the work piece as in Section 2.8.2. and is added to the DAC gain. For initial scanning the sensitivity is then set at twice (i.e. +6 dB) the primary reference level plus transfer loss. The evaluation of flaws for acceptance or rejection is however carried out with the gain control set at the PRE level plus the transfer loss.

The transfer loss may also be determined by another method by noting the difference between the response received from the reference reflector in the basic calibration block and the same reflector drilled in the test specimen.

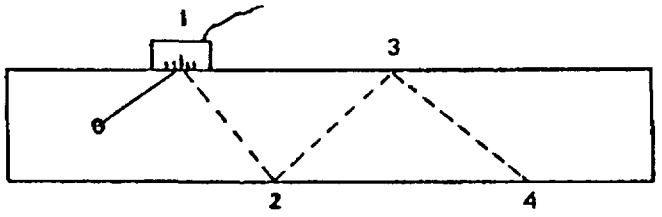


Figure 5.27 : Different probe positions on basic calibration block for drawing DAC curve with angle probes.

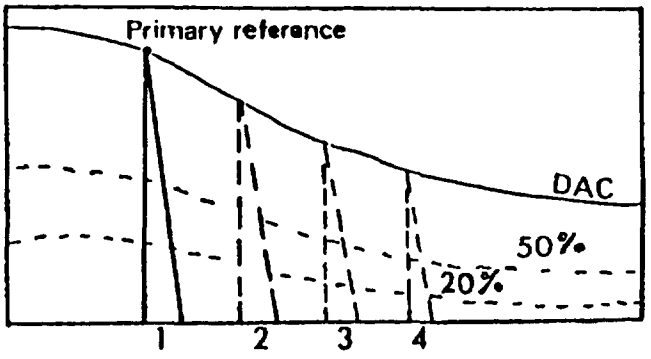


Figure 5.28 : CRT screen presentation for 100%, 50% and 20% DAC.

For normal beam probes the distance amplitude correction curve need not be constructed when the thickness of material is less than 2 inches (50 mm). This correction is only needed for thicknesses greater than 2 inches (50 mm). To construct the DAC curve, the maximized echo height from the drilled hole at 1/4 T distance is set to 50% of full screen height and is taken as the PRE level. Without changing the gain set for the PRE, the probe is positioned for maximum

response from the drilled hole at 3/4 T distance, Figure 5.29 (a). The heights of the PRE and the maximized echo at 3/4 T distance are marked on the CRT screen. The required DAC is obtained by joining these two points with a straight line and extending the line to cover the required testing range as shown in Figure 5.29 (b).

The scanning sensitivity level for normal beam probes, if possible, is then set at twice the PRE level, i.e. the gain control of the flaw detector is set at PRE level gain value plus 6 dB. The evaluation of flaws is, however, carried out at the PRE level gain setting plus transfer loss and attenuation correction.

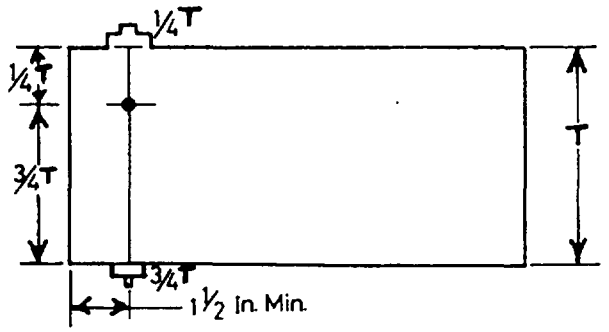


Figure 5.29 (a) : Probe positions for 1/4 T and 3/4 T.

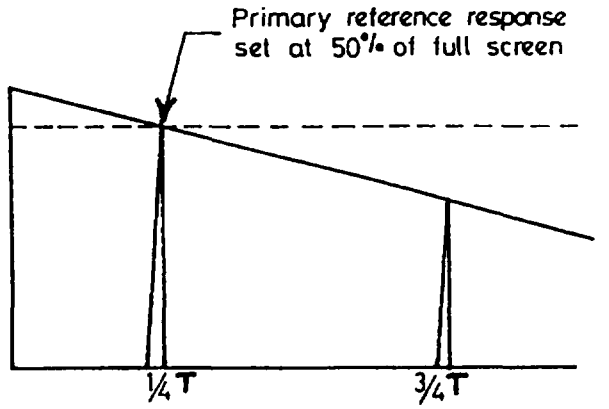


Figure 5.29 (b) : CRT screen presentation for 1/4 T and 3/4 T positions.

5.8 DGS (DISTANCE-GAIN-SIZE) DIAGRAM

Another method which is used to set the sensitivity, i.e. adjusting the gain control of the ultrasonic flaw detection system for testing, is the DGS diagram method. This method makes use of the so-called DGS diagrams, developed by Krautkrämer in 1958.

From a study of the geometry and intensity distribution of a sound beam, following facts can be concluded:

(i) For small reflectors the amount of sound energy reflected back to the probe is a ratio of the reflector area and the cross-sectional area of the sound beam at the location of the reflector. The maximum echo amplitude occurs at one near field length because of focusing of the sound beam. For distances shorter than one near field length the echo amplitudes decrease slightly.

(ii) In the far field and for large reflectors, such as a backwall, the echo amplitude is inversely proportional to the distance from the probe. If the distance is doubled, the echo amplitude decreases by 50%, i.e. -6 dB.

(iii) For small reflectors, such as small inclusions, blowholes and flat bottom holes in the far field, the echo amplitude is inversely proportional to square of the distance from the probe. If the distance is doubled, the echo amplitude is reduced to 25% or by -12 dB.

(iv) For small reflectors in the far field, the echo amplitude also depends upon the area of the reflecting surface and is proportional to the square of the diameter of the reflecting surface, such as a flat bottom hole. If the diameter is doubled, the echo amplitude is increased by four times or by +12 dB.

It is on the basis of these facts that DGS diagrams are drawn by comparing the echoes from small reflectors, namely different diameter flat bottom holes located at various distances from the probe, with the echo of a large reflector such as a backwall, also at different distances from the probe. A typical diagram which can be used for any normal probe irrespective of its size and frequency, and any material is shown in Figure 5.30.

The horizontal scale gives the distance (D) in near field lengths of the sound beam in the subject material. Usually normalized value of D is used which is defined as:

$$D = \frac{s}{N} \qquad \text{----------} \qquad (5.4)$$

where, s = real distance in mm
N = near field length in mm

For a given combination of probe and the test material the value of N can be calculated using equations in Section 2.7.1.2. These are indicated on a logarithmic scale and have values from 0.1 to 100, etc. The vertical scale represents the gain (G) or attenuator values measured in dB. In the diagram these range from 0 to 60 dB. The curves show the echo amplitudes from various sizes (S) of the flat bottom hole reflectors. To make the diagram independent of the diameter of the probe the values of the disc reflector curves are normalized as given below:

$$S = \frac{d}{D_{eff}} \qquad \text{----------} \qquad (5.5)$$

where, S = normalized reflector size
d = real disc reflector diameter in mm
D_{eff} = effective crystal diameter in mm

In the diagram different curves having values of S ranging from 0.05 to 2.0 are given. The last curve on the top showing an infinite value of S represents the backwall.

Since in the case of angle beam probes some of the near field length is contained within the perspex path length and this varies for different designs and sizes of probe, individual DGS diagrams are drawn for each design, size and frequency of angle beam probe. For this reason the scale used in the angle beam probe DGS diagrams is simplified: the D-scale is calibrated in beam path lengths, the G-scale in decibels as before; and the S-scale representing flat bottom hole or disc shaped reflector diameters in mm. Figure 5.31 shows a typical DGS diagram for a particular angle beam probe.

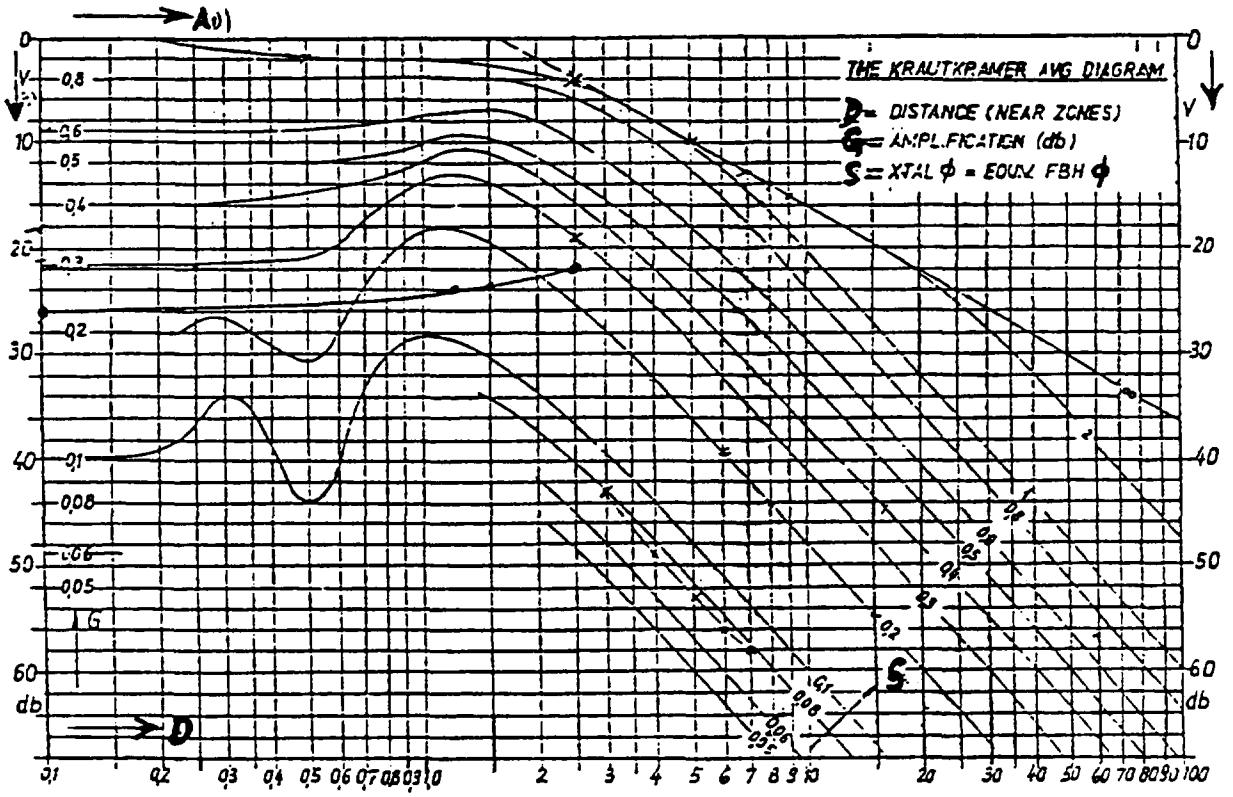


Figure 5.30 : Universal DGS diagram for normal probes.

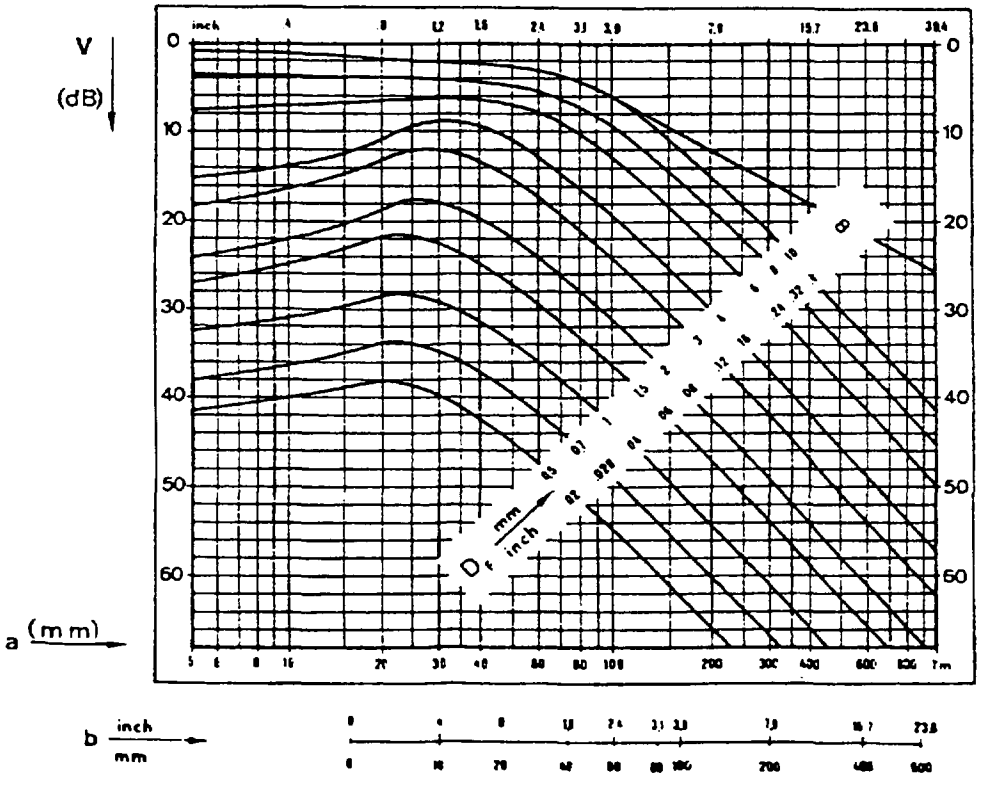


Figure 5.31 : Typical DGS diagram for an angle beam probe.

5.9 COUPLING MEDIUM

Proper coupling medium or couplant should be used between the probe and the test specimen to improve the transmission of ultrasonic energy by eliminating air between the two. Commonly used couplants in ultrasonic testing are glycerine, water, oils, petroleum greases, silicon grease, wall-paper paste and various commercial paste like substances. For the selection of a suitable couplant for a particular ultrasonic inspection task the following points should be taken into consideration:

(i) Surface finish of the test specimen.

(ii) Temperature of the test specimen.

(iii) Possibility of chemical reaction between the test specimen and the couplant.

(iv) Cleaning requirements (some couplants are difficult to remove).

Figure 5.32 shows a comparison of different couplants. This comparison is made by the experimental arrangement shown in the figure. It is obvious from this figure that couplant used during calibration of the equipment and during the testing of the test specimen should be of same type for reliable results. The figure shows the variation of echo amplitude with variations in surface roughness and for different types of couplants. Similar studies can be undertaken for other variables such as temperature of the test surfaces. A simple comparison for the efficiency of coupling between a test block and the test specimen can be made by measuring the echo heights in dB respectively on each using the same couplant.

Water is a suitable couplant for use on a relatively smooth surface; however, a wetting agent should be added. It is sometimes appropriate to add glycerine to increase viscosity; however, glycerine tends to induce corrosion in aluminium and therefore is not recommended in aerospace applications.

Heavy oil or grease should be used on hot or vertical surfaces or on rough surfaces where irregularities need to be filled.

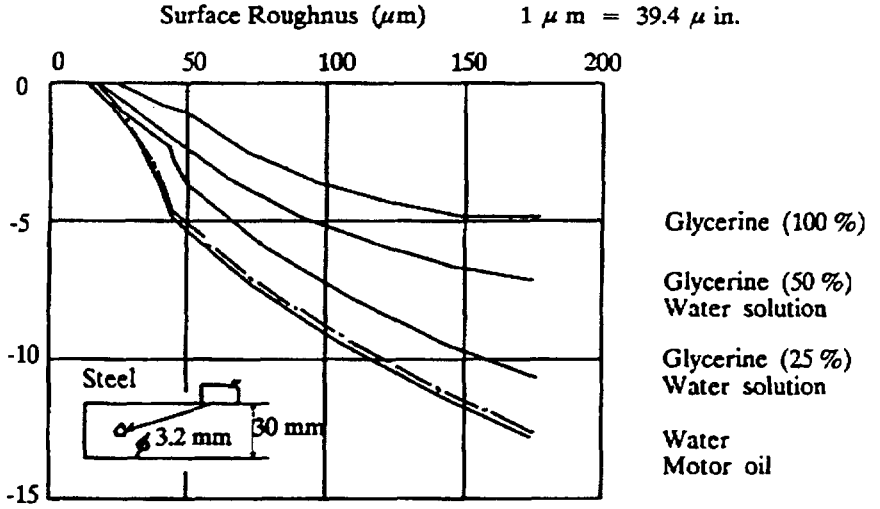


Figure 5.32: Variations of signal amplitude with types of couplants and different surface roughness.

Wallpaper paste is especially useful on rough surfaces when good coupling is needed to minimize background noise and yield an adequate signal-to-noise ratio.

Water is not a good couplant to use with carbon steel test pieces, because it can promote surface corrosion. Oils, greases, and proprietary pastes of a non-corrosive nature can be used. Heavy oil, grease, or wallpaper paste may not be good choices when water will suffice, because these substances are more difficult to remove. Wallpaper paste like some proprietary couplants, will harden and may flake off if allowed to stand exposed to air. When dry and hard, wallpaper paste can be easily removed by blasting or wire brushing. Oil or grease often must be removed with solvents.

Couplants used in contact inspection should be applied as a uniform, thin coating to obtain uniform and consistent inspection results. The necessity for a couplant is one of the drawbacks of ultrasonic inspection and may be a limitation, such as with high temperature surfaces. When the size and shape of the part being inspected permit, immersion inspection is often done. This practice satisfies the requirement for uniform coupling.

6. SPECIFIC APPLICATIONS

6.1 METHODS OF EXAMINATION

6.1.1 Cast work pieces

The defects in materials which occur during casting are piping (shrinkage), cavities or porosities, segregation, coarse grain structure, non-metallic inclusions and cracks.

Piping takes place during the solidification of an ingot. The outer layers are the first to solidify. During this time the liquid metal collects at the top of the ingot where after solidification is complete, a funnel-shaped cavity may appear due to the shrinkage. The shrinkage cavity will be either open or closed and, under certain circumstances, secondary cavities may be found.

The material of an ingot may not be homogeneous. Any variation in composition which arises during solidification is called segregation.

One type of segregation is gravitational, being caused by the separation in the upper part of the ingot of impurities having a lower temperature of solidification and a different density from the surrounding metal. This type of segregation consists primarily of sulphur or phosphorus.

A coarse grained structure may result when the pouring temperature is high and cooling takes place slowly. This sometimes makes it impossible to use ultrasonics because of the high attenuation in the material.

Gases dissolved in steel separate out when solidification occurs since their solubility in liquid metal decreases rapidly at this stage. If the gas content is high, gas cavities are often trapped under the surface or in the interior of the ingot.

Non-metallic inclusions, such as slag or refractories from the steel making process, find their way into the metal during melting or casting and are quite frequently the ultimate cause of fatigue cracks. Longitudinal or transverse cracks may appear during solidification, depending on

the method of construction of the mould, its temperature, the composition of the steel and the temperature of the melt.

In castings flaw detection almost exclusively concerns manufacturing defects such as shrinkage cavities, blow holes, inclusions (usually sand or slag) and cracks (caused by internal stresses during cooling while metal is already solidified).

Pure segregations are very rarely detected and then only by indirect means. Castings are seldom checked for fatigue cracks but, if required, the testing technique is similar to that used for forgings.

Basically, the demand made for the absence of flaws in the testing of castings cannot be as high as for worked components because the small shrinkage cavities and pores which are always present, produce some "grass" and small individual echoes even at low frequencies.

Both shear and compression wave techniques are widely used for the examination of castings. Because the grain structure has an appreciable effect on the attenuation of ultrasonic waves, the test frequencies used in the examination of castings tend to be lower as compared to the frequencies used for the testing of other products. Frequencies of 1.25 MHz to 2.5 MHz are common and occasionally it is necessary to drop to 0.5 MHz in order to penetrate to the far boundary. The most commonly used probes are compression wave (single and twin crystal) and shear wave probes of 45°, 60° and 70°. The ultrasonic flaw detector used for the inspection of castings should therefore cover the frequency range 0.5 MHz to 6 MHz and when used with the probes selected for the job should have good resolution and penetration characteristics.

Penetration characteristics are assessed by placing compression wave probe on the perspex insert of the V1 block, setting gain controls to maximum and counting the number of back wall echoes. A result having two to four back wall echoes indicates a low penetrating power for testing work, and six to ten back wall echoes indicates a reasonably high penetrating power.

In the following some common defects in castings along with the techniques commonly used for their detection are discussed.

6.1.1.1 Shrinkage defects

Shrinkage defects are cavities formed during solidification and are formed during liquid to solid contraction. These defects are normally associated with gas, and a high gas content will magnify their extent.

Typical locations at which shrinkage cavities are most likely to occur are shown in Figure 6.1. Where there is a localized change of section thickness, a hot spot will occur which cannot be adequately fed. This will lead to shrinkage cavitation and should, therefore, be avoided if at all possible. Acute angle junctions (V, X or Y) are least satisfactory and T or L junctions are less of a problem.

Shrinkage defects in steel castings can be considered as falling into three types, namely: Macro-shrinkage, Filamentary shrinkage, and Micro-shrinkage.

(a) Macro-shrinkage

Macro-shrinkage is a large cavity formed during solidification. The most common type of this defect is piping which occurs due to an inadequate supply of feed metal. In good design, piping

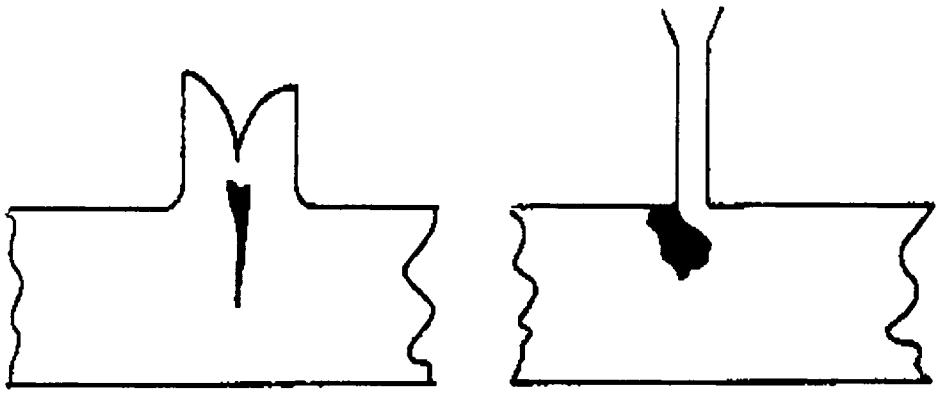


Figure 6.1 : Typical locations for shrinkage cavities.

is restricted to the feeder head. The technique used to detect this defect depends on the casting section thickness.

For sections greater than 75 mm thick, a single crystal compression wave probe can be used, whilst for thickness below 75 mm it is advisable to use a twin crystal probe.

The presence of a defect is shown by a complete loss of back wall echo together with the appearance of a new defect echo. An angle probe should be used to confirm the information gained from the compression wave probe (Figure 6.2).

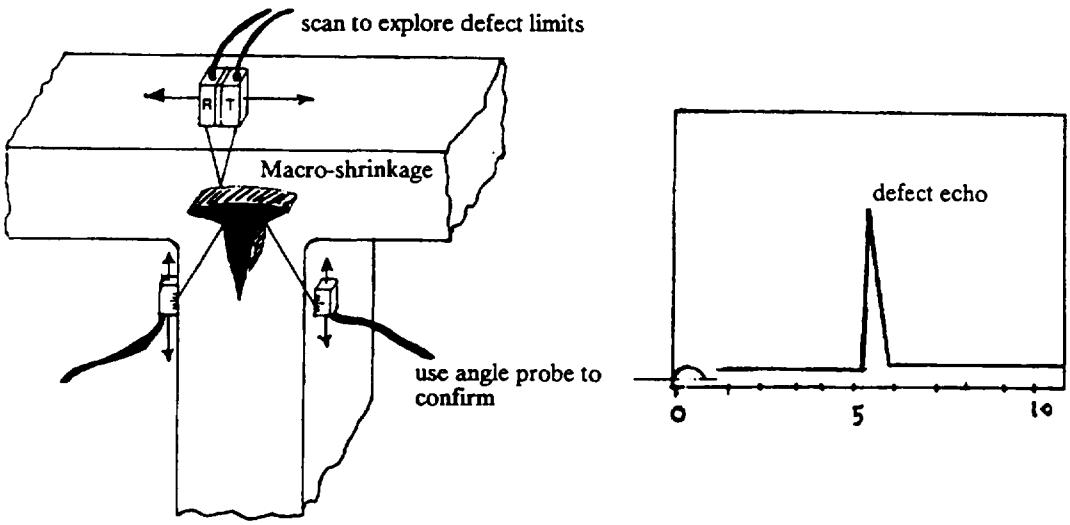


Figure 6.2 : Typical probe positions for testing of casting for macro-shrinkage.

(b) Filamentary shrinkage

This is a coarse form of shrinkage, but of smaller physical dimensions than a macro-shrinkage cavity. The cavities may often be extensive, branching and interconnected.

Theoretically filamentary shrinkage should occur along the centre line of the section, but this is not always the case and on some occasions it extends to the casting surface. This extension to the casting surface may be assisted by the presence of pinholes or wormholes. Filamentary

shrinkage can best be detected with a combined double probe if the section is less than 75 mm thick. Defect echoes tend to be more ragged in outline than for macro-shrinkage. The initial scan should be carried out with a large diameter (20-25 mm) probe and the final assessment with a smaller (10-15 mm) diameter probe (Figure 6.3).

(c) Micro-shrinkage

This is a very fine form of filamentary shrinkage due to shrinkage or gas evolution during solidification. The cavities occur either at the grain boundaries (inter-crystalline shrinkage), or between the dendrite arms (interdendritic shrinkage).

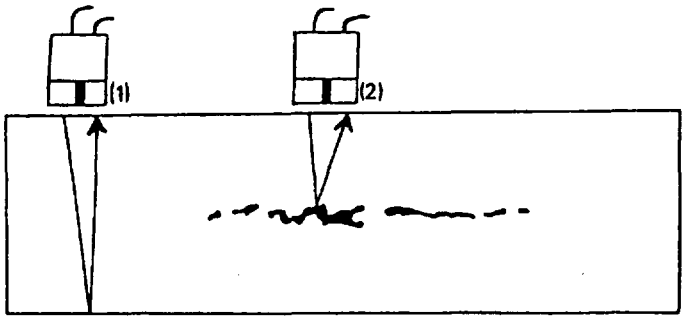


Figure 6.3 : Double probe scanning of cast iron for filamentary shrinkage.

Using a compression wave probe technique, the indications on the CRT screen from micro-shrinkage tend to be grass-like, that is, a group of relatively small poorly resolved echoes extending over some portion of the time base (Figure 6.4). The existence of a backwall echo in the presence of a defect echo will be to some extent dependent on the frequency chosen. For instance there may be no back wall echo when using a 4-5 MHz probe due to scattering of the beam. This might suggest a large angular type of defect. However, a change to a 1-2 MHz probe may well encourage transmission through the defective region to add a back wall echo to the defect echoes and disproving the large cavity impression.

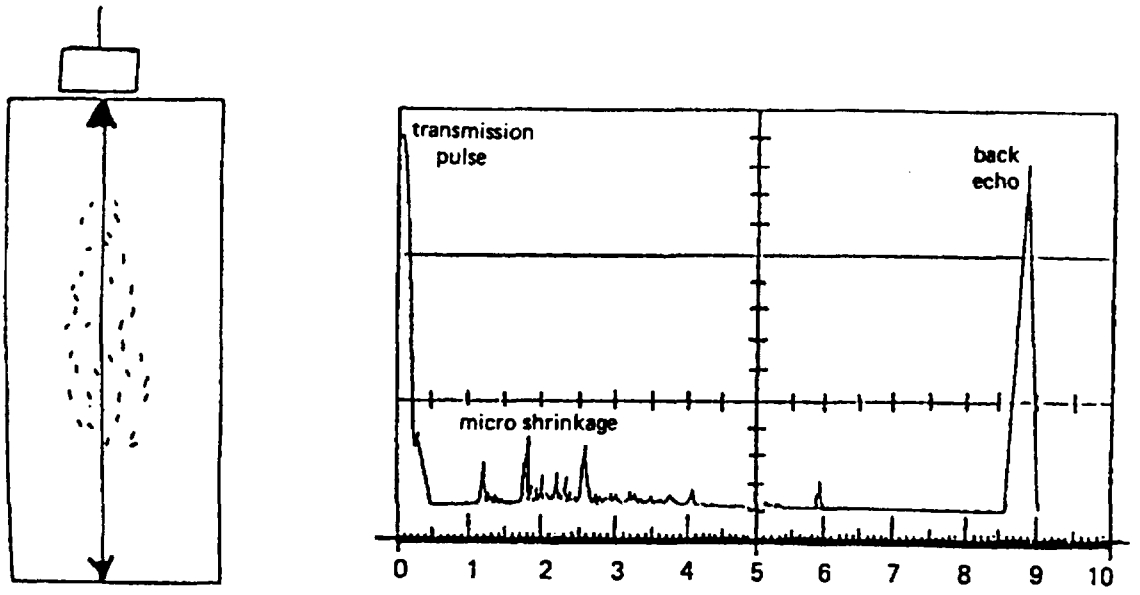


Figure 6.4 : Probe positions and typical CRT appearance for micro-shrinkage.

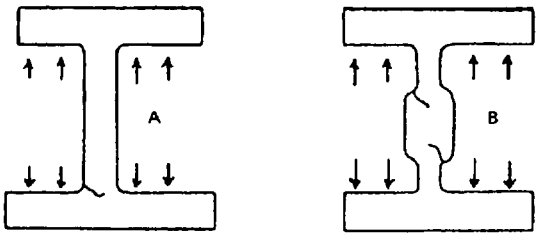
6.1.1.2 Defects associated with hindered contraction during cooling

(a) Hot tears

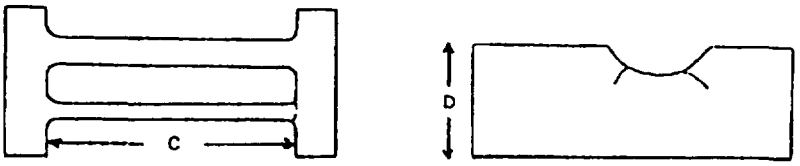
These are cracks which are discontinuous and generally of a ragged form. They are caused by stresses which develop near the solidification temperature when the contraction of the cooling metal is restrained by a mould or core, or by an already solid thinner section. In Figure 6.5 some of the causes and locations of this type of cracking are shown.

(b) Stress cracks

These are well defined, approximately straight cracks which are formed when the metal is completely solid. The location of hot tears or stress cracks can rarely be determined accurately using a compression wave probe because of the orientation of the defects. The most satisfactory technique is to use angled probes. In steel castings, the best way to find cracks or hot tears is by magnetic flaw detection, using ultrasonics to plot the depth of the defect.



Hot tear due to mould resistance along directions A and B.



Hot tear due to casting resistance along length C.

Hot tear due to change in section D.

Figure 6.5 : Hot tears.

6.1.1.3 Defects associated with entrapped gas

(a) Airlocks

When molten metal is poured into a mould, air may be trapped in the metal stream and may appear in the subsequent casting as a cavity or several cavities just below and parallel to the casting surface. They are normally best detected by twin crystal compression wave probes (Figure 6.6).

(b) Gas holes

These defects are discrete cavities, usually greater than 1.5 mm in diameter which are caused by the evolution of dissolved gases from the metal during solidification. A wormhole is the name given to a tubular gas hole which is usually perpendicular to the casting surface. Since gas holes may be close to the surface, twin crystal compression wave probes are the most suitable probes to detect them (Figure 6.7).

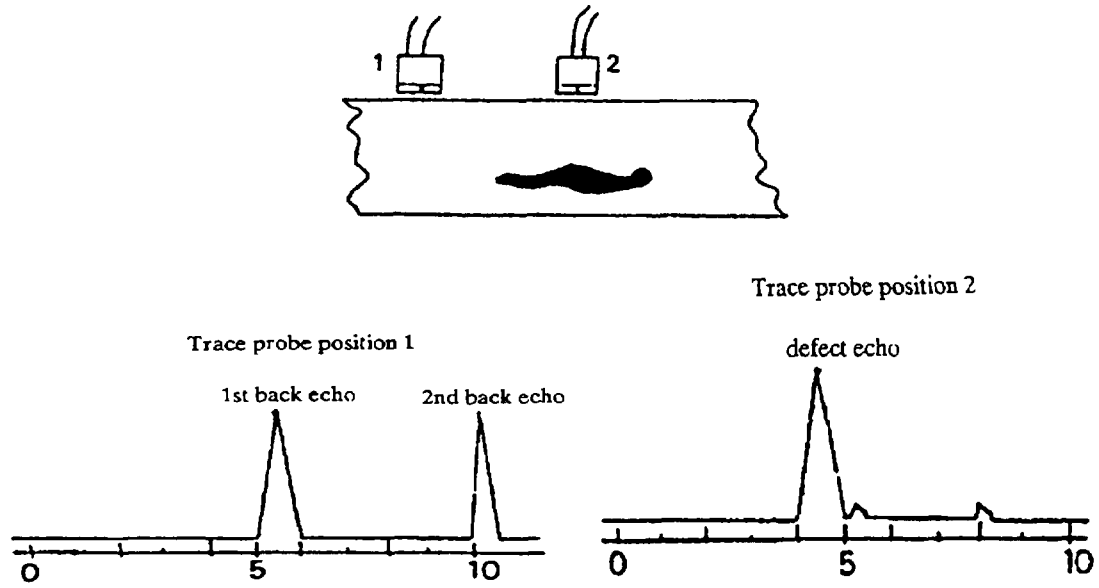


Figure 6.6 : Typical probe positions and resulting CRT screen appearance for testing of air locks.

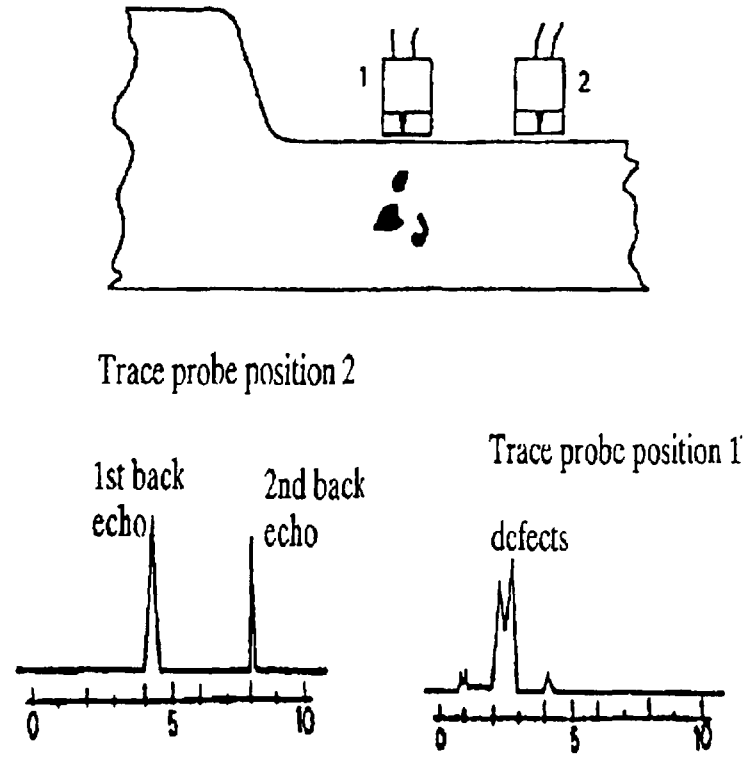


Figure 6.7 : Typical probe positions and CRT screen appearance for detection of gas holes.

6.1.2 Welded work pieces

In the welding process, two pieces of metal are joined together. Molten filler metal from the welding rod blends with the molten parent metal at the prepared fusion faces, and fuses the two pieces together as the weld cools and solidifies. Some of the defects occur because the fusion faces do not melt properly or blend with the filler metal (lack of penetration and lack of fusion defects). Some defects occur because the scale or slag which forms at the top of each pass of the welding, is not chipped away completely before the next pass is made (slag inclusions). Some defects occur because the welding electrode dips into the molten weld and bits of copper or tungsten drop into the weld (dense metal inclusions). Some defects occur in much the same way as casting defects (porosity, piping, wormholes, shrinkage, undercut, etc.). Some defects occur because of the thermal stresses, set up by having part of the component at molten temperature, and the rest of the parent material at much lower temperatures (cracks, tears, etc.).

Many of the defects which can occur in welds do not significantly alter the strength of the weld; others do in varying degrees. However, planar defects (cracks, lack of penetration / fusion) particularly those breaking the surface of the welded joint, give rise to the most severe reductions of weld strength.

6.1.2.1 Types of weld joints

Most welds fall into one of the following categories:

(i) Butt welds

(ii) T-welds

(iii) Nozzle welds

A butt weld is achieved when two plates or pipes of usually equal thicknesses are joined together using any of the weld preparations given in Figure 6.8.

Figure 6.8 shows various weld configurations for butt welds. Figure 6.9 a illustrates the weld preparation for a typical single vee weld and the terms used to describe various parts of the prepared weld area. The same weld after welding is shown in Figure 6.9 b showing the original preparation and the number of passes made to complete the weld.

A T-weld is achieved when two plates are joined at right angle to each other. A T-weld may be fully penetrated (Figure 6.10 a) or only partially penetrated (Figure 6.10 b) by design.

Nozzle welds are those in which one pipe is joined to another as a branch, either at right angle or some other angle. As with T-joints, the weld may be fully or only partially penetrated. The branch may get into the main pipe to let liquids and gases in or out, for instance, or the branch may simply be mounted on to an unperforated pipe, as in the case of a bracing strut in a tubular structure. The two types are shown in Figure 6.11 (a) and (b) in which the shaded portion shows the pipe wall.

Some typical weld preparations for nozzle welds are shown in Figure 6.12. In the diagrams the wall of the main pipe or vessel (called "shell"), and the wall of the branch, stub, or nozzle (called "branch") have been identified.

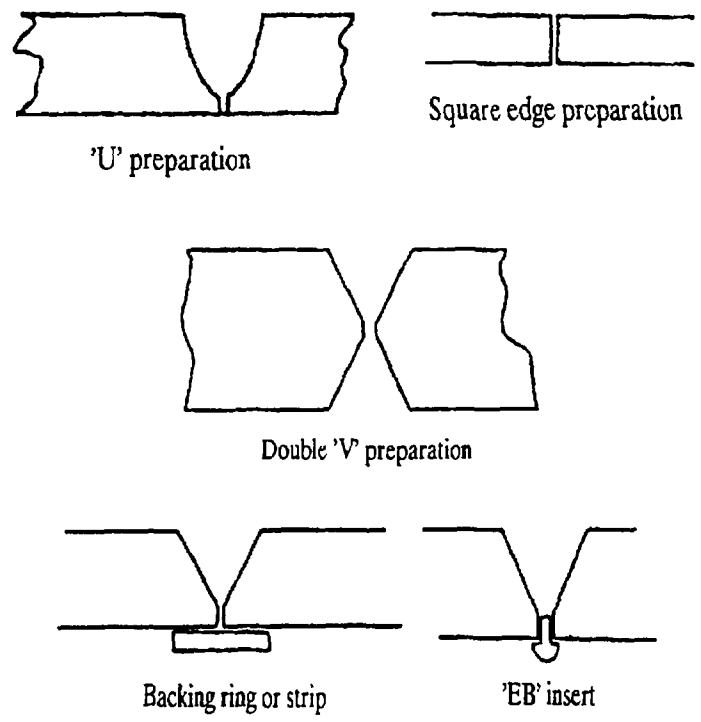


Figure 6.8 : Various weld configurations for butt welds.

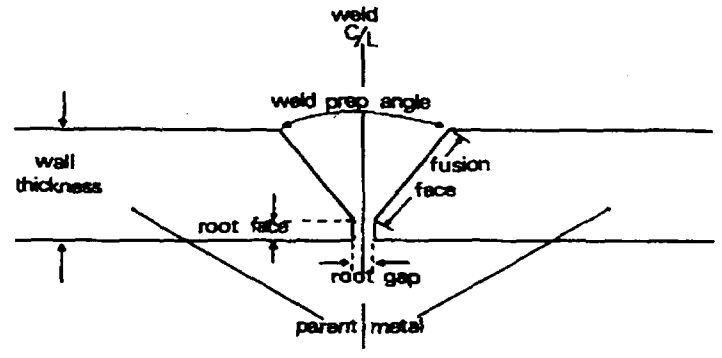


Figure 6.9 a : Terms used to describe various parts of weld area.

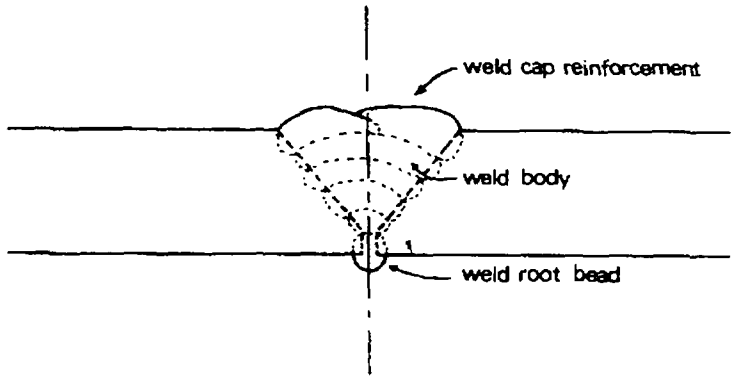


Figure 6.9 b : Original preparation of weld and number of passes made to complete the weld.

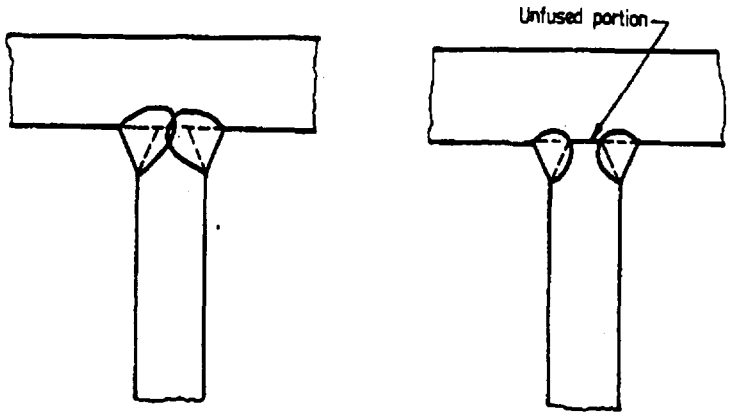


Figure 6.10 : (a) Fully penetrated weld, (b) Partial penetration weld.

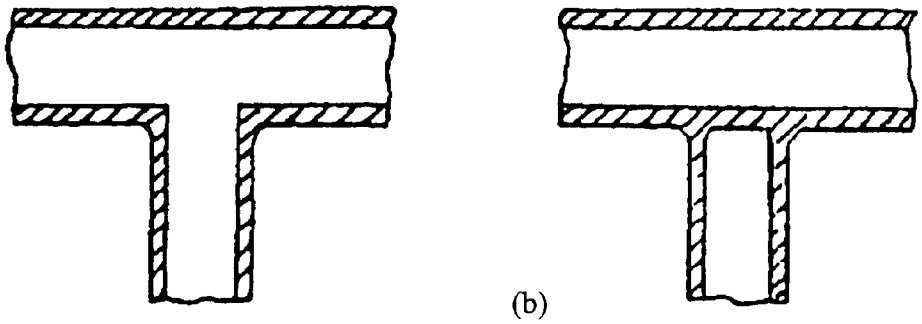


Figure 6.11 : (a) Branch pipe (b) Bracing strut.

6.1.2.2 General procedure for ultrasonic testing of welds

The procedure for the ultrasonic testing of welds outlined below, if adhered to, will result in a speedy and efficient ultrasonic inspection of welds.

(a) Collection of information prior to the testing of weld

The information which has to be collected prior to testing a weld includes the following:

(i) Parent metal specifications.

(ii) Weld joint preparation.

(iii) Welding processes.

(iv) Parent metal thickness adjacent to the weld.

(v) Any special difficulty experienced by the welder during welding.

(vi) Location of any repair welds.

(vii) Acceptance standards.

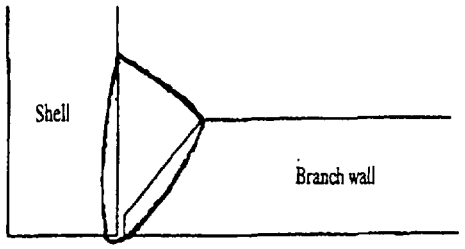


Figure 6.12 a : Fully penetrated "set on" weld.

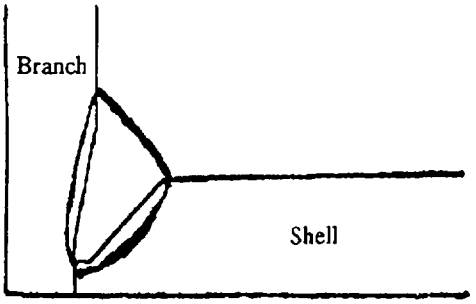


Figure 6.12 b : Partially penetrated "set in" weld.

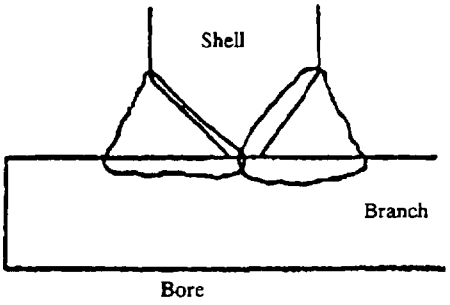


Figure 6.12 c : Fully penetrated "set through" weld.

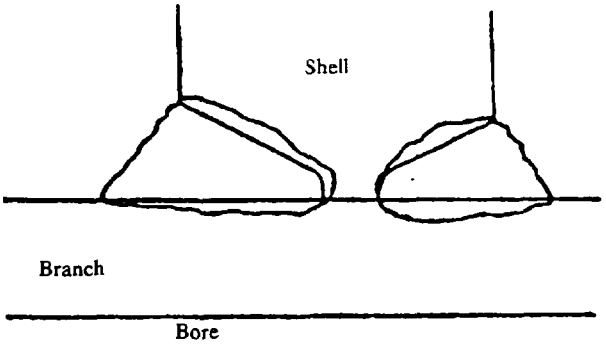


Figure 6.12 d : Partial penetration "set through" weld.

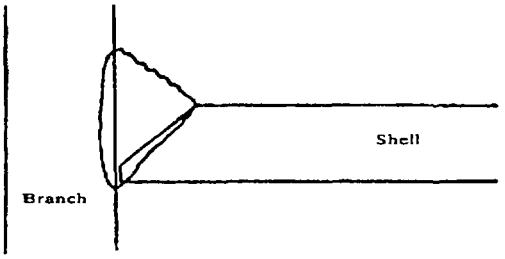


Figure 6.12 e : Structural joint, fully penetrated weld.

(b) Establishment of exact location and size of the weld

To establish the exact location of the centre line of the weld, ideally, the parent metal should be marked on either side of the weld before the commencement of welding. In some cases where the weld reinforcement has been ground flush with the parent material, it may be necessary to etch the weld region to establish the weld width.

The centre line of the weld should be marked accurately on the scanning surface of the weld. For a single vee weld whose reinforcement has been ground flush with the parent metal, the centre line of the weld can be determined by marking the centre point of a normal probe at two or three locations on the weld (Figure 6.13 a) at which a maximum echo is obtained from the weld bead. The line joining these points is then the centre line of the weld. For single vee welds whose weld reinforcement has not been removed an angle beam probe can be used for this purpose, by placing the probe first on one side of the weld (Figure 6.13 b) and marking the probe index on the specimen where the echo from the weld bead is a maximum. On the same side of the weld

two or three such points are obtained. Then the probe is placed on the other side of the weld and the probe index is again marked at different locations when a maximum echo from the weld bead is obtained. The centre points of lines joining these marks are then determined. When these points are joined the centre line of the weld is obtained.

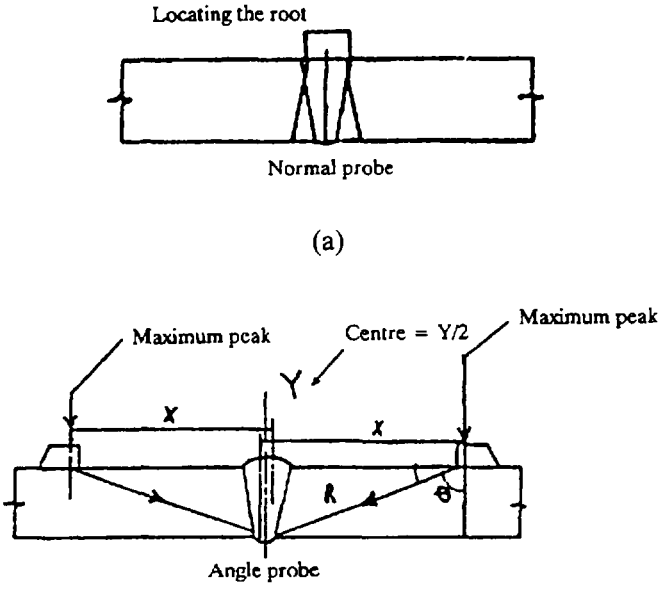


Figure 6.13 : Locating the centre line of the weld.

