IAEA-TECDOC-462

ULTRASONIC TESTING OF MATERIALS AT LEVEL 2

TRAINING MANUAL
FOR NON-DESTRUCTIVE TESTING TECHNIQUES

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FOREWORD

The International Atomic Energy Agency is executing regional projects in the Latin American and Caribbean Region and the Asia and Pacific Region using the syllabi contained in IAEA-TECDOC-407 'Training Guidelines in Non-destructive Testing Techniques .' which has been referenced as being suitable for training NDT personnel by the International Standards Organisation in the draft standard DP9712, 'The Qualification and Certification of NDT Personnel'.

These ultrasonic notes have therefore been prepared essentially in accordance with the syllabus for Level 2 ultrasonic personnel and have been used as the basis for the 80 hour model Level 2 ultrasonic regional training courses conducted by the Asia and and Pacific Project.The notes are the result of contributions from a number of National NDT coordinators in the Asia and Pacific Region who have been organising National NDT Training Courses.

For guidance it is suggested that the minimum 80 hours training recommended by ISO DP9712 be divided as follows;

1.	General knowledge	8 hours
2.	Terminology,physical principles and fundamentals of ultrasonics	8 "
3.	Testing techniques and their limitations	8 "
4.	Equipment and accessories	6 "
5.	Calibration of the testing system	12 "
6.	Specific applications	12 "
7.	Codes, standards,specifications and procedures	10 "
8.	Recording and evaluation of results	10 "
9.	Special techniques	6 "

EDITORIAL NOTE

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1. INTRODUCTION

1.1 Quality and Reliability

An industrial product is designed to perform a certain function. The user buys it with every expectation that it will perform the assigned function well and give a trouble-free service for a reasonable period of time. The level of guarantee or certainty with which a trouble-free service can be provided by any product may be termed its degree of reliability. The reliability of a machine or an assembly having a number of components depends upon the reliability factors of all the individual components. Most of the machines and systems in the modern day world, for example, railways, automobiles, aircrafts, ships, power plants, chemical and other industrial plants etc. are quite complex having thousands of components on which their operation and smooth running depends. To ensure the reliability of such machines it is important that each individual component is reliable and performs its function satisfactorily.

Reliability comes through improving the quality or quality level of the components or products. A good quality product can therefore be termed one which performs its assigned function for a reasonable length of time. On the other hand products which fail to meet this criterion and their failure or breakdown occurs unpredictably and earlier than a specified time may be termed as bad or poor quality products. Both these types of products differ in reliability factors or quality levels.

The quality of products, components or parts depends upon many factors important among which are the design, material characteristics and materials manufacturing and fabrication techniques. Quality may be defined in terms of defects and imperfections present in the materials used for making the product or the presence of such defects and imperfections in the finished product itself. Many defects can also be formed in products during service. The nature of these defects differs according to the process of its design and fabrication as well as the service conditions under which it has to work. A knowledge of these defects with a view to determining them and then minimizing them in a product is essential to achieve a better or an acceptable level of quality.

An improvement in the product quality to bring it to a reasonable quality level is important in many ways. It increases, as already mentioned, the reliability of the products and the safety of the machines and equipment and brings economic returns to the manufacturer by increasing his production, reducing his scrap levels, enhancing his reputation as a producer of quality goods and hence boosting his sales. There is therefore a need to have methods by which the defects in the products can be determined without affecting their serviceability.

1.2. Non-Destructive Testing (NDT) Methods Of Quality Control

The term "Non-destructive testing" is used to describe the material testing methods which, without damaging or influencing the usefulness of a material or component, give information about its properties. NDT is concerned with revealing the flaws in an item under inspection. NDT can not however predict where flaws will develop due to the design itself.

Non-destructive testing (NDT) plays an important role in the quality control not only of the finished product, but also of half finished products as well as the initial raw materials. NDT can be used at all stages of the production process. It can also be used during the process of establishing a new technology by monitoring product quality or when developing a new product. Outside the manufacturing field, NDT is also widely used for routine or periodic control of various items during operation to ascertain that their quality has not deteriorated with use.

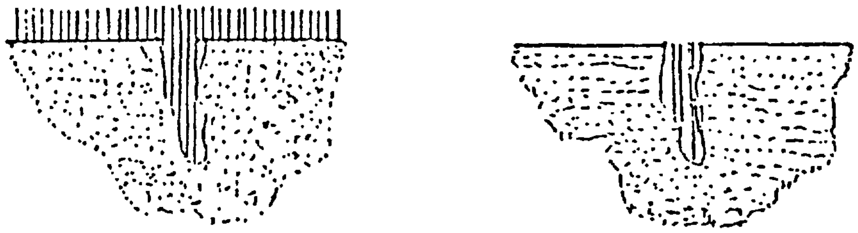
The methods of NDT range from the simple to the complicated. Visual inspection is the simplest of all. Surface imperfections invisible to the eye may be revealed by penetrant or magnetic methods. If really serious surface defects are found, there is often little point in proceeding to the more complicated examinations of the interior by ultrasonics or radiography. The principle NDT methods are Visual or Optical Inspection, Dye Penetrant Testing, Magnetic Particle Testing, Eddy Current Testing, Radiographic Testing and Ultrasonic Testing.

The basic principles typical applications, advantages and limitations of these methods with now be briefly described.

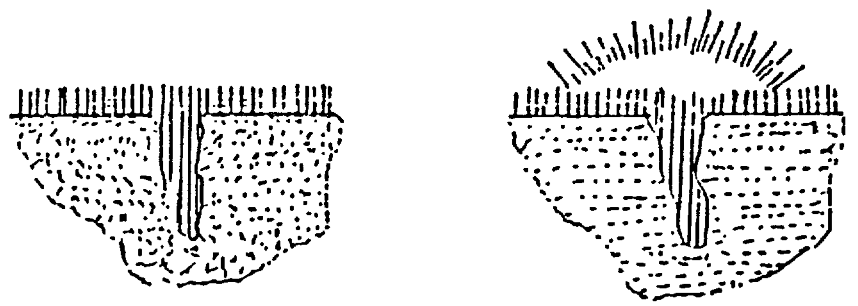
A number of other NDT methods exist. These are used only for specialized applications and consequently are limited in use. Some of these methods are Neutron Radiography, Acoustic Emission, Thermal and Infra Red Testing, Strain Sensing, Microwave Techniques, Leak Testing, Holography etc.

1.2.1. Liquid Penetrant Testing

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. 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 Fig .1.1.



(a) (b)



(c) (d)

Figure 1.1 Four stages of liquid penetrant process:-

(a) Penetrant application and seepage into the discontinuity.

(b) Removal of excess penetrant.

(c) Application of developer, and

(d) Inspection for the presence of discontinuities.

1.2.2. Magnetic Particle Testing

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 magnet, 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 interupts 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 the specimen, these particles are attracted by these magnetic poles to create a visual indication approximating the size and shape of the flaw. Fig. 1.2. illustrates the basic principles of this method.

1.2.3 **Eddy Current Testing**

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 cathoderay tube presentation. Fig. 1.3. gives the basic principles of eddy current testing.

1.2.4 **Radiographic Testing Method**

The radiographic testing method is used for the detection of internal flaws on many different materials and configurations. An appropriate radiographic film is placed behind the test specimen (Fig. 1.4) 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 of the internal structure of the product. This shadow picture, known as a radiograph, is then interpreted to obtain data about the flaws present in the specimen. This method is used on a wide variety of products such as forgings, castings and weldments.

1.2.5. **Ultrasonic Testing**

Ultrasonic inspection is a nondestructive 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 25 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 attendant loss of energy (attenuation) due to material characteristics or are measured after reflection at

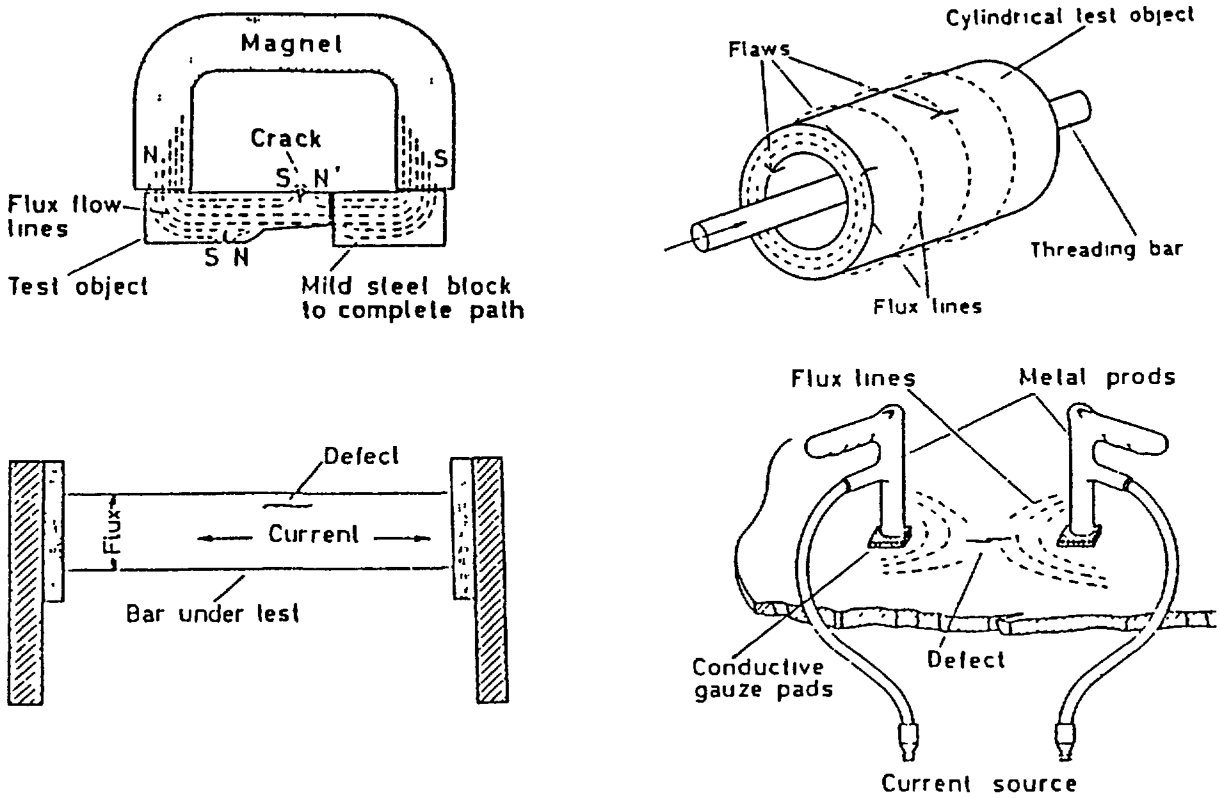


Figure 1.2

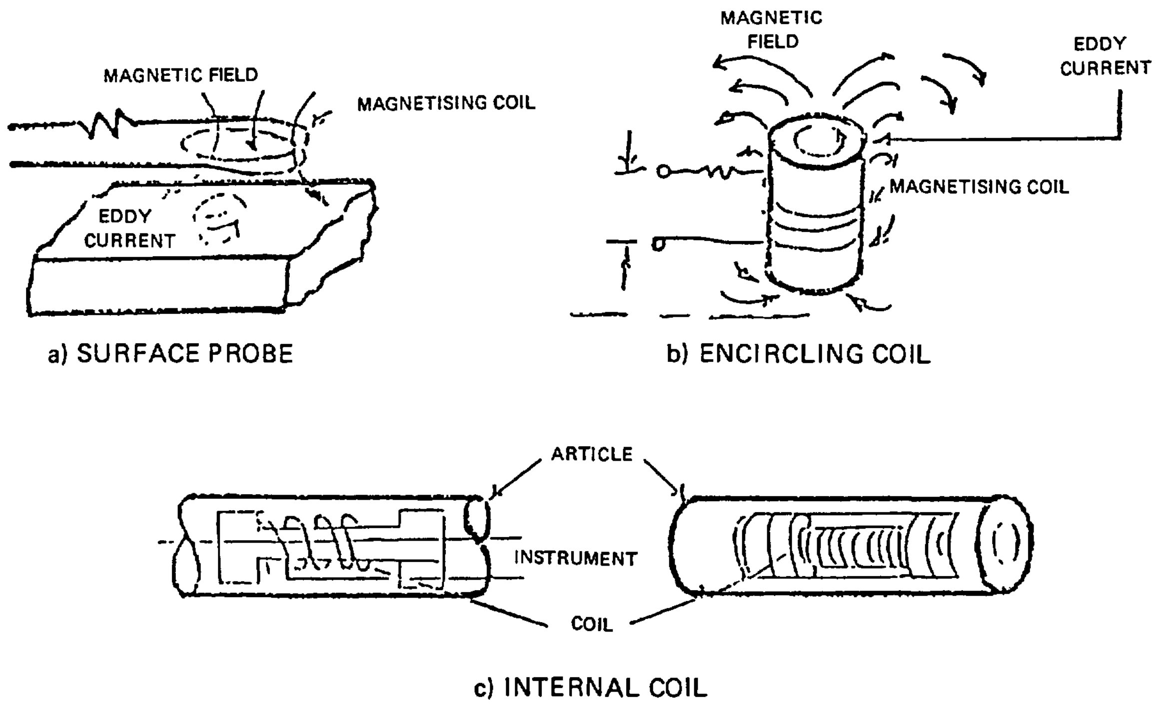


Figure 1.3 Eddy current testing.

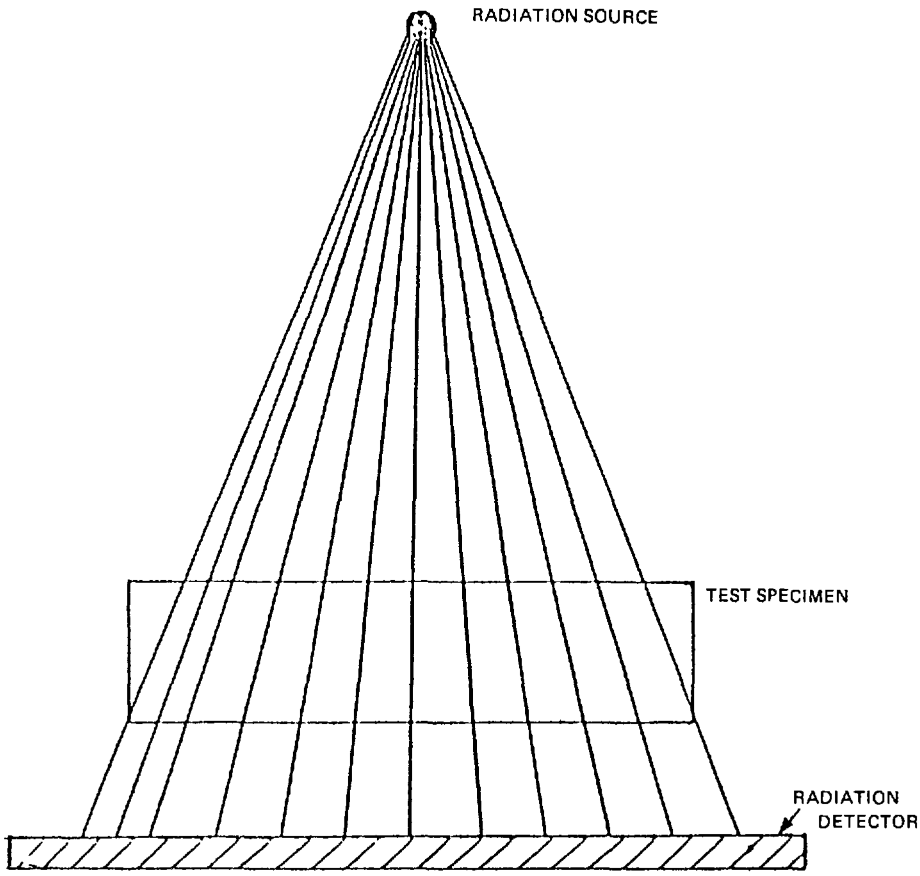


Figure 1.4 Arrangement for radiographic testing method.