(c) Visual inspection

A visual check should be carried out prior to the commencement of testing to make sure that the surface is free from weld spatter and smooth enough for scanning. Some defects, e.g. undercut, etc., may show at the surface and be noticed during the visual examination. If these defects are in excess of the acceptance standard, then they should be remedied before carrying out the ultrasonic inspection. This is not always possible.

Other faults, which should be looked for during visual inspection, are misalignment and mismatch (Figure 6.14). These faults may not always adversely affect weld acceptability, but they might interfere with subsequent ultrasonic inspection.

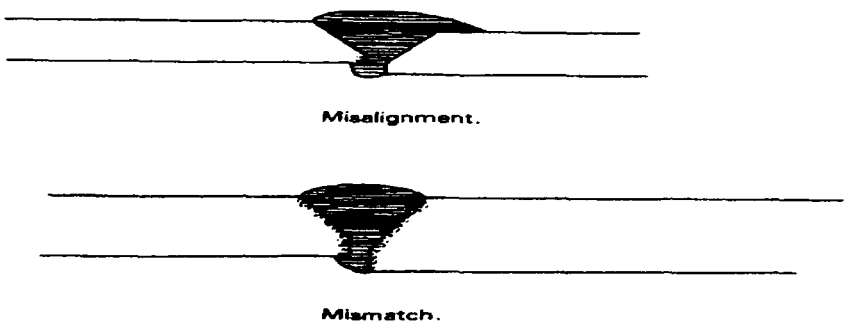


Figure 6.14 : Misalignment and mismatch.

A clue to misalignment is often the widening of the weld cap because the welder tries to disguise this fault by blending the cap with the parent metal on either side.

(d) Parent metal examination

The parent metal should be examined with a normal beam probe to detect any defects such as laminations, etc., which might interfere with the subsequent angle beam probe examination of the weld, and also to assess the thickness of the parent metal.

The examination should be over a band which is greater than the full skip distance for the shallowest angle beam probe (usually 70° probe) to be used, Figure 6.15 illustrates what would happen if a large lamination were present in the parent metal. The presence of a lamination causes the beam to reflect up to the cap giving a signal which might be mistaken for a normal root bead, and at the same time, misses the lack of penetration defect.

For parent metal examination either a single crystal or a twin crystal probe with a frequency that lies between 2 to 6 MHz can be used. The highest frequency in this range is preferred. The setting of sensitivity for this examination should be in accordance with the relevant specification or code of practice.

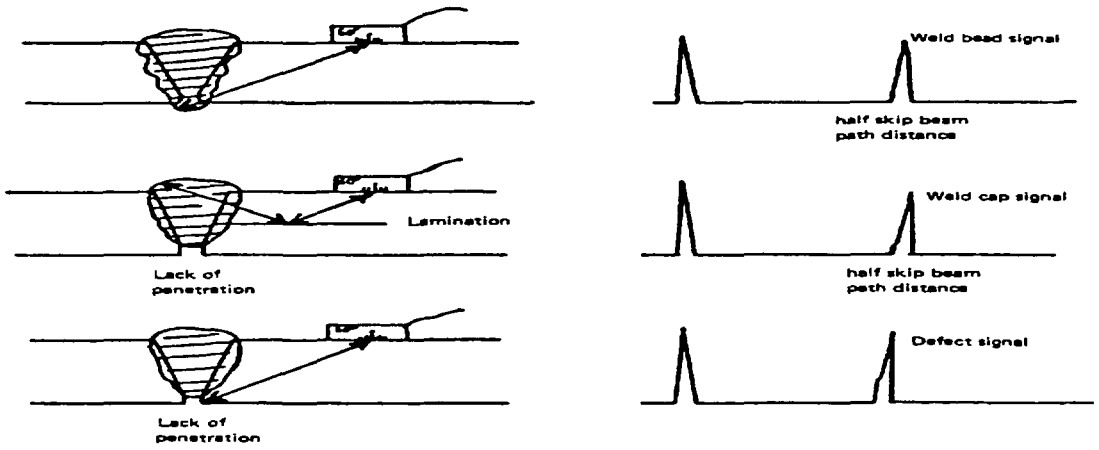


Figure 6.15 : Effect of a large lamination on the ultrasonic examination.

(e) Critical root examination

The next step is to make a careful inspection of the weld root area. This is because it is the root area in which defects are most likely to occur and where their presence is most detrimental. It is also the region in which reflections occur from the weld bead in a good weld and root defect signals will appear very close to the standard bead signal, i.e. it is the region in which the inspector is most likely to be confused. Technical details about the root examination are given in Sections 6.1.2.3 and 6.1.2.6. for single vee and double vee welds respectively.

(f) Weld body examination

After an examination of the weld root, the body of the weld is then examined for defects using suitable angle beam probes. Technical details about the weld body examination are described for each type of weld joint in the subsequent sections.

(g) Examination for transverse cracks

After having examined both the weld root and the weld body the next step is to detect transverse cracks breaking either top or bottom surfaces. Magnetic particle inspection is obviously a quick and effective method for detecting top surface cracks and therefore often ultrasonic inspection is done only to detect cracks breaking the bottom surface. If the weld cap has not been dressed, as in Figure 6.16, this scan is done parallel to the weld centre line

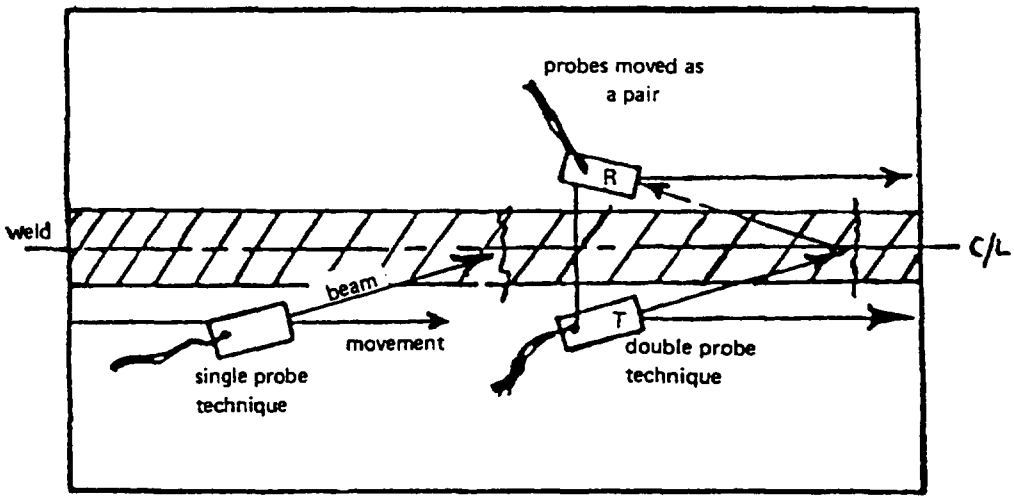


Figure 6.16 : Weld scanning for transverse cracks.

alongside the weld cap with the probe inclined towards the centre. Since a crack tends to have a ragged edge, it is likely that some energy will be reflected back to the transmitter. A safer technique is to use a pair of probes, one transmitting and the other receiving. This is also shown in Figure 6.16. If the weld is dressed, a scan along the weld centre line and several scans parallel to and on either side of the weld centre line, from each direction, are done to give a full coverage of the weld.

(h) Determination of the location, size and nature of the defect

If any defect is found as a result of these examinations the next step is to explore the defect as thoroughly as possible to determine:

i) Its exact location in the weld.

ii) Its size parallel with the weld axis (i.e. length of the defect). For this usually either the 6 dB or 20 dB drop method is used.

iii) Its size through the weld thickness.

(iv) Its nature (slag, porosity, crack, etc.).

(i) Test report

In order that results of ultrasonic examination may be fully assessed, it is necessary that the inspector's findings are systematically recorded. The report should contain details of the work under inspection, the equipment used and the calibration and scanning procedures. Besides the

probe angle, the probe positions and flaw ranges should be recorded in case the results of the report need to be repeated.

6.1.2.3 Examination of root in single vee butt welds without backing strip in plates and pipes

Scanning procedure

The scanning procedure for the examination of the root consists of the following steps:

(a) Selection of probe angle.

(b) Calibration of time base on I.I.W V1 or V2 block for a suitable range. For parent metal thicknesses up to about 30 mm, a time base range of 100 mm is suitable.

(c) Determination of the correct probe angle using I.I.W V1 or V2 block.

(d) Marking the probe index on the probe using I.I.W V1 or V2 block.

(e) Calculation of 1/2 skip distance and 1/2 skip beam path length (1/2 skip BPL) for the selected probe.

(f) Marking of the scan lines at 1/2 skip distance from the weld centre line on both sides of weld (Figure 6.17 a).

(g) Setting the gain sensitivity for scanning and evaluation.

(h) A scan is made by moving the probe slowly from one end of the specimen to the other, so that the probe index always coincides with the scan line. To this end a guide is placed behind the probe in such a way that when the heel of the probe is butted to the guide, the probe index is on the scanning line (Figure 6.17 b). Flexible magnetic strips are very useful for this purpose. Areas with echoes from defects are marked on the specimen for subsequent examination to establish the nature and size of the defects.

(i) With the probe index on the scanning line, a lack of penetration echo will occur at the half skip beam path range. If the weld is a good one, a root bead echo will occur at a small distance (depending on how big the weld bead is) away from the anticipated spot for a lack of penetration echo (Figure 6.18 a). If there is some root shrinkage or undercut, the echo from these defects will occur at a slightly shorter range than the critical range (Figure 6.18 b).

(j) In addition, to determine whether an echo occurring during the root scan is due to lack of penetration, root undercut, root shrinkage, or root bead, the following points should also be taken into consideration:

  (i) Since lack of penetration is a good corner reflector, the echo from it is quite big compared to an echo from root undercut or root shrinkage.

  (ii) With a lack of penetration echo there will be no weld bead echo, whereas with root undercut and root shrinkage, there almost always is.

(iii) The echoes from root undercut and root shrinkage maximize when the probe is moved backwards from the scanning line.

(iv) If the weld bead echo varies a lot in amplitude and position, then there is a great probability of defects in the root area.

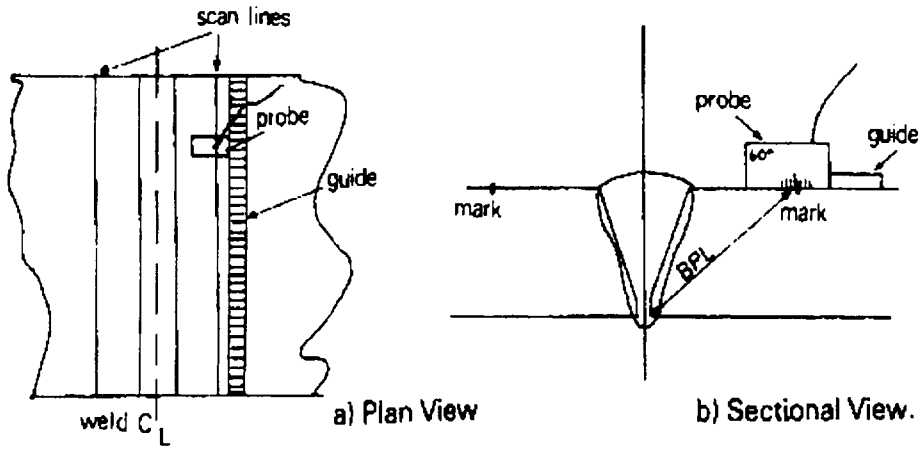


Figure 6.17 : Scan procedure for root of single vee butt weld.

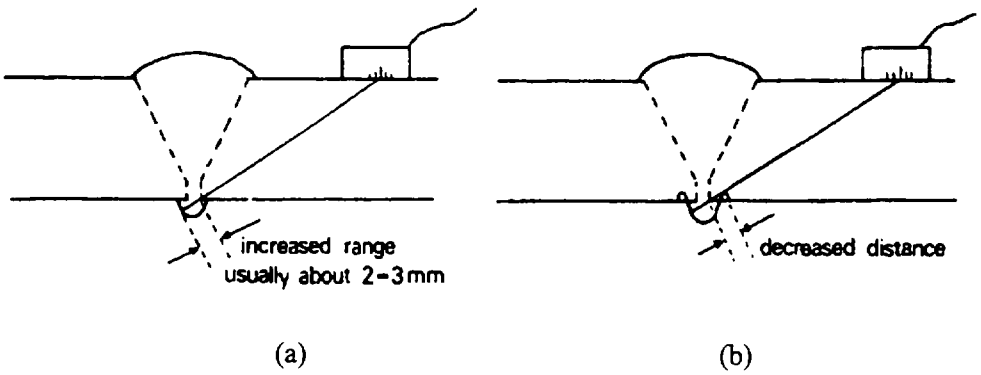


Figure 6.18 : Root scanning; (a) for a good weld, (b) for root shrinkage.

(k) After having carefully examined the root, probing from one side of the weld centre line, a second scan is similarly done from the other side of the weld centre line to confirm the findings of the first scan. In addition, the second scan will also help in interpreting two other types of defects in the root area. The first one of these is shown in Figure 6.19. It is a small slag inclusion or gas just above the root.

This defect might appear just short of the half skip beam path length when doing scan 1, leading to the guess that it might be root undercut or root shrinkage. If this were so scan 2 should put it just further than the critical range. But in fact the inclusion will show about the same place, i.e. just short again. Furthermore, from undercut the echo is expected to maximize when the probe is moved backwards in scan 1, but in the same scan the echo from the inclusion will maximize when the probe is moved forward. The echo from the inclusion will also maximize when the probe is moved forward in scan 2.

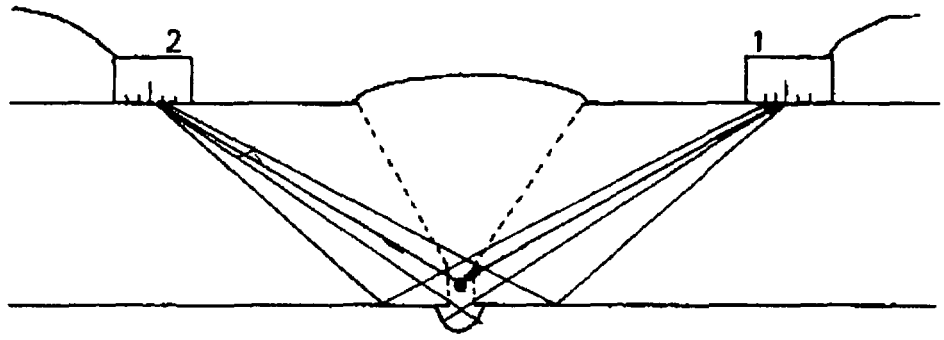


Figure 6.19 : Root scanning for defects just above the root.

The second defect mentioned above is shown in Figure 6.20. This shows a crack starting from the edge of the root bead. From side 1 a large echo will appear just where the echo from undercut is expected and there will be no accompanying bead echo. From side 2, however, it is possible to get a bead echo as well as the defect echo.

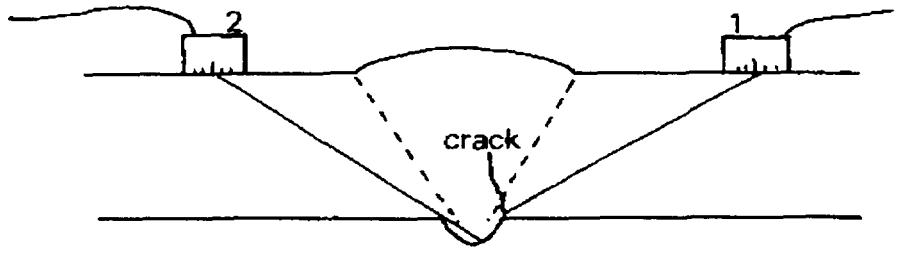


Figure 6.20 : Scanning for a defect starting from the edge of the root bead.

Selection of the angle probe

Angle probe selection is a matter of compromise to obtain the maximum information from any examination, in the minimum time. Use as high a frequency probe as is practicable. In selecting the probe for the particular work in hand, take into account the following factors:

(a) Surface condition: A lower frequency is better on a rough surface from the point of view of coupling efficiency.

(b) Curved surface: small probes do not rock to the same extent as large ones.

(c) Type of material: The transmission of sound waves varies with basic material types, and with the condition of the material. In weld metal, which is often coarsely crystalline, the sound can be greatly impeded. This is especially true for austenitic stainless steel, where large crystals reflect some of the sound back to the receiver, often to the extent that ultrasonic testing is impractical.

(d) Internal metallurgical structure: The grain size in the parent material can also affect the transmission of sound. When the grain size, or the size of precipitates or inclusions begins to get greater than 10% of the wavelength it can refract or reflect sound, leading to attenuation or noise.

(e) Penetration: In a given material, low frequency waves will penetrate further, than high frequency waves.

(f) Resolution: High frequency probes have superior resolution characteristics, so that small flaws can be found more readily, than with low frequency probes.

(g) Accuracy: In general, high frequency probes provide greater accuracy in determining the size of the flaws.

(h) Scanning speed: Where large flaws are to be covered as in initial detection of flaws; large probes of low frequency, provide rapid scanning.

(i) Probe angle: The angle is selected to insure that an echo will be obtained from all flaws. Pay special attention to those that may be so oriented that a significant echo signal is not obtained, unless the probe angle is favourable for normal reflection. These are often the most significant flaws, e.g. lack of fusion on side walls and at the root, and cracks. The probe angles most generally suited to different thicknesses, are as given in Table 6.1 below, unless special conditions apply:

In specific cases a departure from this table might be advisable. In choosing a beam angle, remember, that a beam incident on a reflecting surface at 30° will result in mode conversion, and in a loss of shear wave energy of up to 20 dB (90%). Further, a fraction of surface waves is generated by 80° probes and must be allowed for.

(j) Range selection: Make the beam path, in relation to frequency, sufficiently short, to avoid excessive attenuation. Subject to considerations of probe angle, nature of defects and beam spread, the representative ranges may be up to 200 mm (8 in) for frequencies of 2 to 6 MHz and up to 400 mm (16 in) for frequencies of 1 to 1.5 MHz.

TABLE 6.1 : SUITABLE PROBE ANGLES FOR DIFFERENT THICKNESS RANGES

Probe angle	Thickness range
80°	5 to 15 mm (0.2 to 0.6 in.)
70°	15 to 35 mm (0.6 to 1.4 in.)
60°	35 to 100 mm (1.4 to 4 in.)
45°	50 to 200 mm (2 to 8 in.)
35°	100 to 200 mm (4 to 8 in.)

6.1.2.4 Examination of weld body of a single vee butt weld without backing strip

After the root examination is complete, the weld body examination is then done using the following procedure:

(a) Selection of an appropriate probe angle.

(b) Calculation of the 1/2 skip and fullskip distances and 1/2 skip BPL and full skip BPL for the selected probe angle.

(c) Marking the parent metal on both sides of the weld with lines parallel to the weld centre line and at distances of 1/2 skip and full skip +1/2 cap width.

(d) Calibration of the time base for an appropriate range.

(e) Setting the sensitivity of the probe/flaw detector system for the maximum testing range which in this case is the full skip BPL.

(f) Scanning the specimen in a zigzag pattern between the marked scan limits (Figure 6.21). Each forward scan should be at right angle to the weld centre line, and the pitch of the zigzag should be a half probe width to ensure full coverage.

(g) Mark the areas, in which defect echoes occur, for subsequent location, establishment of nature and sizing of the defects. The probe movement such as in Figure 6.22 may be used to help in establishing the nature and size of defects.

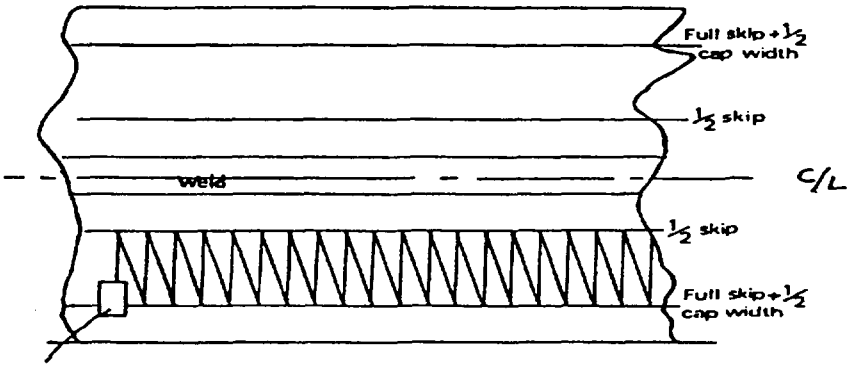


Figure 6.21 : Zigzag scanning of weld body.

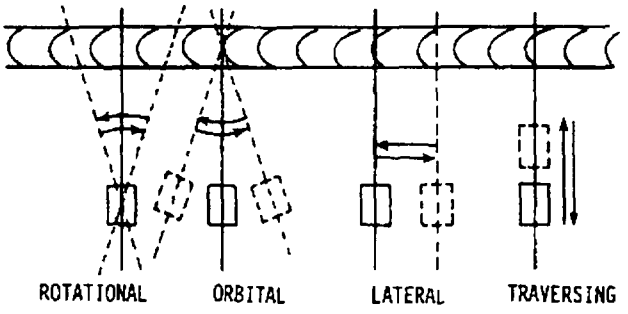


Figure 6.22 : Probe movements for establishing the nature and size of defects.

Selection of probe angle

The initial choice of probe angle for the weld body scan depends upon the weld preparation angle. The angle should be chosen to meet any lack of sidewall fusion at right angle for

maximum response. The exact angle to meet this fusion face at right angle can be calculated from:

Probe angle = 90° - θ/2 ---------- (6.1)

where, θ = weld preparation angle

Example (i):

Weld preparation angle = 60°

Required probe angle = 90° - 60°/2 = 90° - 30° = 60°

Example (ii):

Weld preparation angle = 45°

Required probe angle = 90° - 45°/2 = 90° - 22.5° = 67.5°

In the first case, clearly we would use 60° probe, but in the case of the 45° weld preparation angle, it is not likely that we will have a 67.5° probe, so we would choose the nearest, i.e. a 70° probe.

The probe angle will also need to be altered for a change in the type of material of the test specimen. This is shown in Table 6.2.

TABLE 6.2 : RELATIVE CHANGE IN PROBE ANGLES FOR DIFFERENT MATERIALS

Material	Beam angle (Degrees)				
Steel	35	45	60	70	80
Aluminium	33	42.4	55.5	63.4	69.6
Copper	23.6	29.7	37.3	41	43.4
Grey cast iron (mean value for lamellar cast iron)	23	28	35	39	41

Calculation of various distances for angle beam probes

Half skip and full skip distances and beam path lengths.

Figure 6.23 defines the half-skip distance (HSD), full-skip distance (FSD), half-skip-beam-length (HSBPL) and full-skip-beam-length (FSBPL) for an angle beam probe of refraction angle.

Distance AB = Half-Skip Distance (HSD)
Distance AC = Full-Skip Distance (FSD)
Distance AD = Half-Skip-Beam-Path-Length (HSBPL)
Distance AD + DC = Full-Skip-Beam-Path-Length (FSBPL)

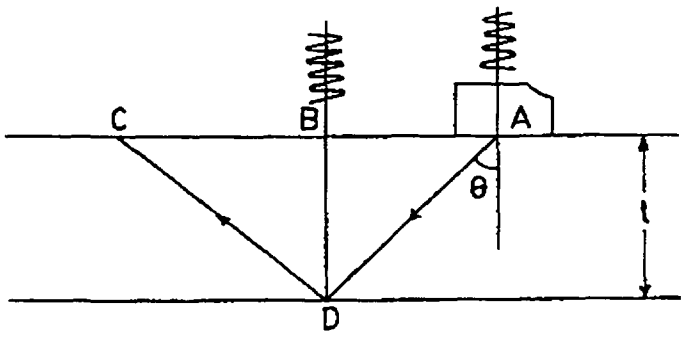


Figure 6.23 : Various skip distances and beam path lengths for an angle beam probe.

The relations used to calculate HSD, FSD, HSBPL and FSBPL for a specimen of thickness t, are given below:

$$HSD = t \times \tan\theta \quad \text{----------} \quad (6.2)$$

$$FSD = 2t \times \tan\theta \quad \text{----------} \quad (6.3)$$

$$HSBPL = t/\cos\theta \quad \text{----------} \quad (6.4)$$

$$FSBPL = 2t/\cos\theta \quad \text{----------} \quad (6.5)$$

If the actual probe angle is exactly equal to the nominal probe angle then these distances can be calculated by the following formula:

$$\text{Distance required} = F \times t \quad \text{----------} \quad (6.6)$$

where F is the appropriate factor from Table 6.3.

TABLE 6.3 : F FACTOR FOR VARIOUS DISTANCES WITH ANGLE BEAM PROBES

Probe angle / F factor	35°	45°	60°	70°	80°
HSD factor	0.7	1.0	1.73	2.75	5.67
FSD factor	1.4	2.0	3.46	5.49	11.34
HSBPL factor	1.22	1.41	2.0	2.92	5.76
FSBPL factor	2.44	2.83	4.0	5.85	11.52

6.1.2.5 Inspection of single vee butt welds with backing strips or inserts

The inspection procedure for such welds only differs from that for single vee welds without backing strips in the detail of the critical root examination. In the root examination of this type of weld, the prime object is to confirm that fusion has taken place between the parent metal, root preparation and the backing strip or insert.

Welds with EB inserts

When properly fused, this weld configuration is like a perfect single-vee weld with a constant root bead profile. Setting up for a root examination is exactly the same as for a single-vee butt weld without a backing strip. Scanning along the probe guide will give a root bead echo which occurs at a particular place on the time base and which remains constant in amplitude (provided, of course, couplant and surface roughness are also uniform). A drop in the amplitude of this echo is a clue that fusion may not be complete. The presence of an echo at exactly half skip beam path length is positive evidence of non-fusion. Since the insert gives a very strong echo as a rule and that echo is only 2-3 mm beyond the half skip beam path length position, a short length of non-fusion is only shown as half skip beam echo sliding up the front of the insert echo (i.e. poorly resolved), as shown in Figure 6.25. The angle of the probe should be chosen to meet any lack of side wall fusion at right angle for maximum response. The exact angle to meet the fusion face at right angle can be calculated from Equation 6.1 .

The range at which the testing is done, particularly using a 70° probe to suit the weld preparation angle, can be quite long and the sensitivity to defects other than lack of side wall fusion may be rather low. In such cases it is reasonable to use 45° or 60° probes to carry out supplementary scans. If the weld cap has been dressed, this problem can be overcome by scanning across the weld centre line from half skip to the far edge of the original cap instead of changing the probe. Care should be taken to ensure that any residual undulation left when the cap is dressed, is not severe enough to lift the probe index clear of the surface (Figure 6.24).

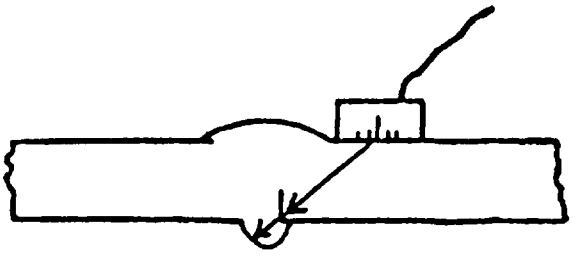


Figure 6.24 : Scan for root bead with EB inserts.

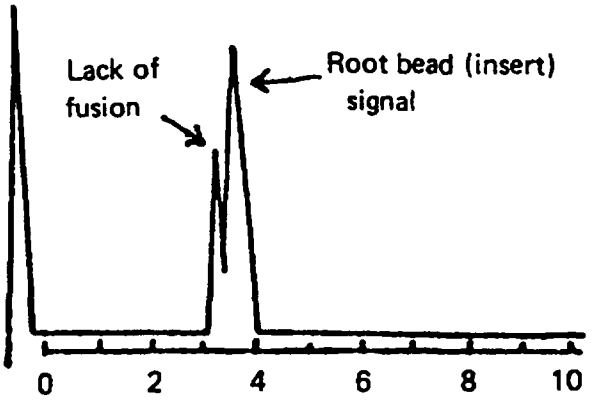


Figure 6.25 : CRT indication for lack of fusion at root.

Lack of fusion at the top of the insert (Figure 6.26) can best be detected by a longitudinal wave probe. For this reason it is desirable for the weld cap to be dressed to allow the normal beam probe scan. If this cannot, or has not been done, this defect can often be found as an echo originating from just above the root, when using an angle beam probe because of distortion or entrapped slag.

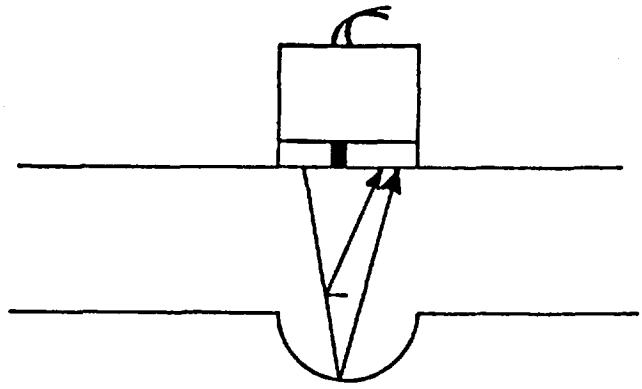
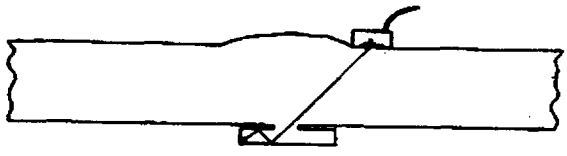


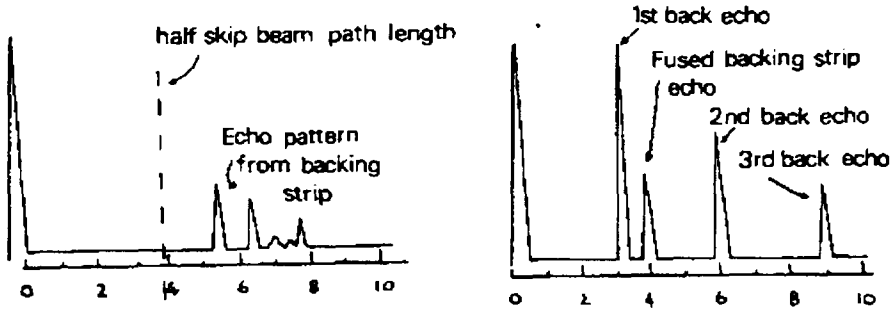
Figure 6.26 : Normal beam probe scan for lack of fusion at the top of EB inserts.

Welds with backing strips

When properly fused the weld cross section looks like the one shown in Figure 6.27 a. An angle beam probe scan allows energy to pass through the root into the backing strip. Reflection from within the strip will be shown as pattern of echoes beyond the half skip beam path length (Figure 6.27 b). A decrease in amplitude or total loss of this pattern indicates non-fusion of the backing strip. Again, it is desirable to have the weld cap dressed so that a normal beam probe can be used to check the root fusion. With a normal beam probe over the weld centre, an echo will be received from the back wall, and from the backing strip. Loss of the backing strip echo indicates lack of fusion (Figure 6.27 c).



(a)



(b) (c)

Figure 6.27 : (a) Cross section of welds with backing strip, (b) CRT indication of root scan with angle beam probe, (c) with normal beam probe.

6.1.2.6 Inspection of double vee welds

The routine for double-vee welds is basically the same as that for single-vee welds. There are some differences in detail in the critical root examination and the weld body scan, because of the difference in weld configuration. These differences are discussed in the following paragraphs.

Critical root scan for double vee welds

The typical weld preparation for a double vee weld is shown in Figure 6.28 which also shows the theoretical lack of penetration defect in this type of weld. It can be seen that, in theory at least, this defect which is planar, vertical and in the middle of the weld volume, ought not to reflect sound back to the probe. In practice, however, there is often enough slag or distortion at the top or bottom of the defect to give a reflection. It is usual, therefore, to use a 70° probe, positioned at 1/4 skip distance from the weld centre line, to carry out the critical root scan. The anticipated time base range for an echo from lack of penetration cannot be predicted as precisely as for single-vee welds, but, of course, echoes from root bead or undercut do not occur in this type of weld configuration.

Another method that can be used for the examination of the root in double vee welds, and for that matter for the detection of any vertical reflecting surface within the volume of a material, is the tandem technique shown in Figure 6.28. Here θ = probe angle, S = separation between probe indices, d = depth of aiming point, and t = specimen thickness. For double vee welds, the beam is aimed at the centre of the weld (i.e. d = 1/2 t), and the probe separation S is equal to half skip distance for that probe angle. For other applications the probe separation for any depth can be calculated from the following formula.

$$S = 2\,(t - d)\tan\theta \qquad (6.7)$$

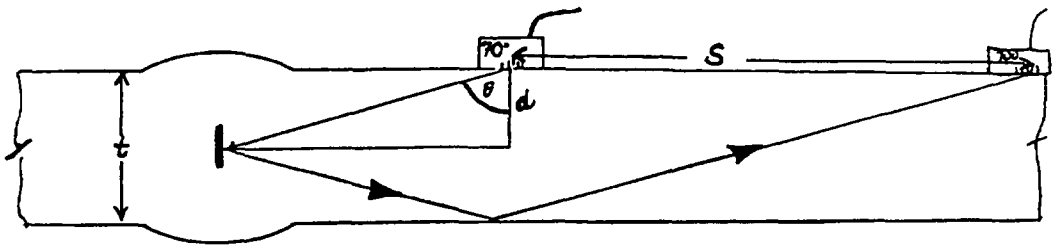


Figure 6.28 : Tandem technique for double-vee welds scan.

Weld body examination for double-vee welds

The weld body examination of double-vee welds is much the same as for single vee welds, but this time the scan starts at 1/4 skip distance from the weld centre and goes back to full skip plus half weld cap width (Figure 6.29). In this type of weld configuration there are four fusion faces to be examined, and the reflections from the bottom weld cap, which occur between half skip beam path length and 3 to 4 mm beyond half skip beam path length, will prevent confirmation of the condition of the lower fusion face on the opposite half of the weld.

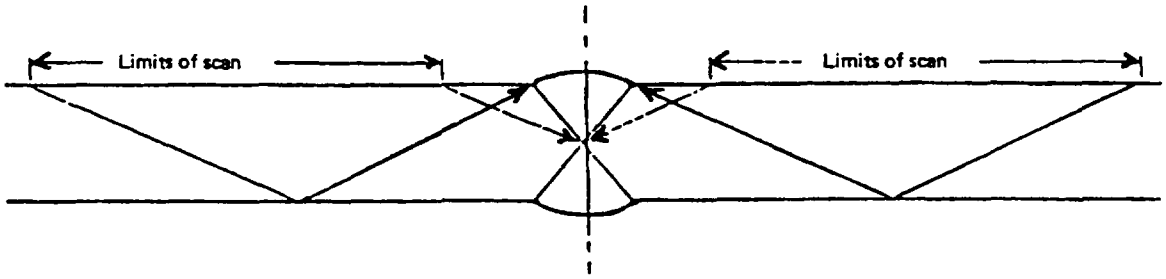


Figure 6.29 : Marking scan area for double-vee welds.

6.1.2.7 Examination of T-welds

In the case of a T-weld configuration, for complete inspection of the weld, access to several surfaces is required. In practice, access to more than one surface may not be available and thus only limited inspection of the weld can be carried out.

The inspection procedure for both partially penetrated and fully penetrated (for types of T-weld configuration see Figure 6.12 a & b) T-welds is much the same, but for partially penetrated welds monitoring of the non-fused portion of the weld is needed to ensure that it is not longer than the design permits. For an ideal case where all surfaces are readily accessible, the scans to be made for the complete inspection of a T-weld are illustrated in Figure 6.30. Scan 1 is done with a normal beam probe to detect laminations, lack of fusion and lamellar tearing. Scan 2 is done with an angle beam probe to detect weld body defects and toe cracks and scan 3 is an angle beam probe scan to detect weld defects and lack of side wall fusion.

As with the previously discussed weld configurations, probe angles and frequencies are to be chosen to suit the particular job. For scan 3 it is useful to choose a probe angle which will produce a beam centre line parallel to the weld cap (Figure 6.31) to reduce the tendency for confusing cap echoes.

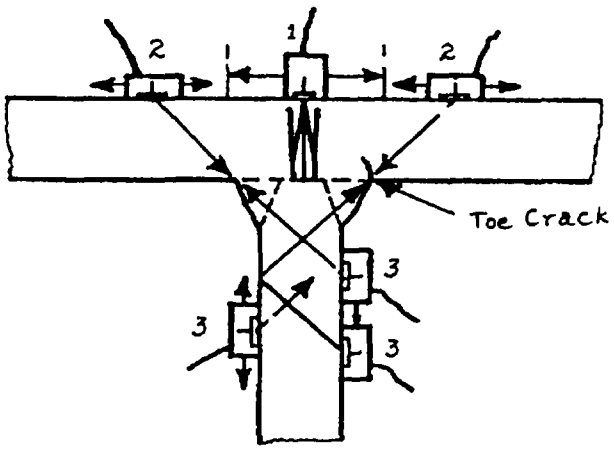


Figure 6.30 : Typical scan positions for "T" welds.

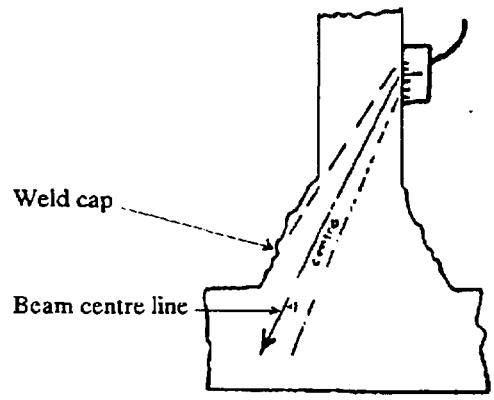


Figure 6.31 : Angle beam probe scan to detect weld defects and lack of side wall fusion.

6.1.2.8 Examination of nozzle welds

As with T-welds, for the complete inspection of nozzle welds access to all the scanning surfaces may not be possible. The following scans are given for fully penetrated set in nozzle welds, and either partially or fully penetrated set through nozzle welds.

The choice of probe angle and frequency, as discussed earlier, depends upon the particular job to be carried out.

Fully penetrated set on welds

The scans to be carried out for this type of weld are shown in Figure 6.32. Scans 1 and 2 are normal beam probe scans of shell and branch respectively to determine:

(a) Thickness of the shell and branch.

(b) Laminations in shell and branch.

(c) Lack of fusion of shell wall.

(d) Weld body defects.

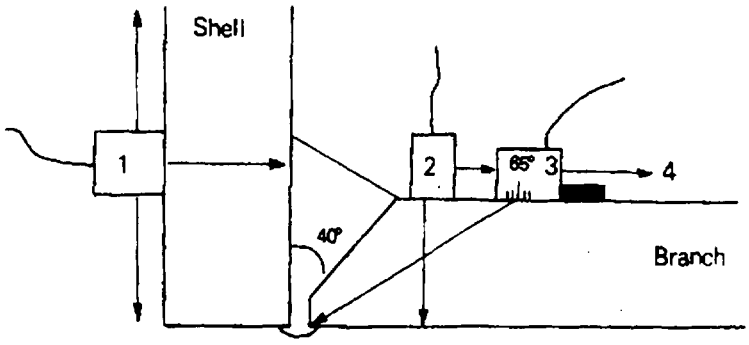


Figure 6.32 : Scans for fully penetrated "set on" welds.

Scan 3 is a critical root scan. Scan 4 is the scan made by moving the probe between half skip and full skip limits. This scan is done to determine lack of side wall fusion and weld body defects.

Partially penetrated set in welds

The scans are similar to those shown in Figure 6.32. However, in this case it is necessary to check the actual penetration achieved and to make sure that the horizontal fusion face is fused. This can be achieved, with practice, by very carefully plotting the root echoes. It is usual to plot both the maximum reflecting point, and, as confirmation, the point at which the echo just disappears (i.e. beam centre and beam edge). From an accurate scale drawing, the intended point of maximum penetration can be determined, and the range of this point, using the beam centre and beam edge, can be measured. Probe positions corresponding to these reflecting points can also be measured and compared to those achieved during the scan.

If, in practice, both points occur at probe positions closer to the shell than the predetermined positions, then the penetration is somewhat deeper than intended. If they occur further from the shell than expected, a condition of unfused face would be suspected.

6.1.2.9 Examination of brazed and bonded joints

(i) Brazed joints

If the wall thickness permits clear separation between back wall echoes, brazed joints can be examined using the standard procedure for lamination testing. However, since the brazed metal separating the two brazed walls will have a slightly different acoustic impedance from that of the brazed walls, a small interference echo will be present for a good braze. The technique is, therefore, to look for an increase in this interface echo amplitude (Figure 6.33 a, b, c).

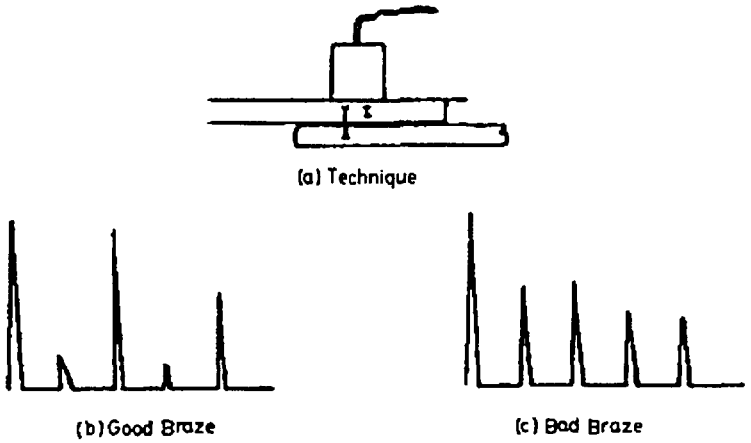


Figure 6.33 (a,b,c) : Ultrasonic inspection of brazed joints.

(ii) Bonded joints

These may include metal to metal glued joints and metal to non-metal glued joints (e.g. rubber blocks bonded to steel plates). The technique used is a multiple echo technique. Each time the pulse reaches a bonded interface, a portion of the energy will be transmitted into the bonded layer and absorbed. Each time a pulse reaches an unbonded layer, all the energy will be reflected. The decay of the multiple echo pattern for a good bond would, therefore, be short because of the energy loss at each multiple echo into the bond (Figure 6.34). However, for an unbonded layer each multiple echo will be slightly bigger because there is no interface loss, and

the decay pattern will be significantly longer (Figure 6.35). If the two brazed wall thicknesses are too thin to permit clear back wall echoes, a multiple echo, as described for lamination testing, can be used.

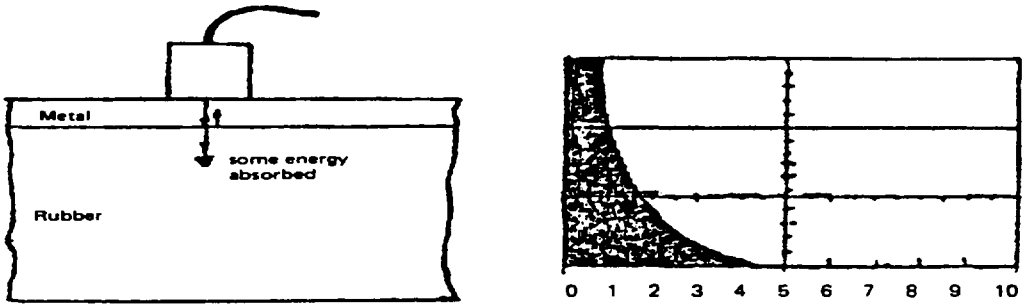


Figure 6.34 : Echo pattern indicating good bonded joint

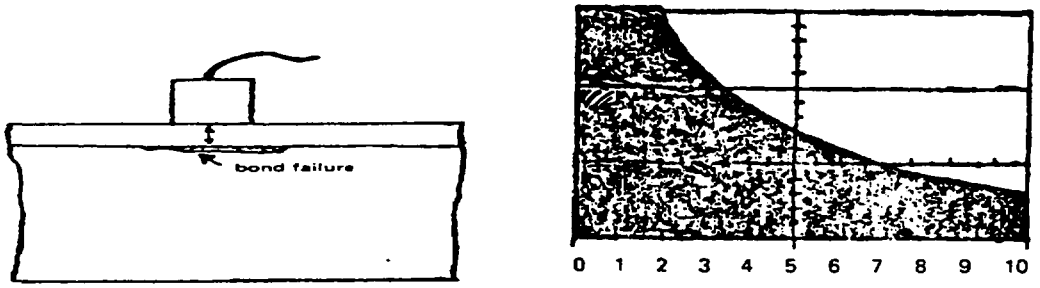


Figure 6.35 : Echo pattern showing lack of bonding.

6.1.3 Components and systems

6.1.3.1 Ultrasonic testing in the automotive industry

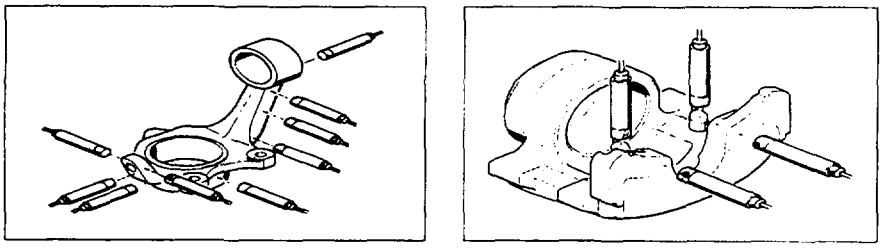
Large production volume and integrated testing in the production line characterize testing in the automotive industry. Therefore, a testing machine must have a high degree of automation and be able to test quickly. The following describes ultrasonic testing machines used in the automotive industry.

Testing of irregular shaped parts

Axle stubs, pivot bearings, brake calipers, etc. are parts which due to the material used (mostly nodular cast iron) and the method of production (casting), must be tested for flaws in critical areas (Figure 6.36 a & b).

Testing of rotational symmetrical parts

Valves, valve seating rings, cup tappets and gears can, due to their symmetrical shape, be rotated within the sound beam of a fixed probe in order to test a certain area. Figure 6.37 (a & b) shows an example of testing round welds (laser or electron beam welds) for inclusions on cup tappets and valve seating rings.

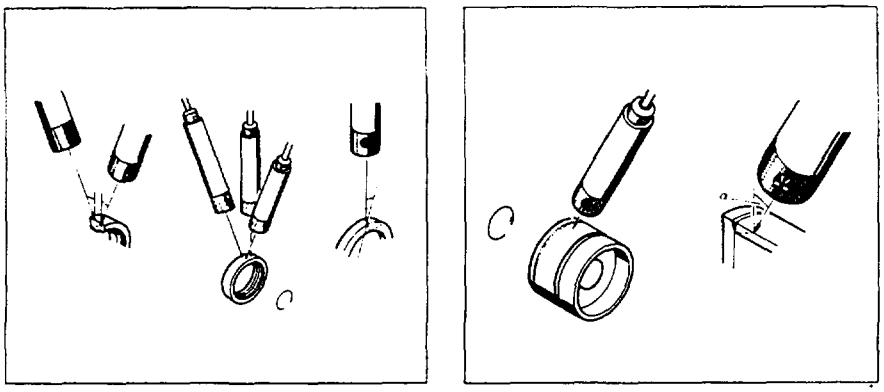


(a) (b)

Figure 6.36 (a & b): Ultrasonic probe arrangements for automatic scanning of irregular shaped automobile parts.

6.1.3.2 Ultrasonic testing in the aerospace industry

Operational safety is of major importance in the aerospace industry. This is the reason why the demands are very high regarding the detection of material flaws and material inhomogeneities together with documentation. The only instruments and systems which fulfill these requirements are the ones with the highest possible resolution power, very good evaluation accuracy and reliable self monitoring functions.



(a) (b)

Figure 6.37 (a & b) : Ultrasonic probe arrangements for automatic scanning of symmetrically shaped automobile parts.

Testing of turbine parts using the immersion technique

These parts are subject to very high stresses. The smallest flaws and inhomogeneities can, with a high revolution rate of the parts, extend and cause a dangerous state of unbalance thus leading to damage. With turbine disks testing must be made at an early processing stage to detect critical flaws in order to avoid further processing costs.

To test these unfinished turbine disks or other rotationally symmetrical parts the ultrasonic immersion testing machine is used. Laminar defects and according to the rate of occurrence and

the distribution, inclusions as well as porosities are critical flaws in rotor blades. Testing of the rotor blades is made via the immersion technique using through transmission method, often using focusing probes. A print out or a C-scan can be made of the test results (Figure 6.38).

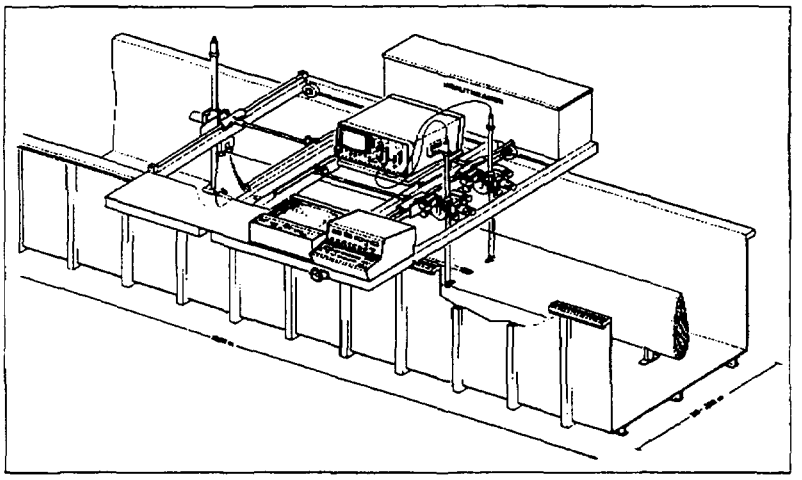


Figure 6.38 : Immersion testing of rotor blades.

6.1.3.3 Ultrasonic testing of rolled products

Rolled products are mostly long and must sometimes be tested in the production line. This nearly always means automatic ultrasonic testing at high transport speeds so that the production flow is not slowed down in any way. It is always better to detect flaws while the product is in the semi-finished state, in this way production of the defective part can be stopped thus saving costs.

Tube testing

For the testing of seamless tubes and welded tubes with the bead ground off there are two different types of testing which can be used depending on the diameter of the tube. Tubes with an outside diameter of up to 180 mm are transported in a straight line through the testing machine. Longitudinal and transverse flaw testing is carried out with probes housed in a water chamber which rotates around the tube. The allocation of further probes enable monitoring of the geometrical data such as wall thickness, outside and inside diameter, ovality and eccentricity. Large tubes with outside diameters of up to 600 mm are spirally transported via water filled tanks which contain the probes (partial immersion technique). With the large tube testing machine up to 40 probes test for longitudinal and transverse flaws as well as measuring the wall thicknesses simultaneously .

By distributing the probes optimally in a number of probe modules, testing of short untested tube ends can be achieved. If wall thicknesses are to be measured only over a number of tracks then in most cases the tube is transported through the measuring position without being rotated.

The same testing techniques as used for round bar testing (Section 6.1.5.2) are applicable to tube testing. The only difference, of course, is that there are no core defects. However, surface flaws can occur on the inner as well as outer surfaces of the tubes. In seamless and rolled pipes, the defects (Figure 6.39) which are of interest are similar to those occurring in rod materials, for example incipient cracks and spills in the internal and external surfaces. Laminations can also appear in the wall as a result of the manufacturing process.

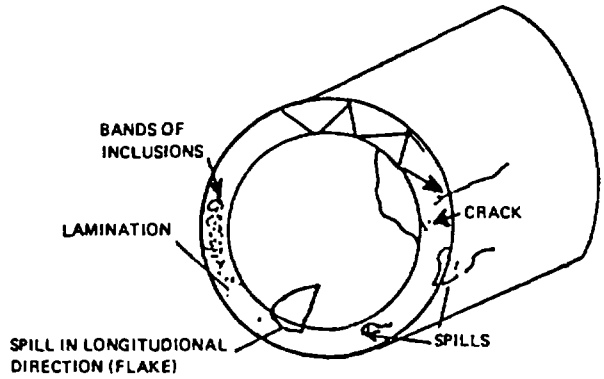


Figure 6.39 : Types of defects and main direction of testing in pipes.

Since the smallest possible angle is 35°, the ratio of wall thickness to tube diameter (d/D), at which a test for internal flaws is still possible, must not exceed 0.20. Should there be a need for testing tubes with thicker wall (i.e. d/D > 0.2) for cracks on their internal surface, the angle of incidence must be less than 35°. This can be achieved by attaching an obliquely ground perspex shoe to a normal probe (Figure 6.40). Since both longitudinal and transverse waves are produced simultaneously, many interfering echoes which are not defect echo indications appear on the screen. Fortunately, these can be distinguished from flaw echoes when the probe or the tube is rotated, since flaw echoes move across the CRT screen whereas the interfering echoes remain stationary.

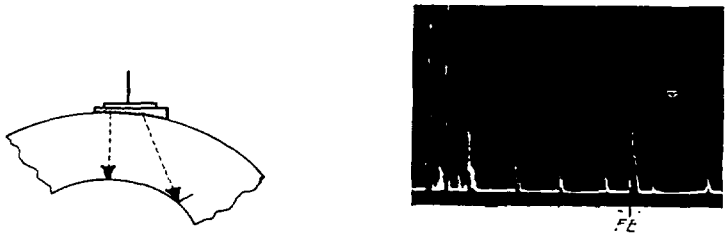


Figure 6.40 : Testing method for detecting longitudinal surface defects on internal surfaces of thick wall tubes using normal probes.

Calculation of maximum penetration thickness for thick wall pipes

The normal range of transverse wave angle beam probes (45°, 60°and 70°) when used on thick wall pipes may not penetrate to the bore of the pipe, but cut across to the outside surface again, as shown in Figure 6.41 and miss the defect.

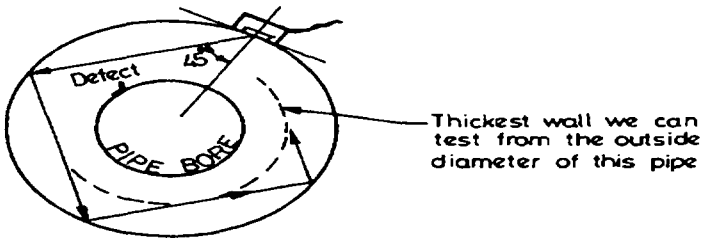


Figure 6.41 : Diagram showing how the defects lying on the inner surface of a thick-wall pipe may be missed by an angle beam probe.

For a given probe angle, the maximum wall thickness of a pipe that allows the centre of the beam to reach the bore of the pipe can be calculated from the following formula:

$$t = d(1 - \sin\theta)/2 \quad \text{----------} \quad (6.8)$$

where,

t = maximum wall thickness
d =outer diameter (OD) of the pipe
θ = probe angle

Equation 6.8 can be rewritten to determine the best angle for a given wall thickness as:

$$\theta = \sin^{-1}(1\text{-}2t/d) \quad \text{----------} \quad (6.9)$$

For convenience Equation 6.6 can be simplified for standard angle probes as

$$t = d \times F \quad \text{----------} \quad (6.10)$$

where

F is the probe factor given in Table 6.4.

TABLE 6.4 : VALUES OF PROBE FACTOR 'F' FOR VARIOUS ANGLES

Probe angle (θ)	35°	45°	60°	70°	80°
Probe factor (F)	0.213	0.146	0.067	0.030	0.0076

Table 6.5 gives values of maximum wall thickness for various pipe sizes and probe angles.

Rod testing

Rods have diameters up to approximately 50 mm and are either round, square or hexagonal in shape. These are often tested only in the core area. In this case it is sufficient to scan the core area with two probes, which are off-set by 90° or 60° around the circumference and move the rods linearly past the probes. With an additional TR probe, rods having diameters between 50 mm and approximately 100 mm are tested. Rods up to 50 mm are transported via two guiding stations through the water filled test chamber. Depending on the profile shape the two probes are off-set by 60°, 90° or 120° (Figure 6.42).

If, with round rods, a greater material area is to be tested beyond the core area then the rotational testing machine should be used as long as the rod diameter does not exceed 180 mm.

For the simultaneous detection of internal and surface flaws on round material with diameters of up to 500 mm the rods are spirally fed over the probe holders, whereby water gap coupling is applied.

TABLE 6.5 : VALUES OF MAXIMUM WALL THICKNESS FOR VARIOUS PIPE SIZES AND PROBE ANGLES

Probe angle / Pipe O.D	Maximum wall thickness		
	35°	45°	60°
4" (100 mm)	21.3 mm	14.6 mm	6.7 mm
6" (150 mm)	31.95 mm	21.9 mm	10.05 mm
8" (200 mm)	42.6 mm	29.2 mm	13.4 mm
10" (250 mm)	53.25 mm	36.5 mm	16.75 mm
12" (300 mm)	63.9 mm	43.8 mm	20.1 mm
14" (350 mm)	74.55 mm	51.1 mm	23.45 mm
16" (400 mm)	85.2 mm	58.4 mm	26.8 mm
18" (450 mm)	95.85 mm	65.7 mm	30.15 mm
20" (500 mm)	106.5 mm	73.0 mm	33.5 mm

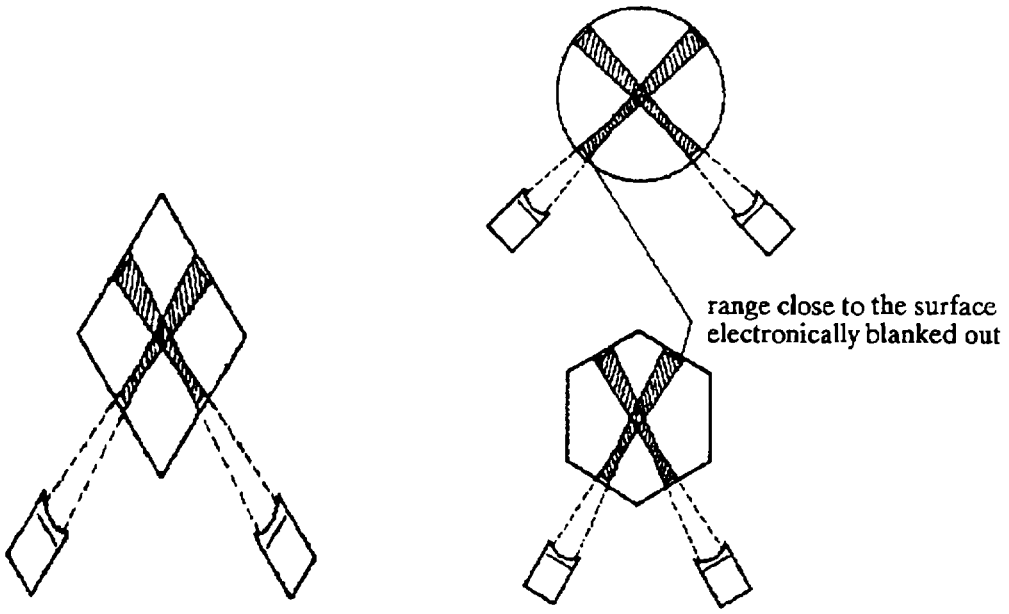


Figure 6.42 : Ultrasonic probe arrangements for automatic testing of rods and billets.

Plate testing

Flaws in plates such as laminar defects and inclusions can, if the plate is further processed, lead to new flaws. If, for example, defective plates are cut and then welded to other components then welding defects in the area of the cut edge of the plate can often be traced back to an inclusion.

Also it is a fact that defects already in the basic material very often cause rejects at the sheet table when the plate is rolled to form sheets.

The standard procedure which is used to test for laminations in plates and pipes, which are to be welded or machined, is given below:

(i) Calibrate the time base to allow at least two back wall echoes to be displayed.

(ii) Place probe on the lamination free portion of test specimen and adjust the gain control so that the second back wall echo is at full screen height.

(iii) Scan the test specimen looking for lamination indications which will show up at half specimen thickness together with a reduction in back wall echo amplitude. In some cases a reduction in the amplitude of the second back wall echo may be noticed without a lamination echo being present. Care must be taken to ensure that this reduction in amplitude is not due to poor coupling or surface condition.

Lamination testing of plate or pipe less than 10 mm in wall thickness may be difficult using the standard procedure because multiple echoes are so close together that it becomes impossible to pick out lamination echoes between back wall echoes. In such cases a technique, called the multiple echo technique, using a single crystal probe can be used. The procedure is as follows:

(i) Place the probe on a lamination free portion of the test specimen or on the calibration block.

(ii) Adjust the time base and gain controls to obtain a considerable number of multiple echoes in a decay pattern over the first half of the time base (Figure 6.43 a).

(iii) Scan the test specimen. The presence of a lamination will be indicated by a collapse of the decay pattern such as the one shown in Figure 6.43 b. The collapse occurs because each of the many multiple echoes is closer to its neighbour in the presence of a lamination.

The above mentioned flaws can be ultrasonically detected by using straight beam probes. With the exception of random testing it is not advisable to carry out a plate test manually. Due to the simple geometry of the test object an automatic test in the production line is the best solution. However, the selection of the most suitable testing machine is determined by the plate thickness, the number of plates to be tested, testing density, the maximum test time and the conditions at the test location (is the testing machine to be integrated into the production line (on-line) or is the test to be made external to the production line (off-line)).

The Plate Test Roller is the simplest plate testing device. It is guided manually over the surface of the plate. The 5 probe holders, each containing dual probes, are adjustable in their spacing to achieve the desired distances between the test tracks (according to the corresponding test specifications).

The testing machine can be equipped with a large number of probes which are adjustable in their spacing. Depending on the total width of the plate either a stand with arm or a bridge can be used. They can either be permanently fixed (when plates are being transported through) or driven by motors (if the plate remains stationary).

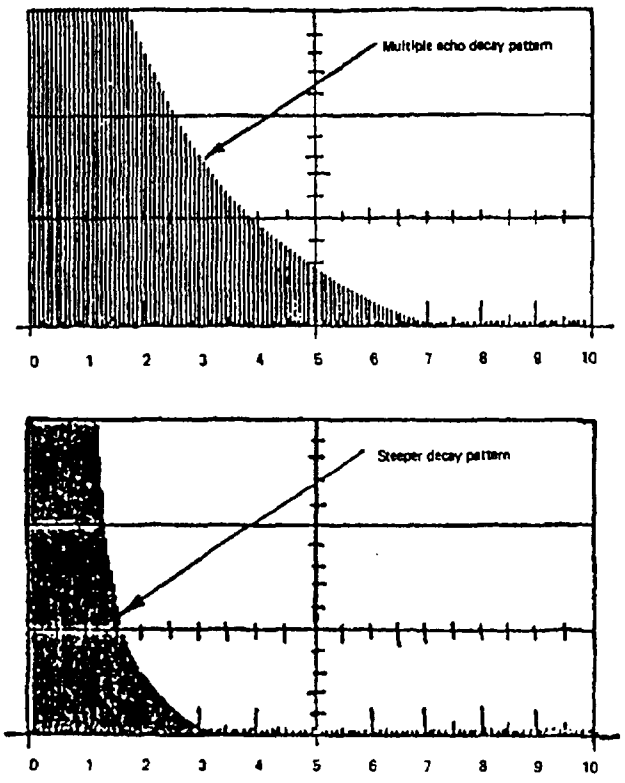


Figure 6.43 : Multiple echo decay pattern from plate; (a) Without lamination, (b) With lamination.

The testing machine is integrated into the roller conveyor of the plate rolling mill and therefore makes an on-line test. The test mechanism is installed beneath the upper edge of the roller conveyor whereby it is protected against damage and does not hinder plate transport by the crane in any way. The most important part of the testing machine is the dual broad beam probe with a test track width of 50 mm. Due to this only a relatively small number of probes are required for coverage of a gapless plate inspection. The test results of all test tracks are issued as a C-scan and fed further to a computer.

Rail testing

Defective rails can lead to very serious accidents and cause extensive damage. Many railways carry out routine checks on the tracks of railway lines. In addition to this rails are tested with ultrasonics during production. Flaws in the rail head, web and foot can be detected during production, in some cases detection of the rail stamp in the web should be possible.

For this type of testing dual probes and angle beam probes are used. Their testing position is dependent on where typical flaws are likely to occur.

6.1.4 Austenitic materials

It is difficult to test cast stainless steel to high degree of reliability because of the coarse grain and highly variable microstate of the material (Figure 6.44 a & b).

Cast stainless steel can have a well defined equiaxed grain structure, a well defined columnar grain structure or mixed grain structure (Figure 6.45 a & b). Because ultrasonic beam distortions are related to the material microstructure and the selected test procedure, the ability to interpret

data depends on knowledge of the microstructure. Because the microstructure can be obtained by measuring the velocity of sound, this is an effective and reliable way to non-destructively assess the inspectability of a component, even under field conditions.

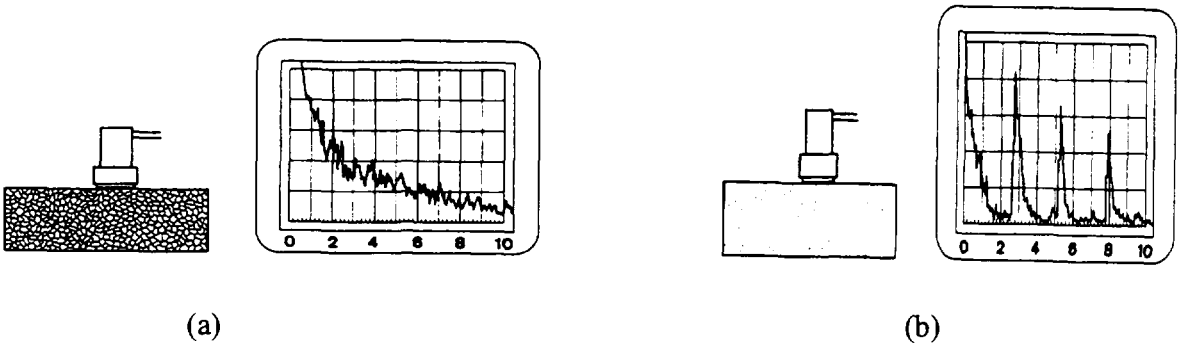


Figure 6.44 : Grain size and CRT screen display; (a) before normalizing, (b) after normalizing.

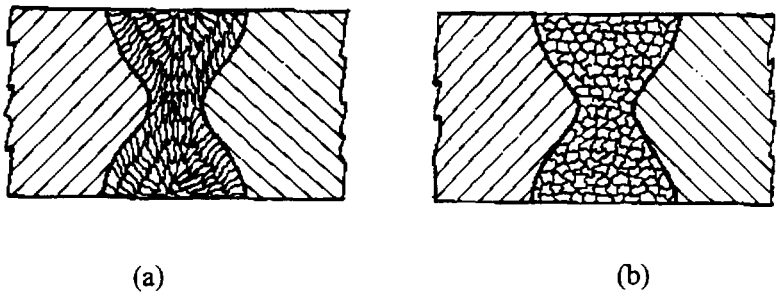


Figure 6.45 : A coarse grain formation; (a) after an austenitic weld structure, (b) after heat treatment.

When cast stainless steel is composed of isotropic equiaxed grain the variation in velocity with propagation direction is small (less than 2 percent). For an anisotropic material composed of columnar grains the variation in velocity may be large, as much as 100 percent for shear waves (Figure 6.46). The magnitude of the sound velocity may also be used as a measure of anisotropy. Relatively low longitudinal wave velocity indicates a columnar grain structure and high velocities indicate an equiaxed structure. Intermediate values indicate the presence of both microstructures.

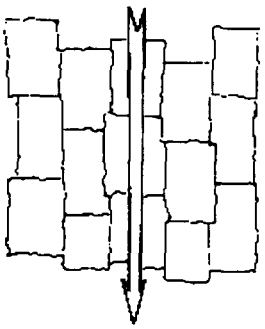


Figure 6.46 : An anisotropic structure.

Ultrasonic angle beam shear waves travel easily from wrought base metal through low alloy carbon steel welds. In austenitic stainless and high nickel alloys welds, the shear beam may be

reflected at the fusion line or deflected in the weld metal because of velocity and grain structure differences. Discontinuity indications from the reflective fusion line may appear to be from incomplete fusion. Reflective fusion line indications can cause the unnecessary repair of good welds. For this reason reflective interface indications are tested with a longitudinal wave beam of the same angle. The longitudinal wave angle beam may not reflect from the interface but does reflect from incomplete fusion permitting identification of the indication.

Improved austenitic weld tests have been reported at low frequencies (1.5 MHz) with short pulse lengths. Focusing or dual transducers improve the signal-to-noise ratio. A narrow sound beam can have favourable effects with regard to testing austenitic welds. The ratio can also be improved by using longitudinal wave angle beams that are not sensitive to grain structure.

6.1.5 Forged work pieces

Manufacturing defects occurring in such semi-finished products can either be internal defects or surface defects. Some internal defects originate from ingot defects in the core such as shrinkage cavities and inclusions which are elongated during rolling, forging or drawing. Others are rolling and drawing defects such as cracks in the core, radial incipient cracks on the rod surface or spills which penetrate to the surface at a small angle. Since most flaws in rods or billets extend in the longitudinal direction, this requires that the axis of the sound beam be in a cross sectional plane (Figure 6.47) either normal or oblique to the surface. Also used are surface waves in the circumferential direction.

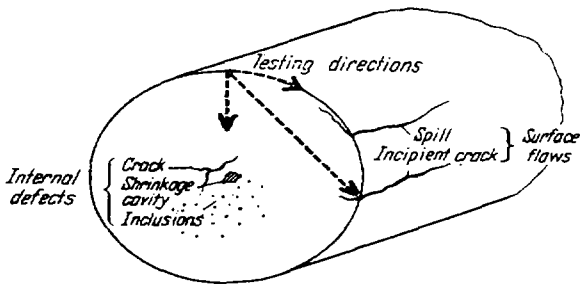


Figure 6.47 : Types of defects in round stock and main directions of testing.

6.1.5.1 Billets

These often have longitudinally directed flaws in the core zone (pipings, cracks and inclusions) or on the surface (cracks).

The core flaws are detected by using two normal probes connected in parallel, as shown in Figure 6.48 for square billets. In this test, a great part of the billet is not tested (Figure 6.49) owing to the beam position as well as the dead zones of the probes. Therefore, when testing square billets with sides shorter than 100 mm, SE probes are used. It goes without saying that SE probes with heavily inclined oscillators cannot be used since their maximum sensitivity is just below the surface. Normally the so-called 0° (zero degree) SE probes are used. Longitudinal surface flaws on square billets are practically impossible to detect with normal, SE or even angle probes.

Because divergence of the sonic beam, even from a probe with a shoe, gives rise to disturbing echoes between the first and second back-wall echoes, core flaws in round billets are usually checked with SE probes (Figures 6.50 and 6.51).

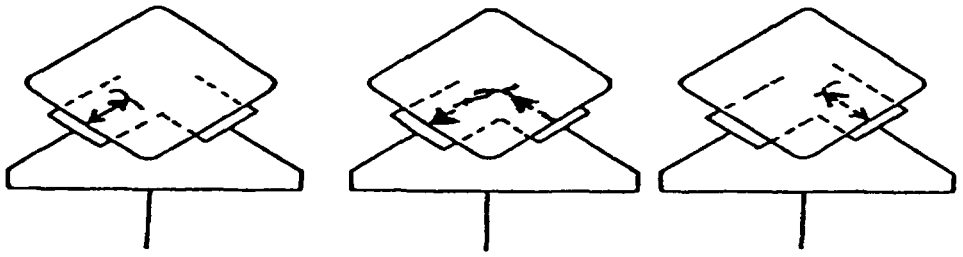


Figure 6.48 : Testing billets with two probes connected in parallel.

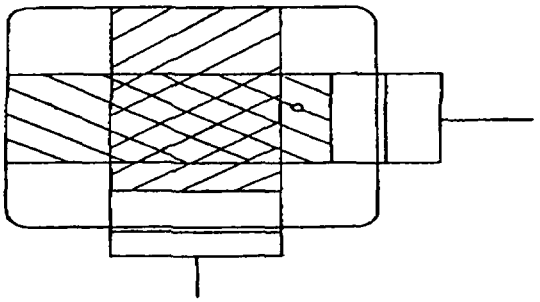


Figure 6.49 : Incomplete coverage by normal probes used for testing of square billets.

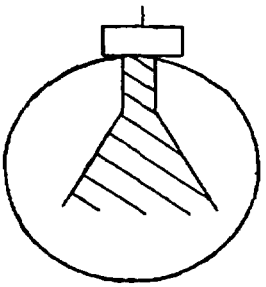


Figure 6.50 : Difficulty in testing round billets with normal probes due to reduced contact area.

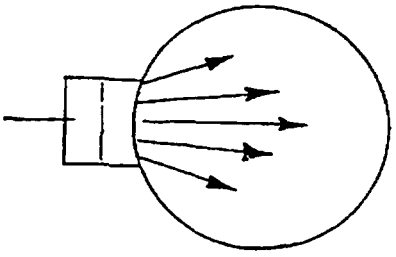


Figure 6.51 : Increase in contact area by using perspex shoe.

Longitudinal surface flaws in round billets can be detected with angle probes provided the surface is not too rough. For a 45° or 60° angle probe which is suitably ground as shown in Figure 6.52, the broad beam, after a few reflections, fills a zone under the surface up to a depth of about one-fifth of the diameter. If a longitudinally oriented surface flaw is present (Figure 6.53), an echo will be visible on the CRT screen; otherwise no echo is visible. It is possible to miss a flaw that is at an acute angle to the surface (Figure 6.54). Therefore, in order to be able to detect all surface flaws, the angle probe must be turned round by 180° and also moved around the billet or the billet itself must be turned. The flaw echo then will move across the screen with alternating heights, having a peak height just before the transmission pulse. With the billet rotating and the angle probe advancing longitudinally, a spiral scan can be performed, enabling all of the billet to be tested.

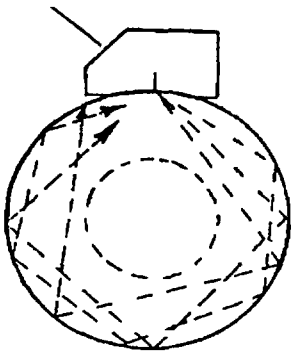


Figure 6.52 : Depth of penetration of oblique transverse waves in round billets.

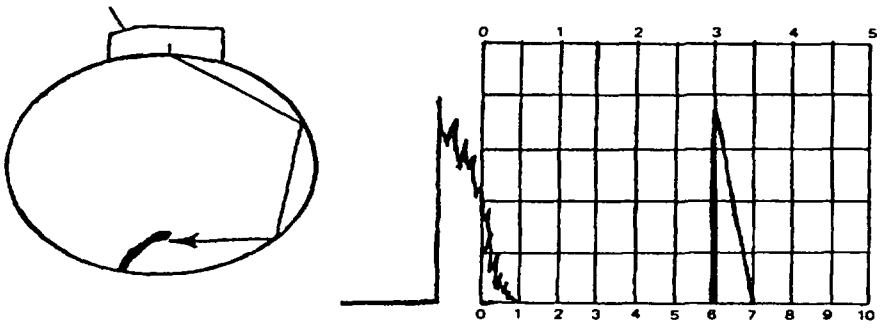


Figure 6.53 : Detection of longitudinal surface flaws in round billets using angle probes.

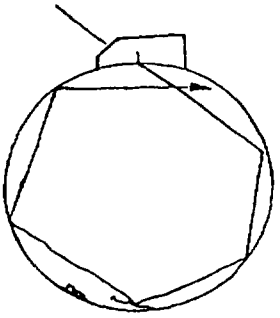


Figure 6.54 : Possibility of missing longitudinal surface flaws in round billets using angle probes.

6.1.5.2 *Rod materials*

There is hardly any difference between testing round billets and bars for cracks, shrinkage or inclusions. To find defects in the core, it is sufficient to scan along at least two longitudinal tracks using a normal or an SE probe depending on the rod diameter. As in round billets, surface defects are detected with oblique transverse waves or with surface waves when the surface is sufficiently smooth.

The use of a twin angle probe allowing a flowing water coupling, enables bars to be tested with increased speed. A bar without a surface flaw will give a large echo on the CRT screen (Figure 6.55). This echo is caused by the sound beam, emitted by one oscillator, being received by the other and vice versa. Both sonic pulses have to cover the same distance corresponding to a circular measure of about 360°. Since the flaw detector is adjusted to half sound path, the common echo will appear on the screen at a distance corresponding to 180°. As the length of the sound path between the oscillators does not alter when shifting the twin angle probe or rotating the bar, provided the bar diameter is constant, the so-called control echo position on the CRT screen remains constant. Hence, any longitudinal surface flaw can easily be distinguished from this echo, since the flaw echo position on the screen is not constant. When the probe is moved in the direction of a surface flaw, the flaw echo arriving at the nearest oscillator and appearing between the transmission pulse and the control echo will move towards the transmission pulse (Figure 6.55). The echo arriving at the farther oscillator is visible at the right of the control echo and moves in the opposite direction. This echo is rather small and therefore is not usually employed for flaw detection. If the probe or rod is moved until the high flaw echo is exactly in the middle between transmission pulse and control echo, the flaw must be located exactly one fourth of the bar circumference from the probe position (Figure 6.56).

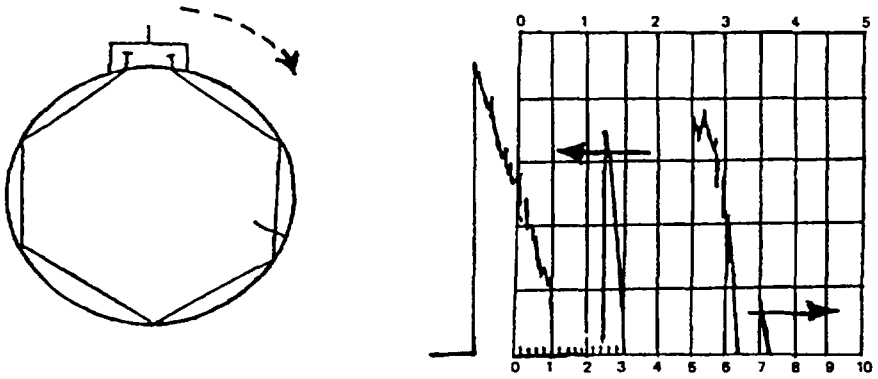


Figure 6.55 : Testing of round bar with twin angle probe.

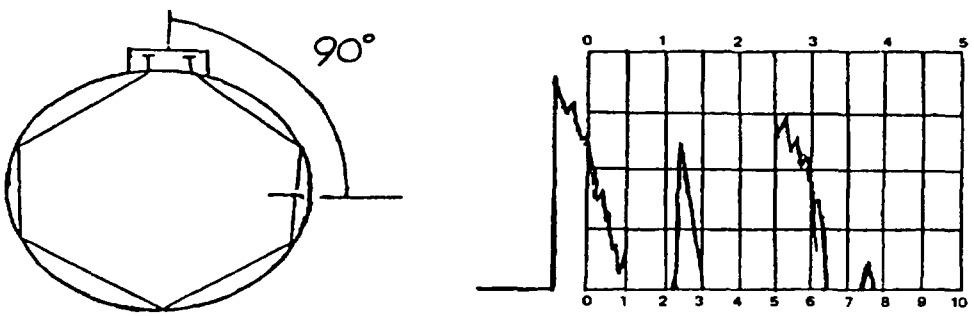


Figure 6.56 : Location of surface flaw on rod using twin angle probe.

6.1.5.3 *Use of immersion technique for billet or rod materials*

Test speed can be maximized by the use of the immersion technique (Figure 6.57), especially for small rod diameters. In this technique, the test specimen is immersed in water and immersion probes are used. When a normal probe is used, it is possible to generate all types of waves (Figure 6.58) by moving the probe position or direction. If the beam is broad, several waves can sometimes be obtained simultaneously. If the surface is not sufficiently smooth, this may give rise to troublesome interfering echoes in a zone behind the interface echo. These interfering echoes are produced by surface waves which, although they quickly decay on the surface, still produce strong echoes from minute rough spots, foreign particles and air bubbles on the surface. Therefore narrow or focussed sound beams should be used.

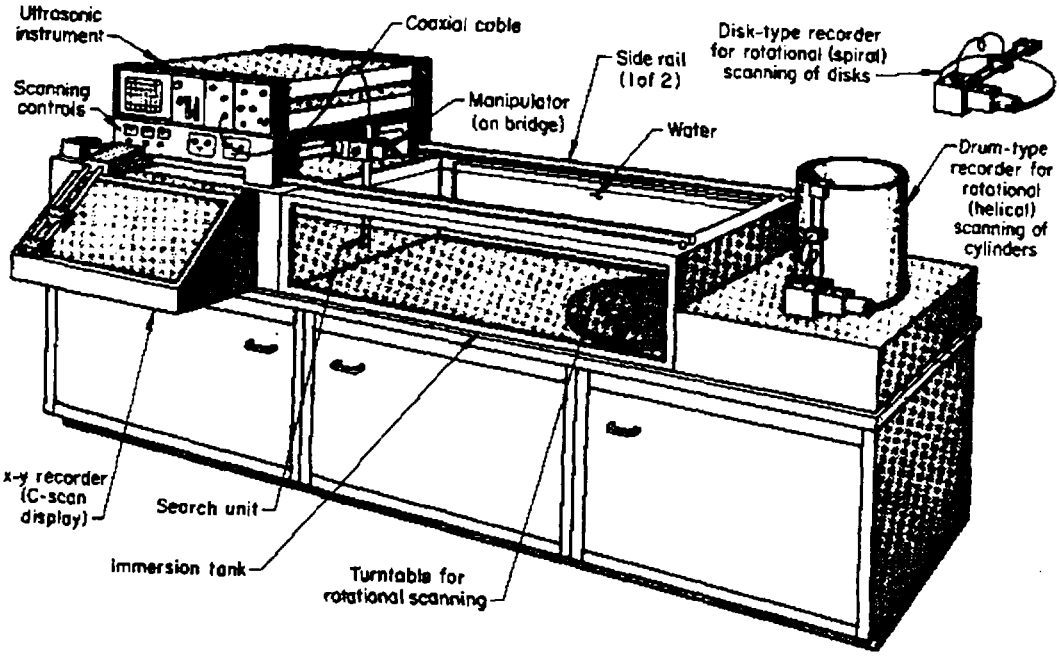


Figure 6.57 : Principal components of a universal unit for immersion scanning of test pieces of various shapes and sizes.

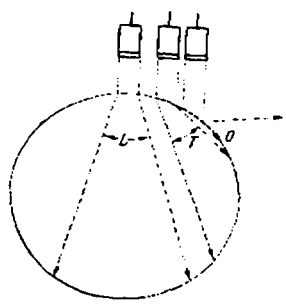
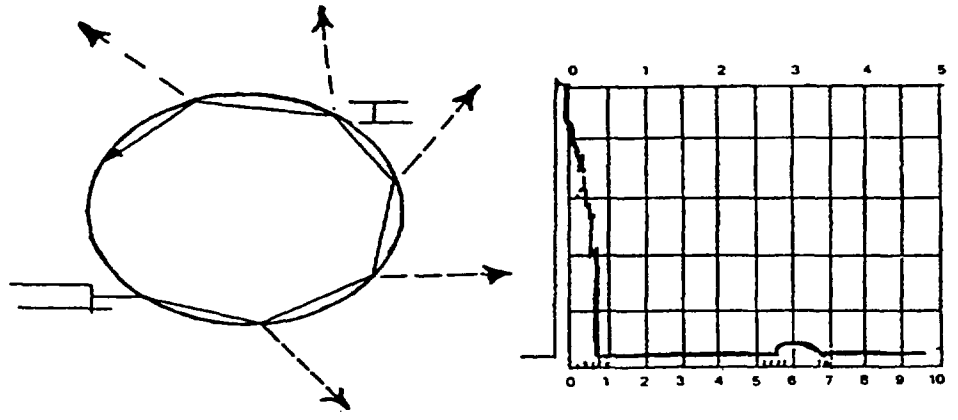
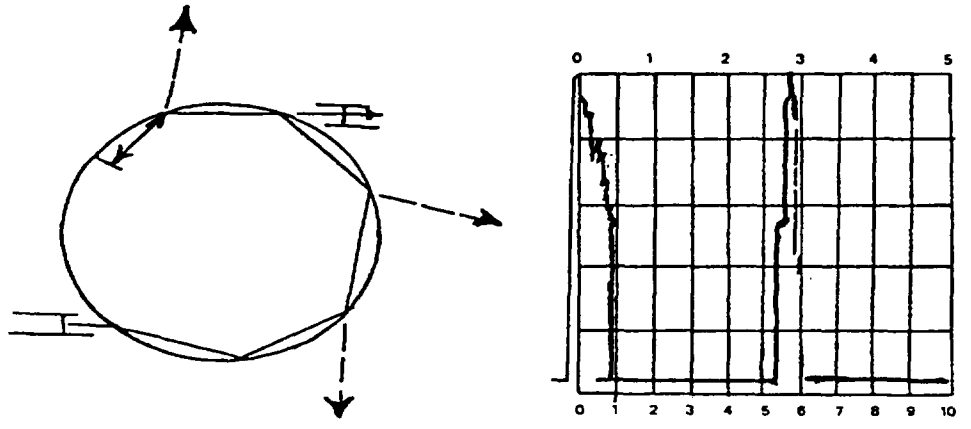


Figure 6.58 : Testing of round stock by immersion technique.

Rod materials are best tested with an SE probe for core defects and with two normal probes, arranged in an immersion tank as shown in Figure 6.59 for longitudinal defects close to the surface. One of the normal probes acts as a transmitter S (T) and the other as a receiver E (R). The longitudinal beam from the transmitter passes through the water and strikes the surface of the rod at an angle. The refracted transverse wave propagates around a polygon and will not give rise to any appreciable echo if the bar is free from surface flaws. With the presence of a longitudinal surface flaw (Figure 6.59 b) the transverse wave is reversed and reflected back in the direction of propagation. The receiver probe then picks up the refracted longitudinal wave. If the rod is rotated, a longitudinal surface defect is indicated by a travelling echo on the CRT screen. From Figure 6.59 a & b it can be seen that there is no possibility that part of the incident longitudinal wave refracted in water can reach the receiver probe. Therefore, it is impossible for any part of the ultrasonic wave to reach the receiver probe when the bar has no surface flaw.



(a)



(b)

Figure 6.59 : Testing of rod material by immersion technique with separate transmitting and receiving probes; (a) rod material with no surface flaws, (b) rod material with a surface flaw.

In order to detect all longitudinal surface flaws independent of their orientation, two pairs of normal immersion probes are used to give opposing directions of sound waves (Figure 6.60). In actual practice, the bar is spirally advanced through a water tank, the holder with its five probes (1 SE and 4 normal probes) sliding on the bar.

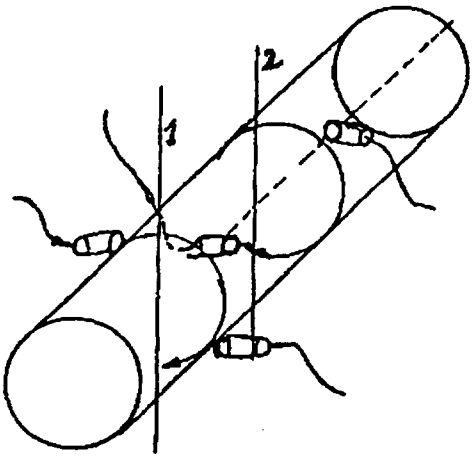


Figure 6.60 : Testing method for longitudinal surface defects on rod material by the immersion technique with two pairs of TR probes.

6.1.5.4 Miscellaneous forgings

The testing of forgings is in many ways more straight forward than the testing of castings. For one thing, the grain is far more refined, giving much lower attenuation and less noise, and allowing a higher frequency to be used.

Secondly, defects such as cavities and inclusions in the original billet are flattened and elongated during the forging/rolling or extrusion process to become better reflectors by becoming parallel to the outer surface. The one exception to this might be cracks which may not be parallel to the scanning surface.

Much of the testing of forgings can be accomplished with compression waves using single or twin crystal probes at frequencies between 4-6 MHz and occasionally up to 10 MHz. Angle shear wave probes are used to explore defects detected by the compression waves and to search for defects which might not be suitably oriented for compression waves. In the testing of forgings, particularly those which have been in service for a period of time, it is very often possible to predict where defects will be, if they exist, and for this reason many specifications only call for a limited scan looking for one particular defect in one location.

The flaws of interest in large forgings are fatigue or strain cracks and those originating from the production processes. Production flaws are searched for as soon as possible before the forgings undergo expensive finishing.

6.1.6 Non-metallic materials

6.1.6.1 Ultrasonic testing of concrete

Determination of pulse velocity in concrete

Measurement of the velocity of ultrasonic pulses of longitudinal vibrations passing through concrete may be used for the following applications:

(a) determination of the uniformity of concrete in and between members

(b) detection of the presence and approximate extent of cracks, voids and other defects

(c) measurement of changes occurring with time in the properties of concrete

(d) correlation of pulse velocity and strength as a measure of concrete quality

(e) determination of the modulus of elasticity and dynamic Poisson's ratio of the concrete

The velocity of an ultrasonic pulse is influenced by the properties of the concrete which determine its elastic stiffness and mechanical strength. The variation obtained in a set of pulse velocity measurements made along different paths in a structure reflects a corresponding variation in the state of concrete. When a region of low compaction, voids or damaged material is present in the concrete under test, a corresponding reduction in the calculated pulse velocity occurs and this enables the approximate extent of the imperfections to be determined. As concrete matures or deteriorates, the changes which occur with time in its structure are reflected in either an increase or a decrease, respectively in the pulse velocity. This enables the changes to be monitored by making tests at appropriate intervals of time.

Pulse velocity measurements made on concrete structures may be used for quality control purposes. In comparison with mechanical tests on control samples such as cubes or cylinders, pulse velocity measurements have the advantage that they relate directly to the concrete in the structure rather than to samples which may not be always truly representative of the concrete in situ.

Ideally, pulse velocity should be related to the results of tests on structural components and if a correlation can be established with the strength or other required properties of these components, it is desirable to make use of it. Such correlations can often be readily established directly for present units and can also be found for in situ work.

Empirical relationships may be established between the pulse velocity and both the dynamic and static elastic moduli and the strength of concrete. The latter relationship is influenced by a number of factors including the type of cement, cement content, admixture, type and size of the aggregate, curing conditions and age of concrete.

The equipment consists essentially of an electrical pulse generator, a pair of transducers, an amplifier and an electronic timing device for measuring the time interval between the initiation of a pulse generated at the transmitting transducer and its arrival at the receiving transducer. Two forms of electronic timing apparatus and display are available, one of which uses a cathode ray tube on which the received pulse is displayed in relation to a suitable time scale.

Any suitable type of transducer operating within a frequency range of 20 to 150 Hz may be used although frequencies as low as 10 Hz may be used for very long concrete path lengths and as high as 1 MHz for mortara and grouts or for short path lengths in concrete. Piezoelectric and magneto-strictive types of transducers are normally used, the latter being more suitable for the lower part of the frequency range. High frequency pulses become attenuated more rapidly than pulses of lower frequency. It is therefore preferable to use high frequency transducers for short path lengths and low frequency transducers for long path lengths. Transducers with a frequency of 50 kHz are suitable for most common applications. The transducer arrangements are such that the receiving transducer detects the arrival of that component of the pulse which arrives earliest. This is generally the leading edge of the longitudinal vibration. Although the direction in which the maximum energy is propagated is at right angle to the face of the transmitting transducer, it is possible to detect pulses which have travelled through the concrete in some other direction. It is possible to make measurements of pulse velocity by placing the two transducers on either,

(a) opposite faces (direct transmission)

(b) adjacent faces (semi-direct transmission), or

(c) the same face (indirect or surface transmission).

These three arrangements are shown in Figure 6.61 (a, b & c)

Figure 6.61 (a) shows the transducers directly opposite to each other on opposite faces of the concrete. It is, however, sometimes necessary to place the transducers on opposite faces but not directly opposite to each other. Such an arrangement is regarded as semi-direct transmission and is shown in Figure 6.61 (b).

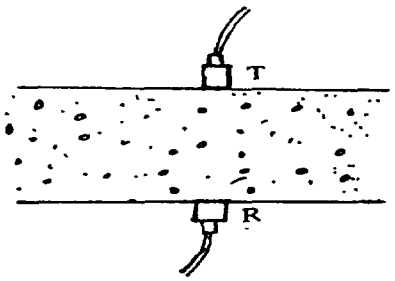


Figure 6.61 (a) : Direct transmission.

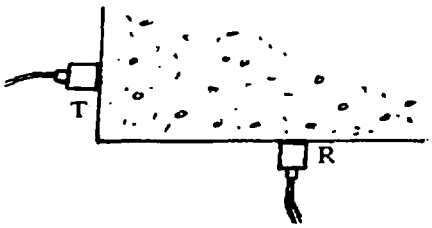


Figure 6.61 (b) : Semi-direct transmission.

Figure 6.61 (c) : Indirect or surface transmission.

Where possible the direct transmission arrangement should be used since the transfer of energy between transducers is at its maximum and the accuracy of velocity determination is therefore governed principally by the accuracy of the path length measurement.

The semi-direct transmission arrangement has a sensitivity intermediate between those of the other two arrangements and, although there may by some reduction in the accuracy of measurement of the path length, it is generally found to be sufficiently accurate to take this as the distance measured from centre to centre of the transducer faces. This arrangement is otherwise similar to direct transmission.

Indirect transmission should be used when only one face of the concrete is accessible, when the depth of a surface crack is to be determined and when the quality of the surface concrete relative to the overall quality is of interest. It has the least sensitivity of the arrangements and for a given path length produces at the receiving transducer a signal which has an amplitude of only about 2% or 3% of that produced by direct transmission. Furthermore, this arrangement gives pulse velocity measurements which are usually influenced by the concrete near the surface. This

region is often of different composition from that of the concrete within the body of a unit and the test results may be unrepresentative of that concrete. The indirect velocity is invariably lower than the direct velocity on the same concrete element. This difference may vary from 5% to 20% depending largely on the quality of the concrete under test. Where practicable, site measurements should be made to determine this difference.

With indirect transmission there is some uncertainty regarding the exact length of the transmission path because of the significant size of the areas of contact between the transducers and the concrete. It is therefore preferable to make a series of measurements with the transducers at different distances apart to eliminate this uncertainty. To do this, the transmitting transducer should be placed in contact with the concrete surface at a fixed point and the receiving transducer should be placed at fixed increments along a chosen line on the surface. The transmission times recorded should be plotted as points on a graph showing their relation to the distance separating the transducers. The slope of the best straight line drawn through the points should be measured and recorded as the mean pulse velocity along the chosen line on the concrete surface. Where the points measured and recorded in this way indicate a discontinuity, it is likely that a surface crack or surface layer of inferior quality is present and a velocity measured in such an instance will be unreliable.

Determination of concrete uniformity

Heterogeneities in the concrete within or between members cause variations in pulse velocity which in turn are related to variations in quality. Measurements of pulse velocity provide means of studying the homogeneity and for this purpose a system of measuring points which covers uniformly the appropriate volume of concrete in the structure has to be chosen. The number of individual test points depends upon the size of the structure, the accuracy required and the variability of the concrete. In a large unit of fairly uniform concrete, testing on a 1 m grid is usually adequate but, on small units or variable concrete, a finer grid may be necessary. It should be noted that, in cases where the path length is the same throughout the survey, the measured time may be used to assess the concrete uniformity without the need to convert it to velocity. This technique is particularly suitable for surveys where all the measurements are made by indirect measurement.

Detection of defects

When an ultrasonic pulse travelling through concrete meets a concrete-air interface there is negligible transmission of energy across this interface. Thus any air filled crack or void lying immediately between transducers will obstruct the direct ultrasonic beam when the projected length of the void is greater than the width of the transducers and the wavelength of sound used. When this happens the first pulse to arrive at the receiving transducer will have been diffracted around the periphery of the defect and the transit time will be longer than in similar concrete with no defect.

It is possible to make use of this effect for locating flaws, voids or other defects greater than about 100 mm in diameter or depth. Relatively small defects have little or no effect on transmission times but equally are probably of minor engineering importance. Plotting contours of equal velocity often gives significant information regarding the quality of a concrete unit.

In cracked members where the broken faces of the members are held in close contact by compression forces, the pulse energy may pass unimpeded across the crack. As an example this

may occur in cracked vertical bearing piles. If the crack is filled with liquid which transmits the ultrasonic energy, e.g. in marine structures, the crack is undetectable using digital reading equipment. Measurements of attenuation may give valuable information in these cases.

The use of the ultrasonic pulse velocity technique to detect and define the extent of internal defects should be restricted to well qualified personnel with previous experience in the interpretation of survey results. Attention is drawn to the potential risk of drawing conclusions from single results.

6.1.6.2 Ceramic materials

Discontinuity detection in ceramics

Ultrasonic techniques for testing ceramics use high frequency elastic waves to probe both green state and sintered ceramic bodies. Discontinuities smaller than 25 μm (1 milli-in) have been detected in monolithic and composite ceramics at depths of about 3 mm (0.1 in) in alumina, silicon carbide and silicon nitride and at depths of about 5 mm (0.2 in.) in zirconia.

Critical discontinuities can be detected in most structural metals with ultrasonic wave frequencies from 1 to 10 MHz. Consequently, most research and development in ultrasonic has concentrated on this frequency range, with little activity occurring above 15 MHz. In conventional monolithic ceramics, the critical discontinuity size is often 20 μm (0.75 milli-in) or less and frequencies of 50 MHz and higher are required.

In addition, detection of such small discontinuities at reasonable depths requires the use of focussed ultrasound and the propagation of such energy through the ceramics surface introduces severe beam aberrations. This condition is made worse by the very high index of refraction of typical ceramics, thus limiting to a few millimetres the depth at which effective focus can be maintained. For these reasons, testing ceramics requires new techniques to ensure the optimum utilization of available energy and to permit detection and characterization of discontinuities as small as 20 μm (0.75 milli-in) or even smaller.

With the important task of detecting critical discontinuities in structural ceramics, there is also a need to develop predictive capability for some of the mechanical properties, based on easily measured material characteristics. This has been achieved for some metals, where a correlation was found between the fracture toughness and attenuation of elastic waves.

High frequency ultrasonic surface waves have been studied by several investigators and shown to be useful for the detection of small surface discontinuities. A 45 MHz ultrasonic surface wave technique has been developed for detecting surface discontinuities less than 100 μm (4 milli-in) deep in silicon nitride and silicon carbide. The technique was found to be sensitive to surface conditions such as grinding damage as well as to discontinuities.