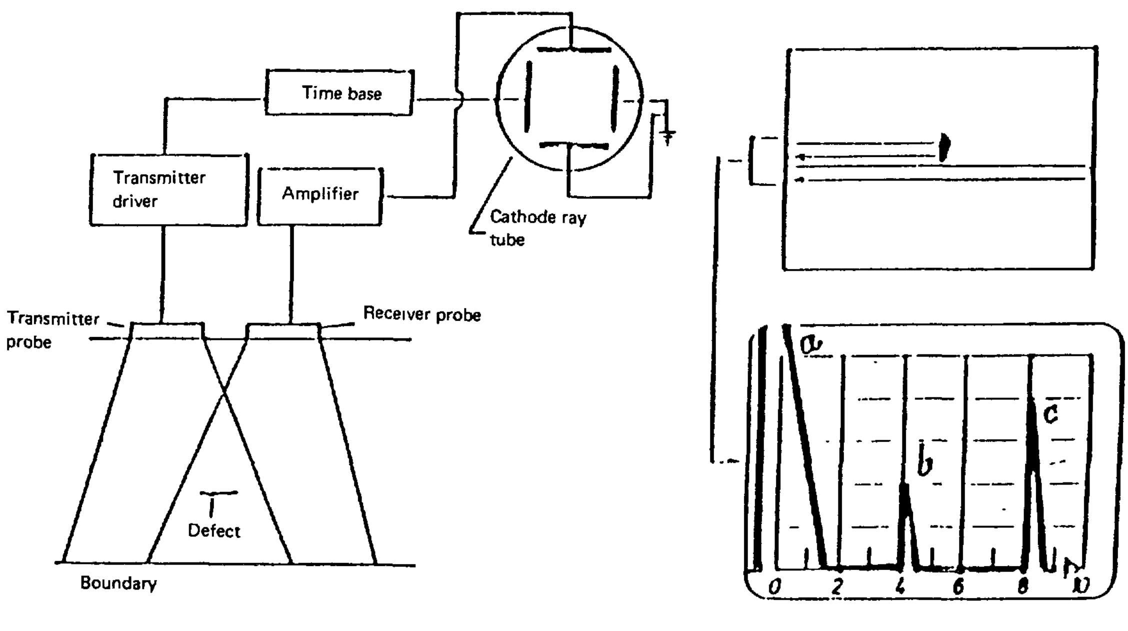


Figure 1.5 : Basic components of an ultrasonic flaw detector.

interfaces(pulse echo) or flaws, or are measured at the opposite surface (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 completerly reflected at metal-gas interfaces. Partial reflection accors at metal-liquid or metal-solid interfaces. Ultrasonic testing has a superior penetrating power to radiography and can detect flaws deep in the test specimen (say upto about 6 to 7 meters 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 Fig. 1.5.

1.3 Comparison of different NDT methods

Frequently it may be necessary to use one method of NDT to confirm the findings of another. Therefore, the 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 program is planned.

Table 1 gives a summary of the most frequently used NDT methods.

Table 1. Guide to NDT techniques

Technique	Access requirements	Equipment capital cost	Inspection cost	Remarks
Optical methods	Can be used to view the interior of complex equipment. One point of access may be enough.	B/D	D	Very versatile little skill required, repays consideration at design stage.
Radiography	Must be able to reach both sides.	A	B/C	Despite high cost, large areas can be inspected at one time; considerable skill required in interpretation.
Ultrasonics	One or both sides (or ends)	B	B/C	Requires point-by-point search hence expensive on large structures, skilled personnel required.

Table 1. Guide to NDT techniques

Technique	Access requirements	Equipment capital cost	Inspection cost	Remarks
Magnetic particle	Requires a clean and reasonably smooth surface	D	C/D	Only useful on magnetic materials such as steel; little skill required; only detects surface breaking on near surface cracks.
Penetrant flaw detection	Requires flaw to be accessible to the penetrant (that is, clean and at the surface)	D	C/D	For all materials some skill required; only detects surface-breaking defects; rather messy.
Eddy current	Surface must (usually) be reasonably smooth and clean.	B/C	C/D	For surface-breaking or near--surface flaws, variations in thickness of coatings, or comparison of materials; for other than simple comparison considerable skill is usually necessary (the exception is Amlec for surface-breaking cracks in steels)

Where A = highest cost.

D = lowest cost.

1.4 DESTRUCTIVE VS. NON-DESTRUCTIVE TESTING

The corresponding advantages and disadvantages of destructive and non-destructive tests are compared in table 2.

Table 2. Comparison of destructive and non-destructive test.

DESTRUCTIVE TESTS Advantages :	NON-DESTRUCTIVE TESTS Limitations :
1. Tests usually simulate one or more service conditions. Consequently, they tend to measure serviceability directly and reliably	1. Tests usually involve indirect measurements of properties of no direct significance in service. The correlation between these measurements and serviceablity must be proved by other means.
2. Tests are usually quantitative measurements of load for failure, significant distortion or damage, or life to failure under given loading and environmental conditions. Consequently they may yield numerical data useful for design purposes or for establishing standards or specifications.	2. Test are usually qualitative and rarely quantitative. They do not usually measure load for failure or life to failure even indirectly. They may, however, reveal damage or expose the mechanisms of failure.
3. The correlation between most destructive test measurements and the material properties being measured (particularly under simulated service loading) is usually direct. Hence most observers may agree upon the results of the test and their significance with respect to the serviceability of the material or part.	3. Skilled judgment and test or service experience are usually required to interpret test indications. Where the essential correlation has not been proven, or where experience is limited, observers may disagree in evaluating the significance of test indications.

Table 2. Comparison of destructive and non-destructive test.

Limitations :	Advantages :
1. Tests are not made on the objects actually used in service. Consequently the correlation or similarity between the objects tested and those used in service must be proven by other means.	1. Tests are made directly upon the objects to be use in service. Consequently there is no doublt that the tests were made on representative test objects.
2. Tests can be made on only a fraction of the production lot to be used in service. They may have little value when the properties vary unpredictably from unit to unit.	2. Tests can be made on every unit to be used in service if economically justifield. Consequently they may be used even when great differences from unit to unit occur in production lots.
3. Tests often cannot be made on complete production parts. The tests are often limited to test bars cut from produotion parts or from special material specimens processed to simulate the properties of the parts to be used in service.	3. Test may be made on the entire production part or in all critical regions of it. Consequently the evaluation applies to the part as a whole. Many critical sections of the part may be examined simultaneously or sequentially as convenient and expedient.
4. A single destructive test may measure only one or a few of the properties that may be critical under service conditions.	4. Many non-destructive tests, each sensitive to different properties or regions of the material or part, may be applied simultaneously or in sequence. In this way it is feasible to measure as many different properties correlated with service performance as desired.

Table 2. Comparison of destructive and non-destructive test.

Limitations :	Advantages :
5. Destructive tests are not usually convenient to apply to parts in service. Generally, service must be interrupted and the part permanently removed from service.	5. Non-destructive tests may often be applied to parts in service assemblies without interruption of service beyond normal maintenance or idle periods. They involve no loss of serviceable parts.
6. Cumulative change over a period of time cannot readily be measured on a single unit. If several units from the same lot or service are tested in succession over a period of time, it must be proven that the units were initially similar. If the units are used in service and removed after various prriods of time, it must be proven that each was subject to similar conditions of service, before valid data can be obtained.	6. Non-destructive tests permit repeated checks of a given unit over a period of time. In this way, the rate of service damage, if detectable, and its correlation with service failure may be established clearly.
7. With parts of very high material or fabrication cost, the cost of replacing the parts destroyed may be prohibitive. It may not be feasible to make an adequate number and variety of destructive tests.	7. Acceptable parts of very high material or fabrication costs are not lost in non-destructive testing. Repeated testing during production or service is feasible when economically and practically justified.

Table 2. Comparison of destructive and non-destructive test.

Limitations :	Advantages :
8. Many destructive tests require extensive machining or other preparation of the test specimens. Often, massive precision-testing machines are required. In consequence the cost of destructive testing may be very high, and the number of samples that can be prepared and tested may be severely limited. In addition such preparation and tests may make severe demands upon the time of highly skilled workers.	8. Little or no specimen preparation is required for many forms of non-destructive tests. Several forms of non-destructive testing equipment are portable. Many are capable of rapid testing or sorting and in some cases may be made fully automatic. The cost of non-destructive tests in less, in most cases, both per object tested and for overall testing, than the cost of adequate destructive tests.
9. The time and man-hour requirements of many destructive tests are very high. Excessive production costs may be incurred if adequate and extensive destructive tests are used as the primary method of production quality control.	9. Most non-destructive test methods are rapid and require far fewer man--hours or actual hours than do typical destructive tests. Consequently the testing of all the production units at a cost normally less than, or comparable, to, the coast of inspecting destructively only a minor percentage of the units in production lots is feasible.

2. TERMINOLOGY, PHYSICAL PRINCIPLES AND FUNDAMENTALS OF ULTRASONICS

2.1 The nature of ultrasonic waves

To understand how ultrasonic wave 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. Fig 2.1a

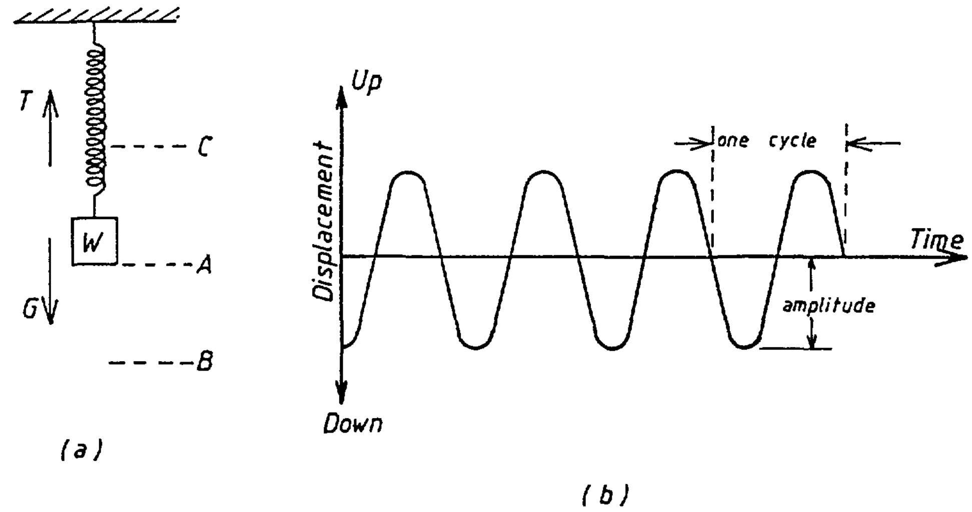


Figure 2. 1 a) Weight attached to a spring

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 toward 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 toward 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 toward 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 $T = \frac{1}{f}$

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 Fig.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.

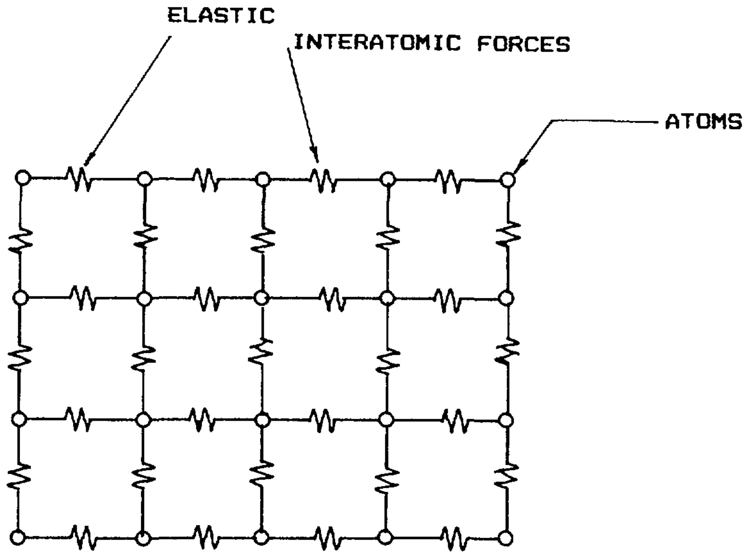


Figure 2.2. Model of an elastic body.

Now if an atom of the material is displaced from its original position by any 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.

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	= 1000	Hz =	1000 cycles per second
1 MHz	= 1000000	Hz =	1000000 cycles per second

2.2.2 Wave Length

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 . Atoms in a medium, separated by distance will be in the same state of motion (i.e. in the same phase) when a wave passes through the medium.

2.2.3 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.

2.2.4 Fundamental Wave Equations

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 :

$$a = a_o \sin 2\pi f t \quad \text{------------------(2.1)}$$

Where a = Displacement of the particle at time t.

a_o = 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

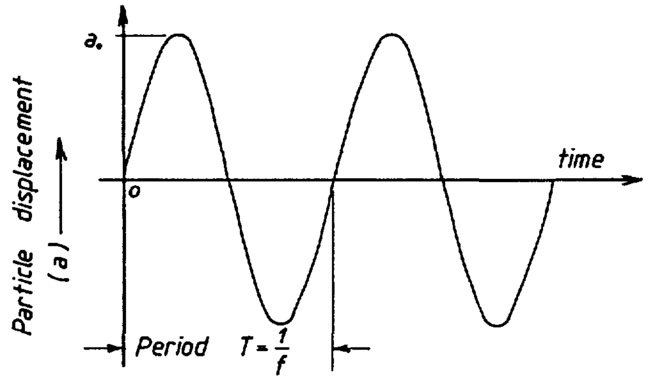


Figure 2.3

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.

$$a = a_o \sin 2\pi f \left(t - \frac{X}{V}\right) \text{------------------} (2.2)$$

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_o = 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 gives the graphical representation of equation 2.2.