Measuring correlated properties.

Ultrasonic technology for discontinuity detection could be used for measuring parameters that correlate with desired material properties. The ultrasonic velocity is a function of the elastic properties of the material and ultrasonic attenuation can be related to bulk microstructure, as well as structural discontinuity (both microscopic and macroscopic). Laboratory studies by several investigators confirm the feasibility of techniques for making such measurements.

Ultrasonic longitudinal and transverse wave velocities have been measured in different directions in hot pressed silicon nitride. Anisotropy was observed and velocities perpendicular to the hot pressing direction were about 5 percent higher than velocities parallel to the hot pressing direction. Ultrasonic attenuation measured with both longitudinal and transverse waves in the 30 to 130 MHz frequency range exhibited a frequency dependent characteristic proportional to the square of the frequency.

Work on siliconized SiC tubes indicated that the velocity of sound changed as a function of the volume fraction of silicon and this may offer a technique for indicating silicon content. The feasibility of using ultrasonic methods to measure elastic moduli, microstructure, hardness, fracture toughness and strength for a wide range of materials, including metals, ceramics and fibre composites has been demonstrated. Ultrasonic methods are particularly useful because they involve mechanical elastic waves that are modulated by some of the morphological factors that govern mechanical strength and dynamic failure processes.

6.1.6.3 Plastics

In view of the wide range of materials which come under this collective heading, the attenuation of ultrasound which determines the testability extends from the mean values applying to solid materials without filters, such as acrylic resins (perspex), ethoxylene resin (cast resin), polystyrene, polyamide and teflon, to the very high values of the soft varieties of polyethylene (PE), polyvinyl-chloride (PVC) and ployisobutylene (Oppanol B). The latter are excellent sound absorbers even at the lowest frequencies used in materials testing. The hardness of a given plastic, unless this has been achieved by filters, is thus an approximate measure of its testability. Plasticizers reduce the testability.

Usually, however, TR probes are used due to their superior near resolution and also for thinner materials, particularly in the case of testing frequencies of 1 MHz and lower. As an example of the possible flaw detectability it should be mentioned that in polyethylene rod material of up to 150 mm diameter, 1 MHz TR probes can detect flaws with an equivalent reflector size of 0.3 mm diameter.

Compared with metals, the immersion technique here offers still better sound transmission, i.e. lower reflection losses and less deflection and splitting of the beam on curved surfaces. Longitudinal waves are used in the specimen even at oblique incidence because transverse waves are usually strongly damped. In this way it is possible, for instance, to check teflon tubes under water for bubbles in the wall using 1 MHz frequency probes. There is possibility of testing butt welded joints in plastics by means of longitudinal waves from angle probes. An angle probe with a wedge material of extremely low acoustic velocity has been developed for this purpose. For pipelines installed in the ground and carrying water or gas, checking of the welded joints is important. Even in the case of pronounced upsetting beads which have not been removed, joints in pipes up to a wall thickness of approximately 15 mm can still be tested. Wall thicknesses up to approximately 30 mm are still feasible if in the case of large pipe diameters the joint is accessible also internally for testing. The test is carried out from both sides, penetrating a depth of up to 15 mm. Usually a 2 MHz angle probe is used which beams longitudinal waves at an angle of 70°. The test should be preceded by an adjustment of the gain on a test piece with reference defects of equal size in all depth ranges. In order to facilitate the evaluation of flaw indications, it is recommended to compensate the strong attenuation with longer distances by an electronic time controlled gain.

7. CODES, STANDARDS, SPECIFICATIONS AND PROCEDURES

7.1 CODES, STANDARDS, SPECIFICATIONS RELATED TO ULTRASONIC TESTING

Different definitions related to codes, standards and specifications have already been explained in section 1.5.2. The process of standardization has been given in section 1.5.2.6 which is sufficient to highlight the importance and need of standards in view of large number of variables which need to be controlled to achieve reliable and reproducible results from NDT tests including ultrasonic testing. This, then can be said to be the underlying need and reason for the existence of different standards apart from many others as have been listed in Section 1.5.4. In this chapter more information will be provided on the subject of standards specially those related to ultrasonic testing of materials.

7.1.1 Standardization organizations

One of the criteria for any document such as a guide or a recommended practice to qualify to become a standard is that it should be issued by a reputed organization which is recognized at national, regional or international level. Some of the organizations whose standards are commonly used in NDT internationally are:

(a) ASME: American Society of Mechanical Engineers

(b) ASTM: American Society for Testing and Materials

(c) IIW : International Institute of Welding

(d) ISO : International Organization for Standardization

(e) DIN : German Standards Institution (Deutsches Institut für Normung)

(f) BSI : British Standards Institution

(g) JISC : Japanese Industrial Standards Committee

(h) AFNOR: French Standardization Body (Association Francaise de Normalization)

(i) SAA : Standards Association of Australia

(j) CSA : Canadian Standards Association

(k) CNS : China Association for Standardization

(l) ASNT: American Society for Non-destructive Testing

(m) JSNDI: Japanese Society for Non-destructive Inspection.

7.1.2 Types of standards

Generally the standards belonging to NDT can be grouped into various categories such as the standards for terminology, equipment, testing method, education, training and certification,

acceptance and rejection and accreditation, etc. These are briefly described below with examples.

7.1.2.1 Standards for terminology

These are the standards which explain the meanings of various technical terms and concepts as employed in NDT. These are therefore essential for avoiding failure to reach an agreement between the user and purchaser of the NDT services. Some examples of such standards are:

(a)	Appendix-A of ASME boiler and pressure vessel code (B & PV)	Glossary of terms used in non-destructive testing
(b)	DIN 54 119 (1981)	Terms and concepts in ultrasonic inspection
(c)	BS 3683: Part 4 (1985)	Glossary of terms used in ultrasonic flaw detection
(d)	ASTM E-500 (1974)	Standard definitions of terms relating to ultrasonic inspection
(e)	JIS Z 2300-91	Glossary of terms used in non-destructive testing

7.1.2.2 Standards for equipment

A prerequisite to standardization of inspection techniques is a regularized method of ensuring that the equipment in use is either inherently capable of or can be adjusted to give a certain predetermined degree of sensitivity and performance. Some of the standards of this type are:

(a)	ISO-2400	Weld in steel - Reference block for the calibration of equipment for ultrasonic testing
(b)	JIS Z-2348 (1978)	Calibration block (type A2) used in ultrasonic testing
(c)	BS 2704 (1978)	Calibration blocks and recommendations for their use in ultrasonic flaw detection
(d)	IIS/IIW 278-67 (1967)	Recommended procedures for the determination of certain ultrasonic pulse echo characteristics by the IIW calibration block
(e)	ASTM E-428 (1971)	Recommended practice for fabrication and control of steel reference block used in ultrasonic inspection
(f)	DIN 25450-90	Ultrasonic equipment for manual testing

7.1.2.3 Standards for testing methods

These standards, usually, entitled as Recommended Practice or Method are issued in order to select an optimal test technique for a particular job. In other words these will help in selecting a technique which reveals only those defects which may be considered harmful without giving prominence to secondary features. Use of these standards will help in obtaining reliable and reproducible results from the tests. Some of the standards of this category are:

(a)	BS 3923 (1978)	Methods for ultrasonic examination of welds
(b)	JIS G 0801 (1974)	Ultrasonic examination of steel plates for pressure vessels
(c)	DIN 54125 (1982)	Ultrasonic testing of welded joints
(d)	ASTM E-164 (1974)	Standard methods for ultrasonic contact inspection of weldments
(e)	ASME B & PV Code (1995), Section V	Article 5: Ultrasonic examination methods for materials and fabrication

7.1.2.4 Standards for education, training and certification of NDT personnel

To avoid unreliable results of an NDT examination besides using standardized equipment and test methods, the persons carrying out the examination must also be properly educated, trained and certified in the method. Various standards are available to cater for this requirement. Lately there is an effort to harmonize the education, training and certification both at the regional as well as international level. Some of the standards of this type are:

(a)	DIN 54160 (1978)	Requirements for non-destructive testing personnel
(b)	IIS/IIW-589-79 (1979)	Recommendations relating to the training of non-destructive testing personnel
(c)	NDIS 0601-77	Rules for certification of non-destructive testing personnel
(d)	ISO 9712 (1992)	General standard for the qualification and certification of non-destructive testing personnel
(e)	SNT-TC-1A (1986)	Recommended practice for non-destructive testing personnel qualification and certification
(f)	BS EN 473 (1993)	General principles for qualification and certification of NDT personnel

7.1.2.5 Standards for acceptance and rejection

After the defects have been investigated by NDT in terms of their nature, size and location, it is important to evaluate their acceptance or rejection. This is done with the help of standards, some examples of which are the following:

(a)	ISO 5948-81	Railway rolling stock material - ultrasonic acceptance testing
(b)	BS 5500-94	Specification for unfired fusion welded pressure vessels
(c)	JIS G 0587-87	Methods for ultrasonic examination for carbon and low alloy steel forgings
(d)	DIN EN 1712-95	Non-destructive examination of welds - acceptance criteria for ultrasonic examination of welded joints
(e)	AS 2824-85	Non-destructive testing - ultrasonic methods - evaluation and quality classification of metal bearing bonds

7.1.2.6 Accreditation standards

These standards help in judging the capability and suitability of NDT laboratories and institutions for undertaking different types of NDT work as well as for education and training of NDT personnel. Examples are:

(a)	ASTM-E 543-93	Standard practice for determining the qualification of non-destructive testing agencies.
(b)	European community standard EN 45002	General criteria for the assessment of testing laboratories
(c)	EN 45013	General criteria for certification bodies operating certification of personnel.
(d)	ASTM E 994	Guide for laboratory accreditation systems
(e)	ASTM A 880-89 (94)	Practice for criteria for use in evaluation of testing laboratories and organizations for examination and inspection of steel, stainless steel and related alloys

*7.1.3 **ASME boiler and pressure vessel code***

7.1.3.1 Establishment process and features

ASME boiler and pressure vessel code, an American national standard, is being extensively used around the world either directly or by adoption. Therefore some of its features are given here in some detail.

Initial enactment of the code was in 1914. It was established by a committee set up in 1911 with members from utilities, states, insurance companies and manufacturers. Whether or not it is adopted in the USA is left to the discretion of each state and municipality. In any event its effectiveness in reducing human casualties due to boiler accidents since adoption is widely recognized.

Rules for nuclear reactor pressure vessels were included in the code in 1953, and now the code is adopted by almost all states of the United States and the provinces of Canada. After the initial establishment, revisions are issued once every three years, so that currently effective is the 1995 edition. One of the features of the ASME code is that partial revisions are issued twice a year, the summer addenda (July 1st), and the winter addenda (January 1st). These addenda used to be made effective six months after the date of issue, but now they are effective immediately upon issuance. Any question about interpretation of rules may be submitted to the committee in a letter of inquiry, and answers from the committee are published as code cases from time to time.

7.1.3.2 Constitution of ASME code

The following contents constitute the ASME code, 1995 edition. Rules for non-destructive examination are collectively prescribed in Section V. Other sections for individual components (Section I, III or VIII) refer to Section V or other applicable rules for examination methods, and SNT-TC-1A (ASNT recommended practice for qualification of non-destructive examination personnel). Acceptance criteria are specified in each section, or in some cases are quoted from ASTM. Various sections of the 1995 version of the ASME code are:

Section	**Title**
I	Power Boilers
II	Material Specifications
Part A: Ferrous materials	
Part B: Non-ferrous materials	
Part C: Welding rods, electrodes and filler metals	
III	Subsection NCA: General requirements for division 1 and division 2
III	Division 1
Subsection NB: Class 1 components	
Subsection NC: Class 2 components	
Subsection ND: Class 3 components	
Subsection NE: Class MC components	
Subsection NF: Component supports	
Subsection NG: Core support structures	
Appendices	
III	Division 2: code for concrete reactor vessels and containments.
IV	Heating boilers
V	Non-destructive examination
VI	Recommended rules for care and operation of heating boilers
VII	Recommended rules for care of power boilers
VIII	Division 1: Pressure vessels
VIII	Division 2: Alternative rules

IX Welding and brazing qualifications
X Fibreglass-reinforced plastic vessels
XI Rules for in-service inspection of nuclear power plant components

ASME code is available in both bound and loose-leaf versions. Either version may be used for ASME certification.

7.1.3.3 ASME boiler & pressure vessel code section V (1995)

This Section contains a total of 22 articles. Article 1 is introductory and covers general requirements such as manufacturer's examination responsibility, duties of the authorized inspector, written procedures, inspection and examination and qualification of personnel. The balance of Section V is organized into two subsections A and B along with 2 Appendices and an Index, Appendix A contains a Glossary of Terms, and Appendix B the SI Units. Subsection A (Articles 2 to 13) defines the specific NDE methods required by the ASME Code. Subsection B (Articles 22 to 30) contains the basic standards, procedures, and recommended practice documents for each of the NDE techniques as adopted from the American Society for Testing and Materials (ASTM). For example ASTM E 94 becomes SE-94 and ASTM A 609 becomes SA-609. In ASME Code Section V, ultrasonic examination is addressed in Articles 4, 5 and 23.

Article 4: Ultrasonic examination methods for in-service inspection

Article 4 describes or refers to requirements which are to be used in selecting and developing ultrasonic examination procedures and in the dimensioning of indications for comparison with acceptance standards.

Article 5: Ultrasonic examination methods for materials and fabrication

Article 5 describes or refers to requirements which are to be used in selecting and developing ultrasonic examination procedures for welds, parts, components, materials, and thickness determinations. In all cases except welds, the Article refers to Article 23 which contains the appropriate ASTM standards. The examination of welds is specified in considerable details since there is no appropriate ASTM standard on this subject.

Article 23: Ultrasonic standards

Article 23 includes various ultrasonic examination standards for materials such as large forgings, steel plates, castings and pipes (including spiral welding), and for each ultrasonic general technique such as resonance method, straight beam method, and immersion method.

These standards are ASTM standards adopted into ASME standards as they are or with some modification. They are assigned the same number as ASTM with a prefix S added. For example ASTM standards A-388, A-577, A-578, A-548, E-114, E-213, E-214 and E-273, etc. will respectively be designated by ASME as SA-388, SA-577, SA-578, SA-548, SE-114, SE-213, SE-214 and SE-273.

Acceptance criteria

As already stated, acceptance criteria are not specified in Section V, but each code section has to be consulted to find the acceptance criterion for specific cases. The examination is therefore conducted in accordance with the appropriate Article, and acceptance or rejection is determined

in accordance with the referencing code section. As an example, acceptance criteria for welds are specified in the same way in all of the following sections:

Section I, PW-52
Section III, Subsection NB, NB-5330, and
Section VIII, Division 1, Appendix 12 (mandatory)

There are generalized acceptance criteria of these sections that may be summed as follows:

(a) Discontinuities are unacceptable if the amplitude exceeds the reference level, and discontinuities have lengths which exceed:

(i) 1/4 in. (6 mm) for t up to 3/4 in. (19 mm), inclusive.
(ii) 1/3 t for t from 3/4 in. (19 mm) to 2-1/4 in. (57 mm), inclusive.
(iii) 3/4 in. (19 mm) for t over 2-1/4 in. (57 mm).

(b) Where discontinuities are interpreted to be cracks, lack of fusion, or incomplete penetration, they are unacceptable regardless of discontinuity or signal amplitude.

7.1.4 Comparison of ultrasonic testing standards

The general aims and objectives of formulation and issuance of standards have been earlier described in Section 1.5.4. It has also been pointed out in Section 1.5.3 that there are numerous variables which affect the results of an ultrasonic test. The standards for testing of various different types of industrial products therefore essentially lay down the values or range of values and conditions for these variables such that when earnestly followed they will give reliable and reproducible results. But still in spite of having the same objective of producing reliable and reproducible results from the inspection of a specific industrial product, the standards from different countries and standard-issuing bodies tend to have some outstanding differences or in other words, there is lack of harmonization between various standards. Consequently no single standard is fully internationally accepted. It is therefore invariably a matter of agreement between the contracting parties as to which particular standard would be used for a particular job. Nevertheless, in spite of the differences, the standards themselves provide a sound basis for moving forward in the direction of achieving international harmonization in testing practices.

Three of the well known standards used in ultrasonic testing are compared in the followings. These standards are:

(a) Japanese Industrial Standard JIS Z 3060-83 (method for ultrasonic manual testing and classification of test results for ferritic steel welds)

(b) ASME Section V, Article 5 (ultrasonic examination methods for materials and fabrication)

(c) British Standard BS 3923 (methods for ultrasonic examination of welds, part 1: manual examination of welded butt joints in ferritic steels)

7.1.4.1 Scope of application

(a) JIS Z 3060-83

Full penetration groove welds made in ferrite steel with thickness above 6 mm. Circumferential weld seams of radius less than one metre, longitudinal weld seams in

shells of radius less than 1.5 metre. Weld joints of pipe branch connections, and welds in manufacturing process of the steel pipes are excluded.

(b) ASME Section V Article 5

Welds as required by referencing code section.

(c) BS 3923 Part 1

Fusion welded joints in ferrite steels not less than 6 mm thick, excluding nozzle.

7.1.4.2 Personnel qualification

(a) JIS Z 3060-83

Personnel performing ultrasonic examination shall have sufficient knowledge and experience about examining welds and other characteristics in ultrasonic examination including fundamental technique. NDI grade 2 personnel are qualified to perform the examination, while the acceptance shall be determined by NDI grade 1 personnel.

(b) ASME Section V Article 5

Personnel shall be qualified and certified to Level-I or higher in accordance with SNT-TC-1A, Recommended Practice of the American Society for Non-destructive Testing. The acceptance shall be determined by personnel qualified to Level-II or higher.

(c) BS 3923 Part 1

Operator shall have technical competence required by the contractor.

7.1.4.3 Sensitivity (reference level)

(a) JIS Z 3060-83

(i) Usual angle beam method

- STB-A2 block: In cases of 60° and 70° probes, the echo height from ϕ 4 x 4 hole is adjusted to H level of the distance amplitude characteristic curve. In the case of 45° probe, the sensitivity is raised by 6 dB after the adjustment to H level as described above.

- Using RB-4 block: Echo height from the calibration hole is adjusted to H level.

(ii) Reference level for scanning on base material adjacent to the weld, scanning directly on the weld, and for straddle scan is to be as agreed by the customer.

(iii) Tandem scan echo height from a defect free area of the test body is adjusted to M level, and then the sensitivity is raised by 10 dB or 14 dB.

(iv) For straight beam method echo height from the calibration hole of RB-4 block is adjusted to H level.

(b) ASME Section V Article 5

The distance amplitude correction curve is prepared by adjusting the maximum echo height from among side-drilled holes, T/4, T/2, and 3T/4, of the reference block to 80%, and plotting echo height from other holes with the same sensitivity maintained. This curve is used as the reference level.

(c) BS 3923 Part 1

Maximum obtainable without noise disturbance. To be agreed upon between the supplier and purchaser.

7.1.4.4 Preliminary testing (scanning sensitivity)

(a) JIS Z 3060-83

Sensitivity higher than reference level may be employed.

(b) ASME Section V Article 5

Sensitivity twice as large as reference level (at least 6 dB higher), when practicable.

(c) BS 3923 Part 1

Not defined.

7.1.4.5 Specified sensitivity for acceptance (evaluation sensitivity)

(a) JIS Z 3060-83

Reference level.

(b) ASME Section V Article 5

Reference level.

(c) BS 3923 Part 1

Not defined.

7.1.4.6 Construction of DAC

(a) JIS Z 3060-83

(i) Angle beam

H level is determined as the echo height obtained from ϕ 4x4 hole of STB-A2 block or the calibration hole of RB-4 block .The line of H level shall be 40% or higher in the range of beam path distance used in examination.

M Level = H Level - 6 dB
L Level = M Level - 6 dB

(ii) Straight beam

Echo heights from the side-drilled hole, 1/4T of RB-4 block, and that from 3/4T hole are connected by a straight line. Several lines are obtained using different sensitivity. H level shall be the third or higher from the lowest line obtained. In addition, the line of H level shall be 40% or higher in the range of beam path distance used in examination.

M Level = H Level - 6 dB
L Level = M Level - 6 dB

(b) ASME Section V Article 5

Distance amplitude correction curve shall be prepared by adjusting the maximum echo height from among side-drilled holes, T/4, T/2, and 3T/4 to 80% with other echoes plotted with the same sensitivity. Curves of 50% of the above reference are also prepared.

(c) BS 3923 Part 1
Not defined.

7.1.4.7 Couplant

(a) JIS Z 3060-83

Generally, glycerine solution of over 75% density. Adequate couplant shall be selected depending on roughness of scanning surface and frequency used.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Adequate liquid or paste.

7.1.4.8 Base metal examination

(a) JIS Z 3060-83

Straight beam examination is conducted as necessary. Second backwall is adjusted to 80% full screen height.

(b) ASME Section V Article 5

Examined with a straight beam probe covering the entire volume where beams from angle probes will be located. This straight beam examination is not for acceptance or rejection.

(c) BS 3923 Part 1

Entire scanning zone of weld examination shall be covered by straight beam examination (2-6 MHz). Where possible, the third backwall echo shall be adjusted to 100%. If the first back wall echo cannot be maintained at 100% this test shall not be conducted.

7.1.4.9 Shape and size of transducer

(a) JIS Z 3060-83

(i) Angle beam
20 x 20 mm or 10 x 10 mm for 2 (2.25) MHz and 10 x 10 mm for 5(4) MHz.

(ii) Straight beam
20, 25, 30 mm for 2 (2.25) MHz and 10, 20 mm for 5 (4) MHz.

(b) ASME Section V Article 5
Not defined

(c) BS 3923 Part 1

(i) Angle beam
Not defined.

(ii) Straight beam
Area 500 mm^2 or less, with both the length and width to be 25 mm or less.

Frequency of transducer

(a) JIS Z 3060-83
2 (2.25) or 5 (4) MHz

(b) ASME Section V Article 5
2.25 MHz (unless otherwise required)

(c) BS 3923 Part 1
1 to 6 MHz

Probe angle

(a) JIS Z 3060-83
Specifies different probe angles for different weld thicknesses as under:

Weld thickness	Probe angle
6-40 mm	70° should be used.
40-60 mm	70° or 60° should be used.
60 mm or more	70° and 45° or 60° and 45° should be used.

(b) ASME Section V Article 5

Not defined.

(c) BS 3923 Part 1

Specifies different probe angles for different weld thicknesses as under:

Weld thickness	Probe angle
35 to 60 mm	45° or 60° should be used.
15 to 35 mm	70° should be used.
6 to 15 mm	80° should be used.

Approach distance

(a) JIS Z 3060-83

Size of transducer (mm)	Nominal angle of refraction (degrees)	Approach distance (mm)
20 x 20	45 60 70	25 30 30
10 x 10	45 60 70	15 18 18

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Not defined.

Resolution of angle beam probes

(a) JIS Z 3060-83

Resolution shall be 15 dB or more when specified test holes of STB-A2 block are measured.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1

Resolution shall be measured using a reference block for this purpose in the same manner as specified for straight beam in BS 2704.

Resolution of straight beam probe

(a) JIS Z 3060-83

Expressed in terms of supplement 3 of JIS Z 2344, it shall be:

Test frequency (MHz)	Classification
2 (2.25) 5 (4)	A or B A

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Shall be checked as required in BS 2704.

Dead zone

(a) JIS Z 3060-83

(i) Angle beam

Transducer size (mm)	Frequency (MHz)	Dead zone
10 x 10	2 (2.25) 5 (4)	25 mm or less 15 mm or less
20 x 20	2 (2.25) 5 (4)	30 mm or less ---

(ii) Straight beam

Frequency (MHz)	Dead zone
2 (2.25) 5 (4)	15 mm or less 15 mm or less

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Not defined.

7.1.4.16 Maximum sensitivity

(a) JIS Z 3060-83

(i) Angle beam

Expressed in terms of appendix 5 of JIS Z 2344, it shall be:

Angle of refraction (degrees)	A2 sensitivity (dB)	A1 sensitivity (dB)
45	40	40
60	20	40
70	20	40

(ii) Straight beam
Expressed in terms of appendix 4 of JIS Z 2344, gain margin shall be 30 dB or more.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1

With echo height from a curvature of 100 R adjusted to 75% of full screen height, gain margin shall be as follows:

40 dB for plate thickness 75 mm or less.
50 dB for pate thickness exceeding 75 mm.

7.1.4.17 Characteristics of instrument

Frequency range

(a) JIS Z 3060-83

2 (2.25) MHz and 5 (4) MHz

(b) ASME Section V Article 5
1 to 5 MHz

(c) BS 3923 Part 1

Not defined, except that transducer shall be 1 to 6 MHz.

Amplitude linearity

(a) JIS Z 3060-83

Expressed in terms of appendix 1 of JIS Z 2344, class 1 or 2.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1

Within 1 dB in the range of 10-50% of full scale.

Time base linearity

(a) JIS Z 3060-83

Within 1% of full scale as expressed in terms of appendix 2 of JIS Z 2344.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1

1% or less of full scale.

Stability against source voltage

(a) JIS Z 3060-83

For normal voltage variation in power source used, change in sensitivity shall be within 1 dB, shifts in ordinate and time base shall be within ±2% of full scale.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Not defined.

Stability against environmental temperature

(a) JIS Z 3060-83

When ambient temperature deviates 20°C, changes in echo height and time base shall be within ±2 dB and ±2% respectively, for each 10°C deviation.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Not defined.

Cathode ray tube

(a) JIS Z 3060-83

Rise-up and top of echo shall be clearly indicated.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Shall be clear and easy to read.

Graticule

(a) JIS Z 3060-83

Both ordinate and time base shall be of linear scale.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Shall be permanent scale marking covering both range and amplitude.

Attenuator

(a) JIS Z 3060-83

One step shall be 2 dB or smaller, total attenuation 50 dB or larger, and error within ±1 dB for total.

(b) ASME Section V Article 5
Shall be stepped to ±20% or ±2 dB.

(c) BS 3923 Part 1
2 dB steps for the control range used for examination. Accuracy shall be within ±1 dB.

Examination procedure

(a) JIS Z 3060-83

General

(b) ASME Section V Article 5
Description is rather simple. Details are not clear in some area.

(c) BS 3923 Part 1
Detailed description is provided for preliminary examination.

Sensitivity correction (transfer method)

(a) JIS Z 3060-83

Sensitivity shall be corrected when scanning surface is rough, or attenuation is great.

(b) ASME Section V Article 5

No sensitivity correction is required because sensitivity is set using a reference block ultrasonically equivalent to the material tested.

(c) BS 3923 Part 1
Not defined.

Flaws to be evaluated

(a) JIS Z 3060-83

When M level is used as the disregard level, indications, echo height of which exceeds M level. When L level is used, indications exceeding L level.

(b) ASME Section V Article 5
Indications exceeding the distance amplitude correction curve corresponding to 20% of reference level.

(c) BS 3923 Part 1
Not defined.

Indicated defect length

(a) JIS Z 3060-83

The area where the echo height exceeds L level is obtained, and the longer length thereof is measured to the accuracy of 1 mm. When plate thickness is 75 mm or larger, and a search unit of 2 (2.25) MHz is used, the distance of probe movement where 50% of the maximum echo height is exceeded shall be measured.

(b) ASME Section V Article 5
Not particularly defined, but generally the length where the distance amplitude correction curve corresponding to 100% or 50% of reference level is exceeded.

(c) BS 3923 Part 1
Difference between distance of movement where indication does not decrease by more than 20 dB from the maximum echo height, and the effective beam width.

Classification of types of defects

(a) JIS Z 3060-83

Not defined.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Defects are classified into three types; isolated pores, elongated cylindrical flaws and planar flaws.

Classification of test results

(a) JIS Z 3060-83

Not defined.

(b) ASME Section V Article 5
Not defined.

(c) BS 3923 Part 1
Not defined.

Acceptance criteria

(a) JIS Z 3060-83

Not defined.

(b) ASME Section V Article 5
Not defined in Section V but in various referencing sections.

(c) BS 3923 Part 1
Not defined.

7.2 TESTING PROCEDURES

Most of the codes and standards relating to ultrasonic testing require the documentation of a written procedure of the examination to be carried out. The procedure outlines, in principle, the scope, purpose, responsibilities, applicable specifications and the technical details of the examination. In other words the procedure is the examination in written form. The procedure must be sufficiently complete and concise to:

(i) Ensure that any competent examiner can perform an examination which would be virtually identical to that performed by an equally competent examiner, i.e. the procedure must ensure the repeatability of examination.

(ii) Allow an auditor or inspector, through its review, to make a reasonable assessment of the examination to be performed prior to the actual performance. This process can save much time by helping to make certain that the finished examination will be acceptable.

The procedure must contain all of the technical details necessary for the performance and repeatability of the examination. These are:

(i) Equipment to be used.

(ii) Scanning procedure to be used.

(iii) Calibration procedures to be used.

(iv) Data to be recorded and techniques for its recording.

(v) Methods of recording data along with samples of data record sheets used in recording data.

Details of (i) to (iii) will be described here in subsequent sections while Chapter 8 should be consulted for details of (iv) and (v). A general procedure for ultrasonic testing has also been given in Section 6.1.2.2.

7.2.1 Selection of equipment

The equipment to be specified in the procedure for carrying out an ultrasonic test must have at least the following characteristics:

(i) For most of the weld inspection the ultrasonic instrument should be capable of generating frequencies over the range of at least 1 MHz to 5 MHz. Instruments operating at other frequencies may be used if equal or better sensitivity can be demonstrated. The equipment should be equipped with stepped gain control calibrated in steps of 2 dB or less.

(ii) The ultrasonic instrument should provide linear vertical presentation within ±5% of full screen height for 20% to 80% of the calibrated screen height (baseline to maximum

calibrating point(s)). The check on the linearity should be made at the beginning of each period of extended use or every three months whichever is less.

(iii) The ultrasonic instrument should utilize an amplitude control accurate over its useful range to ±20% of the nominal amplitude ratio, to allow measurement of indications beyond the linear range of the vertical display on the screen. The check on the amplitude control linearity should be made at the beginning of each period of extended use or every three months whichever is less.

(iv) The proper functioning of the equipment should be checked and the equipment should be calibrated by the use of the calibration standard at the beginning and end of each examination, when examination personnel are changed or at any time that malfunctioning is suspected, as a minimum. If during any check it is determined that the test equipment is not functioning properly, all of the product that has been tested since the last valid equipment calibration shall be re-examined.

(v) Probes used during the examination may contain either single or dual transducer element. Probes with contour contact wedges may be used to aid ultrasonic coupling. Calibration, in such a case, should be done with contact wedges used during the examination. Optimum angle, shape and size of probes are determined by the specific applications. Angle of the probe used should be such as to hit the expected flaw perpendicularly. The probes used in weld testing are usually round, square or rectangular, and their recommended sizes range from 6 mm diameter or 6 mm square to 30 mm diameter or 30 mm square.

7.2.2 Position and direction of scan

The procedure written for a particular test assignment should indicate the surfaces on which the specimen is to be scanned, the extent to which the scan is to be made and the direction and speed of scanning. The surface on which the scan is to be made is known as the examination surface, and it is to be scanned in such a way so as to scan the entire examination volume. To fulfil this requirement, according to ASME Section V, each scanning pass of the probe should overlap a minimum of 10% of the probes piezoelectric crystal dimension perpendicular to the direction of the scan, and the speed of scanning should not exceed 6 in/sec (15 mm/sec) unless calibration is verified at higher scanning speeds.

7.2.3 Calibration

The calibration section of a procedure for an ultrasonic test assignment should, according to ASME Section V, be in line with the following recommendations:

(i) Calibration should include complete ultrasonic examination system.

(ii) The original calibration must be performed on the basic calibration block (see Chapter 5).

(iii) Checks should be made to verify the sweep range (time base) and distance amplitude correction of the entire examination system.

(iv) In all calibrations, it is important that maximum indications be obtained with the sound beam oriented perpendicular to side-drilled holes and notches.

(v) The centre line of the probe should be at least 40 mm from the nearest side of the block, as rotation of the beam into the corner formed by the hole and the side of the block may produce a higher amplitude at a longer beam path. This beam path should not be used for calibration.

(vi) For contact examination, the temperature of the examination and basic calibration block surfaces should be within 25°F.

(vii) For immersion examination, the couplant temperature for calibration should be within 25°F of the couplant temperature used in actual scanning or appropriate compensations for angle and sensitivity changes shall be made.

(viii) Each calibration should be performed from the surface (clad or unclad) corresponding to the surface of the component from which the examination will be performed.

(ix) For angle beam probe the calibration should provide the following measurements:

(a) Sweep range (time base) calibration.

(b) Distance amplitude correction.

(c) Position calibration.

(d) Echo amplitude measurement from the surface notch in the basic calibration block.

(e) Beam spread both in horizontal and vertical planes. These data are intended for use in comparing successive sets of system calibration data. A further intent is to have these data available as more sophisticated methods of flaw sizing are developed. However, this calibration should only be done when ultrasonic testing is applied for the in-service inspection of a vessel.

(f) When an electronic distance amplitude correction device is used, the primary reference response should be equalized at a nominal constant screen height at or between 40 to 80% of full screen height over the distance range to be employed in the examination.

(x) The method of calibration of a normal beam probe should provide the following measurements:

(a) Sweep range calibration.

(b) Distance amplitude correction.

(c) When an electronic distance amplitude correction device is used, the primary reference response should be equalized at a nominal constant screen height at or between 40 to 80% of full screen height over the distance range to be employed in the examination.

(xi) A calibration check on at least two of the basic reflectors in basic calibration block or a check using a simulator should be made at the finish of each examination, every 4 hours during the examination, and when examination personnel (except for mechanized

equipment) are changed. The sweep range and distance amplitude correction should satisfy the following requirements:

(a) If any point on the DAC curve has moved on the sweep line more than 10% of the sweep division reading, then sweep range calibration should be corrected, and this correction should be noted in the examination record. If recordable reflectors are noted on the data sheet, test data sheet should be voided, a new calibration should be recorded, and the voided examination should be repeated.

(b) If any point on the DAC curve has decreased 20% or 2 dB of its amplitude, all data sheets since the last valid calibration or calibration check shall be marked void. A new calibration should be made and the void examination areas should be re-examined. If any point on the DAC has increased more than 20% or 2 dB of its amplitude, all recorded indications since the last valid calibration or calibration check should be evaluated with the corrected calibration and their value should be changed on the data sheet.

(xii) When any part of the examination system is changed, a calibration check should be made on the basic calibration block to verify that 1/4, 1/2 and 3/4 T points on the sweep and DAC curve values recorded satisfy the requirements of (xi) a & b.

(xiii) During calibration, any control that affects the instrument linearity (e.g. filter, reject, etc.) should be in the off or minimum position for linearity check, calibration and examination.

(xiv) Any simulator checks that are used should be corrected with the original calibration on the basic calibration block used during the original calibration. The simulator checks may use different types of calibration reflector or block (such as IIW) and or electronic simulation. However, the simulation used shall be completely identifiable on the calibration sheet(s). The simulator check should be made on the entire examination system. The entire examination does not have to be checked in one operation, however, for its check the probe should be connected to the ultrasonic instrument and checked against a calibration reflector. Accuracy of the simulation check should be confirmed, using the basic calibration block at the conclusion of each period of extended use or every three months whichever is less. The calibration confirmation of (xi) a & b should be met.

7.3 SOME ULTRASONIC TESTING STANDARDS

7.3.1 American Society of Mechanical Engineers (ASME)

Standard no.	**Title**
B & PV Code	Non-destructive Examination.
Section V-95	Article 1 : General requirements Article 4 : Ultrasonic examination methods for in-service inspection Article 5 : Ultrasonic examination methods for materials and fabrication Article 23 : Ultrasonic standards.

ASME Sec. III	NB-2530 : Examination and repair of plate NB-2540: Examination and repair of forging and bar NB-2542: Ultrasonic examinations. NB-2552 : ultrasonic examination of repair of seamless and welded tubular products and fittings NB-2572: Ultrasonic examination of ferritic steel castings. NB-2580 : Examination of bolts, studs and nuts. NB-2584 : Ultrasonic examination for sizes greater than 2 in (50 mm) NB-2585 : Ultrasonic examination for sizes over 4 in (100 mm). NB-5330 : Ultrasonic acceptance standards
ASME Sec. VIII	AM-203.1 : Ultrasonic examination, plate material. AM 203.3: Ultrasonic examination, forgings. Appendix VII : Examination of steel casting UA 82 (3) : Ultrasonic examination. AM 252.2 : Ultrasonic examination for steel casting. ASME Sec. VIII Pressure vessels Appendix XII : Ultrasonic examination of weld joints. Appendix IX : Non-destructive examination Article 9-3 : Ultrasonic examination of welds. PW 52 : Acceptance standard for ultrasonic examination. ASME Sec. XI Rules for in-service inspection of nuclear power plant components IWA-2232 : Ultrasonic examination of class 1 and 2 ferritic steel piping system.

7.3.2 American Society for Testing and Materials (ASTM)

Standard no.	**Title**
A 20-78	General requirements for steel plates for pressure vessels S8 : ultrasonic examination in accordance with A435.
A 21-78	Carbon steel axles, nonheat-treated and heat treated, for railway use 8 : Ultrasonic inspection.
A 25-77	Wrought steel wheels for electric railway service 11.4 : Ultrasonic test.
A 202-78	Pressure vessel plates, alloy steel, Cr-Mn-Si.
A 203-78	Pressure vessel plates, alloy steel, Ni.
A 204-78	Pressure vessel plates, alloy steel, Mo.
A 225-78	Pressure vessel plates, alloy steel, Mn-V.
A 290-78	Carbon and alloy steel forgings for rings for reduction gears, supplementary requirements S3.2 : Ultrasonic test.

A 291-78	Carbon and alloy steel forgings for pinions and gears for reduction gears, supplementary requirements S3.2 : Ultrasonic examination.
A 299-78	Pressure vessel plates, alloy steel, Mn-Si.
A 302-78	Pressure vessel plates, alloy steel, Mn-Mo and Mn-Mo-Ni.
A 338-78	Seamless and welded titanium and titanium alloy tubes condensers and heat exchangers 10.3 : Non-destructive electric or ultrasonic test.
A 353-78	Pressure vessel plates, alloy steel, 9% Ni double normalized and tempered.
A 369-76	Carbon and ferritic alloy steel forged and bored pipe for high-temperature service S3 : Ultrasonic test.
A 372-78	Carbon and alloy steel forgings for thin-walled pressure vessels, supplementary requirements S5 : Ultrasonic examination.
A 376-77	Seamless austenitic steel pipe for high-temperature central-station service S6 : Ultrasonic test.
A 387-78	Pressure vessel plates, alloy steel, Cr-Mo.
A 388-94	Ultrasonic examination of heavy steel forgings.
A 403-78	Wrought austenitic stainless steel piping fittings S6 : Ultrasonic test.
A 418-94	Test method for ultrasonic inspection of turbine and generator steel rotor forgings.
A 426-75	Centrifugally cast ferritic alloy steel pipe for high-temperature service S8 : Ultrasonic test.
A 430-77	Austenitic steel forged and bored pipe for high-temperature service S6 : Ultrasonic testing.
A 435-90	Specification for straight-beam ultrasonic examination of steel plates for pressure vessels.
A 442-78	Pressure vessel plates, carbon steel, improved transition properties.
A 452-75	Centrifugally cast austenitic alloy steel cold-wrought pipe for high-temperature service S8 : Ultrasonic test.
A 460-77	Vacuum-treated steel forgings for generator rotors 7.3 : Ultrasonic inspection.

A 470-78	Vacuum-treated carbon and alloy steel forgings for turbine rotors and shafts 7.3 : Ultrasonic inspection.
A 471-70	Vacuum-treated alloy forgings for turbine rotor disk and wheels 7.3 : Ultrasonic inspection.
A 503-75 (94)	Ultrasonic examination of large forged crankshafts.
A 504-77	Wrought carbon steel wheels 15.5 : Ultrasonic examination
A 508-78	Quenched and tempered vacuum-treated carbon and alloy steel forgings for pressure vessels 7.3 : Ultrasonic-I inspection.
A 511-77	Seamless stainless steel mechanical tubing S3 : Non-destructive tests.
A 515-78	Pressure vessel plates, carbon steel, for intermediate and higher temperature service.
A 516-78	Pressure vessel plates, carbon steel, for moderate and lower temperature service.A 517-78 Pressure vessel plates, alloy steel, high-strength, quenched and tempered.
A 521-76	Steel, closed-impression die forgings for general industrial use S5 : Ultrasonic tests.
A 531/A 531 M-91	Practice for ultrasonic inspection of turbine-generator steel retaining rings
A 533-78	Pressure vessel plates, alloy steel, quenched and tempered Mn-Mo and Mn-Mo-Ni.
A 537-78	Pressure vessel plates, heat treated C-Mn-Si steel.
A 538-77	Pressure vessel plates, alloy steel, precipitation hardening (maraging) 18% Ni.
A 540-77a	Alloy-steel bolting materials for special applications S3 : Ultrasonic test.
A 541-78	Steel forgings, carbon and alloy quenched and tempered, for pressure vessel components S2 : Ultrasonic inspection.
A 542-78	Pressure vessel plates, alloy steel, quenched and tempered Cr-Mo.
A 543-78	Pressure vessel plates, alloy steel, quenched and tempered Ni-Cr-Mo.
A 552-76	Forged or rolled 8 and 9% nickel alloy steel, flanges, fittings, valves, and parts for low-temperature service S1.1 : Ultrasonic tests.
A 553-78	Pressure vessel plates, alloy steel, quenched and tempered 8 and 9% Ni.

A 556-76	Seamless cold-drawn carbon steel feedwater heater tubes S1 & S2 : Non-destructive ultrasonic testing.
A 557-76	Electric-resistance-welded carbon steel feedwater tubes S1 : Non-destructive ultrasonic testing.
A 562-78	Pressure vessel plates, alloy steel, Mn-Ti for glass or diffused metallic coatings.
A 577-77	Ultrasonic, angle-beam examination of steel plates.
A 578-77	Straight-beam ultrasonic examination of plain and clad steel plates for special applications.
A 579-77	Superstrength alloy steel forgings 6.4 : Ultrasonic inspection.
A 583-77	Cast steel wheels for railway service 8.2 : Ultrasonic testing.
A 587-78	Electric-welded low-carbon steel pipe for the chemical industry 6 : Non-destructive test.
A 590-77	Pressure vessel plates, alloy steel, precipitation- hardening (maraging), 12% Ni.
A 600-76	High-speed tool steel S2 : Ultrasonic quality.
A 605-77	Pressure vessel plates, alloy steel, quenched and tempered Ni-Co-Mo-Cr.
A 609-78	Longitudinal beam ultrasonic inspection of carbon and low-alloy steel castings.
A 612-78	Pressure vessel plates, carbon steel, high strength for moderate and lower temperature service.
A 613-76	Special requirements for steel castings for nuclear and other special applications 2.2 : RZ Ultrasonic examination.
A 614-76	Special requirements for bolting material for nuclear and other special applications 14 : RZ Ultrasonic examination.
A 631-74	Cast steel wheels for electrical railway service 11.6 : Ultrasonic inspection.
A 645-78	Pressure vessel plates, 5% Ni alloy steel, specially heat treatment.
A 646-77	Premium quality alloy steel blooms and billet for aircraft and aerospace forgings 7.3 : Non-destructive testing, ultrasonic inspection
A 652-77	Special requirements for wrought steel welding fittings for nuclear and other special applications 17 : UZ Ultrasonic examination.

A 654	Special requirements for steel forgings and bars for nuclear and other special applications 2.1 : RZ Ultrasonic examination.
A 655-77	Special requirements for pipe and tubing for nuclear and other special applications 17 : RZ Ultrasonic examination.
A 658-77	Pressure vessel plates, alloy steel, 36% Ni.
A 660-76	Centrifugally cast carbon steel pipe for high-temperature service S8 : Ultrasonic tests.
A 662-78	Pressure vessel plates, C-Mn for moderate and lower temperature.
A 668-78	Steel forgings, carbon and alloy, for general industrial use S7: Ultrasonic test.
A 671-77	Electric-fusion-welded steel pipe for atmospheric and lower temperatures S10 : Straight beam ultrasonic examination of flat plate - UT1 S11 : Straight beam ultrasonic examination of flat plate - UT2 S12 : Angle beam ultrasonic examination (plate less than 2 in. (50.8 mm) thick) - UT3.
A 672-77	Electric-fusion-welded steel pipe for high-pressure service at moderate temperatures S10 : Straight beam ultrasonic examination of flat plate - UT1 S11 : Straight beam ultrasonic examination of flat plate - UT2 S12 : Angle beam ultrasonic examination (plate less than 2 in. (50.8 mm) thick) - UT3.
A 681-76	Alloy tool steels S1 : Ultrasonic quality.
A 686-73	Carbon tools steels S1 : Ultrasonic quality.
A 691-77	Carbon and alloy steel pipe, electric-fusion-welded for high-pressure service at high-temperatures S7 : Ultrasonic test.
A 703-77	General requirements applicable to steel castings for pressure-containing parts S7 : Ultrasonic inspection.
A 707-76	Flanges, forged, carbon and alloy steel for low-temperature service 14 : Ultrasonic examination S8 : Additional ultrasonic test requirement.

A 711-74	Carbon and alloy steel blooms, billets and slabs for forging S12 : Ultrasonic examination.
A 723-77	Alloy steel forgings for high-strength pressure component applications 8.1 : Ultrasonic examination.
A 724-78	Pressure vessel plates, carbon steel, quenched and tempered, for welded layered pressure vessels.
A 729-77	Alloy steel axles, heat-treated, for mass transit and electric railway service 8 : Ultrasonic inspection.
A 735-78	Pressure vessel plates, low carbon Mn-Mo-Cb alloy steel, for moderate and lower temperature service.
A 736-78	Pressure vessel plates, low carbon age hardening Ni-Cr-Mo-Cb alloy steel.
A 737-78	Pressure vessel plates, high-strength, low-alloy steel.
A 745-77	Ultrasonic examination of austenitic steel forgings.
B 350-73	Zirconium and zirconium alloy ingots for nuclear applications 9 : Ultrasonic test.
B 353-77	Wrought zirconium and zirconium alloy seamless and welded tubes for nuclear service 12 : Ultrasonic inspection Annex A3 : Recommended procedure for ultrasonic testing of zirconium and zirconium alloy tubing for nuclear service Appendices: X1 : An advisory guide to transducer selection X2 : An advisory guide to transducer positioning.
B 495-77	Zirconium ingots for non-nuclear applications 7 : Ultrasonic test
B 509-77	Supplementary requirements for nickel alloy plate for nuclear applications 5 : RZ Ultrasonic examination.
B 510-77	Supplementary requirements for nickel alloy rod and bar for nuclear applications 6 : RX Ultrasonic examination.
B 513-79	Supplementary requirements for nickel alloy seamless pipe and tube for nuclear applications 6 : RZ Ultrasonic examinations.
B 515-79	Welded nickel-iron-chromium alloy tubes 6.5 : Non-destructive tests.

B 516-79	Welded nickel-chromium-iron alloy (UNS No. 6600) tubes 6.4 : Non-destructive tests.
B 517-79	Welded nickel-chromium-iron alloy (UNS No. 6600) pipe 6.3 : Non-destructive tests.
B 521-74	Tantalum and tantalum alloy tubing 7.1 : Ultrasonic test.
B 548-90	Method for ultrasonic inspection of aluminium alloy plate for pressure vessels.
B 594-74	Ultrasonic inspection of aluminium-alloy wrought products for aerospace applications.
C 597	Test method for pulse velocity through concrete.
D 2845-90	Test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock.
D 2966	Test method for cavitation erosion corrosion characteristics of aluminium in engine coolants using ultrasonic energy.
E 49	Measuring ultrasonic velocity in materials.
E 113-74	Ultrasonic testing by the resonance method
E 114-85	Ultrasonic pulse-echo straight-beam testing by the contact method
E 127-75	Fabricating and checking aluminium alloy ultrasonic standard reference blocks.
E 164	Ultrasonic contact inspection of weldments.
E 213-93	Ultrasonic inspection of metal pipe and tubing for longitudinal discontinuities.
E 214-68(91)	Practice for immersed ultrasonic testing by the reflection method using pulsed longitudinal waves.
E 273-93	Ultrasonic inspection of longitudinal and spiral welds of welded pipe and tubing.
E 317-79	Evaluation performance characteristics of ultrasonic pulse-echo testing system without the use of electronic measurement instruments.
E 428-92	Practice for fabrication and control of steel reference blocks used in ultrasonic inspection.
E 453-79(90)	Recommended practice for examination of fuel element cladding including he determination of the mechanical properties.

E 494-95	Practice for measuring ultrasonic velocity in materials.
E 500-74	Ultrasonic testing (standard definitions of terms).
E 587-94	Practice for ultrasonic angle beam examination by the contact method.
E 588-88	Practice for detection of large inclusions in bearing quality steel by the ultrasonic method.
E 664-93	Practice for the measurement of the apparent attenuation of longitudinal ultrasonic waves by immersion method
E 797-94	Practice for measuring thickness by manual ultrasonic pulse-echo contact method
E 1001-90	Practice for detection and evaluation of discontinuities by the immersed pulse-echo ultrasonic method using longitudinal waves
E 1065-92	Guide for evaluating characteristics of ultrasonic search units
E 1158-90 (94)	Guide for materials selection and fabrication of reference blocks for the pulsed longitudinal wave ultrasonic examination of metal and metal alloy production material
E 1315-93	Practice for ultrasonic examination of steel with convex cylindrically curved entry surfaces
E 1324-92	Guide for measuring some electronic characteristics of ultrasonic examination instruments
E 1454-92	Guide for data fields for computerized transfer of digital ultrasonic testing data
F 600	Non-destructive ultrasonic evaluation of socket and butt joints of thermoplastic piping.
G 46	Recommended practice for examination and evaluation of pitting corrosion.

7.3.3 International Institute of Welding (IIW)

Standard no.	**Title**
IIW VC 148-69/OE	Characteristics of ultrasonic flaw detection equipment
IIS/IIW-127-64	Behaviour of ultrasonic waves in the presence of various defects in welds.
IIS/IIW-205-66	Draft recommended practice for the ultrasonic inspection of butt welds.

IIS/IIW-278-67	Recommended procedure for the determination of certain ultrasonic pulse-echo equipment characteristics by the IIW calibration block.
IIS/IIW-310-68	Limitations inherent in the use of ultrasonic for the examination of welds.
IIS/IIW-675-81	Ultrasonic techniques for the quantitative evaluation of weld defects and their limitations.

7.3.4 International Organization for Standardization (ISO)

Standard no.	**Title**
ISO 2400-1972	Welds in Steel - reference block for the calibration of equipment of ultrasonic examination.
ISO-4386	Non-destructive testing.
Part 1-92	Ultrasonic testing of bond in metallic multilayer plain bearings
ISO-7963-85	Welds in steel - calibration block No. 2 for ultrasonic examination of welds.
ISO-9303-89	Seamless and welded (except submerged arc-welded) steel tubes for pressure purposes - full peripheral ultrasonic testing for the detection of longitudinal imperfections.
ISO-9305-89	Seamless steel tubes for pressure purposes - full peripheral ultrasonic testing for the detection of transverse imperfection.
ISO-9764-89	Electric resistance and induction welded steel tubes for pressure purposes - ultrasonic testing of the welded seam for the detection of longitudinal imperfections.
ISO-9765-90	Submerged arc-welded steel tubes for pressure purposes - ultrasonic testing of the weld seam for the detection of longitudinal and/or transverse imperfections.
ISO-10124-94	Seamless and welded (except submerged arc-welded) steel tubes for pressure purposes - ultrasonic testing for the detection of laminar imperfections.
ISO-10332-94	Seamless and welded (except submerged arc-welded) steel tubes for pressure purposes - ultrasonic testing for the verification of hydraulic leak tightness.
ISO-10543-93	Seamless and hot-stretch-reduced welded steel tubes for pressure purposes - full peripheral ultrasonic thickness testing.
ISO-11496-93	Seamless and welded steel tubes for pressure purposes - ultrasonic testing of tube ends for the detection of laminar imperfections.

ISO-12094-94	Ultrasonic testing for the detection of laminar imperfections in strips/plates used in the manufacture of welded tubes.

7.3.5 German Standards Organization (Deutsches Institut für Normung) (DIN)

Standard no.	Title
DIN 54119-81	Ultrasonic testing definitions.
DIN 54120-73	Ultrasonic calibration block No. 1 and its use for adjusting and checking ultrasonic pulse-echo equipment.
DIN 54122	Ultrasonic calibration block No. 2 and its use for the adjustment and control of ultrasonic pulse-echo equipment.
DIN-54123-80	Non-destructive testing - ultrasonic method of testing claddings, produced by welding, rolling and explosion.
DIN-54124-1-83	Non-destructive testing - control of properties of ultrasonic test systems - simple controls.
DIN-54125-89	Non-destructive testing - manual ultrasonic examination of welded joints.
DIN-54126-2-82	Non-destructive testing - rules for ultrasonic testing - requirements for test systems and test objects.
DIN-54127-1-89	Non-destructive testing - calibration of ultrasonic flaw detection equipment echo height evaluation.
DIN EN 583-1-92	Ultrasonic examination - general principles.
DIN EN 583-3-94	Non-destructive testing - ultrasonic examination - transmission technique.
DIN EN 1330-4-95	Non-destructive testing - terminology - terms used in ultrasonic testing.
DIN EN 1713-95	Non-destructive examination of welds - ultrasonic examination - characterization of imperfections in welds.
DIN EN 1714-95	Non-destructive testing of welds - ultrasonic examination of welded joints.
DIN EN 10228-3-95	Non-destructive testing of steel forgings - ultrasonic testing of ferritic or martensitic steel forgings.
DIN EN 10246-15-95	Non-destructive testing of steel tubes - ultrasonic testing of strip/plate used in the manufacture of welded steel tubes for the detection of laminar imperfections.
DIN EN 12062-95	Non-destructive examination of welds - general rules.

AD HP 5/3-89	Manufacture and testing of joints - non-destructive testing of welded joints.
AD HP 5/3 Anlage	Non-destructive testing of welded joints - minimum requirement for 12-89 non-destructive testing methods.

7.3.6 British Standards Institution (BSI)

Standard no.	Title
BS 1881	Testing concrete Part 203-86 : Recommendations for measurement of velocity of ultrasonic pulses in concrete.
BS 2704-83	Specification for calibration block for use in ultrasonic flaw detection.
BS 3059-78	Steel boiler and superheater tube Part 2 Appendix A: Ultrasonic testing of tubes for longitudinal defects.
BS 3683	Glossary of terms used in non-destructive testing Part 4-85 : Ultrasonic flaw detection.
BS 3686	Glossary of terms used in non-destructive testing. Part 4: Ultrasonic flaw detection.
BS 3889	Methods for non-destructive testing of pipes and tubes. Part 1A: ultrasonic testing of ferrous pipes (excluding cast).
BS 3915-65	Carbon and low alloy steel pressure vessels for primary circuits of nuclear reactors Appendix D : Ultrasonic inspection of plates.
BS 3923	Methods for ultrasonic examination of welds. Part 1 : Manual examination of fusion welded butt joints in ferritic steels. Part 2 : Automatic examination of fusion welded butt joints in ferritic steels.
BS 4080-66	Methods for non-destructive testing of steel castings.
BS 4124-91	Methods for ultrasonic detection of imperfections in steel forgings.
BS 4331	Method for assessing the performance characteristics of ultrasonic flaw detection equipment. Part 1 : Overall performance, on-site methods Part 2 : Electrical performance Part 3 : Guidance on the in-service monitoring of probes (excluding immersion probes).
BS 4336-68	Methods for non-destructive testing of plate material. Part 1A: Ultrasonic detection of laminar imperfections in ferrous wrought plate.

BS 4408-74	Recommendations for non-destructive methods of test for concrete. Part 5: 1974 measurement of the velocity of ultrasonic pulses in concrete.
BS 5500-76	Unfired fusion welded pressure vessels 5.6.6.2: Ultrasonic techniques 5.7: Acceptance criteria for weld defects revealed by visual examination and non-destructive testing.
BS 5996-93	Specification for acceptance levels for internal imperfections in steel plate, strip and wide flats, based on ultrasonic testing.
BS 6072-86	Method for magnetic particle flaw detection.
BS 6208-90	Methods for ultrasonic testing of ferritic steel castings including quality levels.
BS 7585	Metallic multilayer plain bearings Part 1-92 : Method for non-destructive ultrasonic testing of bond.
BS 7706-93	Guide to calibration and setting up of the ultrasonic time of flight diffraction (TOFD) technique for the detection, location and sizing of flaws.
BSM 36-84	Method for ultrasonic testing of special forgings by an immersion technique using flat-bottom holes as reference standard.
BSEN 27963-92	Specification for calibration block No. 2 for ultrasonic examination of welds.
DD 28	Method of ultrasonic inspection of turbines and compressor discs using the AVG diagram technique.
DTD 936	Ultrasonic inspection of aluminium alloy forgings.
DTD 937	Ultrasonic inspection of aluminium alloy plate.
M 36	Ultrasonic testing of special forgings by an immersion technique using flat bottom holes as reference standard.

7.3.7 Japanese Industrial Standards Committee (JISC)

Standard no.	**Title**
JIS B 8240-79	Construction of refrigerant pressure vessels 7.8.6 : Ultrasonic testing.
JIS B 8242-77	Construction of horizontal LP gas storage tank 9.2.2 : Ultrasonic testing.

JIS B 8243-77	Construction of pressure vessels 12.8.6 : Ultrasonic testing.
JIS B 8501-76	Construction of steel oil storage tank Section 7, Appendix 6 : Ultrasonic testing for welds.
JIS G 0582-90	Ultrasonic examination for steel pipes and tubes.
JIS G 0584-90	Ultrasonic examination for arc welded steel pipes.
JIS G 0587-87	Methods for ultrasonic examination for carbon and low alloy steel forgings.
JIS G 0601-77	Testing methods of clad steel 5 : Ultrasonic testing.
JIS G 0801-93	Ultrasonic examination of steel plates for pressure vessels.
JIS G 3601-77	Stainless-clad steel 10 : Condition of joint 12.4 : Range of flaw detectors.
JIS G 3602-80	Nickel and nickel alloy clad steel 9 : Condition of joint 11.4 : Range of flaw detectors.
JIS G 3604-80	Copper and copper alloy clad steel 10 : Condition of joint 12.5 : Range of flaw detectors.
JIS H 0516-92	Ultrasonic inspection of titanium pipes and tubes.
JIS Z 2344-93	General rules for ultrasonic testing of metals by the pulse-echo technique Appendix 1: Measurement & classification of amplifier linearity Appendix 2: Measurement of time-base linearity Appendix 3: Measurement & classification of far-field resolution Appendix 4: Measurement of gain margin Appendix 5: Measurement of characteristics of angle-beam probe.
JIS Z 2345-94	Standard test blocks for ultrasonic testing.
JIS Z 2350-92	Method for measurement of performance characteristics of ultrasonic probes.
JIS Z 2351-92	Method for assessing the electrical characteristics of ultrasonic testing instrument using pulse echo technique.
JIS Z 2352-92	Method for assessing the overall performance characteristics of ultrasonic pulse echo testing instrument.
JIS Z 2353-91	Methods for measurement of ultrasonic velocity in solids by pulse technique using reference test pieces.

JIS Z 2354-92	Method for measurement of ultrasonic attenuation coefficient of solids by pulse technique.
JIS Z 2355-94	Methods for measurement of thickness by ultrasonic pulse technique.
JIS Z 3031-75	Non-destructive testing symbols for welds.
JIS Z 3050-78	Method of non-destructive inspection for weld of pipeline 4.3 : Ultrasonic testing.
JIS Z 3060-94	Method for ultrasonic examination for welds of ferritic steel.
JIS Z 3061-83	Method of ultrasonic manual testing for ferritic steel welds on curved materials.
JIS Z 3062-88	Methods of ultrasonic examination for gas pressure welds of reinforcing deformed bats.
JIS Z 3080-95	Methods of ultrasonic angle beam examination for butt welds of aluminium plates.
JIS Z 3081-94	Methods of ultrasonic angle beam examination for welds of aluminium pipes and tubes.
JIS Z 3082-95	Methods of ultrasonic examination for T type welds of aluminium plates.
JIS Z 3871-87	Standard qualification procedure for ultrasonic testing technique of aluminium and aluminium alloy welds.
NDIS 0601-77	Rules for certification of non-destructive testing personnel.
NDIS 2001-83	Ultrasonic testing terms.
NDIS 2103-74	Graticule for ultrasonic flaw detector
NDIS 2105-76	Evaluation of performance characteristics of portable pulse-echo ultrasonic thickness meter.
NDIS 2305-78	Standard test block type A21 and A22 used in ultrasonic angle beam testing.
NDIS 2406-76	Ultrasonic in-service inspection of outdoor oil storage tank.
NDIS 2407-76	Methods for automatic ultrasonic testing of steel welds.
NDIS 2408-79	Measuring method of thickness by portable pulse echo ultrasonic thickness meter.
NDIS 2410-79	Ultrasonic tandem test method and classification of test results for steel welds.

NDIS 2411-80	Standard method of ultrasonic examination and classification of examination results for carbon and low alloy steel forgings.

7.3.8 Standards Association of Australia (SAA)

Standard no.	Title
AS 1065-88	Non-destructive testing - ultrasonic testing of carbon and low alloy steel forgings.
AS 1633-85	Acoustics - glossary of terms and related symbols.
AS 1929-81	Non-destructive testing - glossary of terms.
AS 2083-81	Calibration blocks and their methods of use in ultrasonic testing.
AS 2207-94	Non-destructive testing - ultrasonic testing of fusion welded joints in carbon and low alloy steel.
AS 2452	Non-destructive testing - determination of thickness.
AS 2452.3-85	Use of ultrasonic testing.
AS 2565-82	Non-destructive testing - ultrasonic testing of steel castings and classification of quality.
AS 3670-89	Non-destructive testing - ultrasonic testing of universal beams and columns.
AS 3788-90	Boilers and pressure vessels - in-service inspection.

7.3.9 Standards Council of Canada

Standard no.	Title
CGSB 48-GP-6a	Recommended practices for ultrasonic inspection of structural welds.
CGSB 48-GP-7M	Certification of non-destructive testing personnel (industrial ultrasonic method).
CGSB CAN/CGSB 48.7-93	Certification of non-destructive testing personnel (industrial ultrasonic method)
CSA CAN3-N285.4-M83	Periodic inspection of CANDU nuclear power plant components.

CSA CAN3-N287.7-M80	In-service examination and testing requirements for concrete containment structures for CANDU nuclear power plants.
CSA CAN/CSA-N28.5-M90	Periodic inspection of CANDU nuclear power plant containment components.
CSA CAN/CSA-N285.6.6-88	Inspection criteria for zirconium alloys.
CSA CAN/CSA-N286.0-92	Overall quality assurance programme requirements for nuclear power plants.
CSA CANCSA-N286.4-M86	Commissioning quality assurance for nuclear power plants.
CSA N287.5-93	Examination and testing requirements for concrete containment structures for CANDU nuclear power plants.

7.3.10 American Petroleum Institute (API)

Standard no.	**Title**
API 5A-79	Casing, tubing and drill pipe Sec. 10 : Inspection and rejection.
API 5AC-79	Restricted yield strength casing and tubing Sec. 10 : Inspection and rejection.
API 5AX-76	High-strength casing, tubing and drill pipe Sec. 10 : Inspection and rejection.
API 5L-78	Line pipe Sec. 9 : Non-destructive inspection.
API 5LS-78	Spiral-weld line pipe Sec. 7 : Non-destructive inspection.
API 5LU-78	Ultra high-test heat treated line pipe Sec. 7 : Non-destructive inspection.
API 5LX-78	High-test line pipe Sec. 7 : Non-destructive inspection.

7.3.11 Miscellaneous standards

Standard no.	**Title**
AA 1979 (Aluminium Standard and Data)	Ultrasonic standard for plate; extruded, rolled or cold finished bar and shape; and forgings and rings.

Architectural Institute of Japan, Standards-79	Ultrasonic testing for welds of steel structures for buildings.
ANSI B 31.1-77	Power piping 136.4.6 : Technique and acceptance standards for ultrasonic examination.
ANSI B 31.3-76	Chemical plant and petroleum refinery piping 336.4.6 : Ultrasonic examination.
ANSI B 31.7-69	Nuclear power piping 1-736.5.3 : Ultrasonic examination of welds Appendix B-2 : Methods for ultrasonic examination of welds.
AWS A 2.4-79	Symbols for welding and non-destructive testing
AWS D 1.1-81	Structural welding code (steel)
DD 21-72(Drafts for development of BS)	Sec. 6 : Inspection, Part C : Ultrasonic testing of groove welds. Quality grading of steel plate from 12 mm to 150 mm thick for development by means of ultrasonic testing
JEAC 3202-79	Standards for non-destructive inspection of steam turbine rotors of thermal power plants Sec. 2 : Ultrasonic testing.
JEAC 4205-74	In-service inspection of coolant pressure boundary in nuclear vessels.
JEAC 4701-73	Standards for nuclear pressure vessels 3.9.1(1) : Ultrasonic testing of plates. 3.9.2(1) : Ultrasonic testing of forgings and bars. 3.9.3(2) : Ultrasonic testing of castings. 3.9.4(3) : Angle beam ultrasonic testing of pipes and tubes. 3.9.5(2) : Ultrasonic testing of bolts. 6.2.2 : Ultrasonic testing of weld joint. 6.2.3 : Ultrasonic testing of clad bond.
JFSS 13-75	Standards for ultrasonic inspection of marine forgings.
JRS (1957) (Workshop Dept.)	Standards for ultrasonic inspection of axles.
MIL I-8950 B # I-70	Process for ultrasonic inspection of wrought metals.
MIL U 81055-64	General specifications for ultrasonic immersion inspection of wrought metals.

MITI Notification No. 374	Notification for details of vessel construction in refrigerant facilities Art. 8 : Ultrasonic testing.
MITI Notifications No. 501	Details for structure of nuclear power plant facilities Article 7 : Straight beam ultrasonic testing. Article 8 : Angle beam ultrasonic testing.
MITI Ordinance No. 81	General rules for welding of electric construction Art. 30 : Ultrasonic testing Art. 31 : Ultrasonic testing of clad bond.
MITI Ordinance No. 4	Testing rules for special facilities.
NAKS 0001-79	Ultrasonic inspection standard for gas pressure weld.
SAE J 428a-72	Ultrasonic inspection.
WSP 008-72	Ultrasonic testing for welds of water service steel pipes.

8. RECORDING AND EVALUATION OF TEST RESULTS

8.1 SIGNIFICANCE OF DEFECTS AND NEED FOR PROPER EVALUATION OF RESULTS

It is a fact that there are inherent flaws in materials due to crystal lattice imperfections and dislocations howsoever microscopic they may be in size. Further flaws may come from the manufacturing processes such as welding, casting, forging and surface treatment, etc. (Section 1.3). The materials have to perform under various conditions of stress, fatigue and corrosion, etc. Because of these conditions additional defects may be created or those already present may be aggravated. It has also been established by now that most material failures take place due to these defects reaching dangerous sizes such that the remaining parts of materials cannot withstand the stresses to which they are subjected and therefore fail in a ductile or brittle manner.

There is, therefore, a need firstly to detect these flaws and secondly to evaluate them in terms of their nature, size and location. A further step should be to assess as to how severe and dangerous these flaws are in their present state and whether they need to be removed by repairing the tested component or whether the component is to be scrapped or can the product with these known flaws still be allowed to go into service? This process of judgement and decision is termed as "evaluation" and is, in fact, replacing the concept of non-destructive testing (NDT) by non-destructive evaluation (NDE).

Evaluation should really mean two things. First to make sure that no components with unacceptable level of defects are able to escape inspection and go into service because this, as has been said earlier at numerous places, can lead to catastrophic failures. Second, it is equally

important that components known to have such defects which are not considered to be dangerous for the particular service are not stopped from going into service as this can mean colossal production and material losses. Accordingly there are two basic requirements, firstly to find reliably and accurately the defects in terms of their nature, size and location and secondly to make judgement and decision on their further treatment. The first requirement is met by utilizing appropriate NDT methods for detection and determination of nature, size and location of defects while for the second the judgement of suitability or fitness for purpose is exercised with the help of acceptance standards. The judgement is also made by following a more rigorous fracture mechanics approach wherein the size of the flaw specially a crack is studied under various load conditions and its behaviour response predicted through calculations.

8.2 RECORDABILITY OF DEFECTS

We may start with explaining the concept of flaw detection sensitivity in NDT. This is simply the ability or capability of an NDT technique to detect flaws. If a particular technique can detect minute defects it is said to have a good or high sensitivity while, on the other hand, if it can only detect gross or larger defects it is said to have a poor or low sensitivity.

It is important that the sensitivity of flaw detection chosen is compatible with the requirements of inspection. This means that if, for example, it is required to be able to detect internal flaws of 1 mm size in a particular fabrication then the technique of ultrasonic testing should be such that it would be able to detect this size of flaws under normal circumstances with reliability and reproducibility. Some of the general factors which need to be kept in view include marking of the test specimen and its specific area being inspected in a particular test with a unique identification number. This number is cross referred to the inspection report of the specimen and helps in rectification of the defect if desired or in its periodic monitoring. The objects needing inspection should be segregated and partitioned. This will help in ensuring the certainty and correctness of the test results which are pre-requisite for their reliability. The inspector must know the background of the specimen, its manufacturing history and material. This combined with a knowledge of the technique of testing can help in proper interpretation of test indications.

The sensitivity of flaw detection for ultrasonic testing method is dependent upon the type of the specimen, its geometry and shape, grain structure and surface condition; nature, type, orientation and location of defects; probe characteristics such as frequency, dead zone, near zone and beam divergence; viscosity and acoustic impedance of the couplant; equipment characteristics such as range, resolution and pulse shape; calibration test blocks and procedures; scanning and evaluation procedures and the operator qualifications, skill and experience.

An ultrasonic flaw detector must be set at a minimum level of sensitivity since this is the only means whereby echoes of otherwise uncertain significance can be translated into meaningful information. In principle, the choice of a sensitivity level is based on the reflectivity of the smallest flaw that is to be found at the maximum test range.

Two sensitivities are used during an inspection: the evaluation sensitivity and the scanning sensitivity. The evaluation sensitivity (or reference sensitivity) is the instrument setting which produces a reproducible signal amplitude from a reference artificial reflector with which the instrument setting relating to a discontinuity echo can be compared. The evaluation sensitivity can also be called the Primary Reference Echo (PRE) level. Scanning sensitivity is used during the preliminary scanning of a test piece to locate all discontinuity echoes which have to be assessed at the evaluation sensitivity stage. It is set by increasing the amplification of the

instrument from the evaluation sensitivity instrument settings by a specified amount, e.g. 6 dB. The commonly used methods of setting evaluation sensitivity are described in Section 5.

When a defect is detected during the scan of the specimen, then the next step is that whether it is recordable or not. This means that the defect should be further investigated in terms of its location, size and nature or it should be ignored. For this purpose every standard procedure of ultrasonic testing specifies a certain record level. Record levels of most of the standards such as ASME Code, API-1104 is 20% of the DAC curve or reference level.

In AWS D1.1 (1988), the recordability of a defect depends on the weld thickness and probe angle. In DGS diagram method any defect which gives an echo which is equal to or in excess of the recording curve is recordable.

8.3 DATA TO BE RECORDED

According to most of the ultrasonic standards such as ASME Section V (Article-5), AWS D1.1 (1988) and API-1104 (1994) used during fabrication when a defect is declared recordable, the following characteristics of the defect should be determined: (i) nature of the defect, (ii) length of the defect, and (iii) its reflectivity in dB value above or below the DAC curve or reference level. These characteristics are required for acceptance or rejection of a defect.

The ultrasonic standards which are used during pre-service inspection (PSI) or in-service inspection (ISI) require more extensive data of the defect. The characteristics of the defect which are required to be recorded according to ASME Section V (Article-4) are: (i) the nature, (ii) the depth, (iii) the height or through thickness, and (v) the length of the defect.

Table 8.1 shows how the data is to be recorded for 120% DAC reflector (Figure 8.1) according to Article-4 of ASME Section V.

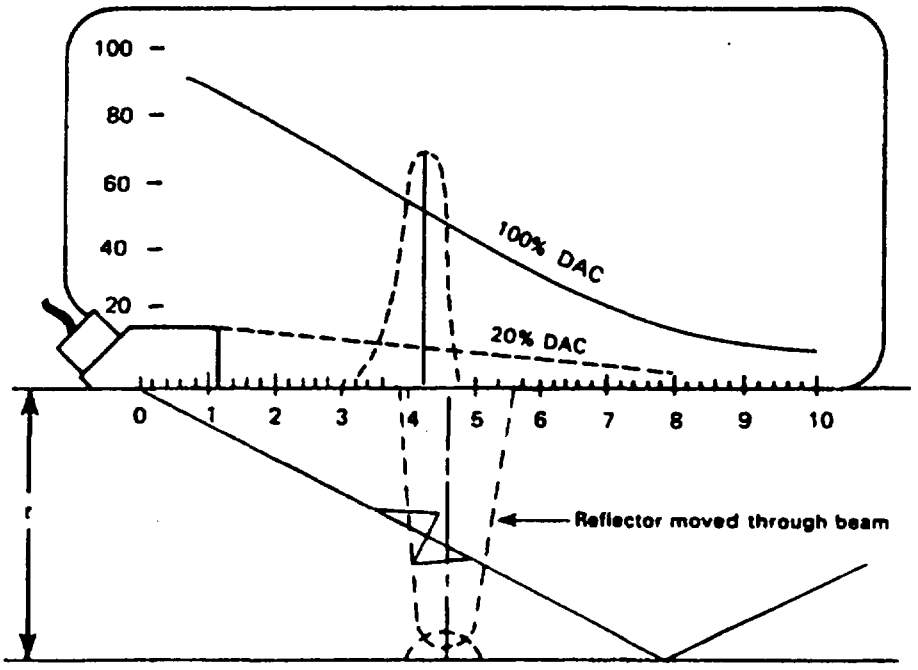


Figure 8.1 : Reflector reading.

TABLE 8.1: RECORDING OF DATA OF A FLAW ACCORDING TO ARTICLE-4, ASME SECTION-V

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	
		Search Unit		20% DAC				% of t		
				Minimum		Maximum			Distance	
Maximum %DAC	Sweep Reading	Position in.	Location in.	Sweep Reading	Position	Sweep Reading	Position	Depth	From Surface	Computation or Remarks
120	4.0	4.6	23	3.6	4.2	4.4	5.2	10	45	(4.4-3.6)/8.0
80	4.0	4.6	22.1	3.8	4.3	4.2	4.8	5	47.5	(4.2-3.8)/8.0
20	4.0	4.6	21.7	...	...	...	...	0	50	.....
90	4.1	4.7	23.9	3.7	4.3	4.3	5.2	7.5	46	(4.3-3.7)/8.0
70	4.1	4.7	24.8	3.9	4.4	4.3	5.2	5	46	(4.3-3.9)/8.0
20	4.2	4.6	25	...	...	...	...	0	50	.....
										depth: 10% t
										length: 3.3 in.

8.4 CHARACTERIZATION OF DEFECTS

8.4.1 Defect location

The location of a defect which has been detected can be read directly from the screen of a flaw detector which has been properly calibrated. In the case of normal probes the location of a defect below the surface is given directly as may be seen from Figure 8.2. But in the case of angle probes the location below the surface has to be calculated from a knowledge of the beam path length and the probe angle.

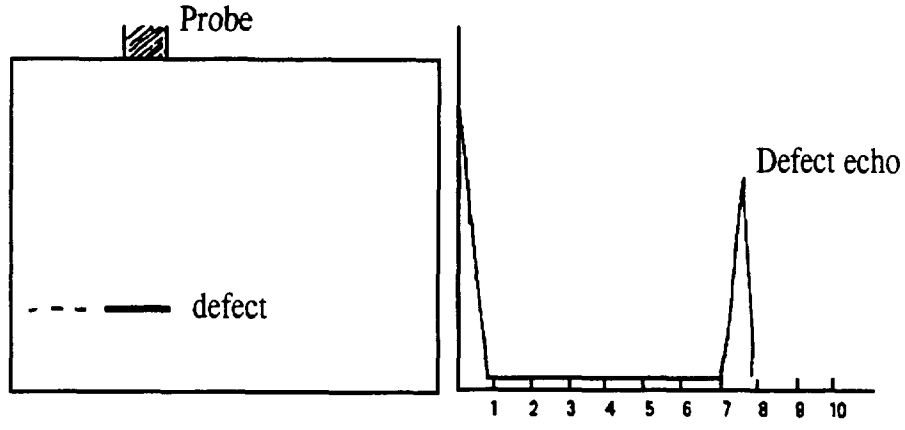


Figure 8.2 : Defect location with a normal beam probe.

For example in Figure 8.3, d/R = cos θ, where "d" is the depth of the defect below the surface, "θ" is the probe angle and "R" is the length of the sound beam path to the defect. "R" is also called 'range' and is read directly from the calibrated screen by noting the position of the defect echo. The location of the defect below the surface can then be determined by calculating "d". Defect location in welding is usually done using a flaw location slide. Defect location can also be determined by producing an accurate sketch or by calculation. It is also necessary to report

the location of the defect along the surface of the specimen with respect to some drawn or reference point.

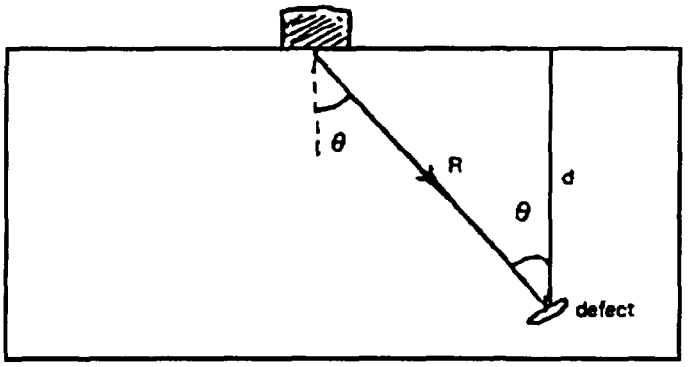


Figure 8.3 : Defect location with an angle beam probe along with defect depth.

8.4.2 Defect sizing

Defect sizing is generally done in terms of echo amplitudes. There are three methods commonly used for the echo amplitude evaluation. These are reference block method, DGS diagram method, and the scanning method. The first two methods are used for the evaluation of echo amplitude resulting from a defect having a size smaller than the size of the ultrasonic beam. The last method is usually used for the echo amplitude evaluation of defects having size larger than the size of the ultrasonic beam.

In reference block method, the echo height in dB with respect to DAC (for construction of DAC, see Chapter 5) is determined and recorded. This is done by changing the setting of the gain control and bringing the echo height to the level of DAC and noting down the value of the new gain control setting. The difference between this new value and PRE (plus transfer loss and attenuation corrections, if any) is the height in dB with respect to DAC. This difference has to be reported in the ultrasonic test report.

In the DGS diagram method, the echo height in dB with respect to the recording curve (for construction of recording curve see Chapter 5) is similarly determined by bringing the echo height to the level of the recording curve using the gain control, the value of the new gain control setting is then noted and its difference with G_{rec} is determined. This difference is the echo height in dB with respect to the recording curve and it should be reported in the ultrasonic test report.

When the defect size is larger than the ultrasonic beam then usually any of the following methods is used for its sizing.

8.4.2.1 Six dB drop method

The basic assumption in this method is that the echo height displayed, when the probe is positioned for maximum response from the flaw, will fall by one half (i.e. by 6 dB and hence the name) when the axis of the beam is brought into line with the edge of the flaw as illustrated in Figure 8.4. The 6 dB method is suitable for the sizing of flaws which have sizes of the same order or greater than that of the ultrasonic beam width but will give inaccurate results with flaws

of smaller sizes than the ultrasonic beam. It is therefore generally used to determine flaw length but not flaw height.

The procedure to determine the dimension of a flaw parallel to the probe movement, i.e. the flaw length, is as follows:

(i) Position the probe to get maximum echo from the flaw;

(ii) adjust the height of the echo to some convenient scale on the CRT screen by using the gain control of the flaw detector;

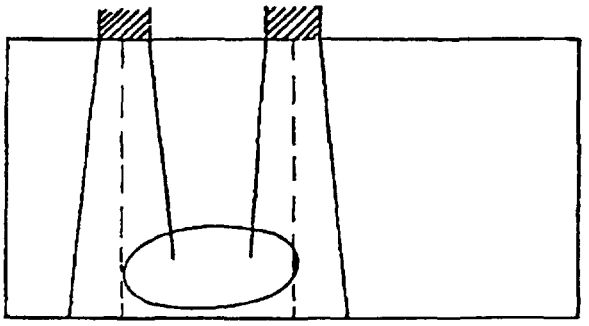


Figure 8.4 : 6 dB drop method.

(iii) move the probe across the flaw in one direction until the echo height falls to one half of the height adjusted in (ii);

(iv) mark the centre of the probe on the surface of the test specimen for this probe position;

(v) now move the probe in the opposite direction through the maximized echo position to the position when the echo height again falls to one half of the height adjusted in (ii);

(vi) mark the probe centre at this position as well;

(vii) the distance between the two marks gives the dimension of the defect parallel to the probe movement.

If the reflectivity of the flaw varies considerably, the probe is moved until the last significant echo peak is observed just before the echo drops off rapidly. This peak is brought to full screen height and then the probe is moved as in (iii). A similar procedure is followed for the other end of the flaw.

The 6 dB drop method is suitable for the sizing of flaws which have sizes of the same order or greater than that of the ultrasonic beam width but will give inaccurate results with flaws of smaller sizes than the ultrasonic beam. It is, therefore, generally used to determine flaw length but not flaw height.

8.4.2.2 Twenty dB drop method

This method utilizes, for the determination of flaw size, the edge of the ultrasonic beam where the intensity falls to 10% (i.e. 20 dB) of the intensity at the central axis of the beam (Figure 8.5).

The detailed procedure to determine the size of the flaw with the 20 dB drop method is as follows:

(i) Position the probe to get a maximum echo amplitude from the flaw;

(ii) adjust the echo amplitude to some convenient scale on the CRT screen using the gain control of the flaw detector;

(iii) move the probe first across the flaw in one direction until the echo amplitude falls to 1/10th of its original height (i.e. by 20 dB);

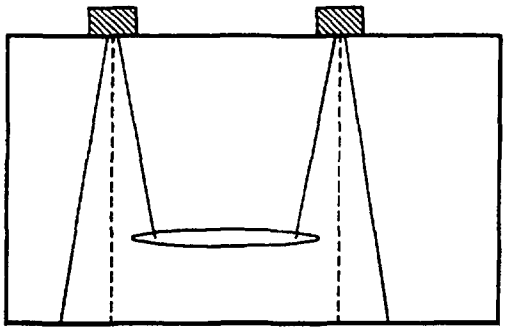


Figure 8.5 : 20 dB drop method.

(iv) mark the position of the probe index on the surface of the test specimen at this position;

(v) now move the probe in the opposite direction through the maximized echo position until the echo amplitude again falls to 1/10th of its original height;

(vi) mark the position of the probe index on the surface at this position;

(vii) measure the distance between the two markings;

(viii) determine the beam width ϕ at the depth, d, of the flaw from the beam profile diagram or from the equation

$$\phi = D + 2\,(d - X_o)\tan\theta \quad \text{----------} \quad (8.1)$$

where,

ϕ = beam width

d = defect depth

X_o = near field length

D = probe diameter

(ix.) (vii) minus (viii) will thus give the dimension of the flaw parallel to the movement of the ultrasonic beam.

The 20 dB drop method gives more accurate results than the 6 dB drop method because of the greater control one has on the manipulation of the ultrasonic beam. However, size estimation using either the 6 dB or 20 dB drop method have inherent difficulties which must be considered. The main problem is that the amplitude may drop for reasons other than the beam scanning past the end of the defect. Some of these reasons are :

(a) The defect may taper in section giving a reduction in cross sectional area within the beam. If this is enough to drop the signal 20 dB or 6 dB, the defect may be reported as finished while it, in fact, continues for an additional distance.

(b) The orientation of the defect may change so that the probe angle is so longer giving maximum response; another probe may have to be used.

(c) The defect may change its direction.

(d) The probe may be twisted inadvertently.

(e) The surface roughness may change.

8.4.2.3 Flaw location slide

The School of Applied Non-Destructive Testing (SANDT) at Cambridge, UK, has developed a flaw location slide for the location and sizing of defects in welds using the 6 dB or 20 dB drop methods. The flaw location slide consists of a beam plotting chart and a transparent cursor. Both parts of a flaw location slide are shown in Figure 8.6 a and b.

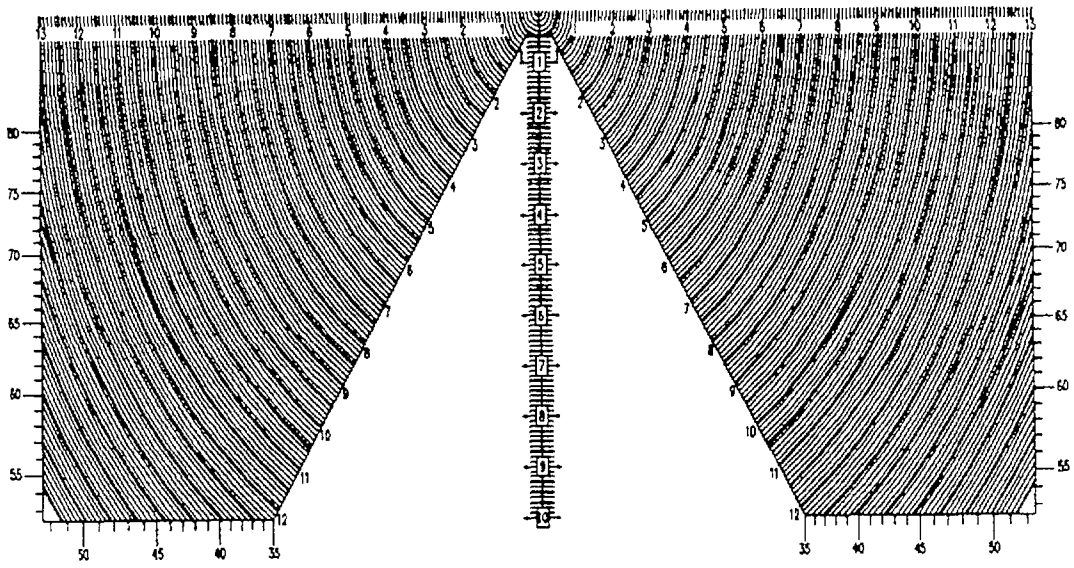


Figure 8.6 a : Beam plotting chart of flaw location slide.

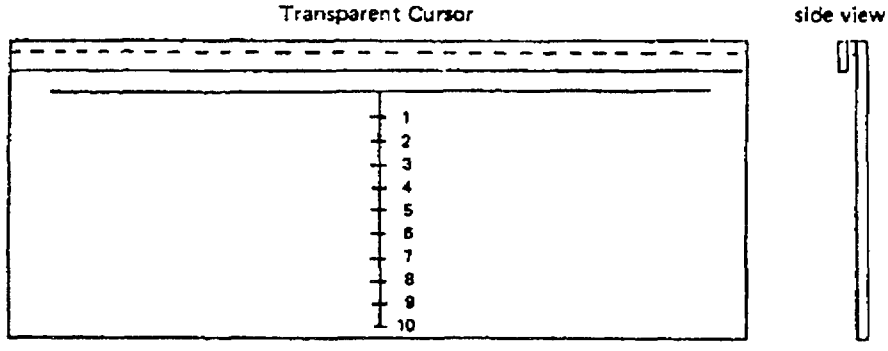


Figure 8.6 b : Transparent cursor of flaw location slide.

Plotting the beam spread (vertical plane) on the flaw location slide

The procedure for plotting the beam spread (vertical plane) on the flaw location slide using the IOW Beam Profile Block is as follows:

(i) Calibrate the time base;

(ii) determine the probe angle and probe index of the probe to be used;

(iii) mark the probe index on the probe;

(iv) draw the probe angle on the beam plotting chart as shown in Figure 8.7;

(v) draw horizontal lines across the beam centre at depths of 13, 19, 25, 32, 43, 50, 56 and 62 mm (Figure 8.7);

(vi) using an I.O.W. beam profile block determine the distances ab and ac (as in vii) and the corresponding beam path lengths (BPL) for each hole;

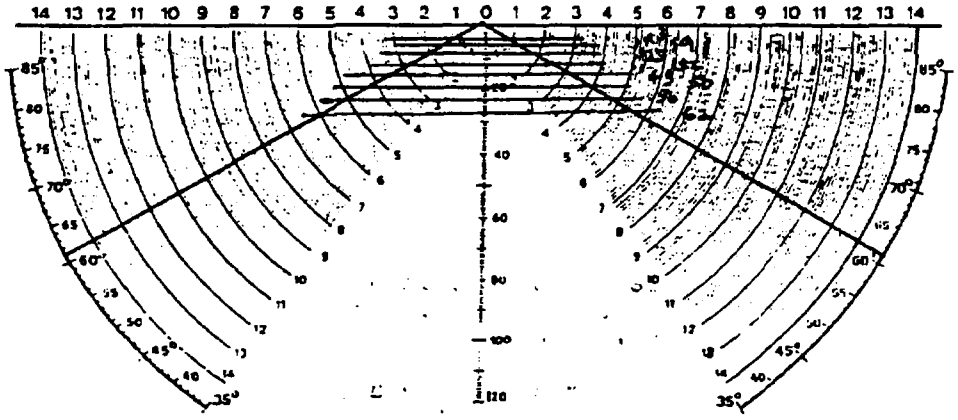


Figure 8.7 : Method for plotting of beam spread using flaw location slide chart.

(vii) Plot points b and c on the beam plotting chart with respect to the point a (point of cross-section of the beam angle and the horizontal lines drawn on the chart for each hole) on the beam plotting chart and draw lines through these points as illustrated in Figure 8.8.

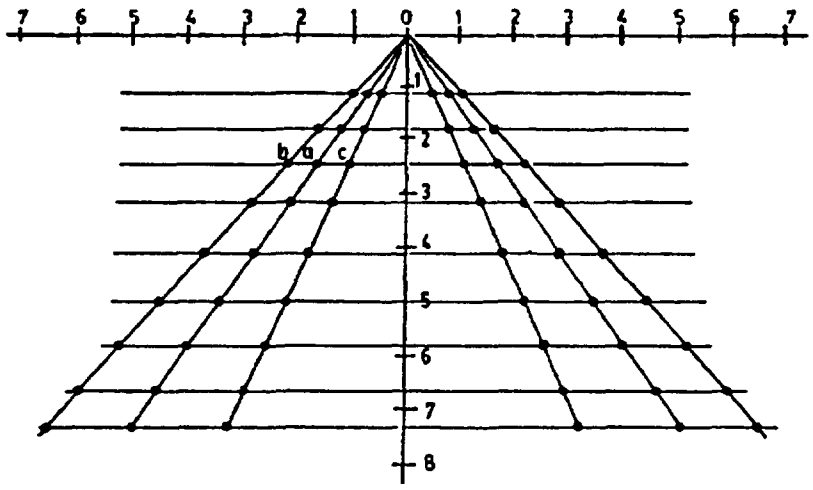


Figure 8.8 : A typical plot of beam profile on the flaw location slide chart.

(viii) Using the procedure outlined above, draw the beam profiles of 45° and 70° probes on one side of the chart and the beam profile of 60° probe on the other side of the chart.

Using the flaw location slide for flaw location in welds

For the location of flaws in welds the flaw location slide is used as follows:

(i) Draw the beam profile (vertical plane) of the probe to be used;

(ii) Draw the scale diagram of the weld preparation and its mirror image, on the transparent cursor as shown in Figure 8.9;

In Figure 8.9 the weld preparation of a single vee weld in 20 mm plate, and its mirror image, is drawn on the cursor;

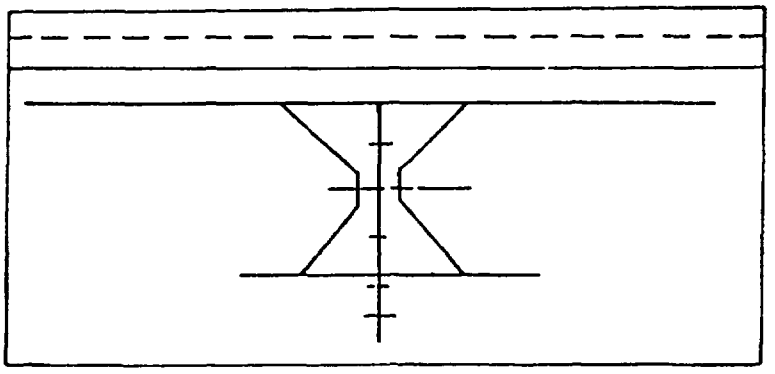


Figure 8.9 : Sketch showing the weld preparation and its mirror image as drawn.

(iii) Let a defect be found in a single vee weld in 20 mm thick plate using a 60° probe. Let the echo of the defect maximize when the probe index is at a distance of 17 mm from the weld centre line. This distance, known as the stand-off distance, is noted along with the beam path length or range from the CRT screen. Let the range for this particular defect be 20 mm. This is illustrated in Figure 8.10.

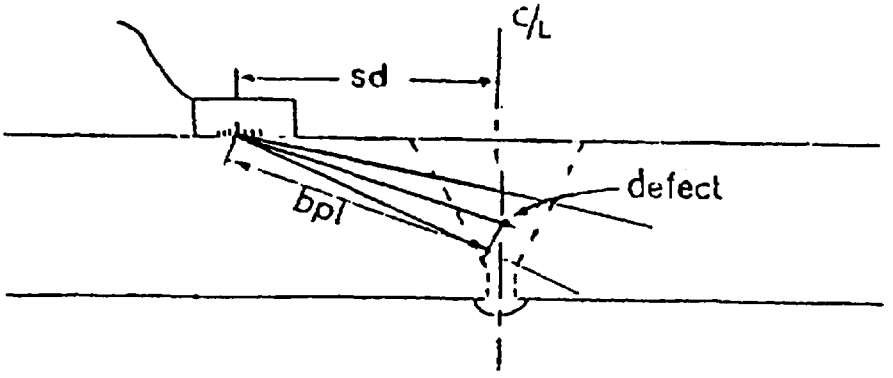


Figure 8.10 : The relevant position of defect, probe, the beam profile and various distances in weld inspection.

(iv) Now set 17 mm on the horizontal scale on the beam plotting chart against the centre line of the cursor, as shown in Figure 8.11;

(v) Against 20 mm down the beam centre line place a fine mark. This is the position of the defect in the weld. In this example it is at the weld centre line and at about half the specimen thickness (Figure 8.11);

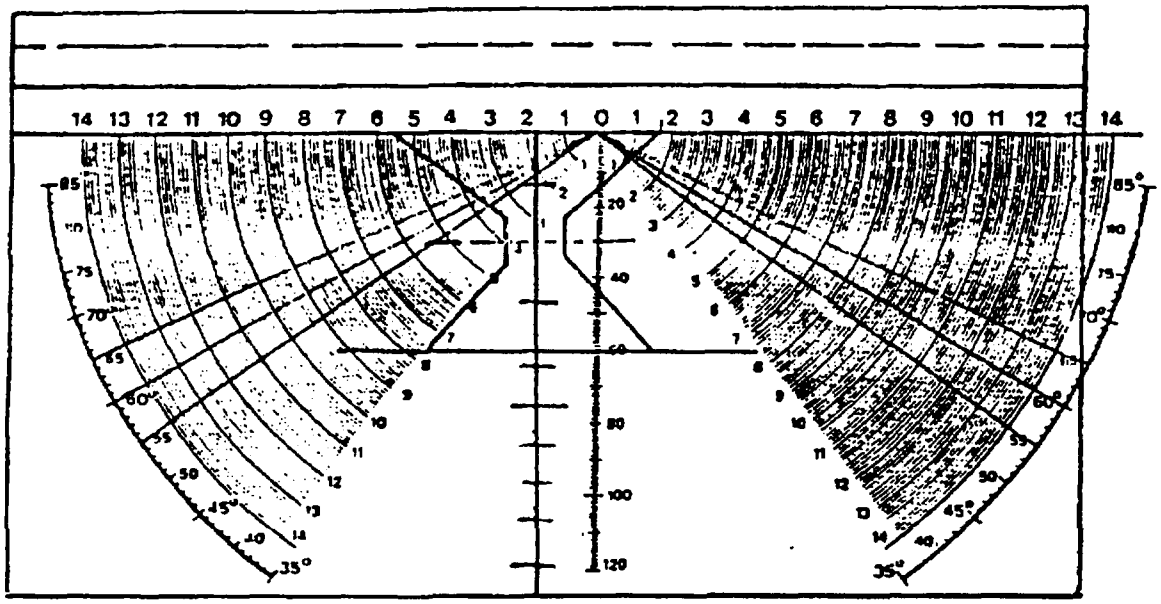


Figure 8.11 : Location of the flaw as shown by the flaw location slide.

(vi) For the location of a flaw, the echo of which maximizes when the probe location is between the 1/2 skip and full skip, use is made of the mirror image of the weld preparation. Let the flaw be detected in the weld by a 60° probe as shown in Figure 8.12;

Let the stand-off distance be 60 mm and the beam path length be 61 mm.

(vii) Align the 60 mm mark on the horizontal scale with the central line of the cursor (Figure 8.12);

(viii) Mark the point 61 mm down the beam centre as shown in Figure 8.12. This point gives the location of the flaw in the weld.