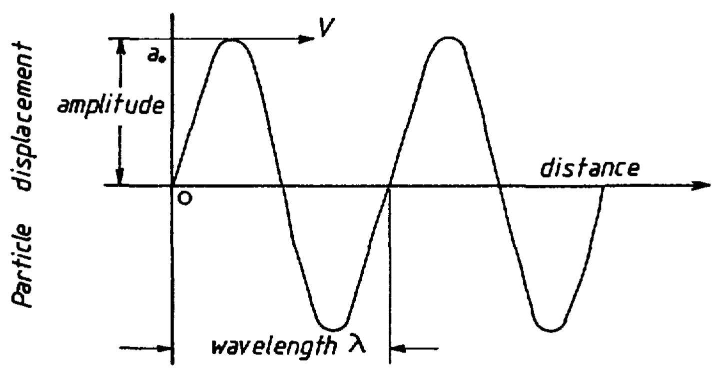


Figure 2.4 Graphical representation of equation 2.2.

Since in the time period T, a mechanical wave of velocity V travels a distance λ in a medium, therefore we have :-

$$\lambda = V\,T$$

$$\text{or} \quad V = \frac{\lambda}{T} \text{ -------------(2.3)}$$

But the time period T is related to the frequency f by

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

Combining equations 2,3 and 2.4 we have the fundamental equation of all wave motion i.e.

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

2.2.5 Ultrasonic Waves

Sound waves are vibrations of particles of gases, solids or liquids. The audible sound range of frequencies is usually taken from 20 Hz to 20 KHz . Sound waves with frequencies higher than 20 KHz are known as ultrasonic waves. 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 5 MHz

2.2.6 Acoustic Impedance

The resistence 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 ρ of the material by the velocity V of the ultrasonic wave in the material i.e.

$$Z = \rho V \text{ -------------(2.6)}$$

Table 2.1 gives acoustic impedances of some common materials.

2.2.7 Acoustic Pressure And Intensity

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

Table 2.1 : Densities, sound velocities and acoustic impedances of some common materials.

Material	Density kg/m^3	c_{trans} m/s	c_{trans} m/s	Z 10^3 Pa s/m
aluminium	2700	3130	6320	17 064
aluminium oxide	3600	5500	9000	32 400
bismuth	9800	1100	2180	21 364
brass	8100	2120	4430	35 883
cadmium	8600	1500	2780	23 908
cast iron	6900	2200	5300	24 150
concrete	2000	-	4600	9 200
copper	8900	2260	4700	41 830
glass	3600	2560	4260	15 336
glycerine	1300	-	1920	2 496
gold	19300	1200	3240	62 532
grey casting	7200	2650	4600	33 120
hard metal	11000	4000	6800	74 800
lead	11400	700	2160	24 624
magnesium	1700	3050	5770	9 809
motor oil	870	-	1740	1 514
nickel	8800	2960	5630	49 544
perspex	1180	1430	2730	3 221
platinum	21400	1670	3960	84 744
polyamide (nylon)	1100	1080	2620	2 882
polyethylene	940	925	2340	2 200
polystyrol	1060	1150	2380	2 523
polyvinylchloride	1400	1060	2395	3 353
(PVC hard)				
porcellaine	2400	3500	5600	13 440
quartz	2650	-	5760	15 264
quartz glass	2600	3515	5570	14 482
silver	10500	1590	3600	37 800
steel (low alloy)	7850	3250	5940	46 629
steel	7850	3250	5920	46 472
(calibration block)				
tin	7300	1670	3320	24 236
titanium	4540	3180	6230	28 284
tungsten	19100	2620	5460	104 286
uranium	18700	-	3200	59 840
water (20 ^{o}C)	1000	-	1480	1 480
zinc	7100	2410	4170	29 607

related to the acoustic impedence Z abd the amplitude of particle vibration a as :

$$P = Z a \quad \text{------------------(2.7)}$$

Where P = acoustic pressure.

Z = acoustic impedence.

a = amplitude of particle vibration.

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.

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

$$I = \frac{P^2}{2Z} \quad \text{------------------------(2.8)}$$

and

$$I = \frac{P\, a}{2} \quad \text{----------------------(2.9)}$$

Where

I = intensity.

P = acoustic pressure.

Z = acoustic impedence.

a = amplitude of vibration of the particle.

2.3 Types of Ultrasonic Waves

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 Waves

These are also called compression 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.

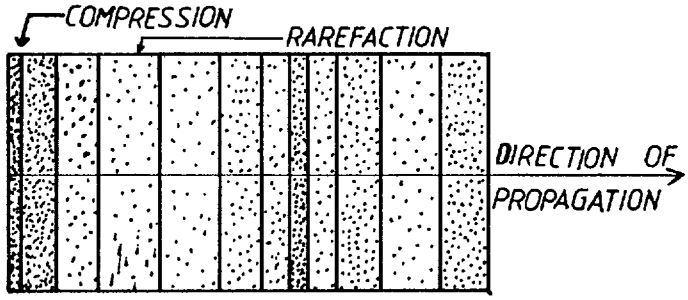


Figure 2.5 Longitudinal wave consisting of alternate rarefactions and compressions along the direction of propagation.

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.

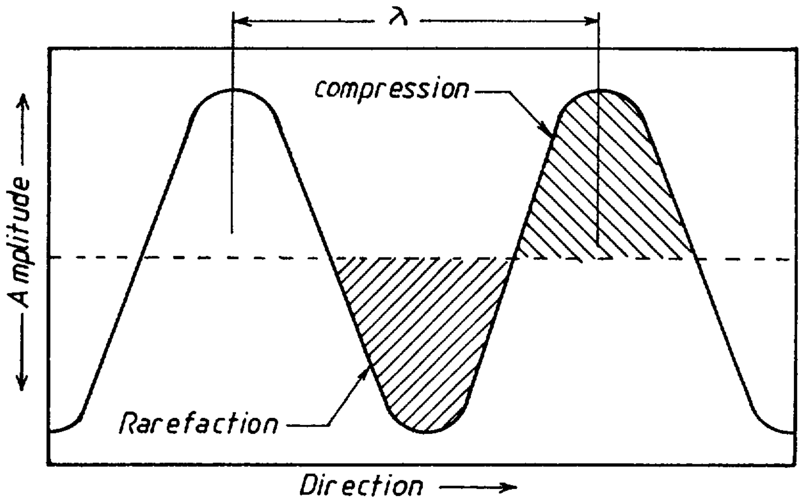


Figure 2.6 Plot of particle displacement versus distance of wave travel.

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 then is 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.

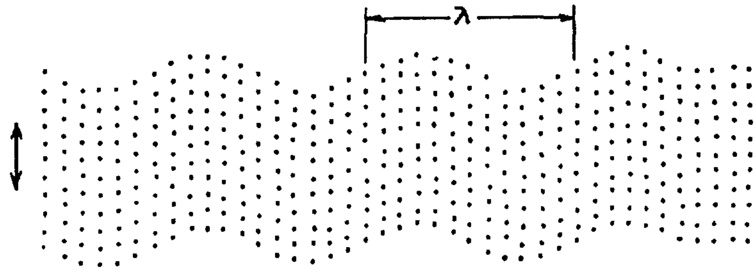


Figure 2.7 Schematic representation of a transverse wave.

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 per cent that of the longitudinal velocity.

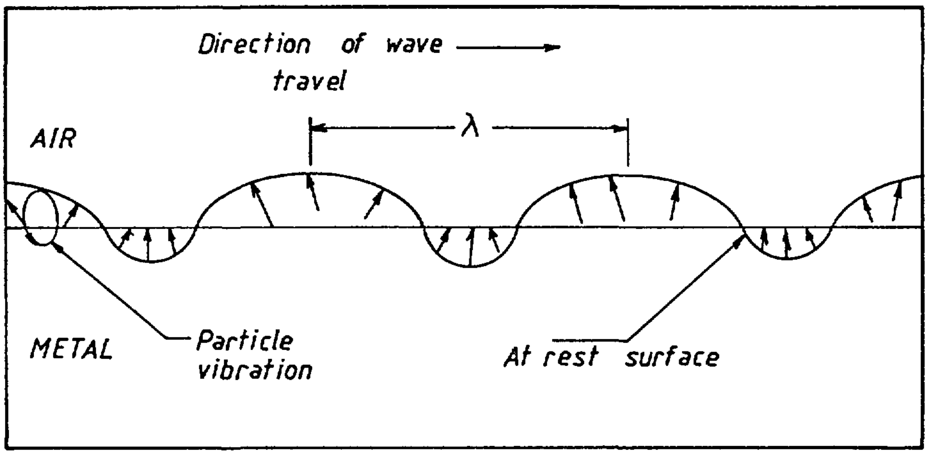
For all practical purposes, transverse waves can only propagate in solids. This is because the distance between molecules or atoms, the mean free path, is so great in liquids and gases that the attraction between them is not sufficient to allow one of them to move the other more than a fraction of its 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 nonexistent elastic forces between gas molecules. Surface waves, therefore, are essentially nonexistent 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 per cent that of an equivalent shear wave in the same material and they can only propagate in a region no thicker than about one wave length beneath the surface of the material. At this depth, the wave energy is about 4 per cent 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.



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

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.

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 wave and because they can flow 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 many complex modes of particle movement. The two basic forms of Lamb waves are : (a) symmeterical or dilatational : and (b) asymmeterical or bending. The form of the wave is determined by whether the particle motion is symmetrical or asymmeterical 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)).

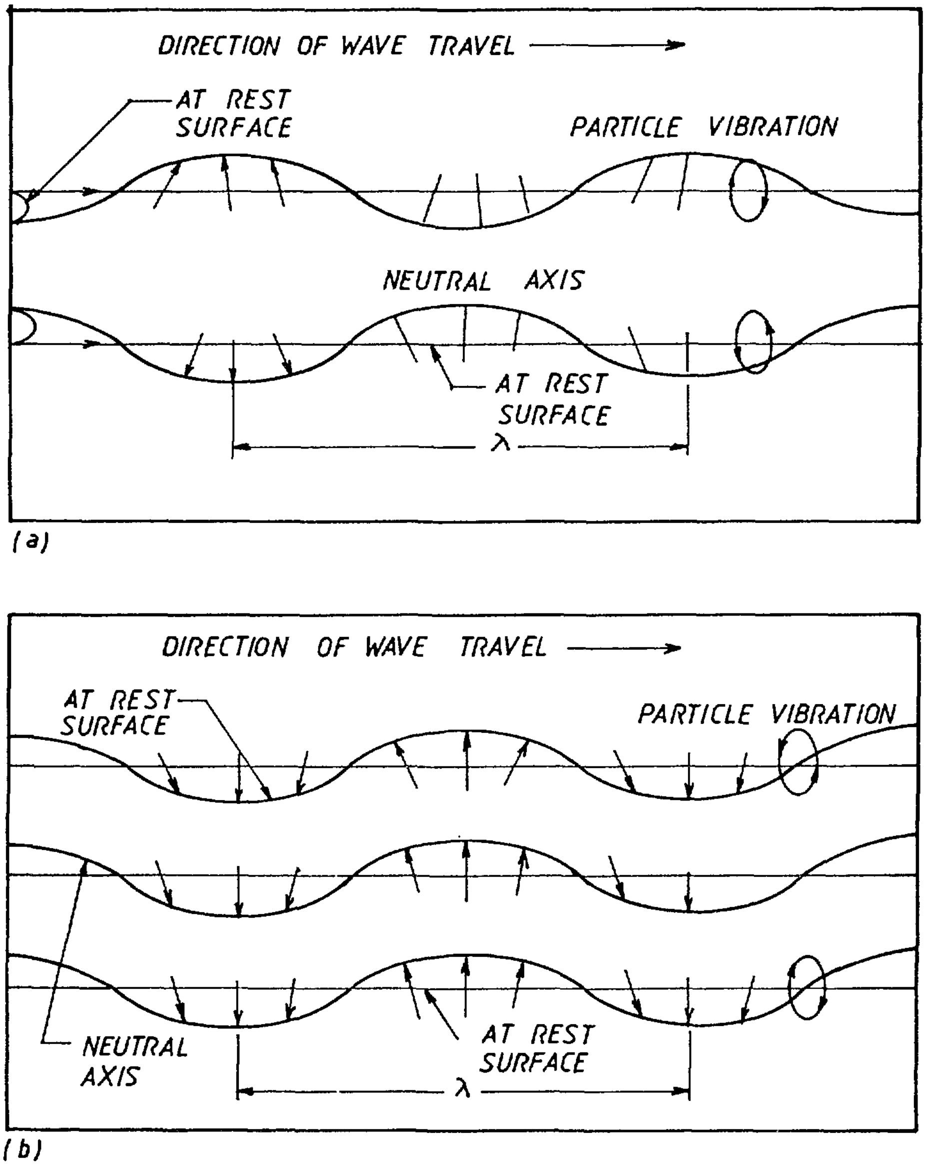


Figure 2.9. Diagrams of the basic patterns of (a) symmeterical (dilatational) and (b) asymmeterical (bending) Lamb waves.

This mode consists of the successive "thickenings" and "thining" 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 asymmeterical(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 asymmeterical 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.

2.3.5 Velocity of Ultrasonic Waves

The velocity of propagation of longitudinal, transverse, and surface waves depends on 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.

$$V_L = \sqrt{E/\rho} \quad \text{----------------(2.10)}$$

$$V_T = \sqrt{G/\rho} \quad \text{----------------(2.11)}$$

$$V_S = 0.9XV_T \quad \text{----------------(2.12)}$$

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

$$\frac{V_T}{V_L} = 0.55 \quad \text{--------(2.13)}$$

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

Equation 2.10 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 givens the velocities of longitudinal and transverse waves in some common materials.

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 incidence at right angles to the boundary (i.e normal incidence) of two media of different acoustic impedences, then some of the waves are reflected and some are transmitted across the boundary. The amount of ultrasonic energy that is reflected or transmitted depends on the difference between the acoustic impedences 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 impedences 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 impedences (Figure 2.10), is given by :-

$$R = \frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^2 \qquad (2.14)$$

Where R = Reflection Co-efficient

Z_1 = Acoustic impedence of medium 1.

Z_2 = Acoustic impedence of medium 2.

I_r = Reflected ultrasonic intensity.

I_i = Incident ultrasonic intensity.

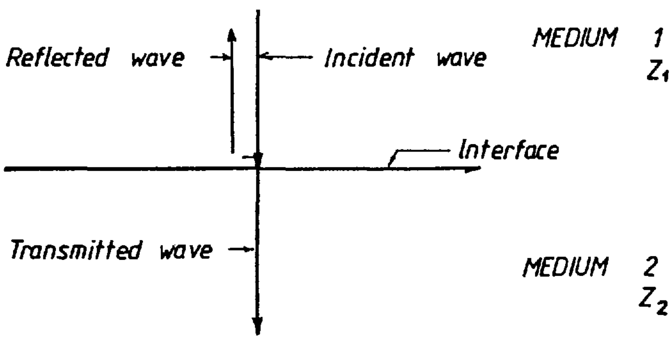


Figure 2.10 Reflection and Transmission at Normal Incidence.