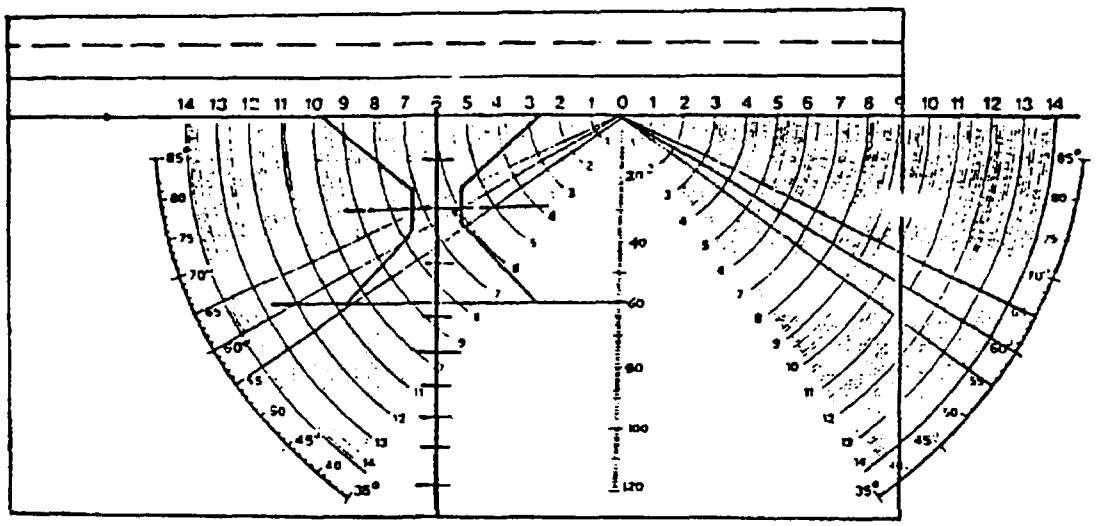


Figure 8.12 : Location of defect as described in 8.1.4.3.2 (vi).

Defect sizing using the flaw location slide

The procedure for determining the size and orientation of a flaw in the vertical plane is as follows:

(i) Find the maximum echo from the defect and plot its position on the transparent cursor using the procedure described in section 8.4.2.3;

(ii) Now move the probe toward the weld centre line from its position of maximum echo until the echo height is reduced by 20 dB;

(iii) Note the stand-off distance and range at this position of the probe;

(iv) Plot this information on the slide as in (i) but this time using the bottom edge of the beam instead of its centre;

(v) Now move the probe away from the weld central line, through the position of maximum echo, until the echo height drops again by 20 dB;

(vi) Note the stand-off and range for this position of the probe;

(vii) Plot this information on the slide using the top edge of the beam this time;

(viii) If the above procedure is used for the sizing of the flaw shown in Figure 8.13 a, the three points on the cursor would have shown the size and orientation of the flaw as illustrated in Figure 8.13 b.

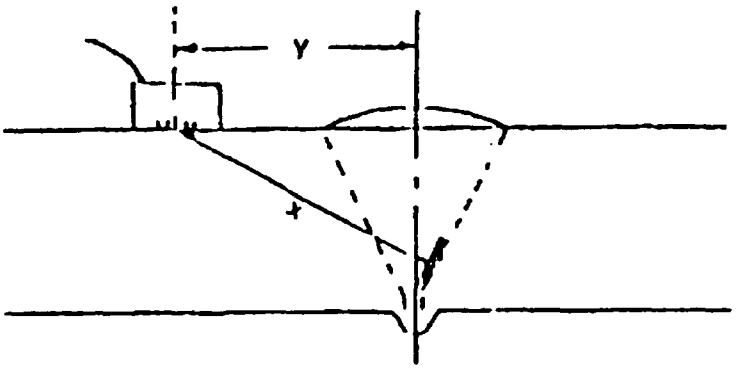


Figure 8.13 a : Probe movement for sizing of defects in welds.

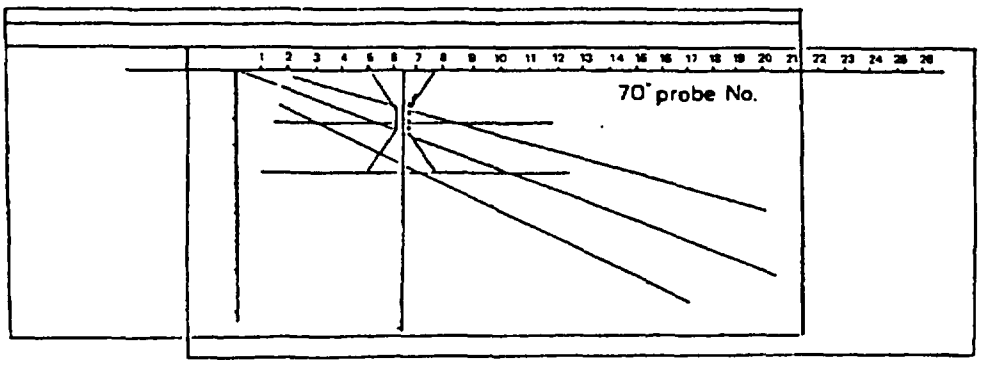


Figure 8.13 b : Flaw size in a weld as indicated on the flaw location slide.

8.4.2.4 DGS diagram method

The DGS diagram method makes use of the so-called DGS diagram, developed by Krautkrämer in 1958 by comparing the echoes from small reflectors, namely different diameter flat bottom holes located at various distances from the probe, with the echo of a large reflector, a back wall reflector, also at different distances from the probe. The difference in the amplitude of echoes of the flat bottom holes and the back wall reflector is determined in decibels, i.e. dB. This diagram relates the distance D from the probe (i.e. along the beam) in near field units thus compensating for probes of different size and frequency, to the gain G in dB for a flat bottom hole (f.b.h.) compared to a particular back wall reflector and the size S of the flat bottom hole as a proportion of the probe crystal diameter (for details see Section 5.8).

For evaluation of flaws using DGS diagrams it should be remembered that the natural flaws such as porosity, foreign materials inclusions, cracks, etc. never have the geometry, shape or orientation like that of the flat bottom holes. Also the echo amplitude of a particular flaw is influenced not only by its size but also by its shape and inclination with respect to the direction of the incoming sound beam, the roughness and other probable parameters. This has given rise to the need of defining the equivalent reflector size (ERS). This is a disc shape reflector such as a flat bottom hole which, if lying perpendicularly to the acoustical axis of the sound beam, will give the same echo height on the screen as the unknown natural flaw. This correlation is allowable as long as the natural flaw is one whose reflection characteristics are similar to that of a disc shaped reflector. This is true of all natural flaws representing small reflectors not exceeding the limits of the sound beam in any direction. The defect evaluation using DGS diagrams is therefore done in terms of ERS and it should always be kept in mind that it does not represent the real size of the flaw.

The procedure for the use of DGS diagrams for evaluation of flaws is as follows:

(i) Determine the flaw echo amplitude in decibels above the reporting level (i.e., above the 2/5th or 80% of full screen height). Let the dB value be A dB;

(ii) Locate the defect depth on the DGS diagram in near field length units for normal beam probes, and mm for angle beam probes. Let the location be marked as X;

(iii) At X determine the dB difference between the record level and attenuation curve already drawn on the DGS diagram. Let this difference be B dB;

(iv) Determine the difference (A-B) dB;

(v) Determine the point of intersection of a line drawn perpendicular to the D-scale at X and the line drawn perpendicular to the G-scale at (A-B) dB;

(vi) Determine the S-value of the curve in the DGS diagram which lies nearest to the point of intersection determined in (v);

(vii) Determine the diameter of the equivalent disc shape reflector in mm as follows:

  (a) for a normal beam probe multiply the S-value by the diameter of the probe crystal;

  (b) for an angle beam probe the S-value itself gives the diameter of the equivalent disc shape reflector.

Example 1 (Normal beam probe):

A steel forging of 200 mm thickness is being tested with a normal probe having a frequency of 2 MHz and a crystal diameter of 10 mm. An assumedly flat bottom hole (f.b.h.) is detected at a depth of 100 mm and its echo amplitude is displayed on the CRT screen. It is required to find out the size of this f.b.h. by evaluating the echo amplitude.

(i) Calculate $N_{steel} = \frac{D^2}{4\lambda} = \frac{D^2 f}{4v} = 8.5$ mm

(ii) Test range in steel, s = 200 mm

(iii) D for back wall $= \frac{200}{8.5} N = 23.5\,N$

(iv) Test range for f.b.h. = 100 mm

(v) D for f.b.h. $= \frac{100}{8.5} N = 11.7\,N$

(vi) In Figure 5.30 draw a line perpendicular to D-axis at 23.5 N and extend it to meet the back wall line (also called the reference line).

(vii) From the point of intersection as in (vi), which is also called the reference point, draw a line perpendicular to the G-axis meeting the G-axis at 23.5 dB.

(viii) Draw also a line perpendicular to the D-axis at 11.7 N.

(ix) Adjust the echo height of the reference reflector (backwall) to say 80% of full screen height (F.S.H). Call this echo height as H, and note the corresponding value of the dB control. Let it be, for example, 14 dB and denoted by G_1.

(x) Without changing the gain look at the echo from the f.b.h. Usually the echo from the f.b.h is much smaller than the reference echo and therefore the difference in amplitudes turns out to be negative.

(xi) Increase the gain until the echo from the f.b.h. also reaches the reference height, i.e. 80% of F.S.H. Say the setting of gain control for this is 34 dB. Call it G_2.

(xii) Thus the echo of the f.b.h. needs an additional increase in gain of 20 dB ($G_2 - G_1$) in order to reach the same screen height as the back wall echo.

(xiii) Locate a point 20 dB below the dB value (as in (vii)) corresponding to reference point (23.5 dB). This is the point 43.5 dB on the G-axis.

(xiv) Draw a line at 43.5 dB and perpendicular to G-axis. Extend this line to meet the line in (viii) at a point.

(xv) Note the S-value corresponding to this point of intersection. This comes out to 0.3.

(xvi) Multiply this value of S in (xv) by the crystal diameter to get the diameter of the f.b.h. This comes out to be 3 mm.

(xvii) The f.b.h. detected at a depth of 100 mm has been evaluated to have a diameter of 3 mm.

Example 2 (Normal beam probe):

Probe frequency = 5 MHz

Probe crystal dia = 10 mm

Sensitivity setting = as described in section 5.7

Near field length = 21 mm

(i) Echo height above the reporting level of 2/5th or 80% of full screen height = 9 dB

(ii) Flaw depth = 42 mm, ($\frac{42}{21}$ = 2 near field length)

(iii) Difference between the record level and the attenuation curve at 4 near field units on DGS diagram of Figure 5.30 is 1 dB.

(iv) Difference between (i) and (iii) = 8 dB

(v) Point of intersection of a line drawn at 2 near field lengths and line drawn at 8 dB lies close to 0.4 S-value line (DGS diagram of Figure 5.30)

(vi) Equivalent disc diameter = 0.4 x 10 = 4 mm

Example 3 (Angle beam probe):

Sensitivity setting = as in Section 5.7

(i) Flaw echo amplitude above the reporting level = 40 dB

(ii) Flaw depth = 50 mm

(iii) Difference between record level and attenuation curve at 50 mm = 12 dB from DGS diagram of Figure 5.31.

(iv) Difference, 40 – 12 = 28 dB

(v) Point of intersection of line drawn perpendicular to the D-scale at 50 mm and the line drawn perpendicular to G-scale at 28 dB above the record level lies close to the 5 mm S-curve.

(vi) Hence the diameter of equivalent disc = 5 mm

8.5 DETERMINATION OF NATURE OF DEFECTS

Response of the nature of a flaw is ascertained by a series of controlled movements of the probe. Different types of probe movements are as shown in Figure 8.14.

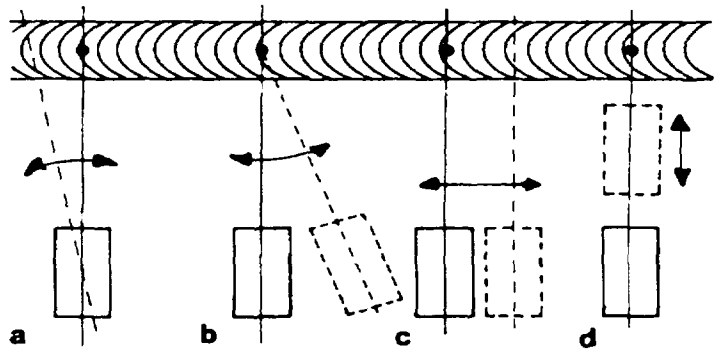


Figure 8.14 : Different types of probe movements; (a) Rotational, (b) Orbital, (c) Lateral, (d) Transverse.

In general, for welds, a flaw can be differentiated as one of the following types.

8.5.1 Isolated pore

A pore, normally being round, is a very poor reflector. Theoretically, only those rays of the beam which hit the pore perpendicularly are reflected to the probe. All rays impacting at an angle are dispersed. Thus, the reflected sound pressure is small as is the echo on the screen (Figure 8.15). The height and shape of this echo does not change when the probe is orbited around the pore at a constant distance even from the other side of the weld seam.

Figure 8.15 : Shape of the echo from a pore.

8.5.2 Porosity

This gives rise to a lot of tiny echoes, depending on the number and distribution of the pores (Figure 8.16).

Figure 8.16 : Shape of echoes from porosity.

In most cases, echo from pore pockets can be distinguished from slag inclusions because the former ones give much smaller echoes whereas the latter ones give high, pine shaped echoes.

During rotational, lateral and transverse scans the echo rises and falls quickly and smoothly as the beam scans through the discontinuity.

8.5.3 *Slag inclusion*

The echo from this flaw can be as high as a crack or lack of fusion but the shape of the echo is quite different. As a result of its rugged surface, which offers many small targets at different distances, the echo rises like a pine tree from the zero line of the screen (Figure 8.17).

Figure 8.17 : Shape of echo from a slag inclusion.

When the probe is orbited around the flaw on both sides of the weld seam the echo height usually will not change; only the branches of the pine tree will show a steady echo signal height over a significant length of scan while a depth scan will show a sharp peak over a short distance. Like pores, slag inclusions have no preferred location in the weld seam.

8.5.4 *Planar defects*

Examples of such defects are cracks and incomplete penetration. They reflect the sound energy totally in a particular direction. The echo height falls off drastically when the probe is orbited around the defect or rotated about its own axis from its position of maximum echo signal (Figure 8.18). Therefore, it should be easy to distinguish a slag inclusion from a planar flaw.

Since cracks, lack of penetration and lack of side wall fusion are all planar flaws, they cannot be differentiated from each other simply by the echo height and shape when being irradiated from one side of the seam. To determine the nature of each flaw with certainty, the location of the flaw in the weld has to be established. Since incomplete penetration and lack of side wall fusion have preferred locations in the weld seam, if a planar flaw is located at the centre of the weld in a single vee butt joint, this flaw will hardly be a lack of side wall fusion. If a planar target is located at the edge of the bead it is probably a lack of side wall fusion. This can be confirmed by irradiating the weld from the other side.

If the flaw is orientated vertically, the echo height will be nearly equal when checking from either side. If it is inclined, the echo height will differ distinctly.

8.5.5 *Miscellaneous*

Although it is easy to recognize a line flaw it is often difficult to decide whether such a flaw is continuous or intermittent. If intermittent, it is even more difficult to determine the extent of the gaps between various portions of the flaw chiefly because of beam spread and the consequent overlapping of successive flaws. The echo height usually fluctuates, the extent of the rise and fall being a function of the length of the gap. A continuous but ragged flaw has a similar effect due to random reflection of the beam. But this can be detected by slight oscillation and swivelling of the probe opposite the point of echo fall. There will then be several points where

the incidence of the beam is most favourable, and echo height will increase sharply. If, however, the flaw is intermittent, the same movements will result in rapid decline of echo height.

With practice, the study of echo response leads to a process of mental integration which enables the UT operator to classify each characteristic sequence with little conscious effort. If necessary, such clarification can be confirmed by suing the flaw location slide.

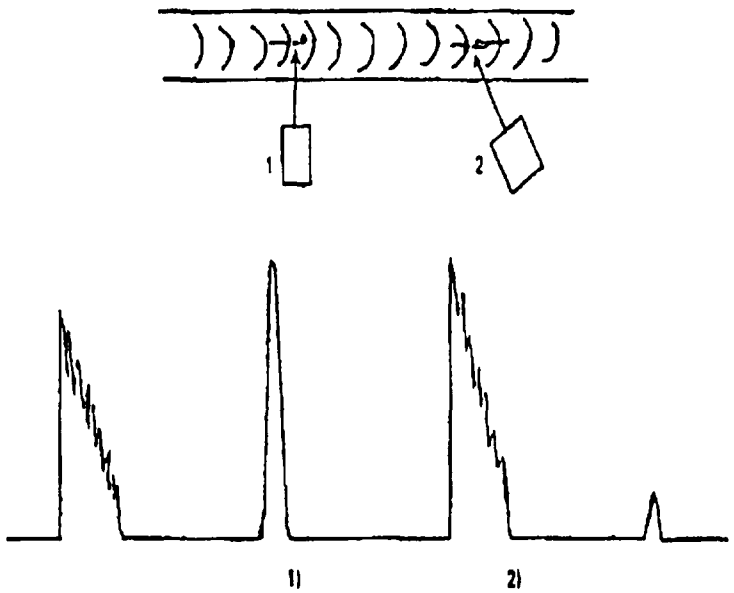


Figure 8.18 : Shape of an echo from a planar defect w.r.t. to probe positions 1 and 2.

8.6 EVALUATION OF DISCONTINUITIES IN ACCORDANCE WITH SPECIFICATIONS, STANDARDS AND CODES

After the prescribed tests have been completed and the flaws characterized according to their nature, size and location, the next question is how to treat the flaws. Some careful considerations in this respect need to be made. The sensitivity of flaw detection is ever increasing with improvements in instrumentation. This is the case, for example, with radiographic testing where at one time sensitivity was of the order of 5% meaning that flaws in the range of 5% of the test specimen thickness could possibly be detected. At that time then defects of this order were being detected and rejected. Now the sensitivities in the range of 0.5 to 1.0 are obtainable which have brought down significantly the level of flaws that can be detected. Similarly in the case of ultrasonic testing there was a time when people were happy to have cracked areas the size of the palm of their hand reliably reported. This has been improved over the years so that areas the size of their fingernail have been reliably reported and now with modern equipment we can detect areas of discontinuity say 1 mm by 1/8 mm. A further example is the assessment of the impressions, dents, gouges and corrosion pits. The availability of improved wall thickness measuring devices with a sensitivity of 0.1 mm and better has led to tighter surface and mensuration inspection so that more materials are re-cycled than previously. This is in spite of research work which shows that corrosion pits of certain sized areas may be down to 20% of the wall thickness and be not harmful, a result which seems to be backed up by field experience.

Now whether such small flaws and thickness variations which are now within the detection capability of various NDT methods should be rejected would remain a matter of subjective judgement unless it is fully established by calculations and extensive experimentation that this level of flaws is really going to be dangerous and therefore parts containing these sorts of flaws should not be allowed to go into service until after their satisfactory rectification. It must also be recognised that irrespective of the non-destructive tests employed, a discreet small percentage of defects will go unreported. Of course, all industrial construction depends to some extent upon a statistical probability of failure, and the job of overall quality assurance is to ensure that the level of this failure probability is kept acceptably low. Except in the most extraordinary circumstances, 100% non-destructive inspection with all the available techniques would never be specified, and of course, even if it were, it would not guarantee 100% freedom from imperfections. In practice, therefore, adequate levels of quality assurance can only be obtained through the development of an integrated system of production control and NDT.

These and many other considerations have gone into preparing acceptance/rejection standards for various products usually tested with non-destructive testing methods. The most serious defects from the loss of strength point of view are planar defects, such as cracks and lack of fusion, and volumetric defects, such as gas holes, are less serious. It is now clear that the through thickness dimension of a defect is more significant than the defect length, and also that surface-breaking defects are more serious than totally internal defects. There is ample evidence that distributed porosity has very little effect on weld strength. As a consequence of these findings, the acceptable level for weld defects is a constantly changing topic, still subject to much discussion and controversy.

8.6.1 Acceptance criteria of ASME Section XI for reactor pressure vessel

The acceptance criteria of the flaw found during in-service inspection (ISI) or pre-service inspection (PSI) are governed by ASME code Section XI considering the structural integrity of nuclear power plant.

8.6.1.1 Flaw characterization

(i) The flaw found during PSI/ISI is characterized by the bounding rectangle or square that fully contains the area of the flaw.

  (a) The length " l " of the rectangle or one side of the square shall be drawn parallel to the inside pressure retaining surface of the component.

  (b) The depth "a" of the rectangle or one side of the square shall be drawn normal to the inside pressure retaining surface and denoted as "a" for a surface flaw and "2a" for a subsurface flaw.

  (c) The aspect ratio " a/l " shall not exceed 0.5.

(ii) Flaws shall be characterized in accordance with IWA-3310 through IWA-3390, as applicable.

(iii) Clad thickness dimension may be taken from the manufacturer's drawings.

8.6.1.2 Surface planar flaws

(i) An indication shall be considered as a surface planar flaw if the detected area of the flaw is oriented primarily in any single plane, other than parallel to the surface of the component and any portion of the flaw penetrates a surface of the component.

(ii) A sub-surface indication shall be considered a surface flaw if any portion of the flaw is less than 0.4d from the component surface nearest the flaw as shown in Figure 8.19.

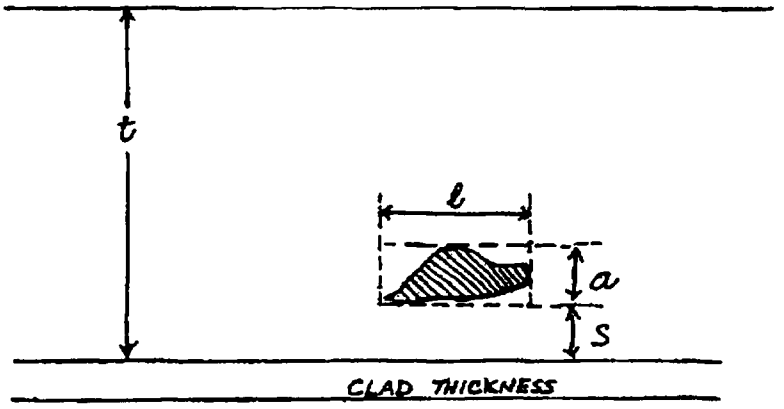


Figure 8.19 : Determination of size in case of surface planar flaw.

(iii) Criteria for a surface flaw:

(a) Find "2d" and "S".

(b) Compare "S" and "0.4d".
If S < 0.4d, consider this flaw as a surface flaw.

(c) "a" = "2d" + "S".

(d) Calculate " a/l " and "a/t".

(e) Compare these values using acceptance criteria.

8.6.1.3 Subsurface planar flaws

(i) An indication shall be considered to be a subsurface planar flaw if the detected area of the flaw is oriented primarily in any single plane other than parallel to the surface of component and if the distance 'S' from the flaw to the nearest surface of the component is equal to or more than 0.4d as shown in Figure 8.20.

(ii) Criteria for a subsurface flaw:

(a) Find "2d" and "S".

(b) Compare "S" and "0.4d".
If S ≥ 0.4d, consider this flaw as a subsurface flaw.

(c) "a" = "d", i.e. 2a = 2d

(d) Calculate "a/l " and "a/t".

(e) Calculate y which is y = S/a.
If y is greater than one, use y = 1.

(f) Compare these values using acceptance criteria.

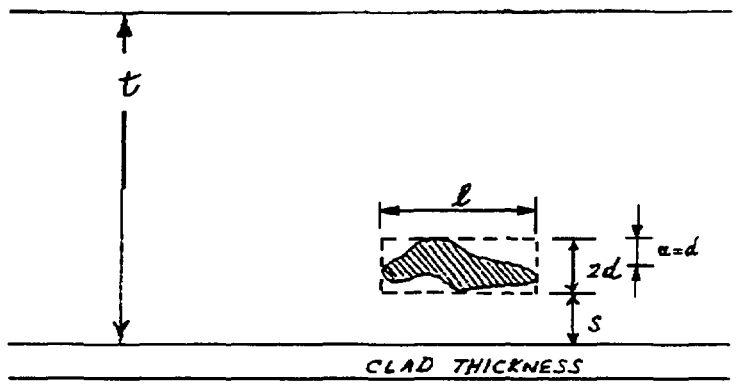


Figure 8.20 : Determination of size in case of subsurface planar flaw.

8.6.1.4 Laminar flaws

(i) Planar indications oriented within 10 degrees of a plane parallel to the surface of the component.

(ii) The area of a laminar flaw shall be 0.75 times the area of the square or rectangle that contains the detected area of those flaws that either overlap or lie within a distance "S" of 1 inch (25 mm).

8.6.1.5 Acceptance criteria

The acceptance criteria of flaws are determined according to the kind of components and flaw shape. Table 8.2 shows an example for ultrasonic testing flaws that can be found in circumferential or vertical welds in a pressure vessel such as steam generator and pressurizer, etc.

Once "a/l " and "a/t" are determined, the acceptance criteria of the flaw can be easily decided.

y* = s/a, flaw to surface proximity factor

8.6.2 Accept / reject criteria for welds according to ASME Section VIII

8.6.2.1 Acceptance standards for welds

All imperfections that produce an amplitude greater than 20% of the reference level shall be investigated to the extent that the operator can determine the shape, identity, and location of all such imperfections and evaluate them in terms of the acceptance standards given in (i) and (ii) below:

(i) Imperfections that are interpreted to be cracks, lack of fusion or incomplete penetration are unacceptable regardless of length.

(ii) All other linear type imperfections are unacceptable if the amplitude exceeds the reference level and the length of the imperfection exceeds the following:

(a) 1/4 in.(6.25 mm) for T up to 3/4 in.(18.75 mm)

(b) 1/3 T for T from 3/4 in. (18.75 mm) to 2 1/4 in.(56.25 mm)

(c) 3/4 in. (18.75 mm) for T over 2 1/4 in.(56.25 mm)

where T is the thickness of the weld being examined. If the weld joins two members having different thicknesses at the weld, T is the thinner of these two thicknesses.

TABLE 8.2 : ASME SECTION XI ACCEPTANCE CRITERIA OF PLANAR FLAWS

Volumetric Examination Method, Nominal Wall Thickness,[1] t, in.				
Aspect Ratio[1] a/l	2½ and less		4 through 12	
	Surface Flaw[2] a/t, %	Subsurface Flaw[2-4] a/t, %	Surface Flaw[2] a/t, %	Subsurface Flaw[2-4] a/t, %
0.00	3.1	3.4Y	1.9	2.0
0.05	3.3	3.8Y	2.0	2.2
0.10	3.6	4.3Y	2.2	2.5
0.15	4.1	4.9Y	2.5	2.9
0.20	4.7	5.7Y	2.8	3.3
0.25	5.5	6.6Y	3.3	3.8
0.30	6.4	7.8Y	3.8	4.4
0.35	7.4	9.0Y	4.4	5.1
0.40	8.3	10.5Y	5.0	5.8
0.45	8.5	12.3Y	5.1	6.7
0.50	8.7	14.3Y	5.2	7.6
Inside corner region	2.5	Not applicable	2.5	Not applicable

NOTES:

(1) Dimensions of a and l are defined in IWA-3300. For intermediate flaw aspect ratios a/l and thickness t, linear interpolation is permissible. Refer to IWA-3200 (b).

(2) See Table IWB-3512-2 for the appropriate component thickness t as a function of flaw location.

(3) The total depth of a subsurface flaw is 2a (Fig. IWA-3320-1).

(4) Y = [(S/t)/(a/t)] = (S/a). If S < 0.4d, the flaw is classified as a surface flaw. if Y > 1.0, use Y = 1.0.

8.6.2.2 Report of examination

The Manufacturer shall prepare a report of the ultrasonic examination and a copy of this report shall be retained by the Manufacturer until the Manufacturer's Data Report has been signed by the Inspector. The Report shall contain the information required by Section V. In addition, a record of repaired areas shall be noted as well as the results of the re-examination of the repaired areas. The Manufacturer shall also maintain a record of all reflections from uncorrected areas having responses that exceed 50% of the reference level. This record shall locate each area, the response level, the dimensions, the depth below the surface, and the classification.

8.6.3 Accept / reject criteria of AWS D1.1 (1988)

Table 8.3 and Table 8.4 show the accept / reject criteria of dynamically loaded and statically loaded structures respectively.

8.6.4. Accept / reject criteria of API-1104 (1994)

8.6.4.1 Linear indications in welds

All indications that produce a response greater than 20 % of the reference level shall to the degree possible, be investigated to determine the location, shape, extent, and type of reflectors and shall be evaluated according to the following criteria:

(a) Linear indications interpreted to be shallow crater cracks or star cracks, located at the weld surface, with a length less than 5/32 inch (3.96 mm) are acceptable. All other cracks are unacceptable regardless of size or location in the weld

(b) Linear indications (other than cracks) interpreted to be open to the surface are unacceptable if they exceed 1 inch (25.4 mm) in total length in a continuous 12 in. (304.8 mm) length of weld or 8 % of the weld length

(c) Linear indications interpreted to be buried within the weld are unacceptable if they exceed 2 inches (50.8 mm) in total length in a continuous 12 inch length of weld or 8 % of the weld length

8.6.4.2 Pipe or fitting (parent metal) discontinuities

Laminations, long seam discontinuities and other discontinuities in the pipe or fittings detected by ultrasonic testing shall be reported to the company. Their disposition by repair or removal shall be as directed by the company.

8.7 RECORDING AND REPORTING THE RESULTS OF A TEST

8.7.1 The test report

The final outcome of a non-destructive test is the test report. It is mostly on the basis of this report that all decisions regarding the further treatment of the defects found by testing and the fate of the tested part are to be made. How far are the reported results reliable and if they are not reliable can the operator be asked to recheck and reconfirm the earlier findings. In other words are the reported results reproducible, and how far has the report helped in the reproducibility of results. In view of these and many other requirements it is essential that the NDT test reports are prepared with utmost care. In many cases reports are the only means of knowing the processes

TABLE 8.3 : AWS (1988) ACCEPT / REJECT CRITERION FOR DYNAMICALLY LOADED STRUCTURES

Flaw severity class	Weld thickness* and search unit angle										
	5/16 thru 3/4	> 3/4 thru 1-1/2	> 1-1/2 thru 2-1/2			> 2-1/2 thru 4			> 4 thru 8		
	70°	70°	70°	60°	45°	70°	60°	45°	70°	60°	45°
Class A	+10 & lower	+8 & lower	-4 & lower	+7 & lower	+9 & lower	+1 & lower	+4 & lower	+6 & lower	2 & lower	+1 & lower	+3 & lower
Class B	+11	+9	+5	+8	+10	+2	+5	+7	1	+2	+4
			+6	+9	+11	+3	+6	+8	0	+3	+5
Class C	+12	+10	+7	+10	+12	+4	+7	+9	+1	+4	+6
			+8	+11	+13	+5	+8	+10	+2	+5	+7
Class D	+13	+11	+9	+12	+14	+6	+9	+11	+3	+6	+8
	& up	& up	& up	& up	& up	& up	& up	& up	& up	& up	& up

Notes:

1. Class B and C flaws shall be separated by at least 2L, L being the length of the longer flaw, except that when two or more such flaws are not separated by at least 2L, but the combined length of flaws and their separation distance is equal to or less than the maximum allowable length under the provisions of Class B or C, the flaw shall be considered a single acceptable flaw.

2. Class B and C flaws shall not begin at a distance less than 2L from the end of the weld, L being the flaw length.

3. Flaws detected at "scanning level" in the root face area of complete joint penetration double groove weld joints shall be evaluated using an indication rating 4 dB more sensitive than described in 6.19.6.5 when such welds are designated as "tension welds" on the drawing (subtract 4 dB from the indication rating "d").

4. For indications that remain on the CRT as the search unit is moved, refer to 9.25.3.2.

*Weld thickness shall be defined as the nominal thickness of the thinner of the two parts being joined.

Class A (large flaws)
Any indication in this category shall be rejected (regardless of length).

Class B (medium flaws)
Any indication in this category having a length greater than 3/4 inch (19mm) shall be rejected.

Class C (small flaws)
Any indication in this category having a length greater than 2 in. (51 mm) in the middle half or ¾ inch(19mm) length in the top or bottom quarter of weld thickness shall be rejected.

Class D (minor flaws)
Any indication in this category shall be accepted regardless of length or location in the weld.

Scanning levels

Sound path (in.)**	Above zero reference, dB
thru 2-1/2 (64mm)	20
> 2-1 to 5 (64-127mm)	25
> 5 to 10 (127-254mm)	35
> 10 to 15 (254-381mm)	45

** This column refers to sound path distance; NOT material thickness.

TABLE 8.4 : AWS (1988) ACCEPT / REJECT CRITERION FOR STATICALLY LOADED STRUCTURES

Flaw severity class	Weld thickness* and search unit angle										
	5/16 thru 3/4	> 3/4 thru 1-1/2	> 1-1/2 thru 2-1/2			> 2-1/2 thru 4			> 4 thru 8		
	70°	70°	70°	60°	45°	70°	60°	45°	70°	60°	45°
Class A	+5 & lower	+2 & lower	-2 & lower	+1 & lower	+3 & lower	-5 & lower	-2 & lower	0 & lower	-7 & lower	4 & lower	1 & lower
Class B	+6	+3	1	+2	+4	-4	1	+1	6	3	0
			0	+3	+5	-3	0	+2	5	2	+1
Class C	+7	+4	+1	+4	+6	-2 to	+1	+3	4 to	1 to	+2
			+2	+5	+7	+2	+2	+4	+2	+2	+3
Class D	+8	+5	+3	+6	+8	+3	+3	+5	+3	+3	+4
	& up	& up	& up	& up	& up	& up	& up	& up	& up	& up	& up

Notes:

1. Class B and C flaws shall be separated by at least 2L, L being the length of the longer flaw, except that when two or more such flaws are not separated by at least 2L, but the combined length of flaws and their separation distance is equal to or less than the maximum allowable length under the provisions of Class B or C, the flaw shall be considered a single acceptable flaw.

2. Class B and C flaws shall not begin at a distance from 2L from weld ends carrying primary tensile stress, L being the flaw length.

3. Flaws detected at "scanning level" in the root face area of complete joint penetration double groove weld joints shall be evaluated using an indication rating 4 dB more sensitive than described in 6.19.6.5 when such welds are designated as "tension welds" on the drawing (subtract 4 dB from the indication rating "d").

4. Electroslag or electrogas welds: Flaws detected at "scanning level" which exceed 2 in. (51mm) in length shall be suspected as being piping porosity and shall be further evaluated with radiography.

5. For indications that remain on the CRT as the search unit is moved, refer to 8.15.3.

*Weld thickness shall be defined as the nominal thickness of the thinner of the two parts being joined.

Class A (large flaws)
Any indication in this category shall be rejected (regardless of length).

Class B (medium flaws)
Any indication in this category having a length greater than 3/4 inch (19mm) shall be rejected.

Class C (small flaws)
Any indication in this category having a length greater than 2 inches (51 mm) shall be rejected.

Class D (minor flaws)
Any indication in this category shall be accepted regardless of length or location in the weld.

Scanning levels

Sound path (in.)**	Above zero reference, dB
thru 2-1/2 (64mm)	14
> 2-1/2 to 5 (64-127mm)	19
> 5 to 10 (127-254mm)	29
> 10 to 15 (254-381mm)	39

** This column refers to sound path distance; NOT material thickness.

involved in the manufacture of the components and the state of their soundness at the time of installation. This information is specially quite valuable while investigating some premature failures. The reports are thoroughly scrutinized and analyzed by the inspection and audit agencies and form an indispensable requirement for quality assurance.

The essential requirements of a good NDT report can be said to be its unambiguity and its reproducibility. Therefore while preparing a format for a report all the variable factors that affect the sensitivity of flaw detection for a particular NDT method should be kept in view. In fact, in principle, the values of all these variable parameters should be fixed and noted in the report form. It should be thoroughly considered whether all the desired information has been given in the report such that using the report it would be possible to reconstruct the exact conditions of the test in case a repetition of the results is required or would the report help in exactly locating the defective areas in the tested parts in case repairs were to be undertaken. We will elaborate these points with an example of the ultrasonic testing and the reports for other NDT methods can then be developed along similar lines.

The details of the type of specimen, its thickness, geometry and shape and the portion being ultrasonically tested should be recorded in the report form. A unique identification number should be allotted to each test and this should appear on the test specimen and in the report. Preferably this number should be linked to the design drawing number. It is only with the help of this identification number that parts can be rejected or repaired or inspections may be repeated if desired.

Applicable procedure which itself should have an independent number should be referred to in the report.

The form of a report may be different, but to achieve the above mentioned objectives, it must contain, clearly and concisely, the following information:

8.7.1.1 Identification

(i) Date of the inspection.

(ii) Time of the inspection.

(iii) Place of the inspection.

(iv) Customer for whom the work is done.

(v) Inspector carrying out the work.

(vi) Component examined, its serial number, description and material.

(vii) Code, specification or standards used.

8.7.1.2 Equipment

(i) Flaw detector.

(ii) Probes, with size, frequency and angle.

(iii) Calibration and reference blocks used.

(iv) Couplant.

8.7.1.3 Calibration

(i) Sensitivity for all probes used.

(ii) Time base/range for all probes used.

(iii) Attenuation and transfer corrections, where appropriate.

8.7.1.4 Technique

(i) Scan modes (limits and coverage with each probe).

(ii) Sizing method used.

(iii) Recording and reporting level used.

(iv) Limitations on inspection quality imposed by shape or situation of object, time or other factors.

8.7.1.5 Results

(i) Indications found.

(ii) Scale drawing showing location and size of defects.

(iii) Relationship between defects found and acceptance standard.

The report should be made in plain language. Technical terms should be used in their correct sense and initials or abbreviations should only be used after they have been used once in association with the full terms, for example, 3 mm diameter (3 mm dia) flat bottom hole (f.b.h.). Results, that are shown in tabular form, or in scale drawings, are easier to follow than long written descriptions.

8.7.2 Other records

In addition to the test report there are some more documents which form an important part of the non-destructive testing process including ultrasonic testing. These are also directly linked to the test report and are always needed whenever the report is to be verified, the tests are to be repeated or for the purposes of quality audits. These records form an important requirement of the quality assurance programme of the organization, and are a means to traceability.

The written and numbered procedure for executing the ultrasonic tests should be present in the organization's records as well as with the persons doing the job. A procedure should include as a minimum the following sections:

(i) Procedure identification number and the date it was written.

(ii) Scope.

(iii) Applicable documents.

(iv) Personnel.

(v) Equipment/calibration/reference standards.

(vi) Identification and type of test object to which the procedure applies.

(vii) Test method.

(viii) Reporting levels/examinations.

(ix) Acceptance criteria.

(x) Marking plan for the test object.

(xi) Reporting.

A written record of the calibration of the test equipment should be maintained. In case the equipment needs periodic calibration the dates of present and next calibrations should be identified. If the calibration has been carried out or checked by a specialist agency, its name should be mentioned.

A documentary record of the qualifications and certification of all the persons involved in doing NDT and writing and signing reports should be available and should be producible on demand. The dates when the validation of certificates becomes due should be mentioned and properly dated certificates of eyes tests of all the operators should be maintained. Evidence should also be maintained on the training received and the education and work experience attained. In fact it would be ideal if a mandatory log book for all the NDT personnel is maintained.

In brief, written documentation is the best way to traceability, reproducibility and ultimate reliability of the tests and consequently the tested parts. In the case of NDT working procedures, this will mean a comprehensive procedure written by a competent (suitably qualified) person, and an inspection carried out by a suitably qualified operator reported accurately on an inspection report form.

9. SPECIAL TECHNIQUES

9.1 SPECIAL INSPECTION PROBLEMS AND TECHNIQUES USED TO SOLVE THEM

9.1.1 Air coupled acoustic measurements

While the majority of ultrasonic tests are performed with liquid couplants or immersion in water, there is an increasing need for tests without conventional couplants. Air coupling is considered for applications where liquid may damage the test material or when the cost of couplant removal is excessive. In tests of large surface areas or high scanning speeds, direct contact with the test object typically results in severe transducer wear, failure and costly operation of the equipment. Air coupled ultrasonic techniques provide an alternative means for resolving these problems.

The key element in successful air coupled applications is a sensitive, well damped transducer. Focal spots less than 0.13 mm (0.05 in.) are commonly available. Focusing can be achieved with a spherically ground active element or with a cast epoxy lens. Small beam diameters and long focal lengths allow the ultrasound to be directed to accommodate geometric variations, to scan small surface areas and to evaluate contours inappropriate for non-focused units.

There are different kinds of transducers specially developed for the purposes of testing through air. There are the bimorphic, electrostatic, piezoelectric and ceramic types each developed for specialized applications.

The acoustic impedance of air is extremely low and therefore air cannot support mechanical vibrations. This value for the impedance of air is the source of the difficulty in coupling and exciting high frequency waves in air.

One way to overcome this difficulty is to use what is known as matching layers between the transducer and the air. Because of the impedance mismatch, large stresses are set up in matching layer leading to large attenuation. A design with multiple matching layers is preferred because the stress fields set up in the matching layers are weaker and the influence of attenuation in each matching layer is reduced. It is generally necessary to have materials of low impedance and low attenuation for matching layers.

It may be noted that air coupled ultrasound cannot universally perform the volumetric non-destructive tests conducted with conventional ultrasonic techniques. Instead, air coupling extends the capabilities of the acoustic methods. Because of the acoustic impedance mismatch of air and test materials, airborne vibrations are usually difficult to introduce into a test object. This causes the reflection of most of the transmitted energy (particularly during tests of dense materials such as metals) and relegates a majority of air coupled applications to external measurements. Volumetric (internal) air coupled tests are typically limited to low density materials such as wood, rubber, particle board, paper or non-metallic composites. In such materials, the acoustic impedance is lower and the resulting transmission coefficient is much greater than those for high density materials. Equipment designed for a wide range of test frequencies is commercially available and may be considered a reliable alternative for tests conventionally performed with mechanical gauging systems. Air coupling is extending its range of application as a means of accurate sensing and guidance for robotic applications using high speed data acquisition rates.

Air coupled thickness measurements (or ranging) can be performed from distances as close as 75 mm (3 in.). For such tests, the axial resolution measurement accuracy is of the order of 0.025 mm (0.001 in.). Beyond 750 mm (30 in.), the resolution deteriorates to 0.25 mm (0.01 in.). Such techniques are often used to check the level of liquids or the level of granules in storage bins, to measure plate and film thickness, to profile surface or to detect the presence of components. Counting, sorting and sensing techniques are based on the principles of precise distance measurement.

Thickness measurements are made with two transducers directed at opposite sides of the test object. By independently using the measurement techniques described above, the spacing between the transducers and the reflecting surfaces can be measured. These measurements are then subtracted from the distance between the two transducers to determine the section thickness. The procedures used to set up such measurements must consider the thickness of the lens material, electronic delays and other sources of possible error. For example, a dial indicator reading between the transducer and the test object may not agree with the instrument distance reading and, therefore, a step gauge is used as the most reliable way of setting up the procedure. If tight tolerances are required, high frequency focused transducers are recommended. This technique provides a contactless measurement to an accuracy of at least 0.05 mm (0.002 in.) under production conditions. These measurements can be acquired at great speeds providing 300 to 500 measurements per second. This exceeds the speed of optical techniques by a factor of two, at a cost of 10 to 20 percent of optical systems.

Ultrasonic testing of tyre carcasses before recapping has been successfully demonstrated. The technique uses a transmission approach and an array of sensors to cover all of the critical areas.

This air coupled test has been used on tires ranging from automobile tyres to aircraft tyres containing a high number of piles (up to 32).

In conventional ultrasonic tests, immersion techniques, squirters or wheel transducers are used to perform area scanning and to produce C-scans. Air coupled ultrasonics can also be used for such applications. The rate of data acquisition (300 times per second) permits high speed area scanning and recording.

Ultrasonic air coupled systems are affected by air turbulence and temperature. Similarly ambient air pressure and humidity may also modify test results. An effective method of compensating for these factors is to use a second transducer exposed to the same environmental conditions as the transducer used for making the measurement. The second transducer and associated instrumentation periodically monitors the conditions by measuring a calibrated distance (such as a step block), determining the air current velocity and automatically recalibrating the measuring channel with accurate data.

9.1.2 Acoustic holography

Acoustic or ultrasonic holography is a technique used to form an optical image of an ultrasonic field. An ultrasonic hologram is made in a way similar to an optical hologram, ultrasonic waves simply take the place of light waves in the illumination beam and the reference beam. The hologram is produced by action of the interfering ultrasound beams impinging on the water surface of a ripple tank to produce a steady-state ripple pattern, the hologram. This may be photographed (under appropriate illumination) to give a permanent hologram from which the image can be reconstructed and made visible by illumination with a visible light laser beam.

In the case of ultrasonic holography sound waves replace the laser light and generation of a hologram is easy because ultrasonic waves generated by a piezoelectric transmitter are coherent. In fact, two different transmitters energised by the same generator also give coherent ultrasonic waves.

There are several methods of generating the ultrasonic hologram and of reconstructing the image. In the relief method, the two transmitters are powered by the same generator and one beam penetrates the object, so generating the object wave, while the other forms the reference wave (Figure 9.1). The hologram is produced by ripples on the surface as produced by the local sound radiation pressure and optical illumination is made using a laser. In this case the hologram is a phase hologram, which by reflecting the laser light can reconstruct an optical object wave by diffraction, the non-diffracted light being suppressed. Though the quality of the resulting image is not bad, the method has not found many applications because of the rapid development of other methods which use piezoelectric scanning.

In the acoustics field, phase-sensitive receivers are readily available in the form of standard piezoelectric transducers which collect all necessary information concerning amplitude and phase.

9.1.3 Acoustic microscopy

Acoustic microscopy is a general term applied to high resolution, high frequency ultrasonic testing techniques that produce images of features beneath the surface of a test object. Because ultrasonic energy requires continuity to propagate, discontinuities such as voids, inclusions, delaminations and cracks can interfere with the transmission or reflection of ultrasonic signals.

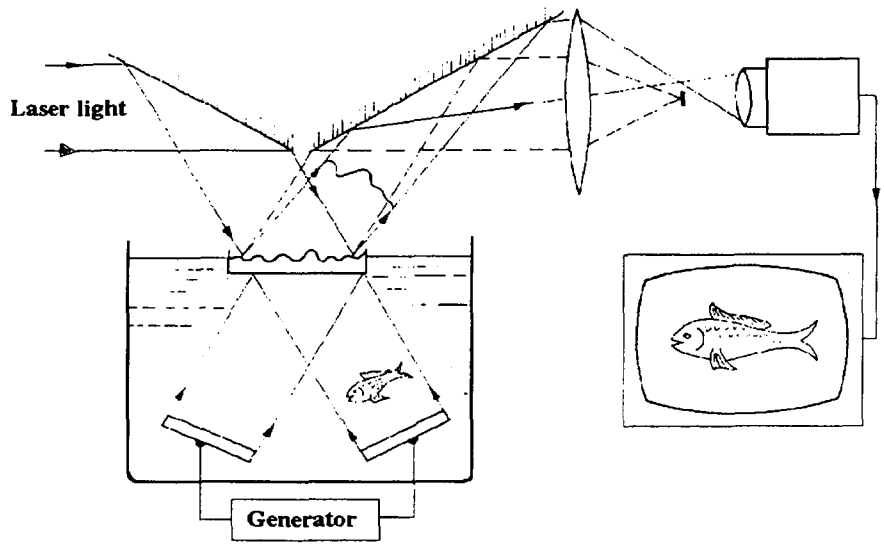


Figure 9.1 : Acoustic holography in real time to allow focusing at a selected depth using the relief method, combined with a TV camera.

Conventional ultrasound techniques operate between 1 and 10 MHz. Acoustic microscopes operate up to and beyond 1 GHz, where the wavelength is very short and the resolution correspondingly high. Acoustic microscopy comprises three distinct methods: (1) scanning laser acoustic microscopy (SLAM), (2) C-mode scanning acoustic microscopy (C-SAM), (3) scanning acoustic microscopy (SAM). Each of these methods has a specific range of applications and most often the methods are not competitive (only one method is best suited to a particular testing problem). Acoustic microscopes have been especially useful in solving problems with new materials and components not previously available.

In scanning laser acoustic microscopy, a collimated plane wave of ultrasound at frequencies up to several hundred megahertz is produced by a piezoelectric transducer located beneath the test object (Figure 9.2). Because this ultrasound cannot travel through air (making it an excellent tool for crack, void and disbond detection), a fluid couplant is used to bring the ultrasound to the test object. Distilled water, spectrophotometric grade alcohol or other more inert fluids can be used, depending on user concerns for test object contamination. When the ultrasound travels through the test object, the wave is affected by the homogeneity of the material. Wherever there are anomalies, the ultrasound is differentially attenuated and the resulting image reveals characteristic light and dark features, corresponding to the localized acoustic properties of the test object. Multiple views can be made to determine the specific depth of a discontinuity, as is performed by stereoscopy.

A laser beam is used as an ultrasound detector by sensing the infinitesimal displacements (rippling) at the surface of the test object created by the ultrasound. In typical test objects, that do not have polished, optically reflective surfaces, a mirrored plastic block or coverslip is placed close to the surface and is acoustically coupled by fluid. The laser is focused onto the bottom surface of the coverslip, which has an acoustic pattern that corresponds to the test object surface. By rapid sweeping of the laser beam, images are produced in real-time (30 images per second) and are displayed on a high resolution monitor. In contrast to less accurate uses of the term real-time, the scanning laser acoustic microscope can be used to observe events as they occur, for example, a crack propagating under an applied load.