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

$$T = \frac{I_t}{I_i} = \frac{4 Z_1 Z_2}{\left(Z_1 + Z_2\right)^2} \quad \text{------------- (2.15)}$$

Where

T = Transmission co-efficient.

Z_1 = Acounstic impedence of medium 1

Z_2 = Acounstic impedence of medium 2

I_t = Transmitted ultrasonic intensity.

I_i = Incident ultrasonic intensity.

The transmission co-efficient T can also be determined from the relation :-

$$T = 1 - R \quad \text{-------------------- (2.16)}$$

Where

T = Transmission co-efficient

R = Reflection co-efficient

2.4.1.2 Refleoted and Transmitted Pressures

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

$$P_r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad \text{------------------ (2.17)}$$

and

$$P_t = \frac{2Z_2}{Z_1 + Z_2} \quad \text{------------------ (2.18)}$$

Where

Pr = amount of reflected acoustic pressure.

Pt = amount of transmitted acoustic pressure.

Z_1 = acoustic impedence of material from which the waves are incident.

Z_2 = acoustic impedence of material in which the waves are transmitted.

As is clear from equations 2.17 and 2.18, Pr may be positive or negative and Pt 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 Pr is positive and Pt $>$ 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 2.17 and 2.18 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 (equation 2.8) although the transmitted intersity in steel is low, the transmitted acoustic pressure is high because of the high acoustic impedence 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.

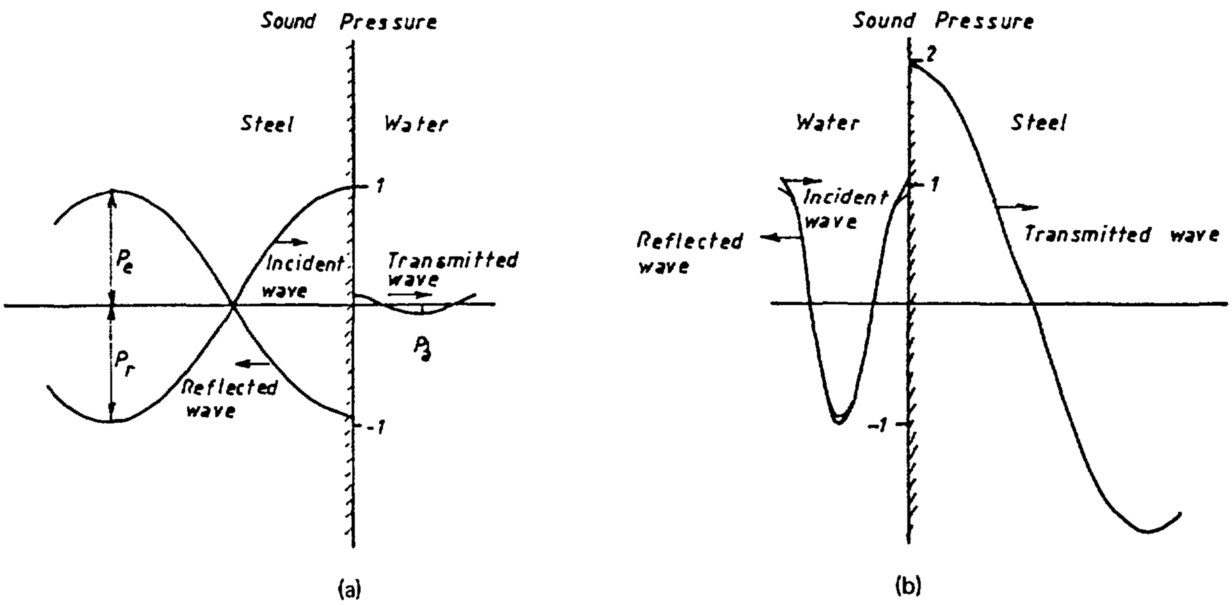


Fig. 2.11 Acoustic pressure values in the case of reflection on the interface steel/water, incident wave in steel (a) or in water (b).

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, than the reflection and transmission of the waves become more complicated than that with normal indidence. 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 2.12 shows what happens when a longitudinal wave strikes a boundary obliquely between two media. Of course, there is 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 transverse ultrasonic wave strikes a boundary between two media. The refracted transverse component in medium 2 will disappear if medium 2 is not a solid.

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

$$\frac{\sin \alpha}{\sin \beta} = \frac{V_1}{V_2} \qquad (2.19)$$

Where

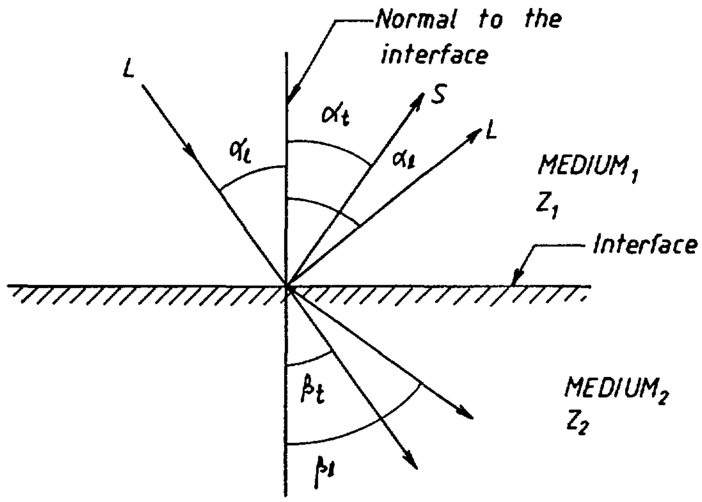
α = the angle of incidence.

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.



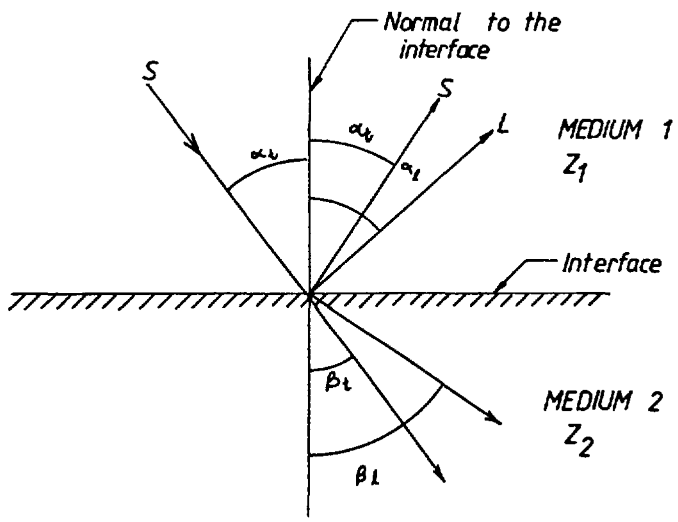
α_l = Angle of incidence of longitudinal wave.

α_t = Angle of reflection of transverse wave.

β_t = Angle of refraction of transverse wave.

β_l = Angle of refraction of longitudinal wave.

Figure 2.12 Refraction And Mode Conversion For An Incident Longitudinal Wave.



α_t = angle of incidence of transverse wave.

α_t = angle of reflection of transverse wave.

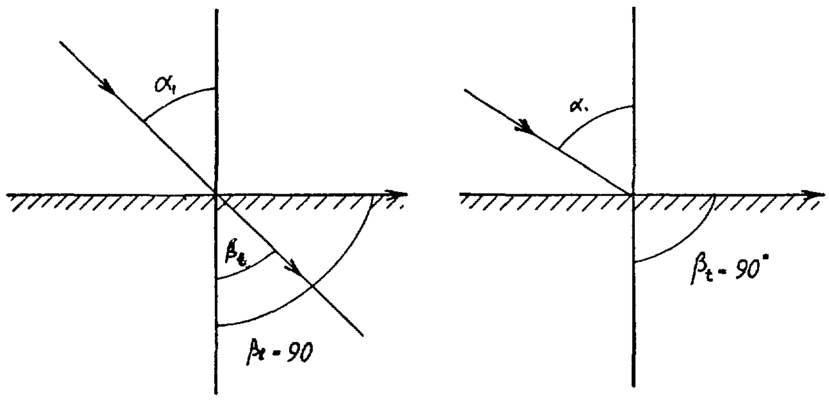
β_t = angle of refraction of transverse wave.

β_l = angle of refraction of longitudinal wave.

Figure 2.13 Refraction And Mode Conversion For An Incident Transverse Wave.

2.4.2.3 First And Second Critical Angles

If the angle of incidence α_1 (figure 2.13) 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 angle of incidence is increased, the angle of refraction also increases. When the refraction angle of a longitudinal wave reaches 90° the wave emerges from the second medium and travels parallel to the boundary (figure 2.14 a). The angle of incidence at which the refracted longitudinal wave emerges, is called the <u>first critical angle</u> . If the angle of incidence α_1 is further increased the angle of refraction for the transverse wave also approaches 90^{o} . The value of α_1 (figure 2.14 b) for which the angle of refraction of the transverse wave is exactly 90^{o} , is called the <u>second critical angle</u>. 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.



a) First Critical Angle   b) Second Critical Angle

Figure 2.14.

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.

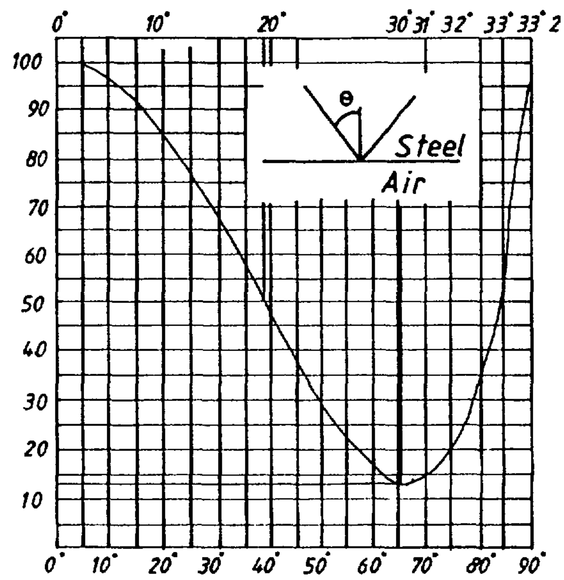


Figure 2.15 Acoustic pressure of reflected waves Vs angle of incidence.

The angle of incidence of longitudinal waves is shown by the 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 should be noted from figure 2.15 that :

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

b) 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.

c) 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.

2.5 PIEZOELECTRIC AND FERROELECTRIC TRANSDUCERS

2.5.1 Piezoelectric Effect

A transducer is a device which converts one form of energy into another. Ultrasonic tranducers 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 2.16). 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 2.17). The direct piezoelectric effect is used in detecting and the inverse piezoelectric effect in the generation of ultrasonic waves.

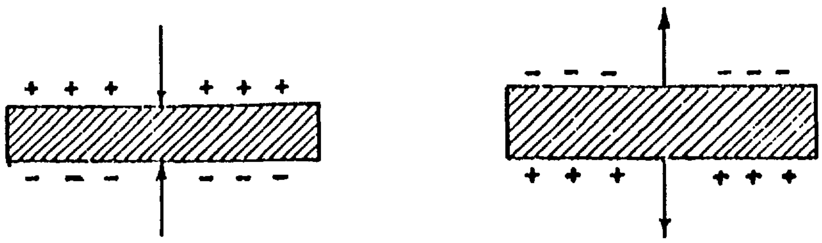


Figure 2.16 Direct piezoelectric effect.

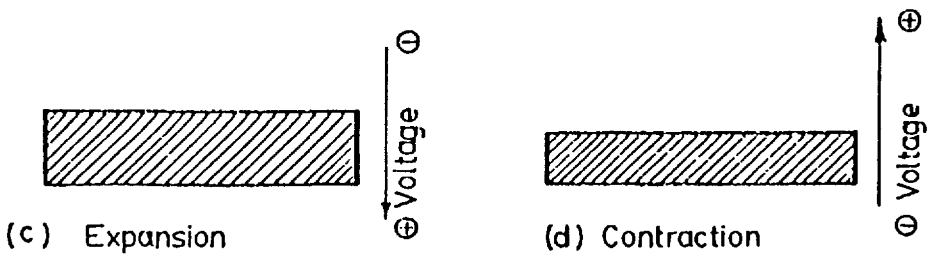


Figure 2.17 Inverse piezoelectric effect.

2.5.2 Types of Piezoelectric Transducers

Piezoelectric transducers can be classified into two groups. The classification is made based on the type of piezoelectric materal 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 polarized ceramic transducers.

2.5.2.1 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.

(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.

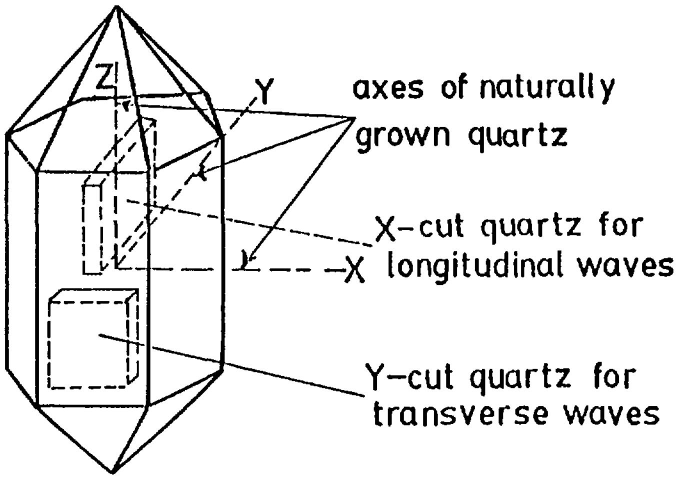


Figure 2.18 System coordinates in a quartz crystal (simplified) and positions at X and Y-cut crystals.

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 2.19) while Y-cut crystals are used for the generation and reception of transverse ultrasonic waves (Figure 2.20). 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 impedences when a longitudinal ultrasonic wave strikes the interface at an angle.

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.

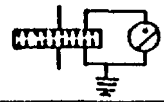
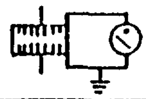
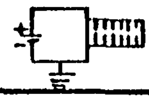
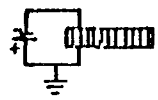
	CAUSE	SCHEDULE	EFFECT
direct piezo-electric effect	crystal being compressed		positive voltage on faces
	crystal being expanded		negative voltage on faces
inverse piezo-electric effect	positive voltage on faces		expansion of crystal
	negative voltage on faces		contraction of crystal

Figure 2.19. The piezoelectric effect of quartz (X-cut, schematic).