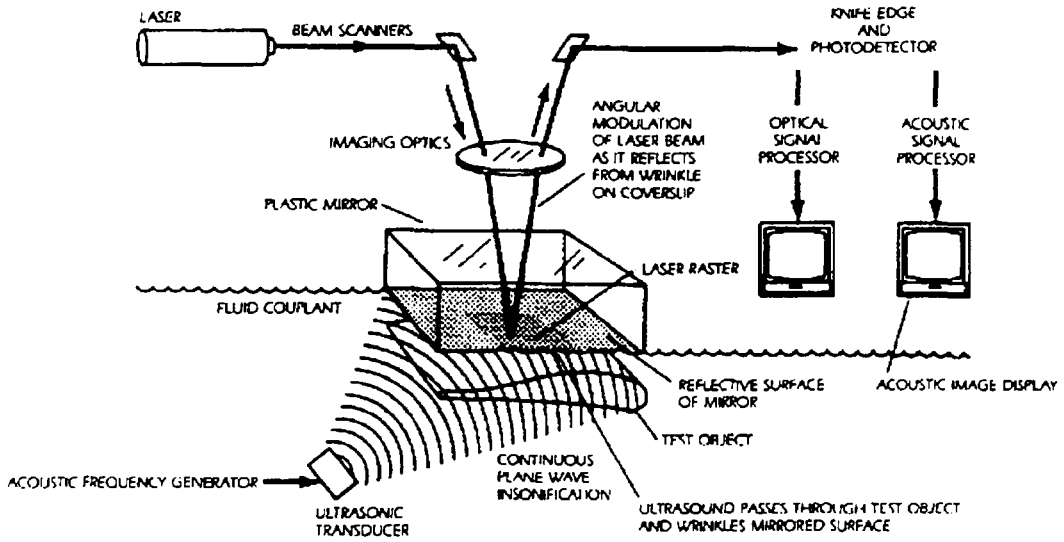


Figure 9.2 : Diagram showing principal components of a scanning laser acoustic microscope.

The simplest geometries for scanning laser acoustic microscopic imaging are flat plates or disks. However, with proper fixturing, complex shapes and large test objects can also be accommodated. For example, tiny hybrid electronic components, large metal plates (250 mm or 10 in. square), aircraft turbine blades and ceramic engine cylinder liner tubes have been tested with scanning laser acoustic microscopy.

The C-mode scanning acoustic microscope is primarily a pulse echo (reflection) microscope that generates images by mechanically scanning a transducer in a raster pattern over the test object. A focused spot of ultrasound is generated by an acoustic lens assembly at frequencies typically ranging from 10 to 100 MHz. The ultrasound is brought to the test object by a coupling medium, usually water or an inert fluid. The angle of the rays from the lens is generally kept small so that the incident ultrasound does not exceed the critical angle of reflection between the fluid coupling and the solid test object. Note that the focal distance into the test object is shortened considerably by the liquid/solid refraction. The transducer alternately acts as sender and receiver, being electronically switched between the transmit and receive modes. A very short acoustic pulse enters the test object and return echoes are produced at the object surface and at specific interfaces within the test material. The pulse return times are a function of the distance from the interface to the transducer. An oscilloscope display of the echo pattern (an A-scan) clearly shows these levels and their time-distance relationships from the test object surface. This response provides a basis for investigating anomalies at specific levels within a test object. An electronic gate selects information from a specified level while it excludes all other echoes. The gated echo brightens a spot on a cathode ray tube displaying the C-scan. The CRT beam follows the transducer position and is brightened by signals in the gate. Older, conventional C-scan instruments produce monoamplitude output on thermal paper when a signal exceeds an operator selected threshold. By comparison, the output of the C-SAM is displayed in full grey scale (the gray level is proportional to the amplitude of the interface signal). The grey scale (Figure 9.3) can be converted into false colour and the images can be colour coded with echo polarity information. The colour coded enhanced microscope is further differentiated from conventional C-scan equipment by the speed of the scan. Here, the transducer is positioned by a very fast mechanical scanner that produces images in tens of seconds for typical scan areas of the size of an integrated circuit.

The scanning acoustic microscope is primarily a reflection microscope that generates very high resolution images of surface and near surface features by mechanically scanning a transducer in a raster pattern over the test object (Figure 9.4). In the normal mode, an image is generated from echo amplitude data over an X,Y scanned field of view. As with SLAM, a transmission interference mode can be configured for velocity of sound measurements. In contrast to C-SAM, a more highly focused spot of ultrasound is generated by a very wide-angle acoustic lens assembly at frequencies typically ranging from 100 to 2,000 MHz. The angle of the sound rays is well beyond the critical cut-off angle, so that there is essentially no wave propagation into the material.

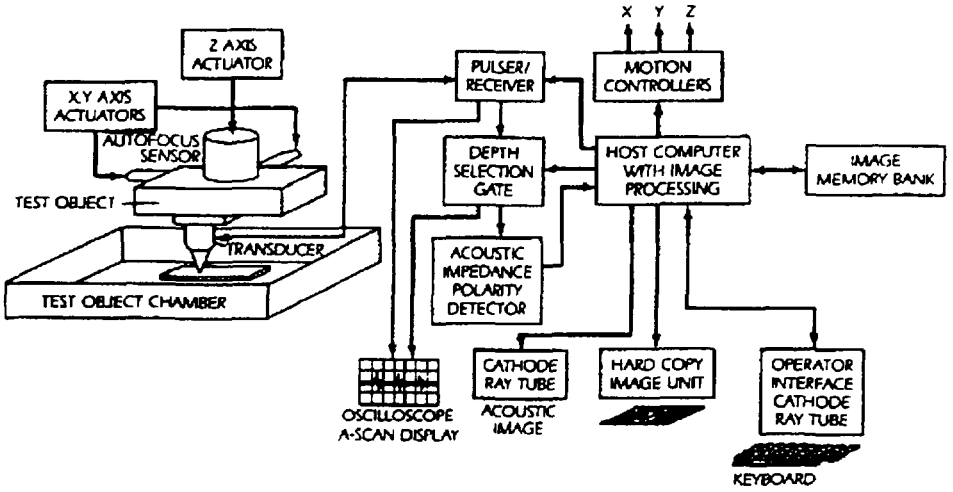


Figure 9.3 : Diagram of a C-mode scanning acoustic microscope with a high speed mechanical scanner and an acoustic impedance detector to produce high resolution C-scan images.

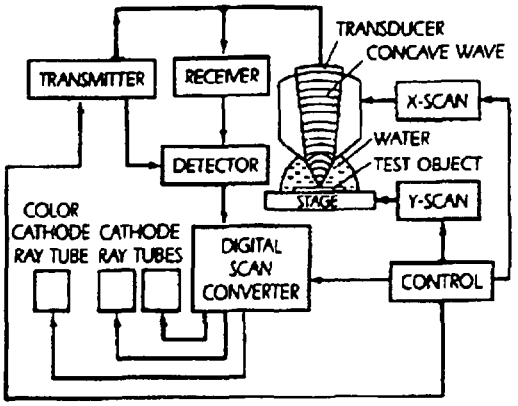


Figure 9.4 : Diagram of a reflective scanning acoustic microscope that uses mechanical scanning of a highly focused transducer to test an object's surface at high magnification.

Applications of acoustic microscopy include the study of composite and polymer materials at the microscopic level. Ceramic materials such as silicon nitride, silicon carbide, aluminium oxide and zirconia, etc. are used in electronics and are also being studied for combustion engine applications. Acoustic microscopy is used to detect small discontinuities that may contribute to localized stress concentrations which are very critical to structural integrity. Acoustic microscopy can be used for non-destructive testing and metallographic analysis of metals. In typical microscopy and metallography, it is necessary to polish and etch a test object to reveal

the microstructural pattern. With scanning acoustic microscopy, this may not be necessary. Microelectronic components and integrated circuits can be studied for electrical connections and bonding.

9.1.4 Detection of intergranular stress-corrosion cracking

Many of the high strength alloys, unfortunately, are highly susceptible to stress-corrosion cracking. Stress-corrosion cracking may occur at stress levels far below the nominal strength of the material, and may proceed at a rate orders of magnitude faster than the usual rate of corrosion in the absence of mechanical stress. Intergranular stress-corrosion cracking typically occurs near welds or in their heat-affected zones. These are branched, tightly and irregularly shaped cracks. Generally these cracks are poor reflectors of ultrasonic waves and may be difficult to detect. Part of the reason for this is that the echo signals from cracks are hard to separate from the weld signals. Also, ultrasonic waves can be distorted to give an echo that looks like a crack echo but is not. In addition, the environment may be difficult to work in, specially in case of inspection of nuclear reactor pressure vessels and primary piping in which high radiation fields, high humidity, elevated temperatures and high pressures are common.

Both manual and automated methods of ultrasonic testing are employed for the detection of intergranular stress-corrosion cracking. Using the manual method and testing through the base metal, an inspector uses a typical 45° angle beam probe operating in a frequency range of 0.5 to 5 MHz and observing the A-scan echoes on the screen. Couplants must be certified for total sulfur and halogen content in accordance with ASTM D-129-64 and D-808-63. Calibration blocks should reproduce as closely as possible the geometry and microstructure of tested components. It has been found that the probability of detecting and correctly interpreting the crack signals is of the order of 70 to 80% for manual inspection. An advanced computer system may be used to assist in manual testing.

Automation could improve the repeatability of ultrasonic test results while reducing radiation exposure in case of inspecting nuclear pressure vessels for detection of stress-corrosion cracking. In a semi-automated system, scanning is done manually. A computer is used to monitor, position and to analyze and present the ultrasonic data. In a fully automated system, the scanning is also under computer control. A semi-automated system is smaller and can be used in areas too small for a fully automated system. All automated systems provide an A-scan display and integrate the transducer position with the maximum amplitude to permit B-scan and C-scan displays. Colour or grey scale images of an anomaly are presented and in some systems the radiofrequency signal can be stored in memory. Displays in three dimensions are possible, as well as temporal signal averaging, pattern recognition, ultrasonic holography, synthetic aperture focusing and artificial intelligence. However, the overall effectiveness of every automated system is dependent primarily on the quality and design of the transducer. (also see Section 9.2.4.5)

Having detected the stress-corrosion cracks, it is important to find their characteristics of size, depth and orientation. The conventional methods of 6 dB and 20 dB are not found to be satisfactory and, therefore, usually the crack tip echo method, which is more accurate, is employed. A four part procedure for flaw size determination is outlined here. The first step is to establish whether the crack is more than 50 percent through-wall. Both the high angle longitudinal wave and full-V path corner reflection technique are used for this. If neither technique shows that the crack is deep, then the crack tip diffraction and half-V path techniques are used. A multimode method, in which both launched and mode converted longitudinal and shear waves are used to interrogate the discontinuity, should be used to verify results. Depths should be determined at several places along the crack length. The high angle longitudinal wave

method of sizing is useful only for deep discontinuities (greater than 50 percent through-wall). This method relies on high angle longitudinal waves reflected from the tip of the discontinuity or from deep parts of the discontinuity. The time of flight is used to calculate the remaining ligament. Calibration of each transducer used for this type of testing is critical, since a successful measurement depends on the use of properly designed and characterized transducers.

The presence of shear waves at about 30 degrees, reflecting off the inner wall, complicates the analysis of the echo pattern. In the full-V method, an echo is searched for at the full-V path (if the crack is nearly through-wall, a full-V path echo should be evident).

In the crack tip diffraction method, a low amplitude reflection from the tip of the discontinuity is sought. By comparing the arrival times of the tip diffracted signal and the corner reflection, the depth of the discontinuity can be established. The difficulty with this method is that the crack tip signal can be easily missed because of its low amplitude.

Since the process of stress-corrosion cracking is limited to the surface of the metal, it is natural to apply surface wave methods for detection. In fact, first the correlation between the cracks and the rate of attenuation of surface waves can be developed. Then the cracks can be detected by pulse echo method.

9.1.5 In-service inspection

In non-destructive testing the research and development efforts of the late 1960s and early 1970s concentrated on remote mechanized equipment and conventional testing methods, principally ultrasonics, for in-service testing. Ultrasonics has become a widely used tool not only for detection of discontinuities but also for characterization and evaluation of discontinuity type and size. This change in emphasis from detection to characterization came about because of an interest in estimating the remaining service life of systems and components. The change paralleled the development of fracture mechanics and other life management disciplines which require quantitative information about the severity of discontinuities. The principal reason for in-service tests of systems and components is to increase their reliability, availability and safety. The regulatory reason for in-service testing is to ensure that systems and components are maintained in a safe condition during service. The components are inspected and if unflawed, returned to service. The return to service interval is determined by a fracture mechanics calculation of critical size as well as the crack growth rate. If the crack is less than the detection threshold, the component is returned to service. This procedure is repeated until a crack of the critical or greater size is detected, at which time the component is retired. When a defect is detected by non-destructive testing, it becomes a matter of importance to evaluate it in relation to the strength of the material in which the defect is detected. This evaluation can be made by utilizing the fracture mechanic analysis. This can also help in deciding the interval between various in-service as well as maintenance schedules.

For both types of test, production and in-service, mechanized scanning of highly stressed parts is often necessary. In most cases, however, it will not be possible to use the results of production testing as a basis for the later in-service test because then other criteria apply and also because scanning equipment has to be specially designed for use on site, for example, in power stations. The first or pre-service inspection has, therefore, to be performed on the piece in the ready-for-use condition, i.e. at a time when the piece after having been accepted on the basis of production tests, has not yet been affected by its conditions of service. This pre-service test, also called the finger-print inspection, forms the basis for later in-service inspections since they can all be evaluated by comparison with it.

In-service tests using ultrasonics are also carried out for detection of intergranular stress-corrosion cracking in pipes (Section 9.1.4); for creep detection in steam lines, superheater tubes and turbine components; measurement of hydrogen damage produced in steels exposed to a high hydrogen environment at high temperatures; testing of long, narrow cylindrical objects such as bolts, studs, valve stems or pump shafts; testing of turbine disk rims for intergranular stress-corrosion cracking; inspection of keyways for stress-corrosion and fatigue cracking; testing of vehicular axle housing seam welds; testing of expansion bellows; underwater thickness measurements; detection of failed fuel elements in nuclear reactor fuel assemblies and inspection of composite structures in aircrafts.

Because of the very high safety demands for nuclear power stations, all components of the primary circuit, which include reactor pressure vessel, steam generator, pressure regulator and connecting pipes, have to undergo several detailed ultrasonic tests. Before the plant is put into service, the so-called zero test or "fingerprint" inspection is made. The zero or base test provides full data on the initial state of the plant before it enters service. Later tests are compared with these initial results to reveal changes caused by the relevant service conditions. In-service tests often have to be performed under so-called hot conditions in an environment of intense radiation levels so that they must provide for remote control and rapid mechanized testing procedures. Short testing times are also desirable from the view of costs and in-service tests are frequently combined therefore with plant shut-downs for other operations such as the change of fuel elements. The pressure vessel is the most important and critical component of the reactor. The inside surfaces are cladded with austenitic stainless steel several millimetres thick as a protection against corrosion. Figure 9.5 shows two typical pressure vessels for two different types of nuclear reactors while Figure 9.6 shows a special manipulator for internal tests on such reactors.

The testing of welds in piping, pressure-control valves and heat exchangers has also been mechanized. For the internal surface test of these tubes the eddy-current method is also applied, as for example in the combined probe. For subsurface defects creeping-wave techniques are also used. To reduce the exposure to radiation for operators, permanently built-in rails are also installed on components of the primary circuit.

A special system has been developed for testing leaking fuel-element cans so that any water-filled fuel element can be removed and replaced. A twin probe containing transmitter and receiver crystals is slipped over the canning tube and if the tube is water-filled the through-transmission signal is strongly reduced. Each 10-MHz probe has a thickness of only 1.5 mm, to fit in between the tubes. Length scanning is carried out mechanically as well as the transfer from one tube to the next.

9.1.6 Material property characterization

While a structure may be free of distinct identifiable discontinuities, it may still be susceptible to failure because of inadequate or degraded mechanical properties. This can arise from faulty material processing, overaging, degradation under aggressive service environments or from numerous other factors (see Sections 1.3 and 1.4). Because of poor microstructure and morphology, a solid may lack strength, toughness or may exhibit degraded resistance to impact, fatigue or fracture. For these reasons, it is important to have non-destructive methods for characterizing local or global anomalies in microstructure or morphology and their associated mechanical property deficiencies. The best approach to reliability assurance combines non-destructive characterization of discontinuities with characterization of material environments in which the discontinuities reside. Assessment of structural integrity and service life can be

improved by providing more complete information for fracture analysis and life prediction. This approach is needed to assess the structural reliability and residual life of components made of advanced materials in systems that demand efficient performance under extreme operating conditions.

To different degrees, elastic moduli, material microstructure, morphological conditions and associated mechanical properties can be characterized with ultrasonics. Elastic moduli are determined by velocity measurements. Material microstructure can be characterized by velocity and attenuation measurements. Ultrasonic assessment of mechanical properties (strength or toughness) is indirect and depends on either theoretical inferences or empirical correlations.

Four categories of ultrasonic materials characterization include: (1) measurements that determine elastic constants such as tensile, shear and bulk moduli; (2) microstructural and morphological factors such as grain size and distribution, grain aspect ratio and texture; (3) diffuse discontinuity populations such as microporosity or microcracking; and (4) mechanical properties such as strength, hardness and toughness. The mechanical properties are extrinsic and depend on elastic properties and material microstructure and morphology. The directly measured quantities are ultrasonic velocity and attenuation.

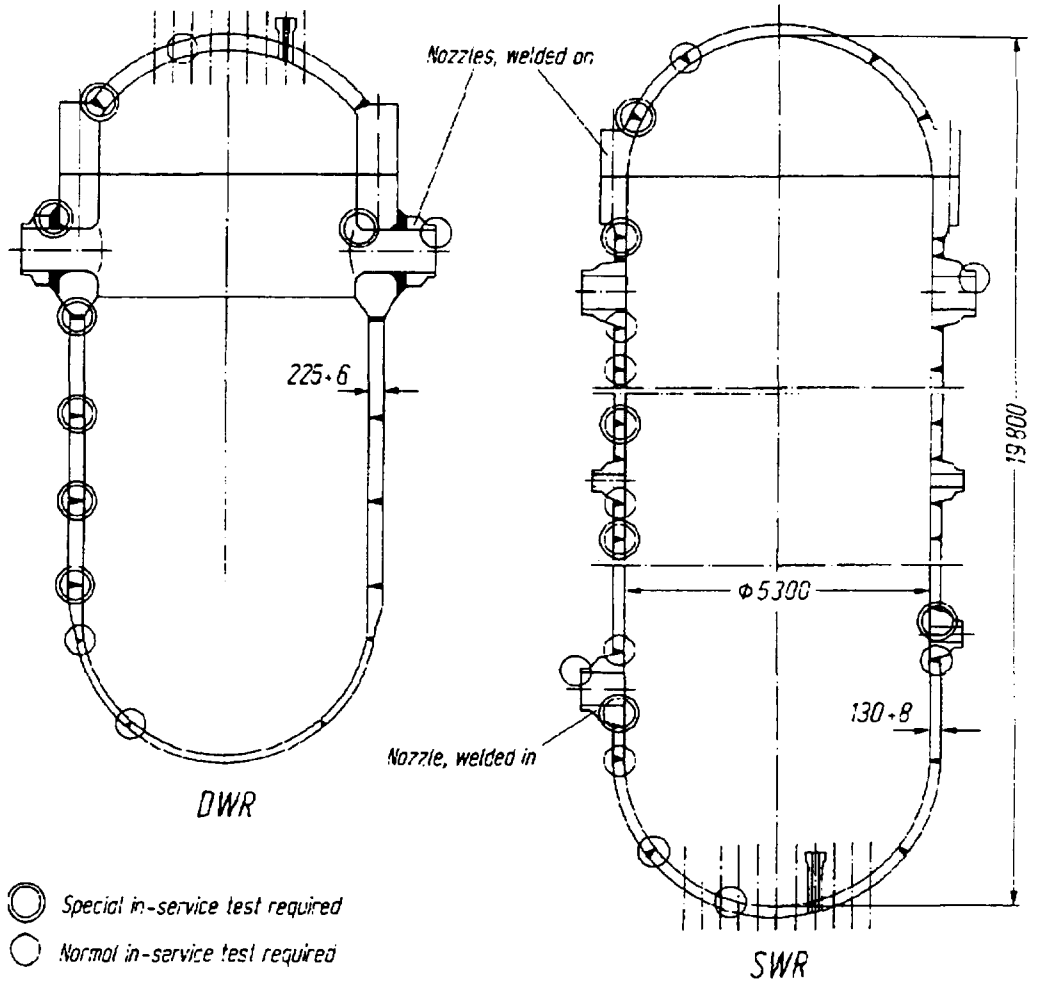


Figure 9.5 : Pressure vessels for pressurized-water reactor (DWR) and boiling-water reactor (SWR) of equal power (600 MW), older design, schematic. Testing zones circled.

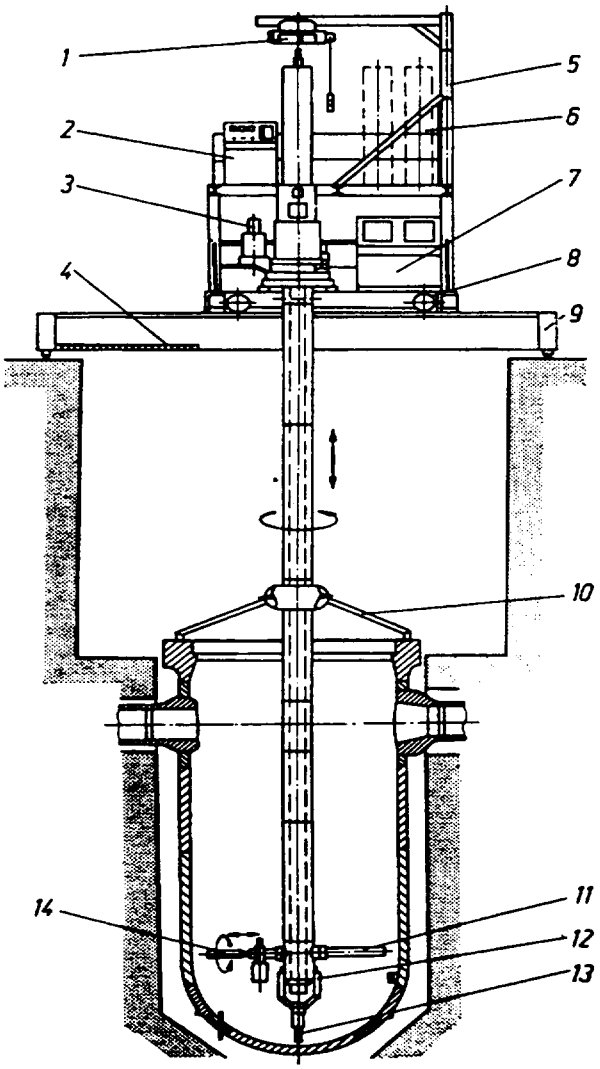


Figure 9.6 : Manipulator for internal tests on nuclear reactors, schematic (Design MAN-Krautkrämer)

1=Monorail hoist; 2=control pane; 3=mast bearing; 4=maintenance platform; 5=slewing crane; 6=mast sections; 7=electronic panel; 8=cross-bridge; 9=manipulator bridge; 10=pider support; 11=telescopic tube; 12=swivel arm; 13=probe system mount for hemispherical bottom; and 14=probe system mount for cylindrical wall and nozzles.

Dynamic resonance testing assesses physical and mechanical properties of certain materials by evaluating the resonant vibration frequency. If excited properly, most solids exhibit sonic resonances, typically in the frequency range below 20 kHz. Elastic moduli can be calculated if the dimensions, density and resonant frequency are known. There are direct empirical relations between tensile strength and resonant frequencies of structural components. It is possible to quickly confirm mechanical properties of a test object by comparing it with a known reference standard having the same shape and dimensions. The underlying relation is that the resonant frequency is the product of a shape factor and a physical factor. The shape factor is a combination of modulus, density and Poisson's ratio.

While dynamic resonance uses sustained forced vibrations, damping measurements use the vibration's free decay. The test object is isolated from external forces after excitation and either of two quantities can be measured: (1) the specific damping capacity or internal friction of the

material or (2) a comparative structural damping factor of actual components. Structural damping is not as sensitive as dynamic resonance to size, shape and other geometric factors. Although there are exceptions, damping values tend to be small in most engineering materials. Damping measurements are generally sensitive to discontinuities and damage, provided that extraneous damping from supports and fixtures is minimized. With simple excitation methods (point impulse), several simultaneous vibrational modes can be excited. These can be analyzed separately by computer for all frequency components and modes.

Damping and resonant frequency measurements can be used to monitor phase transformations, plastic deformation, hardening, cold working and alloy composition effects. Dynamic sonic and damping methods are used to evaluate porosity and density in ceramics, fibre-to-resin ratios in composites, bond strength in laminates, nodularity and texture in metals and strengthening by dispersoids in alloys. In its basic form, dynamic resonance affords a quick and convenient check for determining whether an object has appropriate mechanical properties or has undergone loss of elasticity or tensile strength. Elastic moduli and dynamic constants of structural materials can be assessed for predicting dynamic response.

Acoustic emission can arise when a material undergoes metallurgical transformations (twinning) or dislocation movements, plastic yielding or microcracking. The objective of acoustic emission testing is the detection and location of incipient discontinuities. The spontaneous stress waves that constitute acoustic emission can be analyzed to obtain information concerning discontinuities' characteristics, location, abundance and distributions during the loading or proof testing of structures. Acoustic emission is applied where it is important to monitor the presence and severity of growing cracks, plastic deformation or delaminations. The acoustic emission technique also affords a means for monitoring structural integrity and dynamic response and for inferring the current internal condition or state of degradation in structural components. Examples of in-process monitoring of materials are available in the literature, especially for solidification processes such as spot welding and heavy section welding.

The ultrasonic pulse echo technique is a key method for materials characterization. It is widely used for making precise measurements of ultrasonic velocity and attenuation. These two measurements are the basis for accurately evaluating elastic moduli, characterizing microstructure and for assessing mechanical properties.

The backscattering of ultrasonic waves is caused by discontinuities in density and velocity, that is, by the jump in acoustic impedance encountered at phase and grain boundaries in metals or fibre matrix interfaces in composites. The usual application of backscattering measurements is for non-destructive grain size determination. The backscatter approach has also proved useful for measuring global inhomogeneities such as those from segregations and inclusions in metals and ceramics. In addition, backscatter measurements can be applied to surfaces and substrates to determine relative roughness, to measure case hardening depth, to rank adhesive bond quality and to monitor texture and porosity in metals and composites.

Through transmission method using two well aligned transducers (Section 3.1.1) is often used for making comparative property measurements with time of flight velocity measurements and relative attenuation measurements. Single transit, through-transmission is used if there is high signal attenuation because of test object thickness. The method is often used in a comparator configuration where the test object's transit time delay is compared with the transit time delay in a reference standard, as when measuring relative changes in elastic moduli.

The dual transducer pitch and catch method uses a pair of transducers displaced from each other by a fixed distance, on the same side or opposite sides of a test object. The usual objective with pitch and catch techniques is discontinuity location and characterization. The method can also characterize material properties. In either case, the positions of the transducers are calculated to recover specific signals that have traversed well defined paths along the surface or in the bulk. The paths usually involve simple reflections from the back surface or surface waves that are intercepted by the strategically placed receiving transducer. The pitch and catch method often uses surface waves and guided waves, such as Rayleigh waves and plate waves, respectively. Lamb waves and leaky Lamb waves are used to evaluate bonds and interfaces by using angle beam immersion tests. Variations in bonding are observed through variations in the spacing of null zones over a range of frequencies.

Laser ultrasonics involves laser-in laser-out excitation and detection without the need for contact or immersion in a coupling medium (Section 9.1.7). It allows high speed scanning and convenient test object contour following. Laser ultrasonic techniques provide good attenuation and velocity measurements for materials characterization.

Ultrasonic spectroscopy is done with single or dual transducer configurations. The objective is to analyze modulations of ultrasonic waves caused by variations in microstructure and morphology. The spectral signature analysis approach is an excellent means for comparing subtle and often significant variations in material microstructures. Digital fast Fourier transform methods are necessary to obtain quantitative results. Ultrasonic spectrum analysis is used routinely in pulse echo, acousto ultrasonic and related testing methods. Appropriate analytical procedures include spectrum analysis, spectral partitioning, regression analysis and the method of moments. The latter utilizes statistical parameters to describe spectral signatures. Additional data processing techniques include pattern recognition and adaptive learning network theory. Ultrasonic spectroscopy is comparative and relies on a repertoire of spectral signatures for a wide range of materials and boundary conditions. Ultrasonic spectroscopy has been widely used for both qualitative and quantitative microstructure characterization. Attenuation spectra provide a powerful way to assess mean grain size in polycrystalline solids. In addition, porosity and other morphological factors can be assessed with ultrasonic spectroscopy. Analysis of ultrasonic spectral features can yield quantitative correlations with material properties that are governed in turn by microstructure. These correlations include the ultimate strength and interlaminar strength of composite laminates and toughness in metals.

Acoustic microscopy reveals density, texture, grain structure, porosity, fatigue damage, solid state weld bonding, fibre matrix interface quality and microelastic variations in metals, ceramics and composites (Section 9.1.3). Multiparametric scanning goes beyond producing images of material microstructure and microelastic domains. The goal is to collect an assortment of raw ultrasonic data and analyze them to give numerical values to a wide range of parameters. Selected parameters that can be colour mapped against the test object image include phase and group velocities, attenuation at selected frequencies, surface and internal reflection coefficients, and elasticity and stress values. Multiparametrics also comprise measurement of ultrasonic interactions with other forms of energy (thermal or magnetic).

9.1.7 Laser ultrasonics

Laser ultrasonics involves the optical means of generating and detecting ultrasonic signals. When light radiation is absorbed by the irradiated portion of a test object, thermal expansion results, producing elastic ultrasonic waves. A contribution might also come from the momentum

transfer of the reflected light but these radiation pressure effects are extremely small compared to those associated with light absorption. With increasing incident optical intensity, the temperature rise at the object surface can be so great that vaporization of the material may occur. The momentum transfer of the ablated material leaving the surface results in a force normal to the surface that also gives rise to elastic waves.

To generate ultrasound in these modes, a pulsed laser is used. Many reported studies have been performed with Q-switched solid lasers (ruby or Nd-YAG) with pulse lengths in the 5 to 30 ns range. Pulsed gas lasers may also be used. Optical methods for ultrasonic wave detection can be grouped into two categories. The first includes those methods that permit real-time detection of ultrasonic disturbances at a single point or over a single zone on a test object surface. The second category includes full field methods that provide maps of the acoustic energy distribution over an entire field of view at one instant in time. A technique called optical heterodyning or simple interferometric detection uses a wave scattered by the surface to interfere with a reference wave directly derived from the laser. The second detection method, called velocity interferometry or time delay interferometry, is based on the Doppler frequency shift produced by surface motion and its demodulation by an interferometer having a filter response

Optical probes for detection of ultrasound can be used to map ultrasonic fields at the surface of test object or at the surface of ultrasonic transducers. Probes based on optical heterodyning are preferred for this purpose because they can be easily calibrated and allow the measurement of the absolute value of ultrasonic displacements. Although not yet routinely used, optical probes appear to be useful testing devices for the detection of ultrasonic transducer malfunctions resulting from improper manufacturing or aging. Optical probes can also be used to clarify complicated ultrasonic field over the surface of a test object.

Because a laser generates longitudinal and shear waves at the same time, both velocities can be deduced from the measurement of the two propagation times. Assuming there is a suitable model to link velocities and elastic constants, these constants can also be determined. The measurement of ultrasonic velocities can also be used to monitor phase of inclusions.

Application of this technique to elastic constant determination has been reported for various materials, including metals (aluminium and steel), ceramics and metal ceramic composites, at room temperature and at elevated temperatures. These experiments were performed by generating ultrasound with a short pulse laser (generally a Q-switched Nd-YAG) on one side of the test object. Detection was done with a point detecting probe based on optical heterodyning on the opposite side.

Although laser ultrasonics is not likely to replace traditional techniques (because of sensitivity, cost and complexity), it does have its own range of applications, likely to include metrology, specialized or research laboratory testing of hot or complex products. The absence of a coupling medium for generation and detection allows the use of laser ultrasonic tests in outer space and it could be speculated that applications will multiply with increases in low gravity activities (also see Sections 9.1.2 and 9.1.3)

9.1.8 Electromagnetic acoustic techniques

The electromagnetic acoustic techniques (EMAT), also sometimes referred to as magneto-inductive methods, are based on the excitation and detection of ultrasonic waves in conductive or magnetic materials through the use of Lorentz force. The physical principles of EMAT

operation are shown in Figure 9.7. Suppose that a wire is placed adjacent to a metal surface and driven by a current at the desired ultrasonic frequency. Eddy currents J_ω are induced within the metal and if a static magnetic bias induction B_0 is also present, the eddy currents experience periodic Lorentz forces F_L given by:

$$F_L = J_\omega \times B_0 \qquad \text{----------} \qquad (9.1)$$

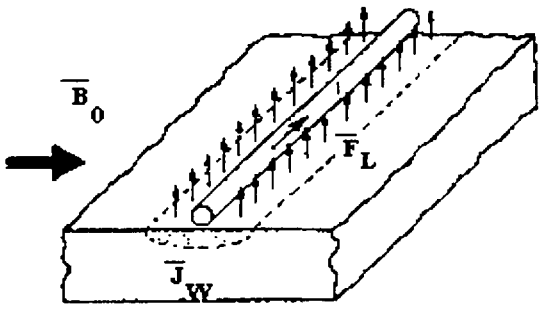


Figure 9.7 : Single element of an electromagnetic acoustic transducer, showing applied current I, induced eddy currents J_ω, magnetic bias induction B_0 and Lorentz forces FL.

The Lorentz forces on the eddy currents are transmitted to the solid by collisions with the lattice or other microscopic processes. These forces on the solid are alternating at the frequency of the driving current and act as a source of ultrasonic waves. The process is, in many ways, similar to that which creates motion in an electrical motor. Reciprocal mechanisms also exist whereby waves can be detected, a process analogous to operation of an electrical generator. If the material is ferromagnetic, additional coupling mechanisms are found. Direct interactions occur between the magnetization of the material and the dynamic magnetic fields associated with the eddy currents. Magnetostrictive processes are the tendency of a material to change length when magnetized. These processes can also play a major role in generating ultrasound. Again, reciprocal processes exist whereby these mechanisms can contribute to detection. Practical electromagnetic probes consist of much more than a single wire. It is usually necessary to wind a coil and design a bias magnet structure so that the distribution of forces couples to a particular wave type. Consequently there are probes that couple to (1) radially polarized shear beams, (2) longitudinal or (3) shear plane polarized beams propagating normal to the surface and (4) longitudinal or vertically polarized shear beams or (5) horizontally polarized shear horizontal beams propagating at oblique angles. The meander coil electromagnetic acoustic transducer can also excite Rayleigh waves on surfaces or Lamb modes in plates.

The major motivation for using electromagnetic acoustic transducers is their ability to operate without couplant or contact. Important consequences of this include operation on moving objects, in remote or hazardous locations, at elevated temperatures, in vacuum and on oily or rough surfaces. Moreover, alignment problems many be reduced because the direction in which the wave is launched is primarily determined by the orientation of the test object surface rather than the probe. Finally, electromagnetic acoustic transducers have the ability to conveniently excite horizontally polarized shear waves or other special wave types that provide test advantages in certain applications. It must be noted that the cost of realizing these advantages is a relatively low operating efficiency. This is overcome by the use of high transmitter currents, low noise receivers and careful electrical matching. In ferromagnetic materials, the

magnetization or magnetostrictive mechanisms of coupling can often be used to enhance signal levels.

Different applications of EMATs will now be described briefly. Ultrasonic techniques are widely used for thickness gauging and electromagnetic acoustic transducers expand the possible range of applications. Because of the EMAT's ability to operate at high speed and elevated temperatures, thickness gauging is well suited for on-line measurements during materials processing. With these transducers, it is also particularly easy to generate shear waves. This has advantages when measuring thin materials because the shear velocity is roughly half the longitudinal wave velocity. For a given thickness, the echo occurs later, is more easily resolved from electrical leakage and the change in arrival time per unit change in thickness is greater.

The testing of austenitic welds in clad materials can be strongly influenced by wave speeds in the weld metal. Because of the strong elastic anisotropy of weld materials, the difference leads to reflection and refraction of the ultrasonic wave at the interface. These phenomena have been studied in detail for vertically polarized shear and longitudinal waves, most of the existing work covers propagation in austenitic weld metal. EMATs can be successfully used for testing of such welds. Also reflection and transmission at the interface between a ferrite base metal and austenitic cladding have been studied as further examples of the interactions of shear horizontal waves at an interface between an anisotropic and isotropic medium.

Electromagnetic acoustic transducers are well suited for high temperature measurements because no fluid coupling is required. In general, there are three options available for designing these transducers for high temperature environments: (1) cool both the radiofrequency coil and the magnet, (2) cool only the magnet or (3) cool neither the magnet nor radiofrequency coil. In practice, all three approaches have been used successfully. High temperature interferes with the operation of electromagnetic acoustic transducers in several ways. The insulation on standard copper magnet wire for electric motor windings is seldom rated above 220°C (430°F). Most magnetic steels cannot be used as magnet pole materials above 550°C (1,000°F) but some cobalt alloys function as magnet poles up to 820°C (1,500°F). Most permanent magnet materials cannot be used above 120°C (250°F) and some high field materials degrade rapidly above 100°C (212°F). Consequently, these magnets require some cooling for operation near surfaces such as hot aluminium or steel and their wirings need special heat-resistant insulations. One of the most important applications of high temperature electromagnetic acoustic transducers is for testing metal products at fabrication mill. The transducer must not only be made of materials that withstand high temperatures, but also be powerful enough to overcome the high attenuation in metals near their melting points.

To achieve electromagnetic coupling, an EMAT coil and magnet need only be brought close to a metal surface. There is no need to have an operator available to adjust the transducer alignment or to optimize the thickness of the coupling fluid layer. This allows in-line tests of buried gas pipelines without interrupting the flow of the gas. In such an application, no coupling liquid is available and the test device must move unattended through many kilometres of moderate diameter pipe at speeds averaging 6.7 $m.s^{-1}$. Another important application of moving electromagnetic acoustic transducers is found in steel mill applications and is based on surface acoustic waves (Rayleigh waves) that are easily excited by electromagnetic acoustic transducers using a meander coil. By directing these waves around the circumference of tubular products, common discontinuities such as laps, seams and pits can be detected. More important, simple signal processing techniques can be used to obtain a quantitative measure of the depth of laps

and seams at production line speeds so that the manufacturer can immediately segregate materials according to the amount of rework needed for specified quality.

EMATs can be used for inspection of parts which are produced at high rates of, say, one per second. Most practical ultrasonic stress and texture measurements are made using EMATs. Among the advantages of EMATs are high temperature tests; moving tests; tests in vacuum; high speed, self alignment, phased array operation; and the excitation of horizontally polarized shear waves for the measurement of stress or tests of anisotropic weldments. The major drawback is lower efficiency than piezoelectric transducers. Careful modelling is sometimes required to design an optimum ultrasonic EMAT test. Considerable knowledge about the principles and engineering characteristics of these devices is, however, available to draw on in the consideration of new applications.

9.1.9 Ultrasonic tomography

Computed tomographic imaging is the reconstruction by computer of a tomographic plane or slice of a test object. Such imaging is achieved using several different types of energy, including ultrasound, X-rays, electrons, alpha particles, lasers and radar. By definition, a tomograph of an object is a two-dimensional visualization of a very thin cross-section through the object (the literal translation of tomo- is slice). This true cross-section is a two-dimensional reconstruction of many one-dimensional A-scans taken from many directions. This cross-sectional method eliminates the superposition of features that occurs when a three-dimensional object is displayed in a two-dimensional imaging format. The superposition, sometimes called structural noise, makes discontinuity detection and characterization more difficult because reflective objects from outside the plane of interest are included. Tomographic imaging is much more highly detailed. In addition, the use of computers to reconstruct the image also provides access to image enhancement algorithms. Tomography can be divided into two types with different applications, reflective and transmission tomography (Figure 9.8). Reflective ultrasonic tomography is used to locate and size discontinuities, erosion and corrosion of metals and can be used to characterize voids and inclusions. Transmission ultrasonic tomography can be used for determining differentiations in material density, composition or residual stress.

Ultrasonic tomography is more difficult than X-ray tomography because the ultrasonic beam can be totally reflected at solid boundaries within the test object. At weak boundaries, the sound beam may be transmissive and reflective. Therefore, there are the two types of ultrasonic tomography, each with its own parameters (Figure 9.8). Reflective tomography is analogous to the pulse echo technique and transmission tomography is analogous to typical through-transmission tests. Transmission ultrasonic tomography can be further subdivided into two types dependent on the properties of the test material. If the velocity of ultrasound through the material is constant, then the attenuation at each pixel is the parameter to be calculated, as in X-ray tomography. If the attenuation of the sound wave remains small throughout the volume of interest, then the velocity at each pixel is the parameter to be calculated. The quantity measured at various positions on the outer boundary of the test object is the total sound absorption in the first case and the total velocity for the second case. Both sides of the test object must be accessible and the lateral resolution is limited by the lateral resolution of the transmitting and receiving transducers.

Ultrasonic reflection tomography is an outgrowth of the transmission technique and is designed for providing quantitative images displaying a specific acoustic parameter of the test material. The size and location of the detected discontinuity or material interface can be closely estimated

by the amplitude and time of flight of the reflected signal. The gross shape of the discontinuity or material interface can be estimated by successive scans around the outside boundary of the discontinuity. However, because most ultrasonic energy is scattered in the forward direction, the receiving transducer must have high sensitivity and electronics are required to measure back-scattered signals at high signal-to-noise ratios.

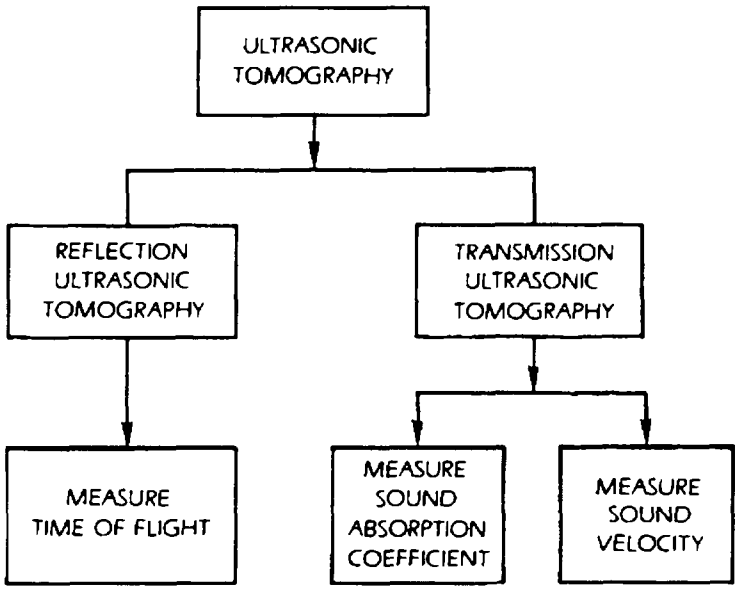


Figure 9.8 : Parameters determined in ultrasonic tomography.

This demonstrates why ultrasonic tomography requires more computer hardware and soft-ware than conventional ultrasonic techniques. The hardware has three basic components: (1) data acquisition, (2) data storage and processing systems and (3) image display of the processed data. A data acquisition system consists of the transducer (single or phased array) in an immersion tank and can be either normal to the material surface or at an oblique angle. During scanning the transducer is moved across the plane of the test object. This movement can be with several degrees of freedom to follow the contour of irregularly shaped components. The storage and processing system stores the raw scanned data and then calculations are performed on the data to produce the cross-sectional image. The image may be a two-dimensional plot constructed by comparing many adjacent cross-sections. Software is required to perform this processing. A tomographic image takes several minutes to construct because of the number of scans required and the large amount of processing.

Ultrasonic computed tomography has several applications in non-destructive testing, including test of complex, three-dimensional objects and fully assembled components, the detection of linear and planar discontinuities, characterization of discontinuities' size and location in both planar and volumetric detail. The feasibility of an ultrasonic transmission tomographic system has been demonstrated for mapping stress concentrations in steel using time of flight data and the algebraic reconstruction technique. This technique is an iterative reconstruction method that derives a value for the velocities that best fit the equations. The image improves with each iteration and the solution converges in a least square sense. Under compressional stress the velocity decreases and under tensile stress the velocity increases. The increases and decreases are about three percent.

Ultrasonic tomography provides several advantages for non-destructive tests: (1) increased spatial resolution by an order of magnitude limited by the length of the ultrasonic pulse, (2) reduced sonographic speckle arising from averaging various views over a number of directions, (3) reduced imaging errors and (4) wide dynamic range. Another advantage is the fact that computed tomographic images are capable of delivering quantitative as well as qualitative information. This occurs primarily because the data are not strictly measured but mathematically derived. A related advantage is that the images are digital, so that image enhancement algorithms can be used. The technician can manipulate the display parameters to adjust the contrast and latitude for optimal viewing.

9.1.10 Miscellaneous special techniques

The ultrasonic testing techniques that could not be discussed in the preceding sections will be briefly described here. In fact, if we think carefully, every test object that has a different geometry, shape and material would require a special dedicated technique for its testing. To this category would belong the large steel forgings; miscellaneous machined and semi-finished parts; railway axles, rails and other materials; plate and strip testing; rivets and rivet holes; laminar joints produced by soldering, brazing, plating and with adhesives; laminates, compound materials and composites; bearing boxes; shrink fits; pressure vessels and numerous other components in nuclear power as well as fast breeder reactors; different forms of metallic and non-metallic materials, etc. The solutions to some of the test problems related to these areas can be inferred from the ultrasonic techniques described in Chapters 3 and 6 and the preceding Sections of this chapter. For others the reader may need to seek help from various references listed in the bibliography.

9.2 AUTOMATED AND SEMI-AUTOMATED TESTING TECHNIQUES

9.2.1 Need and importance

Automatic and remote control systems of ultrasonic examination are rapidly improving and are now used in a very wide range of industries and in many different applications. There are many reasons why automatic inspection is preferable to manual testing. It reduces the operational variables and personal errors caused by manual examination. The data obtained is more accurate and reliable. In many situations manual testing is difficult to perform either due to inaccessibility of the test region or due to hostile environment such as high temperature or high radiation levels. In such situations manual operation is difficult and sometimes even impossible to perform. Automatic testing can be very fast thereby saving working time and manpower costs. It can give a large throughput of tested components thereby keeping in step with the high rates of production. The analysis and evaluation of results can be done through computerized systems thereby increasing the efficiency as well as reliability of data processing.

9.2.2 Components of an automated system of ultrasonic testing

There are many possible applications of automatic ultrasonic examination and the method used depends on the test materials, environmental conditions, costs, techniques and required data; each system has its own characteristics due to the situation requiring automation. Although a simplification, it is convenient to consider an automatic system as being composed of the following subsystems:

(i) Handling and guiding of the test objects.

(ii) Mechanical and remote operation of the probe or probes.

(iii) Automatic supply of couplant.

(iv) Automatic gain control.

(v) Automatic adjustment of the equipment gain to the specified working sensitivity (automatic distance amplitude correction.).

(vi) Self-checking or monitoring system.

(vii) Ultrasonic data processing system.

(viii) Applications of B-scope, C-scope, Quasi-three dimensional, etc.

(ix) Feedback and corrective action.

9.2.3 Designs and functions of various components

9.2.3.1 Handling systems for test specimens

Test objects handling systems could vary greatly depending upon the shape and geometry of the test specimen, its weight and dimensions and its physical and chemical state. Most of these arrangements will become more clear when the individual applications in Section 9.2.4 are described. Also the test object handling set-ups will be made in relation to the handling and manipulation of probes. In general these arrangements may include cranes and rails, special rollers, adjustable or fixed guides, motors and fixtures to tilt and rotate the test object, moving belts and conveyers, system-fitted immersion tanks of varying sizes for manipulation of test objects, etc.

9.2.3.2 Transducers for automated systems

There is a variety of designs of the ultrasonic transducers which are in use for automatic testing. Generally the probe must be held in contact with the test surface using an appropriate pressure, or else be kept at a specified distance from the test surface (immersion method). Oscillating scanning, transverse movement of the probes, angular oscillation, and pitch and catch technique, etc. are performed mechanically in as smooth a manner as in manual operation. Hundred percent coverage of the specified test area is required. Location of the probe and the direction of the ultrasonic beam must be exactly monitored and recorded. Installation, replacement and repairing must be easily carried out. In view of the need and importance of mechanized and automated inspection in industry, a lot of efforts have been directed towards developing the specialized probes needed for this purpose. These efforts mainly focused on, firstly, the developments to employ new piezoelectric materials to improve higher efficiency of electric mechanical energy conversion, and stable output of acoustic energy and, secondly, the development of new types of transducers involving new principles and techniques. The results of these efforts are summarized below:

High resolution transducers

Distance resolution generally depends on continuation period of pulse, Q of electric circuit, damping of transducer, frequency characteristics of amplifier, and dynamic ranges of amplifier and oscilloscope. The piezoelectric ceramic transducers with less time of ringing, and higher efficiency of dampers combined with damping material and sound absorber to compose the probes are required to obtain higher resolution. Recently improved higher resolution transducers which have higher damping with broad band (broad range of frequency) are employed and are

called "shock wave type transducers". These can possibly resolve multiple bottom reflections from steel plate 0.15-0.25 mm (0.006-0.10") in thickness. Application of this type of transducer is expanding to the aerospace and some of atomic energy industries. Problems with this type of transducer are, at this moment, lower sensitivity and poor amplitude linearity.