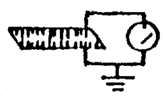
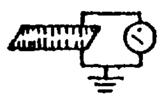
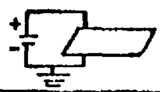
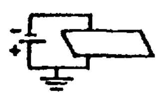
	CAUSE	SCHEDULE	EFFECT
direct piezo-electric effect	shearing strain deforms crystal to the left		positive voltage on faces
	shearing strain deforms crystal to the right		negative voltage on faces
inverse piezo-electric effect	positive voltage on faces		shearing motion of crystal to the right
	negative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

Figure 2.20. The piezoelectric effect of quartz (Y-cut schmatic).

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 a high voltage for its operation.

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 impedence.

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^{o} C.

2.5.2.2 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 2.21). 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 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. 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 eg. lead metaniobate Curie point 550^{o} C.

Limitations

i) Piezoelectric property may decrease with age.

ii) They have low resistance to wear.

iii) They suffer from mode conversion.

2.5.2.3 Comparison of Piezoelectric Transducers

Piezoelectric transducers can be compared from data similar to that shown in Table 2.2. The Piezoelectric modulus 'd' is a measure of the quality of a piezoelectric transducer as an ultrasonic transmitter. Greater values of 'd' reflect a transducer's greater efficiency as a transmitter. Table 2.2 shows that lead-zirconate-titanate has the best transmitter characteristics. The piezoelectric deformation constant 'H' is a measure of the ability of a transducer to act as an ultrasonic receiver.

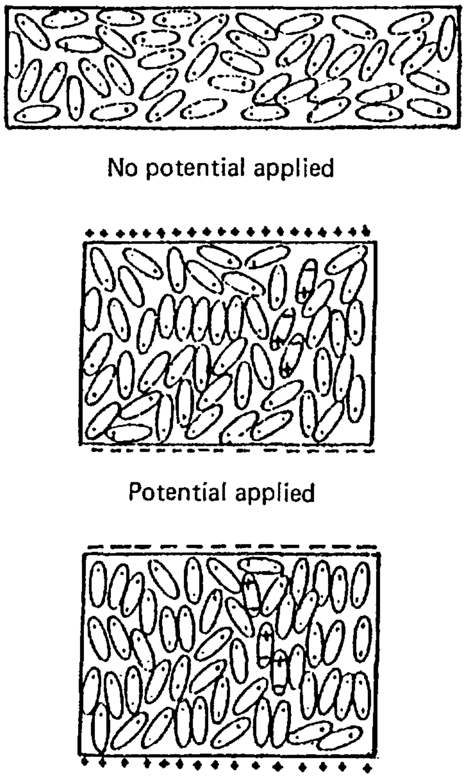


Figure 2.21 Domains in Ferroelectric material.

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 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-meta niobate, lead-zirconate-titanate and barium-titanate lie in a comparable order. A satisfactory resolution power requires that the coupling factor for radial oscillation Kp is as low as possible. Kp 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-meta-niobate 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 c m/s	4000	5100	3300	5460	5740	7320
Acoustic impedance $x\ 10^6$ kg/m^2 s	30	27	20.5	11.2	15.2	34
Electro-mechanic k	0.6 - 0.7	0.45	0.4	0.38	0.1	0.2
Piezoeletric modulus d	150 - 591	125 - 190	85	15	2.3	6
Piezoeletric 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 THE CHARACTERISTICS OF THE ULTRASONIC BEAM

2.6.1 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 2.22 . Two distinct regions of the beam exist and are classified as the near field region and far field region.

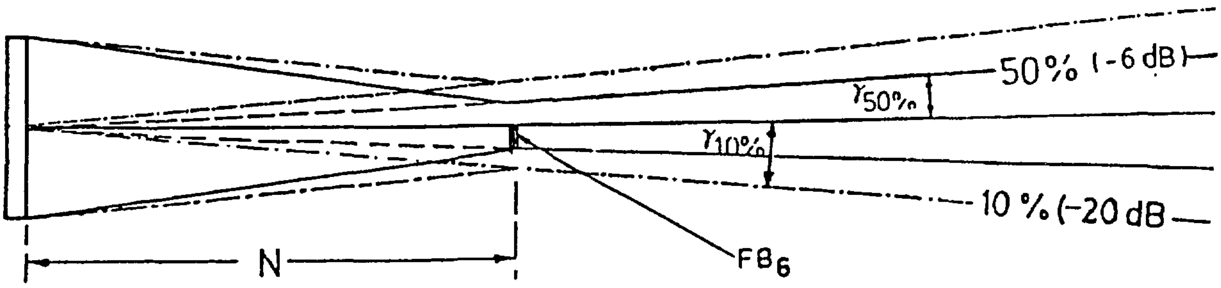


Figure 2.22

2.6.1.1 **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 2.23). These 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. The shape of the wave front in the near field, is as shown in figure 2.23 and is planer.

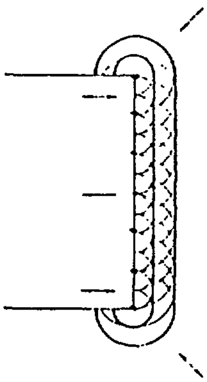


Figure 2.23

The intensity variation along and across the axial distance for a typical transducer are shown in figures 2.24 & 2.25 respectively.

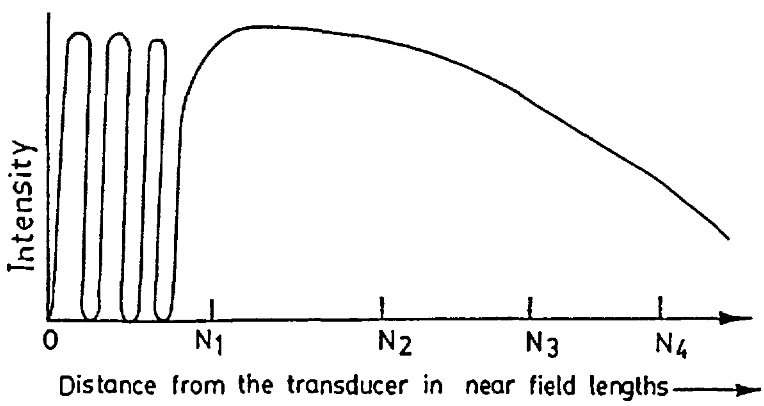


Figure 2.24 Distribution of intensity along the axial distance.

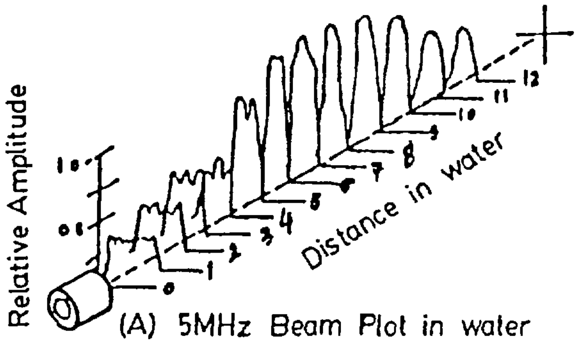


Figure 2.25 Beam plot in water of a 5 MHz, 5/8 inch diameter round transducer.

Flaws appearing in the near field must be carefully interpreted because a flaw occuring 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.

2.6.1.2 Calculation Of Near Field Length

The length N of the near field depends upon the diameter of the transducer and the wave-length 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 :-

$$N = \frac{D^2}{4\lambda} = \frac{D^2 f}{4\,V} \qquad (2.20)$$

Where

N = Near field length.

D = Diameter of transducer.

V = Velocity of sound in material.

f = Frequency.

(i) Longitudinal Wave Probe With Circular Transducer

Since because of glueing the effective transmitting area of a transducer is 97 % D, he near field length for a circular transducer of a longitudinal wave probe is more accurately given by :

$$\text{Near field length} = N = \frac{D^2_{eff}}{\lambda\,4} = \frac{0.94\,D^2}{\lambda\,4} = \frac{0.94.\ D.f}{4\,V} \qquad (2.21)$$

Where D_{eff} = 0.97 D

D = diameter of the transducer.

λ = wave-length of ultrasound in the material.

f = frequency of ultrasound in the material.

V = velocity of ultrasound in the material.

(ii) **Angle Probe With Ciroular Transducer**

$$N = \frac{D^2}{4\lambda} - \text{Perpex depth} \times \frac{\text{velocity in perspex (longitudinal)}}{\text{velocity in steel (transverse)}} \quad (2.22)$$

(iii) **Angle Probe With Square Or Rectangular Transducer**

$$N = \frac{1.3 \times \begin{matrix}\text{length of the}\\ \text{transducer}\end{matrix} \times \begin{matrix}\text{width of the}\\ \text{transducer}\end{matrix} \times 0.97 \times \begin{matrix}\text{frequency of the}\\ \text{transducer}\end{matrix}}{4 \times \begin{matrix}\text{Transverse wave}\\ \text{velocity in the}\\ \text{material}\end{matrix}} \quad (2.23)$$

$$- \text{Perspex depth} \times \frac{\text{velocity in perspex (longitudinal)}}{\text{velocity in steel (transverse)}}$$

where the factor 1.3 in equation (2.23) is the factor of conversion from circular shape to rectangular shape and the factor 0.97 is because of the fact that only about 97 % area of the transducer is active due to glueing. A simplified formula for probes with almost square transducers, where the difference in lengths of the edges is a maximum of 12 % , is

$$\text{Near field length} = N = 1.3 \frac{a_{eff}^2}{\lambda} = 1.3 \frac{a_{eff}^2 \cdot f}{V} \quad \text{---} \ (2.24)$$

where a_{eff} is half the effective length of the larger side which is given in the manufacturer's data sheet of the probe.

2.6.1.3 **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 planer. 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 planer 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 occuring 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.

$$\text{Intensity of reflection} \propto \frac{1}{\text{distance}}$$

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.

$$\text{Intensity} \propto \frac{1}{(\text{distance})^2}$$

2.6.2 **Beam Spread**

There is always some spreading of the ultrasonic beam in the far field as the waves travel from the transducer. The intensity of the beam is a maximum on the central axis and decreases in proportion to the distance from the transducer. The angle of beam spread or divergence angle γ (Figure 2.22) can be calculated from the following equation :

$$\gamma_n = \sin^{-1} \frac{K_n \lambda}{D} \qquad \text{------ (2.25)}$$

Where λ is the wave length 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 % (20dB) and 0 % (extreme edge) of the maximum amplitude. The subscript "n" in γ_n and K_n denotes the respective edge e.g. γ_6 is the divergence angle for 6 dB edge and γ_{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 back wall 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 indication 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 a circular transducer 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 % (0 - 00)	1.22	1.00
10 % (20 - dB)	1.08	0.60
50 % (6 - dB)	0.54	0.91

Table.2.4 Values for K for circular and rectangular transducers as determined by pulse echo technique.

Edge % (dB)	K circular	K rectangular
0 % (0 - 00)	1.22	1.00
10 % (20 - dB)	0.87	0.74
50 % (6 dB)	0.51	0.44

In the case of angle beam probes with rectangular transducers, the width of the beam in the horizontal plane is not equal to the width of the beam in the vertical plane. The half beam widths at one near field distance in the horizontal and vertical planes, in this case, are called the focal length and focal width and are denoted by FL and FB respectively (Figure 2.26).

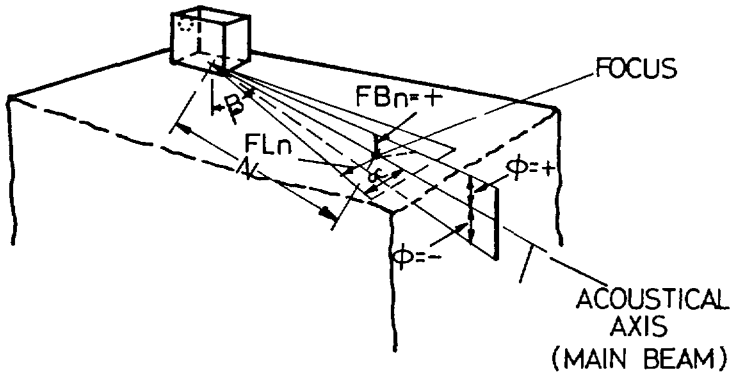


Figure 2.26. Definition Of Sound Field Data.

In Figure 2.26 the other notation used are :

β = angle of refraction of the beam in steel.

ϕ = angle of beam divergence in the vertical plane.

Because of refraction this angle might be different for the upper and lower parts of the beam, this is, therefore, usually given by ϕ = + or ϕ = - in the data sheet of a probe, if there is appreciable difference in the two angles. Accordingly the focal width (FB) for the two parts are given as FB_N = + and FB_N = - .... in the data sheets.

γ = angle of beam divergence in the horizontal plane.

In the data sheets of the pulse echo type probes, data is usually given for the 6 dB or 50 % intensity edge. To determine the data for the 20 dB edge from the data sheets the following equations are used :

$$FB_{20} = 1.74\ FB_6 \quad \ldots\ldots\ldots\ldots\ (2.26)$$

$$FL_{20} = 1.74\ FL_6 \quad \ldots\ldots\ldots\ldots\ (2.27)$$

$$\gamma_{20} = 1.74\ \gamma_6 \quad \ldots\ldots\ldots\ldots\ (2.28)$$

where FB_{20} and FB_6 are half the widths of the beam at one near field distance from the transducer (They are known as focal widths) and γ_{20} and γ_6 are the angles of beam divergence for the 20 dB and 6 dB edges respectively.

In the case of pulse echo type angle beam probes with the probes having rectangular transducers, the width of the beam in the horizontal direction is not equal.

The beam width Y at a distance X from the transducer is given by :

$$Y = 2X \tan \theta \quad \text{----------}\ (2.29)$$

Where

θ = the angle of beam divergence, which may be either equal to γ_n or ϕ_n depending on which plane the beam width is required to be determined.

2.7 ATTENUATION OF ULTRASONIC BEAMS

The intensity of an ultrasonic beam that is sensed by a receiving transducer is considerably less than the intensity of the initial transmission. The factors that are primarily responsible for the loss in beam intensity are discussed below :-

2.7.1 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 has radically different acoustic impedance and consequently 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.

2.7.2 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. As 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.

2.7.3. 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 of the couplant. A typical example is shown in Fig. 2.27 .

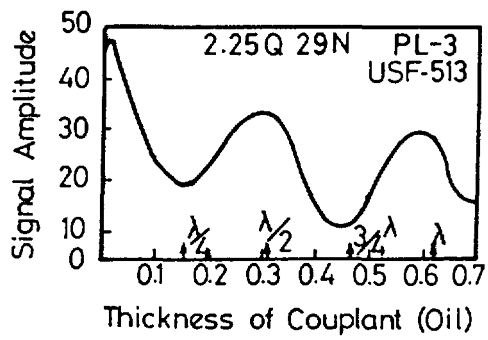


Figure 2.27 Variations of signal amplitude and couplant thickness.

The variation of signal amplitude with the type of couplant for various surface roughnesses is shown in Figure 2.28, which indicates that the surface roughness should preferably be less than 25 um.