Focused probes

Different concepts for achieving a focusing effect in probes are shown in Figure 9.9.

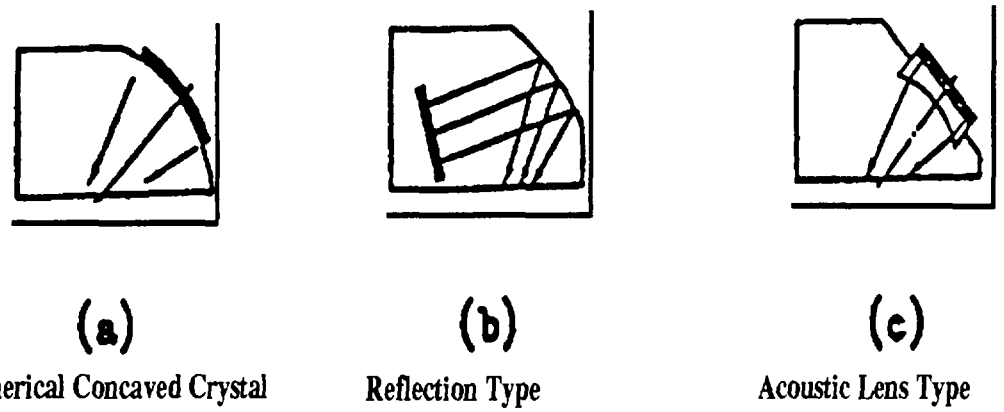


Figure 9.9 : Different ways of making focused probes.

Advantages of spherically concave crystal focusing probe are that the sound path is simple and short in wedge and smaller size is available. Disadvantage is difficulty to fabricate concave crystal in true spherical face.

Advantage of reflection type focusing probe is that it is easy to fabricate the flat faced crystal and outside curvature of the wedge, but, longer sound path in the wedge and larger size of the probe are a disadvantage. The focusing probe with use of acoustic lens can be available in smaller size. The flat faced crystal and longer focal distance are advantageously used. Interface between the lens and wedge reflects the sound. Material of the lens and fabrication of the concave lens are expensive.

Probes for improvement of signal-to-noise (SN) ratio

For examination of austenitic stainless steel and its weldment and casting, etc., it is required to improve SN ratio. Approaches for the improvement of the SN ratio are made by making focused probes to reduce the beam spread, by using longitudinal wave angle probes, by using a double crystal (pitch and catch type angle probe) having a focus at the most appropriate distance and by having different frequency transducers arranged to concentric circles.

High temperature probes

The probes have been designed to work at elevated temperatures. Some of these can work for short periods at 400-600°C while others can be continuously used at 200-250°C.

Electromagnetic acoustic transducers (EMAT)

These have been developed. In these the ultrasonic waves are generated by electromagnetic force at metal surface with use of magnets and electric coils, producing Lorenz force. These

transducers are used without contact with the surface of test specimens and without use of couplant materials (also see Section 9.1.8).

Immersion tire type probe

The probe is installed in tire type enclosure filled with couplant and the tire is rolled on the test surface. The beam angle is remote controlled(Figure 9.10).

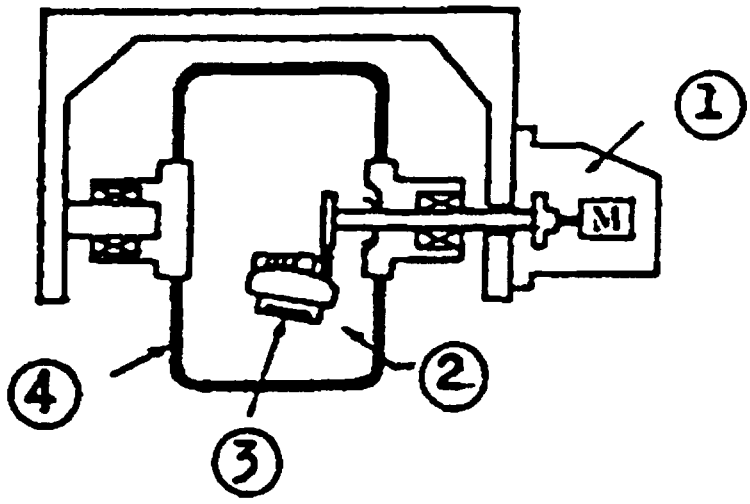


Figure 9.10 : Immersion tire type probe: 1. remote control system, 2. pressurized liquid, 3. crystal, 4. rubber tire.

Water jet type probe

The water jet is applied to the test surface from a nozzle containing the probe to keep very accurate distance from the transducer to the test surface. (Figure 9.11).

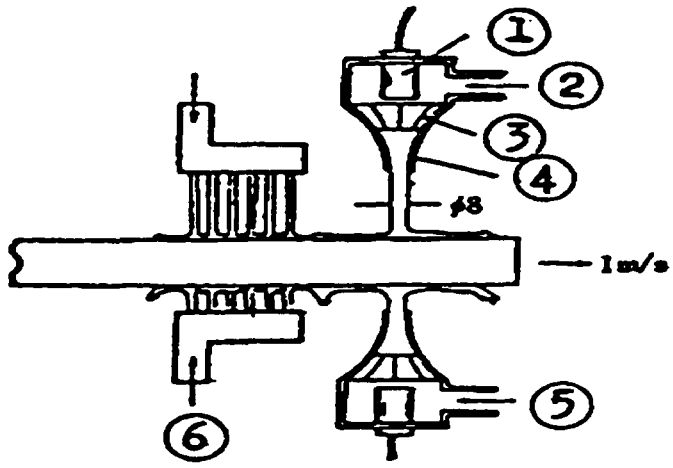


Figure 9.11 : Water jet type probe: 1. Probe, 2. Water, 3. Rectifier, 4. Nozzle, 5. Water, 6. Precooling water.

9.2.3.3 Automated supply of couplant

In most cases of the automatic ultrasonic examination, the automatic supply of the couplant is required. Many varieties are found in the automatic supply method, for example, water jet, circulating container, automatic supply blush and so on. The test object as a whole may also be immersed in water. The adequacy of coupling needs to be verified. The first bottom reflection, if available, is used in most cases for monitoring of the acoustic coupling. The echo signal height of the first bottom echo is monitored by data processing system in conjunction with the equipment. A typical monitoring system may consist of both normal and angle probes on a wedge. When the coupling is not satisfactory, alarm system, record system or stopping the examination are to be automatically operated.

9.2.3.4 Automated equipment calibration

Automatic calibration of sensitivity and automatic distance-amplitude correction is performed, with use of standard reference test blocks as specified for the manual ultrasonic examination. Where a considerable number of probes are working at one time, sensitivity of all are calibrated electronically at one time coincident with calibration of equipment.

9.2.3.5 Automated data processing

All the data and signals are automatically processed by a data processing system (Section 9.3) which consists of receiving of the signal, converting it to digital form by the use of analogue to digital converters and then recording it either on strip chart recorders or presenting it on the CRT screen using various imaging methods such as B-scan, C-scan or acoustic holography, etc. All these steps are controlled automatically by a computer.

9.2.3.6 Feedback and control

Most of automatic testing is performed for on-line inspection of products. In such cases it is desirable that when rejectable defects are detected, the defective portions are identified for purposes of segregation and possible rectification. At the same time a feedback has to be given for taking the necessary action for process alteration and control. The identification is done with the help of squirters which throw some kind of a dye on the defective portion immediately on receipt of the signal indicating defects. The feedback is also given in the form of signals on the receipt of which the mechanism responsible for control of process parameters are actuated and the needed corrective action is taken.

9.2.4 Examples of automated ultrasonic testing in industry

9.2.4.1 Rails and wheels

Manufacturing defects in rails depend on the origin of the steel, those manufactured from cast ingots have rolled-out flaws, and those from continuous casting contain a fine dispersion of non-metallic inclusions. The defects usually occur in the transition zone below the rail head and in the upper part of the web. In addition transverse cracks (the so-called kidney cracks) can occur in the head and true rolling defects are folds in the region beneath the web. Figure 9.12 indicates the most appropriate positions for the application of probes for detection of most of these cracks.

During service small cracks and inclusions can act as the origin of the kidney cracks lying transversely in the head of the rail. They are especially dangerous because they can occur in

groups over short distances and can therefore cause a short piece of the rail to breakout. Similar cracks start at wheel burns, where wheels skid during starting, for example in front of signals, leading to local thermal cracking as a result of overheating.

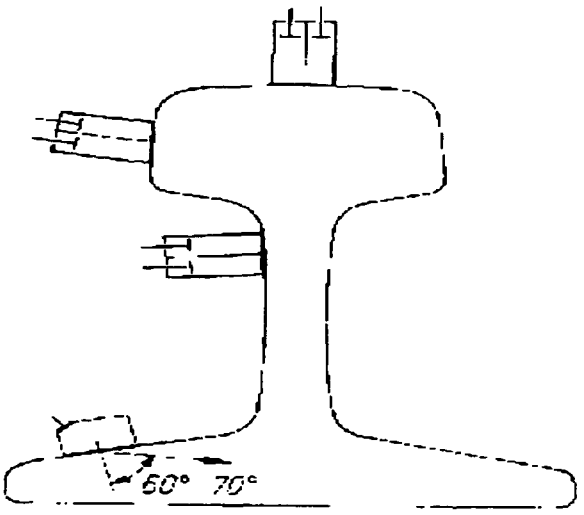


Figure 9.12 : Typical probe positions for rail testing.

Automatic testing of rails is done with the help of a rail-testing train. It consists of three cars, of which the middle one contains the testing equipment. The two outer ones contain the diesel engines and arrangements for housing the crew. Beneath the middle car the testing carriage is suspended, containing the pairs of 35° and 70° angle probes and the normal TR probe, one set for each rail. These can be raised or lowered hydraulically either separately or together with the testing carriage. For each rail two ultrasonic probes are arranged additionally directing air-borne ultrasound onto the transition between foot and web to detect welding beads.

The 35° angle probes are switched in parallel, so that each receives the pulse originating from the other after reflection at the bottom face and in addition echoes from fish-plate bolt holes, oblique cracks from the holes and transverse cracks in the foot provided they reach under the web. The coupling face is made from plastic and has only to be changed after several thousand kilometres. The several cubic metres of coupling water required for the daily testing distance of 200 km is contained in a tank.

9.2.4.2 Sheets (plates) and strips

The testing of plate for manufacturing defects is very diversified covering a range of thickness from 1 mm to more than 100 mm. Classification into medium and heavy plate for thickness above about 4.5 mm and sheet and strip for thickness less than this, seems practical in view of the different problems involved.

Most testing is done automatically. A number of methods of different detailed designs have been used for many years but they differ regarding the test method, the scanning programme and the evaluation of data. Firstly there has been the through-transmission method with coupling by free water jets. Then there comes the pulse-echo method with TR probes and water-gap coupling. Some heavy-plate testing installations are designed to test separately cut plates in which each plate stops, and one or several probes check the face and the edges according to a programme (e.g. first testing of all four edges, then scanning of the face of the plate along a meander).

Arrangements using large immersion tanks have also been developed. Most installations, however, are designed as "transit tests", the plate being tested on a roller bed during normal transport at testing velocities of 1 m/s and higher. The probes are arranged in the form of a comb and in some instances the testing comb oscillates transversely to the rolling direction in order to improve the detectability of long narrow flaws.

9.2.4.3 Pipes and tubes

In seamless rolled tubing the defects which are of interest are similar to those occurring in rod material, that is cracks and laps on the internal and external surfaces as well as inclusions and laminations in the wall which are caused by the manufacturing process as they are in rolled plate.

In the factory automated testing installations are installed almost exclusively using the full or partial immersion technique for mass produced tubes such as boiler and main-supply tubes, high-pressure tubes, oil-field tubes, precise tubing and nuclear-fuel canning tubes. Usually two complete probe assemblies are used but separated in the longitudinal direction of the pipe, and with sound beam paths in opposite directions of inclination. To detect transverse defects an additional simple arrangement of a single-probe is used, which generates a 45° zigzag wave along the tube wall in the longitudinal direction. To ensure that unfavourably oriented defects are also detected a second probe pointing in the opposite direction can be added.

Tube testing installations can be divided in general into two groups of different mechanical design. In the first type the probe arrangement is stationary and the tube is rotated and transported longitudinally to achieve a spiral scan. In the second type the tube is longitudinally transported and the probes rotate around it giving an arrangement which fits better into the production line. In a typical arrangement for testing of nuclear fuel canning tubes an immersion tank contains four point-focused probes of 10 MHz arranged in two planes perpendicular to the tube. One pair tests for longitudinal defects but with opposing beam directions, and the other pair detects transverse defects. Additionally a further probe can measure the wall thickness, or a pair arranged in 180° positions can measure the complete geometry of the tube including wall thickness and outer and inner diameters. Defects as small as 0.03 mm with a length of 0.75 mm can be detected, because of the very precise guidance system of the probe assembly, achieved by riding on the tube. Testing speed, depending on the minimum defect length to be detected is 2 to 5 m/min. If the diameter of the tubes becomes large, rotating of the probe assembly can become very difficult. In such a case the water filled tank together with the fixed probe assembly can be manipulated and pressed against the tube after it has entered the test machine. In other installations for testing tubes the rollers provide linear transport and simultaneously the complete roller system is rotated around the tube axis. The mechanisms for rotating probe systems around the tube are in use for testing a wide variety of tubes up to 600 mm diameter. In most installations up to 250 mm the probes are housed in a closed water tank and circulate around the tube, also incorporating probes for wall-thickness and geometry measurement. For larger tube diameters water-gap sliding probes are used. The testing speeds can be as high as 8,000 rpm. The probes can be adjusted automatically by a computer aided system. In addition to flaw detection, wall thickness measurements can also be made and some machines are also capable of inspecting welded pipes and tubes.

9.2.4.4 Rotors

Automated tests for rotor forgings have been carried out for many years in order to achieve a continuous test. A newly developed automatic examination system to apply to large sized

turbine rotor shafts for nuclear power plants is described here. This is composed of a multi-probe system which scans the surface of the rotor using flowing oil as a couplant. The rotor itself can be supported and rotated on rollers. The oil container is carried on the test car along with the flaw detector and recording devices alongside the rotor on rails. Both direct contact or gap scanning can be used. The data can be recorded in all the three modes, i.e. A-, B- or C-scans. The data is electronically processed. In a typical Japanese machine for rotor testing, rotors of up to 2000 mm diameter and 10 m length can be accommodated. The transducers used are of 2-5 MHz frequency. The shaft is rotated and the recording is done through a polaroid camera for B-scan presentation and through a printer for C-scan presentation.

Installations for testing of rotors are also available using large immersion tanks. Because of the very uniform coupling, testing frequencies up to 10 MHz can be used. Test facilities have also been designed whereby the rotors can be tested without having to remove them from the casing.

9.2.4.5 Automated inspection of nuclear reactor pressure vessel

A mention of the nuclear reactor pressure vessel testing has earlier been made in Section 9.1.5. Here we will try to explain how this testing is performed automatically. A number of testing systems exist, for example, American, French, Canadian and German, etc. We will describe two systems to bring out the salient features of automated inspection of a nuclear reactor pressure vessel (refer to Figure 9.6).

The first is the SUTARS (Search Unit Tracking And Recording System) developed by South-West Institute, USA. The system works in conjunction with a manipulator having a number of arms in which various types of probes can be housed and remotely adjusted. Basic components of SUTARS are shown in Figures 9.13.

Brief description of various components is given below:

(a) Data collection system

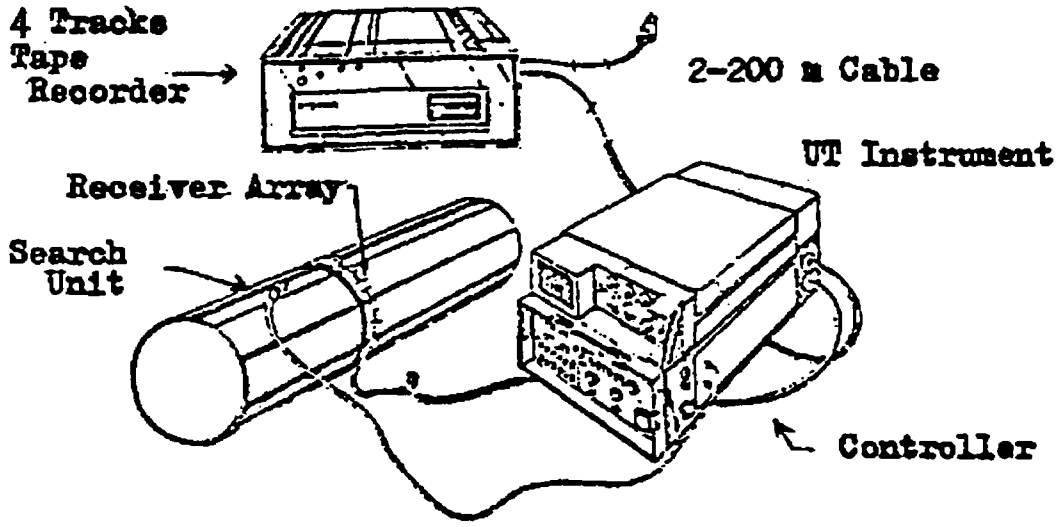
The system consists of three channels of ultrasonic equipment and controller to control position of scanning devices, scanning velocity, and couplant supply system. The ultrasonic equipment has an adjustable DAC at six points.

(b) Data processing system

This includes data digitization by analogue-to-digital (A/D) converter, pre-processing device for examination results and parameters to be input to computer, digital display panel for indication of device location and examination results, tape player, computer, accessories for data processing and records.

(c) Data collecting modes

(a) Normal mode: Amplitudes over the threshold value are recorded.
(b) Limit mode: When the amplitude over the threshold value is obtained, wave form is recorded.
(c) Peak's mode: Peaked values of the amplitudes over the threshold value are recorded.



SUTARS Data Collecting System

SUTARS Data Processing System

Figure 9.13 : Components of SUTARS for automated inspection of a nuclear reactor pressure vessel.

9.2.4.6 Miscellaneous applications

Based on the concepts of automated ultrasonic testing as outlined above there are number of other areas where the automated methods are applied. One such area is the testing of solid billets, rods and wires. The techniques of testing are more or less similar to those used for testing of pipes and tubes. Systems also exist for automatic testing of T-frame welds in submarine pressure hulls, testing of austenitic steel welds, testing of car bumpers, testing of aircraft parts and honeycomb structure, testing of bearing boxes, testing of bolts, bolt sockets and nuts of pressure vessels, thickness measurements in piping, creep damage measurements in piping, underwater thickness measurement for corrosion, failed fuel pin tests in nuclear reactors, testing of heat exchanger tubes, testing of thick-walled containers, for sound velocity measurements and flaw testing on safety parts of automobiles (castings, wheels, etc.).

In conclusion, it may be said briefly that the automated inspection can provide significant advantages of processing a large volume of data exceeding human efficiencies, providing the information needed for multiple transducer tests in real time, improving efficiency and costs on a production line, providing control of systems in changing environments or complex conditions, facilitating accept/reject decisions using complex criteria.

9.3 SPECIAL TECHNIQUES FOR DATA PROCESSING

9.3.1 Introduction

Data processing in ultrasonic testing may be visualized to mean the collection of information regarding the internal structure of a test specimen by sending ultrasonic waves or pulses into it and then transferring back the collected information in a manner which is suitable to obtain unambiguous, meaningful, reliable and discrete information about the characteristics of the tested material. Ultrasonic pulses that go into the material wander around (of course according to some principles) and investigate the interior portions and return to the surface laden with information or data about the grain structure of the material, density, acoustic impedance, elastic moduli, applied or residual stresses, thickness and the nature, size and location of discontinuities and inhomogeneities. At the surface these pulses are received by the transducer which initiates the long and complex process of interrogation and extraction of the information or data carried by them – the process of data processing. The transducer, using the reverse piezoelectric effect, first of all converts the ultrasonic pulses into voltage or current pulses also called voltage or current signals. It is these voltage or current pulses or signals which are further processed and converted into a meaningful form. Therefore the terms data processing and signal processing are interchangeably used in literature. Putting it in another way in electrical terms a signal is a parameter (usually voltage or current) which varies with time and is used to convey information from one place to another. Processing is the alteration of this information. Signal processing is commonly used in NDT instrumentation often without the NDT technologist even being aware of it. For example, the "signal" which appears on the screen of an ultrasonic flaw detector has often undergone several stages of signal processing in order to make it more readily assimilated and understood by the operator. Various steps involved in data or signal processing are briefly explained in the following sections.

9.3.2 Signal transmission and detection

It is well known how the ultrasonic pulses are generated in ultrasonic probes. There are two main types of electrical signals, namely, the analogue signal and the digital signal.

The analogue signal is the one which varies continuously with time. This can be explained with the help of a simple example. Suppose it is intended to convey some information between two cities. A transmitter which could simply be a battery producing different voltages through a variable resistor could be placed in one city and a receiver, which could just be a voltmeter to measure different voltages, in the other. The transmitter and the receiver could be connected with the help of a wire. By varying the resistor the voltmeter would register a change in voltage. If the information to be sent is, for example, in the form of "yes", "no" or "may be" and if it was agreed beforehand that, say, any voltage above 10 volts represented the word "yes", any voltage below 5 volts the word "no" and any voltage in between the word "maybe", then a simple communication system would have been established, albeit a rather limited one! This system, since it uses continually varying voltage, could be thought of as an "analogue" system. The electric voltage or current output is proportional to the echo-signal height. Analogue signal shall be normally required to have linearity of ±5%, drift of ±5% of full scale and dynamic range of more than 20 dB. If the variable resistor were to be replaced with a simple on/off switch and the voltmeter with, say, a light bulb then with the switch closed a current will flow and bulb will light (perhaps signalling "yes"), whereas with the bulb switched off signal "no" will be indicated. Then we seem to have a problem, because the bulb can only be on or off, that is, how to signal "maybe" ? But this can, in fact, be done quite easily using a code made up of sequences of on and off. This communication link would effectively be a "digital" system, and the familiar Morse Code is a good example of a digital signalling method. Thus the digital signal in a simple form may be defined as one which is discontinuous with time and has discrete and quantized numerical values.

9.3.3 Data (signal) processing

Continuing with the example of sending and detecting signals between two cities, let us suppose that now we want to talk to the other person rather than just signal "yes" or "no". We could replace the variable resistor or switch with a microphone and the voltmeter or light bulb with a loudspeaker, and would in fact have a rudimentary "telephone"! How well the sound could be heard and understood at the receiver depends on the frequency bandwidth of the overall system. Intelligible speech sounds are contained in a frequency band extending from about 300 Hz to 3400 Hz and an overall bandwidth of 4 kHz is, therefore, used for telephone messages in order to cover all the sounds likely to be encountered. Overall bandwidth refers to the complete system consisting of mouthpiece, line and earpiece. Similarly for hearing a good "hi-fi" music, we need a wide frequency bandwidth of about 4 to 5 times that in a telephone. May be it is not physically possible or economical to use wires to connect the transmitter to the remote receiver. How can the communication channel then be set up ? One way is to record the speech or music on a magnetic tape or vinyl record, or better still, digitally encode it onto a compact disc and then send it through the post. Alternatively, if a quicker route was required the message could be sent through the atmosphere using a "wireless" or radio. Radio signals are generated using an oscillator which produces a radio-frequency sine wave (for example, BBC Radio 4 broadcasts at 200 kHz) known as a carrier wave. This is in the form of an electromagnetic wave (just like light waves but much lower in frequency), not acoustic waves (like the ones produced when you speak). In order to convey information the carrier wave is modulated by the speech or music which means that the carrier and information waves are mixed together, or "processed", in some way. In the case of amplitude modulation (am), for example, the strength or amplitude of the carrier wave is modulated by the information signal, with frequency modulation it is the frequency which is modulated.

In a microphone sound waves are converted into electrical signals. Similar is the case for an ultrasonic transducer. In this case a short electrical pulse is applied to the transducer element in the probe (the "piezoelectric" element) in order to produce a short elastic wave in the material under inspection. The frequency of elastic wave generated, for NDT purposes, is typically in the range of 1 to 15 MHz. This is much higher than the highest sound (pressure wave) a human being can hear, which is typically about 20 kHz. The frequency content of the ultrasonic signal (its bandwidth) is determined largely by the thickness of the piezoelectric element and the material surrounding it. The voltage spike causes the piezoelectric element to "ring" at its natural frequency. If the piezoelectric element is surrounded by air it will produce a ringing pulse which is not much used for NDT inspection because it leads to poor resolution which means that echoes from defects close together become jumbled up and cannot be separated or "resolved". The ultrasonic pulse, then, is usually shortened by damping the piezoelectric element using a material of a similar acoustic impedance thereby widening its bandwidth and stopping it from ringing so easily.

Referring back to the journey of the ultrasound waves, the electrical pulses generated at the receiving transducer, called the signal, are very weak. The signal must be processed to make it stronger so that it can continue its journey to the screen or other signal detection devices. This enlargement process is called amplification. The amplifier has its own frequency bandwidth characteristics and may not only amplify but also change the shape of the signal. Sometimes it is important not to alter the shape of the signal and , therefore, a wide bandwidth amplifier characteristic is selected. Normally an increased bandwidth is obtained at the expense of a loss in gain or how much the signal is amplified. These parameters in an amplifier are often referred to as the gain-bandwidth product.

Passing a signal through an amplifier, whose bandwidth is smaller than the signal, has the effect of filtering the signal by cutting out the frequencies above and below the amplifier's frequency range. It is sometimes useful to deliberately filter signals in this way to improve their final appearance and flaw detectors usually incorporate these filtering features but very often as part of the "frequency" control. Amplifiers exhibiting filtering effects are sometimes called active filters. Passive filters can also be used (i.e. those which do not use any amplification) and, like active filters, these can exhibit high-pass (i.e. letting the higher frequencies pass through), low-pass or band-pass characteristics and can be of extremely complex design to allow very special features in the signal to be extracted. Low-pass filters tend to make a signal look "smoother" because they cut out the "sharper" high frequencies and are, therefore, sometimes called "smoothing" circuits.

In many cases signal-to-noise ratio in ultrasonic systems can be improved by rejecting certain portions of the received signal spectrum. For example, receiver noise increases in proportion to the square-root of bandwidth; thus, it is evident that excessive bandwidth will result in increased noise and, hence, degraded signal-to-noise ratio. If the transmitted pulse is a coherent burst containing several cycles of the carrier frequency, then most of the useful energy is contained in a relatively narrow band centred about the carrier frequency. Thus, signal-to-receiver-noise ratio can be maximized by limiting receiver bandwidth to that required to adequately pass the ultrasonic pulse.

A digital computer operates on the measured parameters of the echo signals and upon the known characteristics of the fitting set of defects to, in effect, fit a complex equation to the available data. A second set of known defects, called the "selection set", is used to define the adaptive learning network by eliminating those echo signal parameters which have small effect. After completion of the learning and defilement processes, the network may be fed with the echo

signal from an arbitrary flaw of the same general type used in training. The network then computes the value of the specific defect characteristic which it was trained to recognize and qualify. As an example the method was used to measure diameters of flat-bottom holes drilled to uniform depths in metallic test blocks. Ultrasonic pulse-echo signals were used as inputs to the network. Three sets of test blocks were used in developing the network; these were called the "fitting", "selection", and "evaluation" sets whose purposes were, respectively, (1) to train the network initially, (2) to refine the network and eliminate relatively insignificant variables, and (3) to test the trained network. Out of 96 candidate waveform parameters, 15 were found to contain information about flat-bottom hole diameter. These included parameters related to shape, area and frequency content of certain parts of the received signal. It is interesting to note that echo amplitude, which is often used to estimate defect size, was not significant in the adaptive learning network for flat-bottom hole diameter measurement. The resulting adaptive learning network implemented an eighth-degree function of the 15 input waveform variables. The reported synthesized non-linear adaptive learning network correctly measured the diameters of 46 out of 48 flat-bottom holes in the evaluation set.

The signals may be amplified to such a large extent that they may not fit vertically on the screen and the peak signals are cut off ("saturated") or distorted. So, before passing them to the screen, the signals are passed through an attenuator to reduce them in amplitude. The attenuator is usually calibrated in fixed steps of a convenient measure known as decibels. A decibel (or dB for short) is merely a convenient way of expressing voltage ratios.

The signals which are originally generated at the receiving probe are in the form of sinusoidal waves having both positive as well as negative portions. But the echo peaks that we usually see on an oscilloscope screen do not have any negative portions. To bring the sinusoidal wave signals into the form of echo peaks, the signals are rectified to remove the negative-going parts of the cycles. This is usually followed by "smoothing" to make the signal less "peaky". Some of the steps involved for signal processing in an ultrasonic flaw detector are illustrated in Figure 9.14.

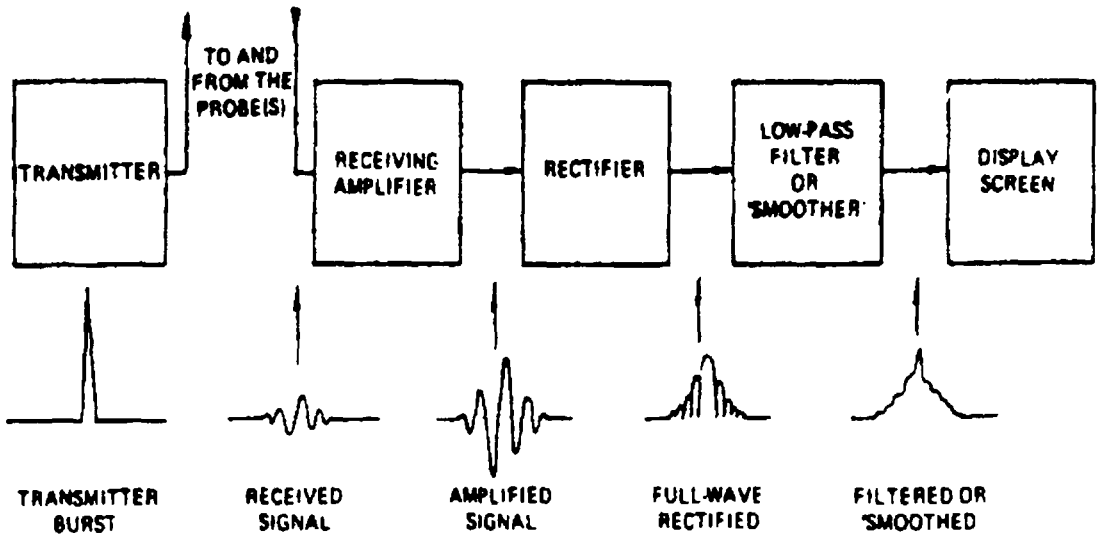


Figure 9.14 : Some stages of signal processing in an ultrasonic flaw detector.

Rectifying the signal tends to make some functions easier to implement in the electronics. For example, an amplitude threshold can be easily applied, above which signals are retained, or

suppression can be used to remove unwanted low-level signals or noise. This can be achieved by using a circuit known as a comparator which, as its name suggests, compares the signal with a d.c. voltage, usually selected by the operator on the front of the flaw detector.

Gates perform similar functions of rejecting or accepting signals but are more selective in that they can pick out parts of the overall A-scan rather than the whole trace. In most flaw detectors the gate width and delay can be varied as well as its height (i.e. the reject/accept threshold). Usually, a signal appearing in the gate sets off an audible or visual warning to alert the operator to the presence of a flaw at some specified range, for example. Very often the signal in the gate is used to provide a further signal which can be used to feed other equipment, controlling a strip chart recorder, perhaps.

9.3.4 Digitization of data

The analogue signal can be converted into a digital form. Digital systems are rapidly gaining favour with NDT technologists and there are now several excellent microprocessor- and minicomputer-based NDT systems on the market. Any analogue signal, for example, the familiarly known A-scan from the CRT screen of an ultrasonic flaw detector, is continuous with time but if we sample it at regular intervals (the sampling interval or sampling frequency) we can still make the signal look very much like the original as long as the samples are taken at short enough intervals (Section 4.3.5). The original analogue signal, then, can be reduced to a discontinuous series of numbers or digits; in other words a digital signal. The process of turning an analogue signal into a stream of bits is called, perhaps not surprisingly, analogue-to-digital conversion. We have said already that this process of conversion involves electronically sampling the waveform at regular intervals, noting the signal level at each sample against a fixed scale of values, such as voltage. Digitization of the analogue signal offers some distinct advantages. The first useful thing that can be done is to store the signal for future use. Once in digital form the signal can be transferred, via the computer, to a magnetic disc or tape storage device for permanent storage or core memory for immediate use. Other information, such as probe and instrument details, can be stored along with the data signals to give a permanent record of the whole inspection process. In ultrasonic inspection, for example, a whole series of "A-scans" can be stored and then plotted out together to form "B-" or "C-scans" and the resulting displays can be encoded with colour or grey-scales to improve interpretation, like the almost photographic images which are now being used for medical monitoring and aiding diagnosis.

Inspection data can be compared from one inspection period to the next to look for differences, perhaps due to flaw growth, and this can be done automatically to eliminate human error. Images can be processed to enhance certain features or suppress others. Patterns in the data can be recognized, either by the expert human or automatically by the expert system and the operator can interact with the data easily and quickly to focus his attention on salient features. Of course, all of this could be done with analogue signals and displays but it is usually much more difficult, slow and costly. Other advantages of digital systems are that they are easier to design than analogue systems since they are primarily made up of logic circuits, or "gates" (not the same gates as described earlier for the flaw detector !). They are also more accurate, faster and a higher level of electronic circuit integration is possible. But there are some disadvantages ! The real world is analogue and in practice most natural information such as temperature, pressure, weight and time, is analogue. Conversion of analogue information to digital data, and the reverse, can be complicated and therefore expensive. In addition the conversion process inevitably introduces inaccuracies and takes a finite amount of time, both of which may be

critical. Analogue processing is usually simpler too. Finally, digital systems are slower at transmitting information than analogue. Nevertheless, the advantages of digital systems are beginning to outweigh those of analogue and this can already be seen in the NDT world with the increase of digital equipment.

9.3.5 Data presentation and recording

After the signals have been treated in one, few or many ways outlined in the foregoing section, it is now desired to have a look at them by making them visible with a view to retrieve the information/data they contain and to analyze that information in terms of material characteristics including the flaws. Finally there is a need to record this data in a proper format for the purposes of still further analysis, evaluation, documentation and record.

The most familiar way of making the signals visible is through the screen of a cathode ray tube in a conventional ultrasonic flaw detector (Section 4.1.1.1).

The other familiarly known data visualization methods are the B-scope and C-scope imaging methods (Section 4.3). More recent are the film methods in which a camera in front of the pulse echo instrument photographs continuously the simple A-, B- or C-scan images on the CRT screen. In the digital record systems a digital output is recorded. Some of the auxiliary equipment used in this system are digital printer, X-Y plotter, multi-pen recorder, line printer, CRT character display, etc. Figure 9.15 shows a digital print out of signals from a defect in the weld. A mention needs to be made of multi-threshold recording monitors which are used in making digital presentation of the image. A recording monitor is a gated amplifier which indicates the echo of a signal as soon as the former appears in a preselected transit time zone (the gate) and exceeds a preselected amplitude reading, in the form of a voltage pulse. If the echo voltage is placed on an analogue-to-digital converter, the output furnishes a numerical information. The digital output can be converted into defect display image using the planar recording systems. These help to record the signals to a projection on horizontal plane or vertical plane. There are also recording systems now available (such as tomography) to furnish images in three dimensions.

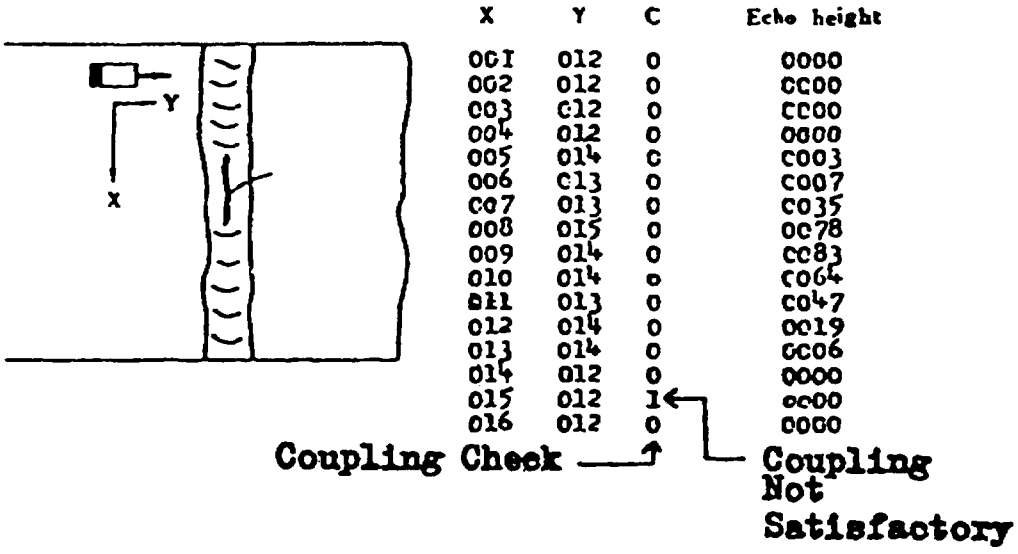


Figure 9.15 : A typical print out from a digital recording system.

A double two-dimensional recording system combining the B- and C-scope systems is presented in Figure 9.16.

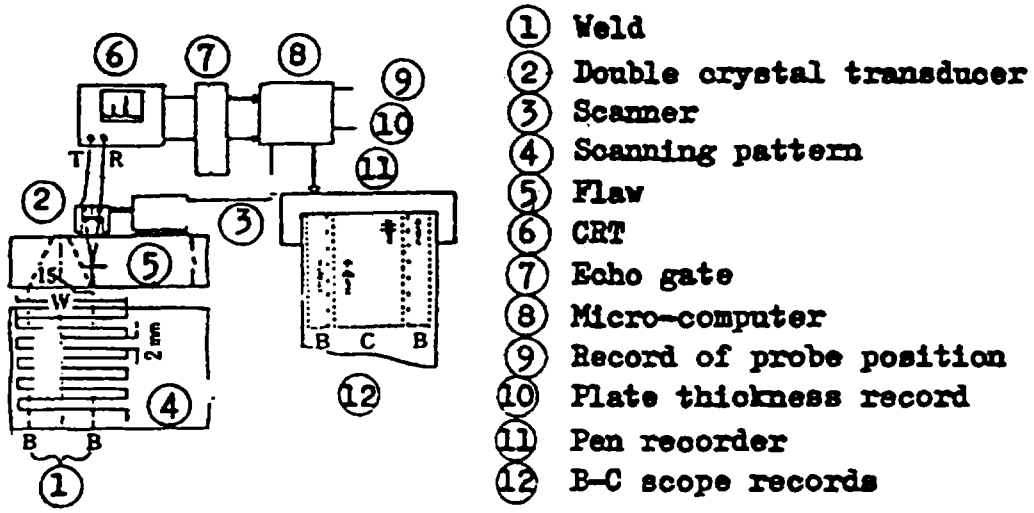


Figure 9.16 : B-C scope combined recording system.

Acoustic holography is another method of recording the ultrasonic pulses as they emerge from the test specimen. Both the options of optical as well as numerical reconstruction can be utilized with this (Section 9.1.2).

Multiple frequencies from the waves reflected from internal flaws can be displayed on charts and these are useful to characterize and to measure the extent of the flaws.

In many instances, a suitable documentation of the test results is desirable, frequently after signal evaluation by a data processing installation. Complete documentation of all test results of a given test piece is not feasible for economic reasons. This would require not only the recording of all three space co-ordinates but also information concerning the size of the flaw for every point of the three-dimensional test piece. Fortunately, usually several of these data can be omitted. Direct recording methods and instruments use either moving recording systems which produce deflections at right angles to the movement of the strip chart, or stationary recording pens which merely record go/no-go signals in the form of a dotted line. The first method is used for the proportional documentation of the results (echo amplitudes or transit times), whereas the second method is used specifically in the form of go/no-go recordings. Movable recording systems have a mechanical cut-off frequency which in the case of inkfed recording pens is far below 100 Hz; those using a moving stylus and wax paper have a maximum cut-off frequency of some 100 Hz. In the case of the light-spot recorder which produces an instantly visible record on sensitized paper with the aid of a strong UV light beam and a mirror system, the cut-off frequency is some 1000 Hz. Optimal resolution and maximum speed are obtained with the pulse recording method; the pulse output voltage of the recording monitor is placed directly on the recorder. At a repetition frequency of 130 Hz the instrument, therefore, records 130 peaks per second whose heights are proportional to the echo height. This recording system permits scanning speed of 1 to 2 m/s. Since at present still faster recording systems are not available, this probably represents the limit of direct recording.

In the case of linear scanning of a long test piece, e.g. a rod, a billet or a rail, the chart feed of the recorder usually corresponds to the scanning motion on the test piece. Sometimes both are coupled to each other directly. The recording thus reveals the position of a given flaw in one co-ordinate, viz. the longitudinal direction of the specimen, in the form of a go/no-go trace or a proportional trace. This solution is acceptable in such simple cases which do not require a more exact indication of the position of the flaw. This method requires only a simple recorder with narrow strip chart and a fixed recording system. The so-called XY recorders would make it possible to simulate on a stationary sheet of chart paper the scanning movement of the probe in two co-ordinates, as in the case of the C-scan. In practice, however, this would be too slow. For disc-shaped specimens such as turbine discs the answer is a type of gramophone-record scanning combined with a suitable recording system. Both the specimen and the recording chart rotate, while the probe and the recording system are shifted slowly in the same sense, either rectilinearly or along an arc as in the case of a gramophone record.

Frequently spiral records on electrochemical chart paper are used for C-scan presentation. In this system the strip chart is stretched over a cylinder having a raised metal spiral, e.g. a wire, which is fixed to its surface in a pitch extending over the full width of the chart. A straight metal bar presses the chart down against the spiral. If the cylinder with the spiral turns, the contact point where the current passes from the bar through the paper and into the cylinder travels from one end of the chart to the other. The rotation of the spiral cylinder is coupled to the scanning movement of the probe which, for instance, scans a band-shaped specimen transversely to its direction of feed. Scanning of the test piece along a zigzag line can be achieved by a different design using two contra-rotating spirals with one half pitch each over the full length of the cylinder. During the first half turn of the cylinder the contact point then travels from left to right, and travels back again during the second half turn.

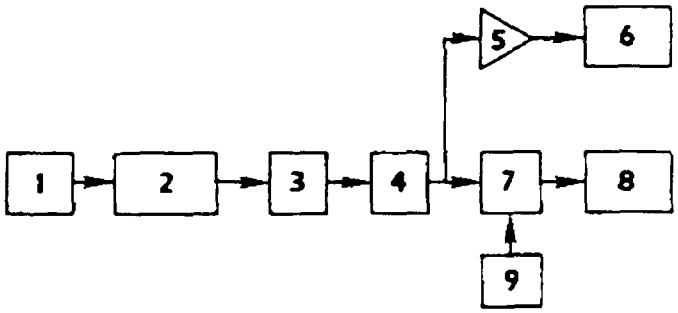
To an increasing extent printers are being used for the documentation of test results. These methods require that the test results are available in digital form. In all instances where wall thickness, or quite generally transit times are measured, the readings already usually are available digitally for evaluation and display. In installations where the test pieces are scanned continuously at high speed, frequently the number of the go/no-go flaw signals produced over a given scanning distance are used for evaluation. By means of this method of evaluation the number of flaw signals per recording section is obtained digitally and can be printed. The test result is presented on the printed strip as a sequence of numbers which are correlated to the consecutive sections of a given scanning line.

9.3.6 Some data processing systems

In the foregoing sections various components of data processing have been mentioned in a relatively rather over simplified way. We will, in this section, outline a few typical ultrasonic testing systems incorporating data processing in order to demonstrate the interfacing and integration of various individual components as well as to show the complexity of the system.

Figure 9.17 shows the components of a traditional analogue data processing system.

Figure 9.18 shows an enhanced data processing system used in automated multi-channel ultrasonic testing of large components. The system records the complete ultrasonic waveform for up to seven channels at routine in-service scanning speeds and is compatible with most ultrasonic testing techniques. The system provides the inspector with an extensive set of tools to confirm system operation in real-time, to validate acquired testing data and to provide efficient rapid analysis, reporting and auditing of the systems.



LEGEND

1. TRANSDUCER
2. RECEIVER
3. SIGNAL GATE
4. VIDEO DETECTOR
5. VIDEO AMPLIFIER
6. CATHODE RAY TUBE
7. COMPARATOR
8. ALARM
9. THRESHOLD LEVEL

Figure 9.17. : Block diagram for an analogue data processing system.

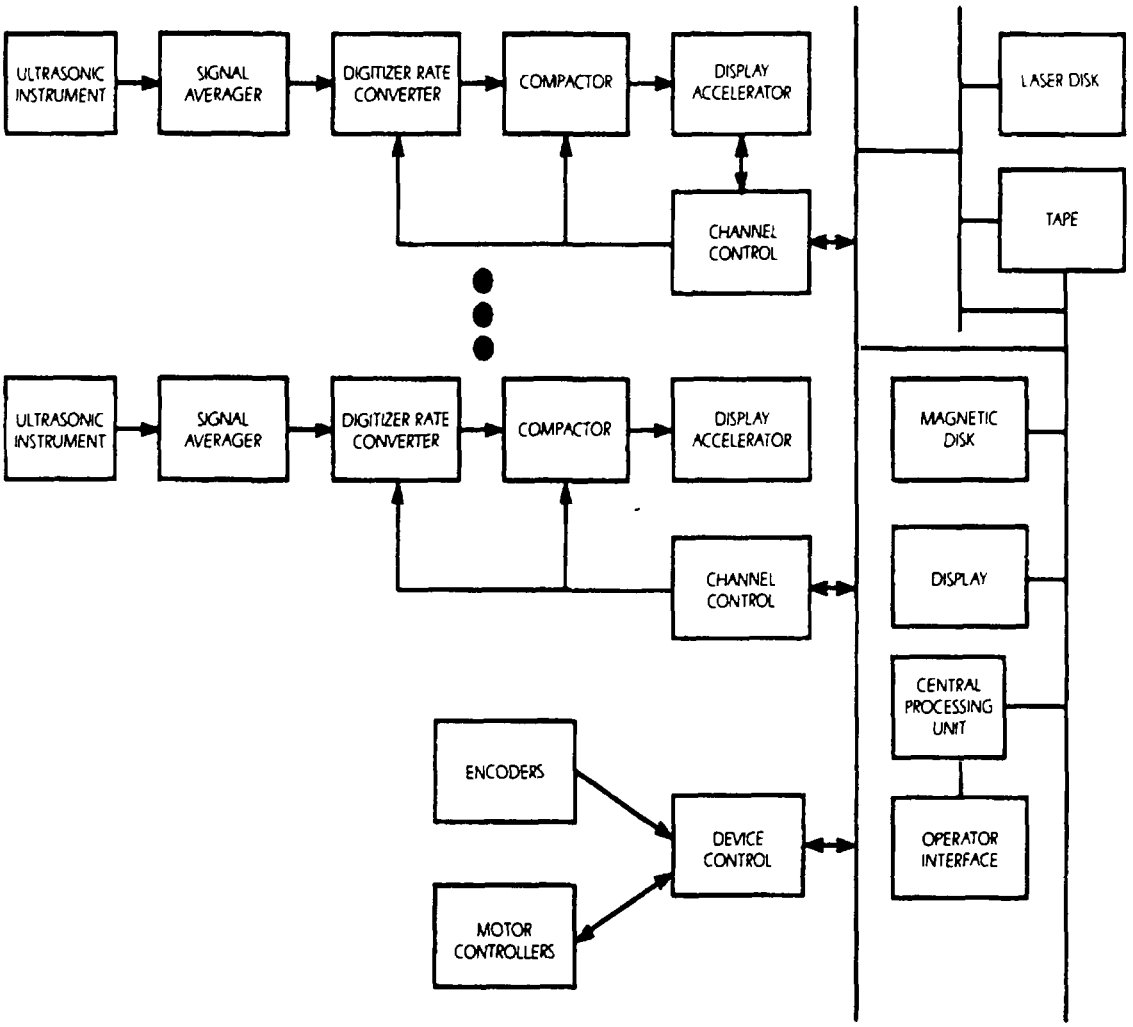


Figure 9.18 : Block diagram of a complex data processing system used in ultrasonic testing.

The data acquisition subsystem can interface with a variety of ultrasonic testing instruments, as well as an assortment of testing tools. The subsystem is also compatible with time corrected gain systems. Calibration activities may be performed in parallel with testing activities. It is usually composed of a replication of independent channels. Each channel functions under the control of a channel processor. The channel processor is responsible for data acquisition, generation of data for real-time display, generation of data for three-view display and housekeeping tasks. Each channel interfaces with a high speed signal averager and a commercially available ultrasonic test instrument. System interface with scanner mechanisms is accomplished.

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