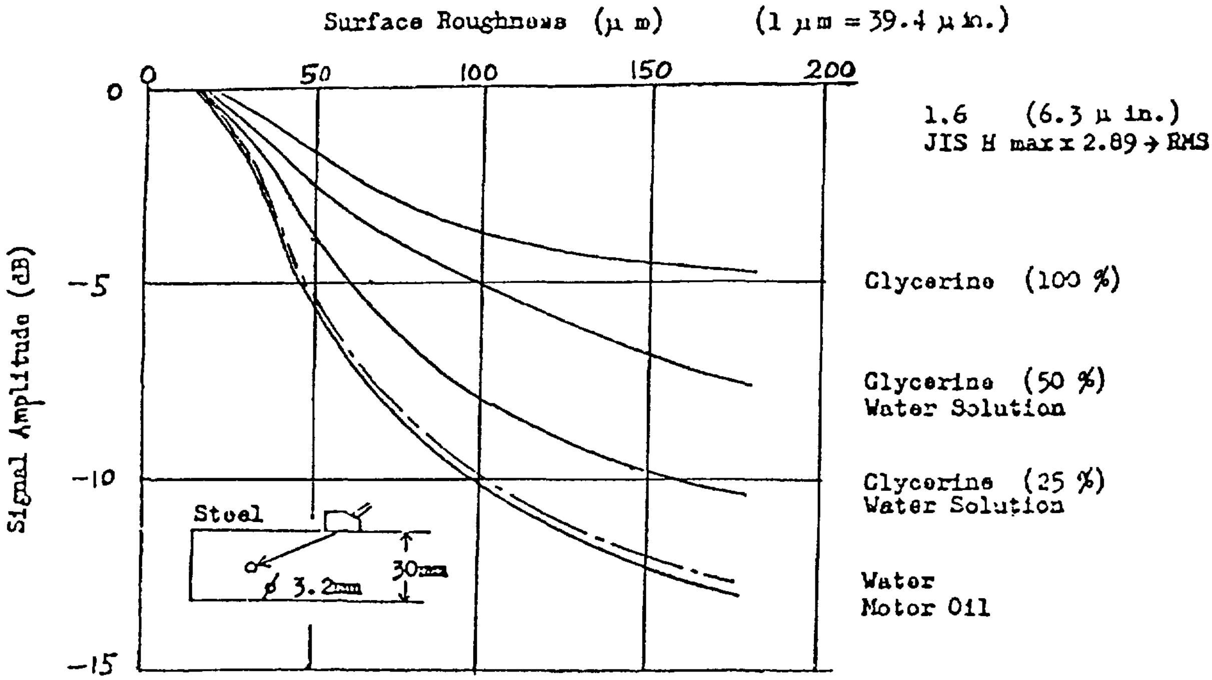


Figure 2.28 Variations of signal amplitude with types of couplants for various surface roughness.

The transmission loss due to surface roughness is best observed when a reference calibration block is used. A reference block is generally made of a material acoustically equivalent to the test specimen. However, the test specimen cannot always have the same surface roughness as the calibration block. This difference leads to a transfer loss at the contact surface.

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 2.29.

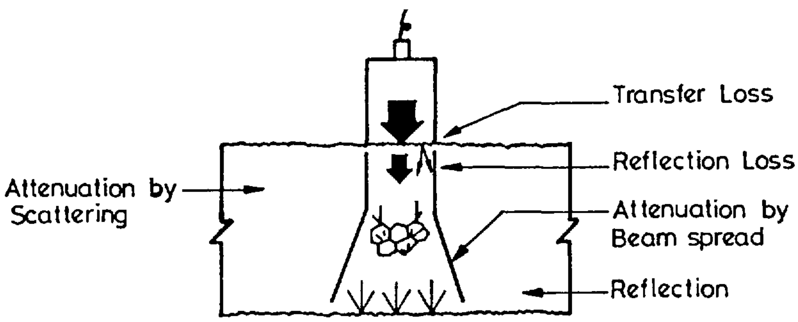


Figure 2.29 Attenuation losses during transmission.

The variation of acoustic pressure with distance due to divergence and attenuation and beam spread is shown in Figure 2.30.

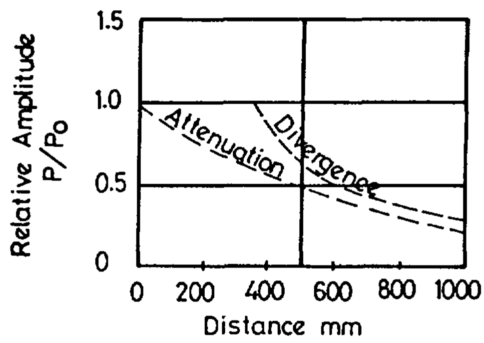


Figure 2.30 Variation of signal amplitude with distance due to divergence and attenuation losses (Linear representation)

The sound pressure which decreases as a result of attenuation by scattering and absorption can be written in the form of an exponential function :

$$P = Po\ e^{-\alpha d}, \quad ....(2.30)$$

Where
- Po = initial pressure at $d = o$
- P = final pressure at distance, d.
- d = total beam path in the material.
- α = attenuation coefficient.

The natural logarithm of this equation gives

$$\alpha d = \ln\left(\frac{Po}{P}\right) \quad Np$$

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,

$$\alpha d = 20 \log\left(\frac{Po}{P}\right) \quad dB$$

$$\alpha = \frac{20}{d} \log\left(\frac{Po}{P}\right) \quad dB/m \ .....(2.31)$$

Since the sound pressure is proportional to the oscilloscope echo height, H ,

$$\alpha = \frac{20}{d} \log \left(\frac{H_o}{H}\right) \quad \text{dB/m} \quad \ldots .(2.32)$$

The attenuation coefficient depends on the nature of the medium (i.e. material for transmission) and the frequency of the waves. Generally, the attenuation coefficient or the sound attenuation increases with an increase in frequency. If it is a matter of pure absorption, this occurs as the square of the frequency and with attenuation due to scatter the sound reduction occurs at an even higher rate. Figure 2.31 shows a typical relationship between attenuation and frequency for a solid. At low frequencies there is a linear variation between these factors, attenuation being due to absorption. At frequencies for which the wavelength approaches the grain size, the phenomenon of scattering occurs.

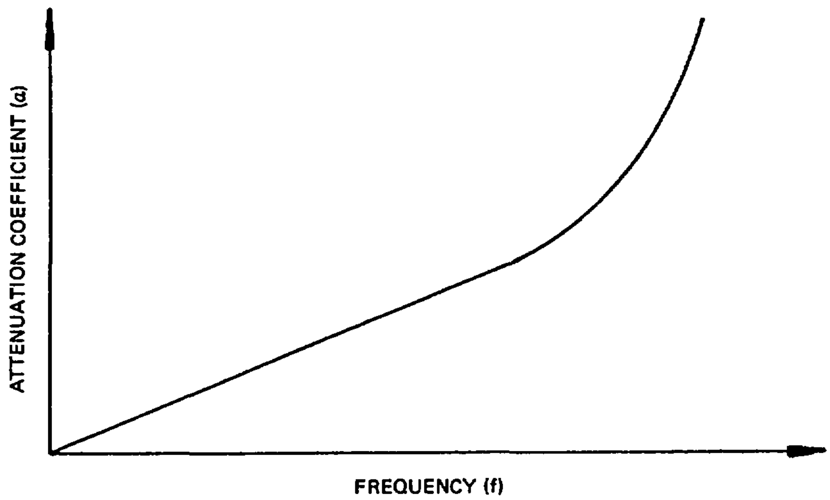


Figure 2.31 Variations of attenuation coefficient of the transmitting material with frequency of waves.

The effects of attenuation loss due to interaction between the sound wave and the material can be observed experimentally. 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 .

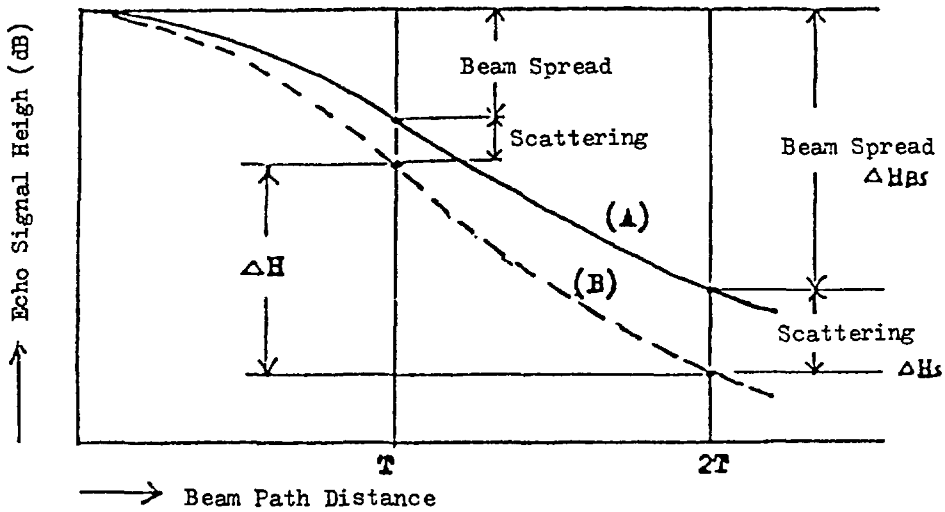


Figure 2.32 Attenuation by beam spread and scattering.

$$\text{Thus} \quad \Delta H = H_{B1} - H_{B2}$$

$$= \Delta H_{BS} + \Delta H_{S}$$

The amplitude difference, ΔH, between the multiple back reflections can be read out on the equipment gain (or attenuator). The attenuation difference, ΔH_{BS}, by the beam spread is possible to obtain from the DGS diagram. Hence, the attenuation difference, ΔH_{S}, by scattering and absorption is expressed as follows :

$$\Delta H_{S} = \Delta H - \Delta H_{BS}$$

If ΔH_{S} is divided by the total distance travelled, the result is called the attenuation coefficient,

Thus,

$$\alpha = \frac{\Delta H_{S}}{2T} = \frac{\Delta H_{S} - \Delta H_{BS}}{2T} \quad \text{(dB/m)....(2.33)}$$

Where T is the specimen thickness.

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 ΔH_{BS} = 6 dB and the attenuation coefficient α is calculated, as follows :

$$\alpha = \frac{\Delta H - 6}{2\,T} \quad \text{dB/m} \quad \text{...........(2.34)}$$

$$(T \geqslant 3N)$$

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 3N (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 = 10 dB. Total beam distance between second and fourth echo = 120 mm. Therefore, the attenuation of the plate material at 4 MHz is

$$\frac{10 - 6}{120} = \frac{1}{30} \quad \text{dB / mm or 33 dB/m}$$

2.8 Diffraction

An important property of ultrasonic waves is there 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 2.33a) . A second example of this phenomenon is the bending of ultrasonic waves near the edge of a specimen (Figure 2.33b). This bending may divert the ultrasonic wave from where it would normally be received, to some other point.

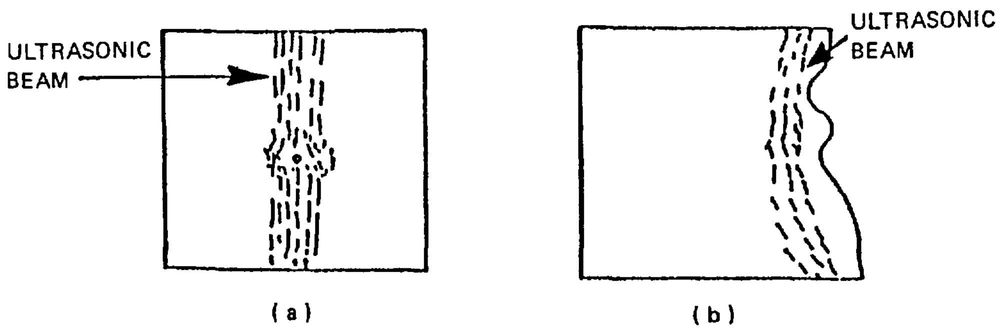


Figure 2.33 Diffraction of ultrasound in solids.

(a) Around the defect.
(b) Near the irregular edge.

3. ULTRASONIC TEST METHODS, SENSORS AND TECHNIQUES

3.1 Basic Ultrasonic Test Methods

Ultrasonic waves arriving at an interface between two media are partially reflected in to the medium from which they are incident and partially transmitted in to 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 make use of the reflected portion of the waves is classified as the pulse echo test method. An other 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 side of the specimen as shown in Figure 3.1.

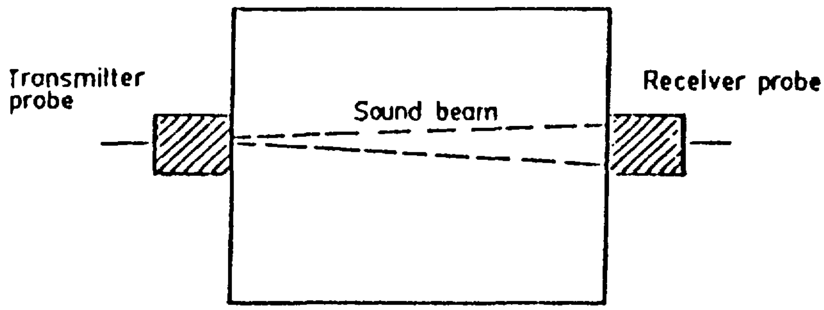


Figure 3.1. Position of transmitter and receiver probes in the through transmission method of ultrasonic testing.

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) and (c) .

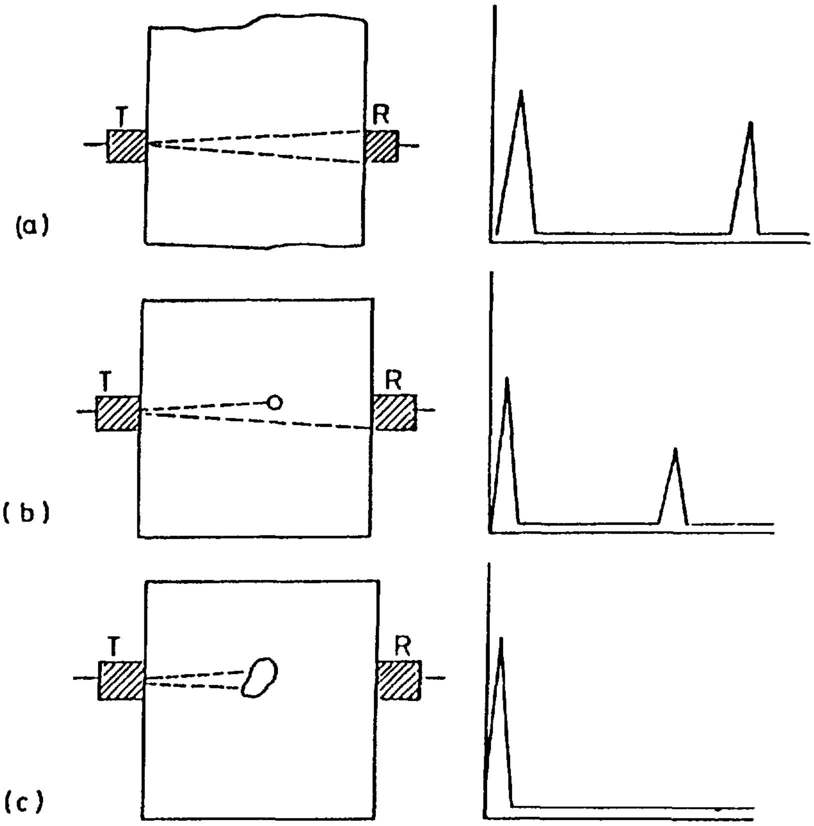


Figure 3.2 (a), (b), (c). CRT screen appearance for defects of varying sizes in the through transmission method.

(a) Defect free specimen.

(b) Specimen with a small defect.

(c) Specimen with a large defect.

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 back wall echo. 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 back wall 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) and (c).

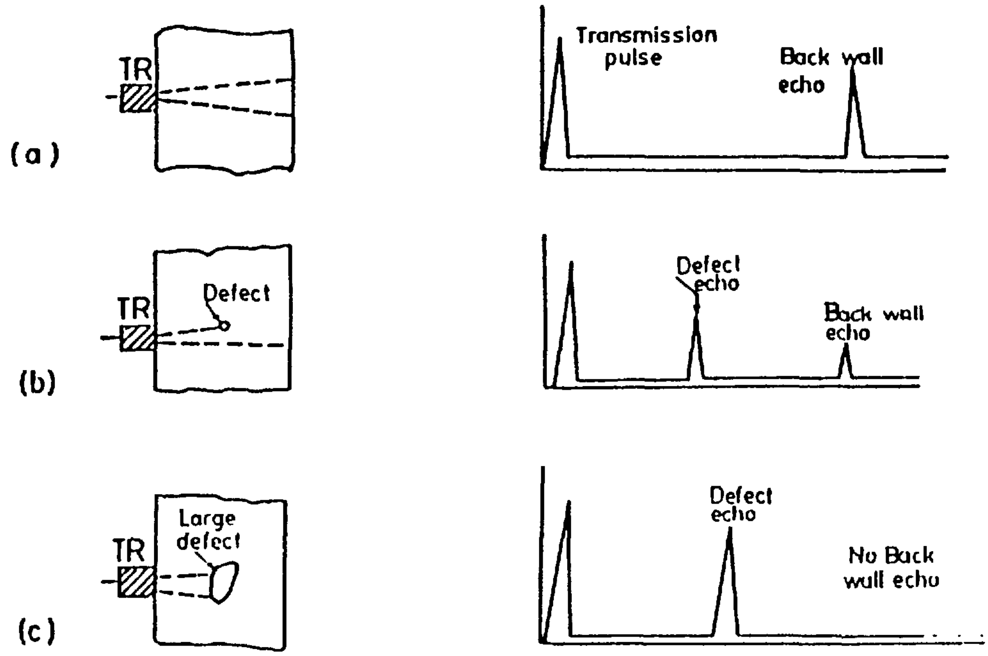


Figure 3.3 Principle of pulse echo method of ultrasonic testing.

(a) Defect free specimen.

(b) Specimen with small defect and

(c) Specimen with large defect.

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 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 :-

$$t = \frac{V}{2f} \qquad (3.1)$$

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 :-

$$t = \frac{V}{2(f_n - f_{n-1})} \qquad (3.2)$$

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 be largely superceded by the pulse echo method because of improved transducer design.

3.2 SENSORS

3.2.1 Ultrasonic Probe Construction

An ultrasonic probe (Figure 3.4) consists of :

(i) A piezoelectric transducer.

(ii) A backing material.

(iii) A matching transformer which matches the piezoelectric transducer electrical impedance to that of the cable to the flaw detector, 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.

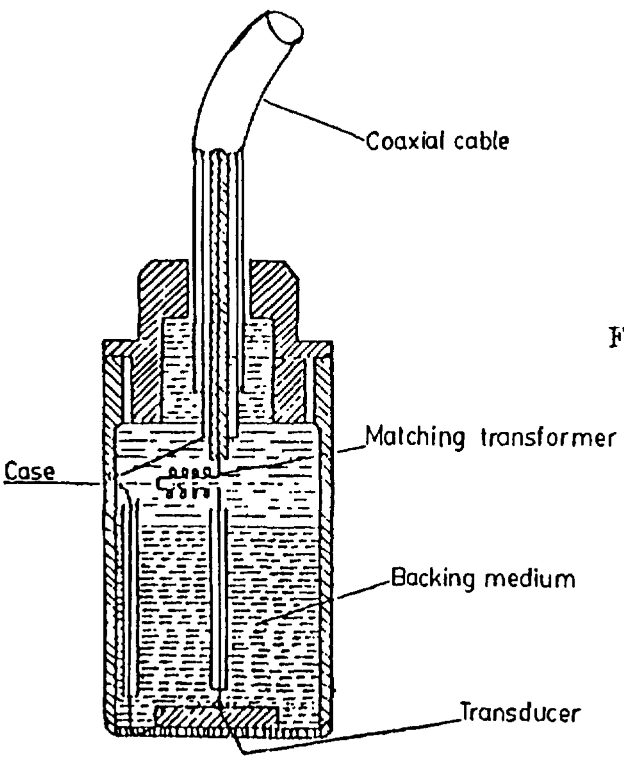


Figure 3.4 An Ultrasonic Probe.

(a) Piezoelectric Transducers

Piezoelectric transducers are already discussed in detail in section 2.5 . 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 :

$$f_r = \frac{V}{2t} \qquad \text{(3.3)}$$

Where

f_r = resonance frequency of the transducer.

t = thickness of the transducer.

V = longitudinal wave velocity of ultrasound in the transducer .

Equation 3.3 is used to determine the thickness of the transducer required to construct an ultrasonic probe of a particular frequency.

(b) Backing Material

The backing material in a probe is used to control the two basic performance characteristics of the probe - 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. But to have a high sensitivity probe, the damping of the transducer vibration should be as low as possible. The two requirements are contradicatory 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. This matching of the acoustic impedances of transducer and backing material allows the ultrasound to pass easily from the transducer into the backing material. The backing material should also provide a high degree 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. Backing materials for pulse echo probes are often made of fibrous plastics or metal powders combined with various plastic materials. Attenuation can be controlled by the grain size of the powder and the impedance by the proportions of metal powder and plastic.

3.2.2 Types of Ultrasonic Probes

3.2.2.1 Contact Type Probes

Contact type probes are scanned in direct contact with the surface of the test specimen. In normal probes of this type a wear plate is often used to protect the transducer from wear. When using protected probes 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. Different contact type probes are discussed below.

(a) Normal Beam Contact Type Probes

As the name indicates these probes transmit ultrasonic waves, usually longitudinal , in to the test specimen in a direction perpendicular to the surface of the test specimen. Various direct contact type normal beam probes, which are commonly used in ultrasonic testing of materials, can be classified according to their mode of operation as follows :

(i) Single Transducer (Single Crystal) Normal Beam Probe

These probes use a single transducer (Figure 3.5) as a transmitter and receiver of ultrasound. This transducer has a common connection to the transmitter and amplifier units of the flaw detector (Figure 3.6). Because of this common connection to the transmitter and receiver unit, the single transducer probes have a large 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 measurements.Short pulse length probes are now available which have shorter dead zones thus making them more useful for testing thin material.

(ii) Double Transducers (Twin Crystal) Probes (or SE probes)

To avoid the limitations encountered in the use of single transducer normal beam probes for thin wall thickness

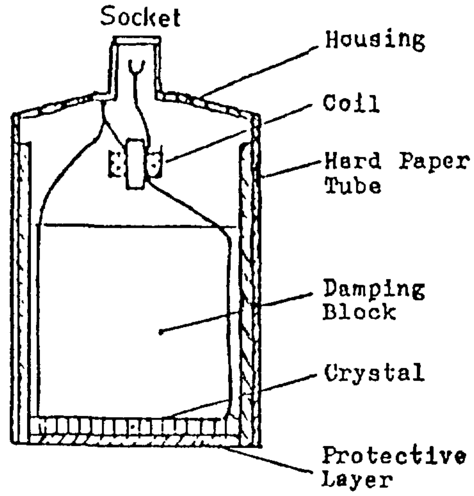


Figure 3.5 Normal beam single crystal contact type probe.

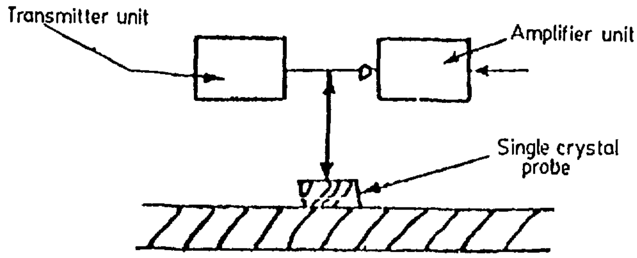


Figure 3.6 Mode of operation of single crystal probes.

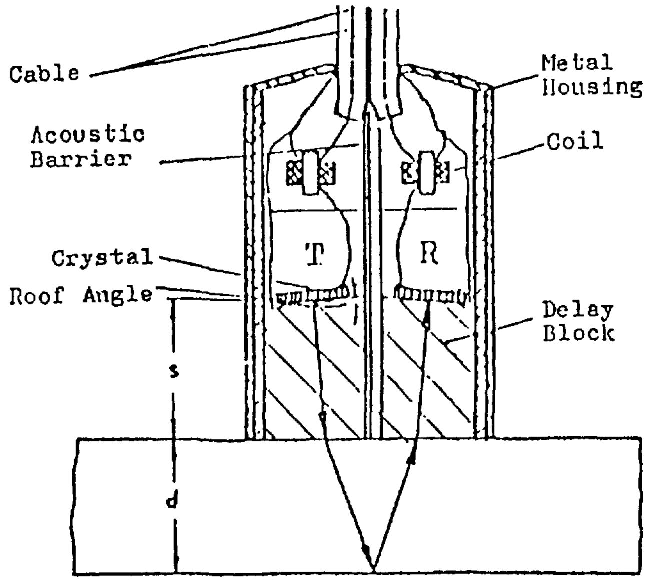


Figure 3.7 Twin crystal contact type probe and its ultrasonic propagation.

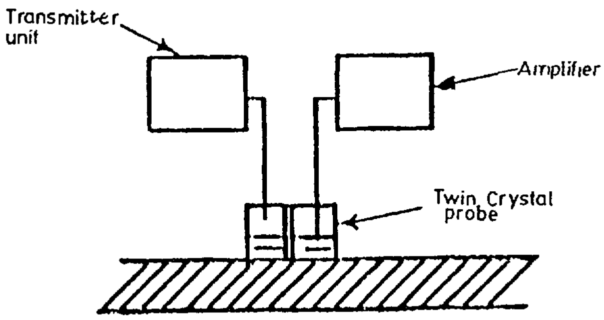


Figure 3.8 Mode of operation of twin crystal probe.

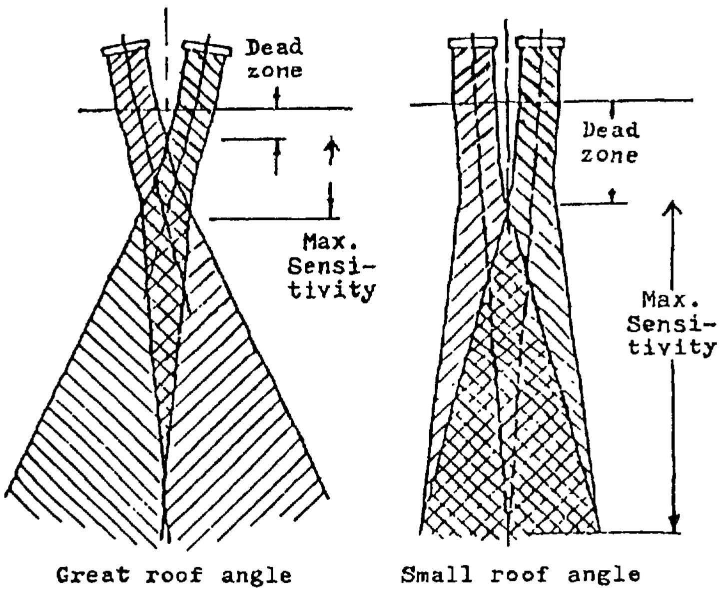


Figure 3.9 Ultrasound propagation at great and small roof angles of a double crystal probe.

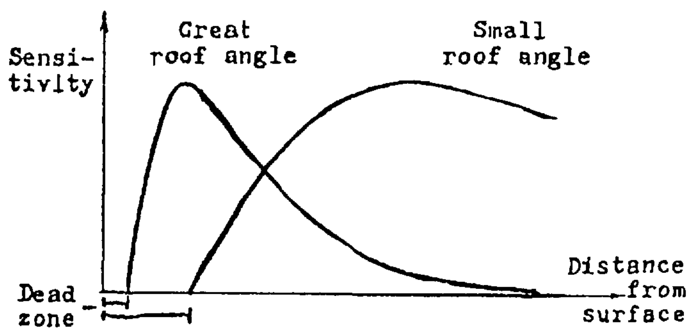


Figure 3.10 Influence of roof angles over sensitivity of twin crystal probe.

measurements and near surface flaw detection, double transducer normal beam probes are used. These are probes which incorporate two transducers in a single case. These transducers are separated acoustically from each other by an acoustic barrier (Figure 3.7). 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 3.8, thus eliminating the transmission pulse.

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" (Figure 3.9 & 3.10).

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 occuring in the near field and also helps in producing a shorter dead zone for the probe for a smaller roof angle.

(iii) Angle Beam Contact Type Probes

In angle probes, refraction and conversion of wave modes are used to transmit ultrasound in to the test specimen at various angles to the surface. A typical construction of an angle beam contact type probe is shown in figure 3.11 .

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 the specimen. The longitudinal portion is reflected back in to 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

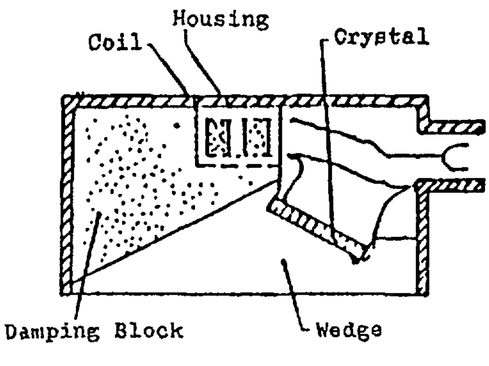


Figure 3.11 Angle beam contact type probe.

avoided. The refracted angle for steel specimens and the beam exit point, generally known as the probe index, are marked on the metal case of the probe.

A surface wave probe is an angle beam probe insofar 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 in to acount.

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 large angles .

3.2.2.2 Immersion Type Probe

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 3.12 shows the construction of an immersion type probe.

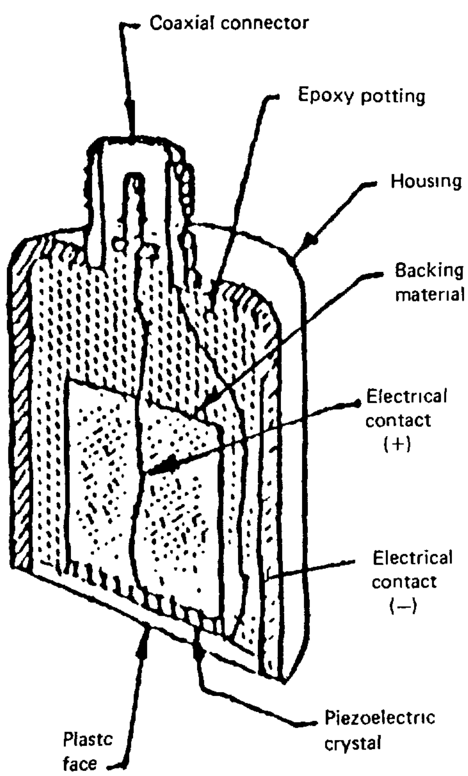


Figure 3.12 Construction of an immersion type probe.

3.3 PULSE ECHO TESTING TECHNIQUES

Techniques of ultrasonic testing are either of the contact type or the immersion 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 in to the test specimen. In the immersion type, a waterproof probe is used at some distance from the test specimen and the ultrasonic beam is transmitted in to the material through a water path or water column.

3.3.1 Contact Type Techniques

Contact techniques are divided in to three types. These are normal beam technique, angle beam technique and surface wave technique.

3.3.1.1 Normal Beam Techniques

In the normal beam technique the ultrasonic beam is projected perpendicularly in to the test specimen. This technique may use either single, double or SE normal beam probes. With the single probe, the transducer of the probe acts as both transmitter and receiver. In this technique an ultrasonic beam pulse is projected at in to the specimen and echoes from the flaws within the specimen and from the back wall of the specimen are received (Figure 3.13). The occurance of a large transmission pulse when using single transducer probes renders the single probe technique in effective for the detection of near surface flaws and for thin wall thickness measurements.

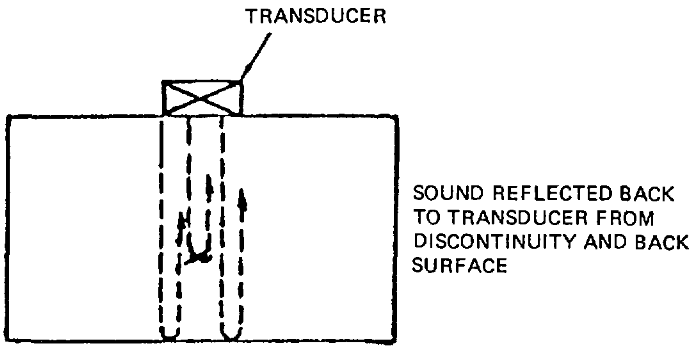


Figure 3.13 Single Transducer Pulse-Echo Technique.

Double normal beam probe techniques are useful when the specimen shape is irregular and the back surface is not parallel with the front surface. One probe transmits the ultrasonic beam in to the specimen and the other receives the echoes from the flaws and back wall (Figure 3.14).

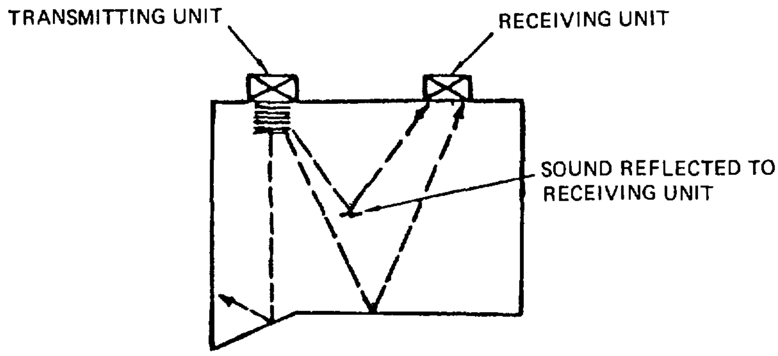


Figure 3.14 . Double Transducer Pulse-Echo Technique

In S.E. normal beam probe techniques the two transducer are in the same case with one of the transducers acting as a transmitter and the other as a receiver. With these techniques thin wall thickness measurements and near surface flaw detection are possible because of the elimination of the transmission pulse.

3.3.1.2 Applications of Contact Type Normal Beam Probes

(a) Thickness Measurement

(i) Using Single Crystal Probes

One of the most important uses is that of thickness measurement. When a normal beam probe is placed on a plate like test specimen, the CRT screen displays a transmission pulse and one or more back wall echoes. The distance between two consecutive back wall echoes corresponds to the thickness of the test object. Consequently by calibrating the CRT screen in millimetres using a calibration block, it is possible to have a direct reading of the thickness of the unknown test specimen.

The thickness of the test specimen can be read by using either a single back wall echo or for better accuracy using multiple echoes. In the case of the single echo technique the thickness of the specimen is determined from the point where the left hand edge of the first back wall echo rises from the base line, while in the case of the multiple echo technique the thickness of the last multiple echo is read and then the thickness of the specimen determined by dividing this thickness by the total number of back wall echoes. The multiple echoe technique is used for thinner specimens. The limit to the multiple echo technique is the merging of the first back wall echo in to the transmission pulse and the consequent difficulty in determining the total number of back wall echoes. With good resolution probes the smallest wall thickness that can be measured with the multiple echo method is about 3 mm. To be able to measure smaller thicknesses, S.E. probes are used.

(ii) **Using S.E. Probes**

With S.E probes it is possible to measure wall thicknesses down to 1 mm. Although the design of S.E probes results in a very good near surface resolution, it also calls for a special calibration procedure to obtain accurate thickness measurements. The special calibration block for SE probes is a stepped reference block VW (Figure 3.15) having 8 or 10 steps from either 1 mm to 8 mm or from 1 mm to 10 mm.

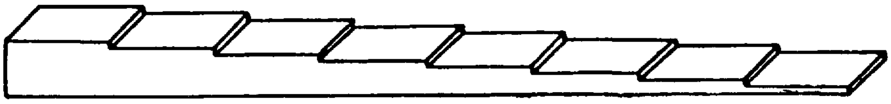


Figure 3.15

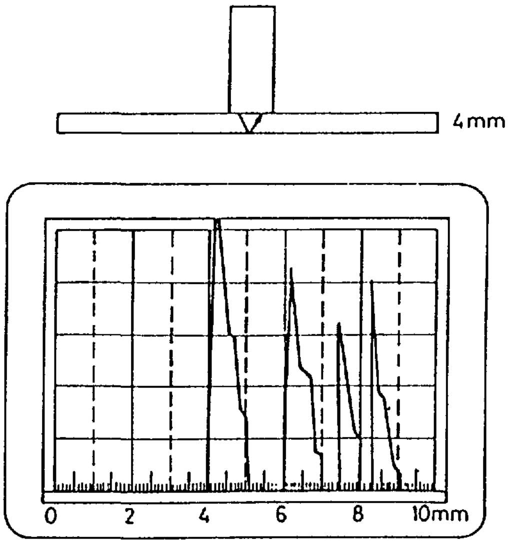


Figure 3.16

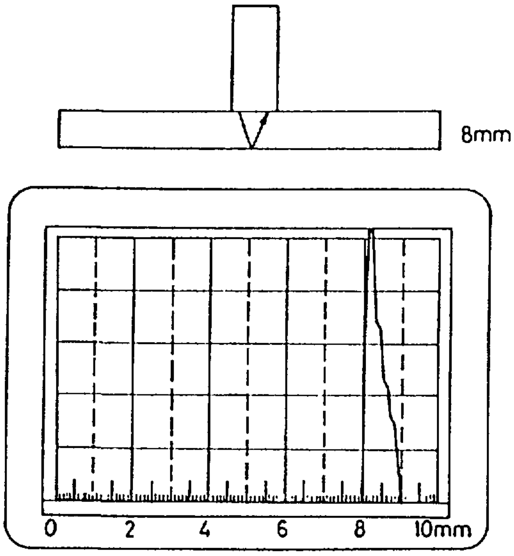


Figure 3.17

To calibrate the CRT screen for an SE probe, two suitable steps of the VW block which are in the desired range are chosen. The probe is first coupled to the thinner step and using the delay control the back wall echo is brought to the corresponding scale position. The probe is then coupled to the thicker step and using the testing range control, the back wall echo is brought to the corresponding scale position. These two adjusting steps are repeated until both echoes stand on the right scale positions.

Figure 3.16 and 3.17 illustrate the two calibration steps for the 4 mm and 8 mm steps of the VW calibration block. The two additional echoes between the first and second back wall echoes in the case of the 4 mm step are because of the mode conversion effect at the back wall.

The error in the measurement of thickness due to the V shaped path of the ultrasonic beam (Figure 3.18), becomes negligibly small if the thickness of the test specimens lies between the two step thickness used for the calibration of the CRT screen and if the difference in thickness between the two steps is not too large.

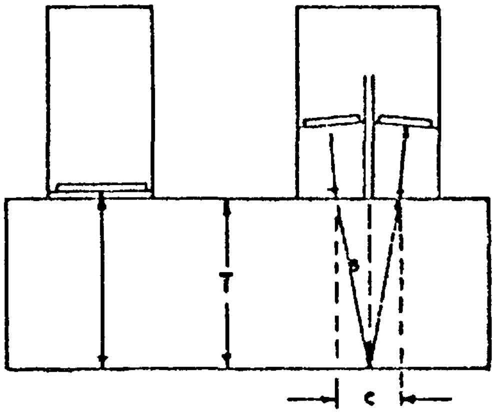


Figure 3.18

(iii) **Velocity Correction**

If the calibration block used for the time base calibration is a different material than that of the material of the specimen, then the measured thickness of the specimen has to be corrected for the difference in velocities in the calibration block and the test specimen.

The correction is made as follow :

$$\text{Thickness of the specimen} = \text{Indicated thickness} \times \frac{\text{Longitudinal velocity in specimen}}{\text{Longitudinal velocity in calibration block}}$$

(b) **Testing For Laminations**

1. **Standard Procedure**

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 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.

2. Multiple Echo Technique

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 3.19).

Figure 3.19

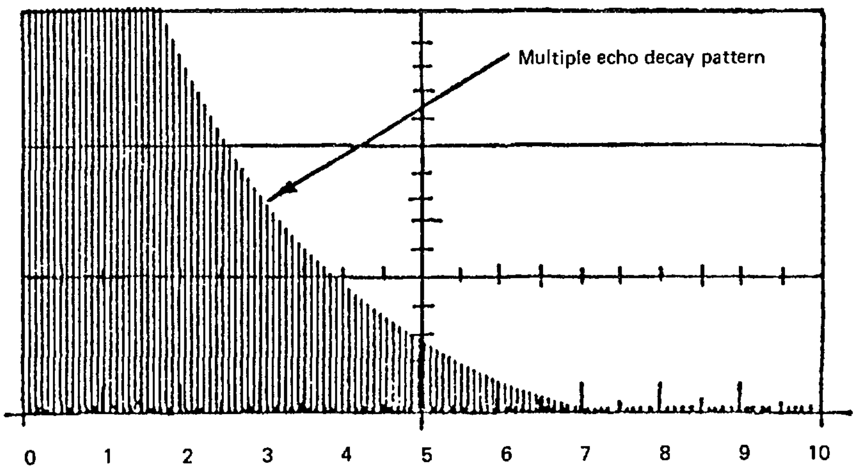
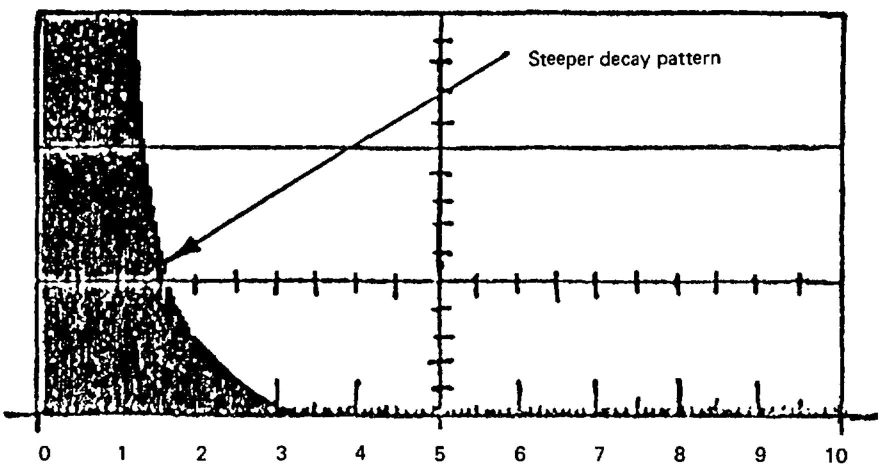


Figure 3.20



(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 3.20 . The collapse occurs because each of the many multiple echoes is closer to its neighbour in the presence of a lamination.

(c) 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 slighty different acoustic impedence to 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 3.21 a,b,c).

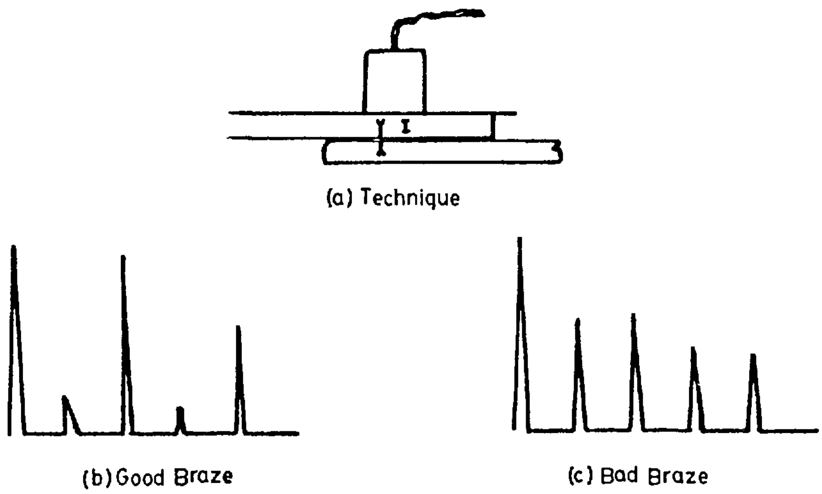


Figure 3.21 (a,b,c)

If the two brazed wall thickness are too thin to permit clear back wall echoes, a multiple echo, as described for lamination testing, can be used.

(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 in to 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 in to the

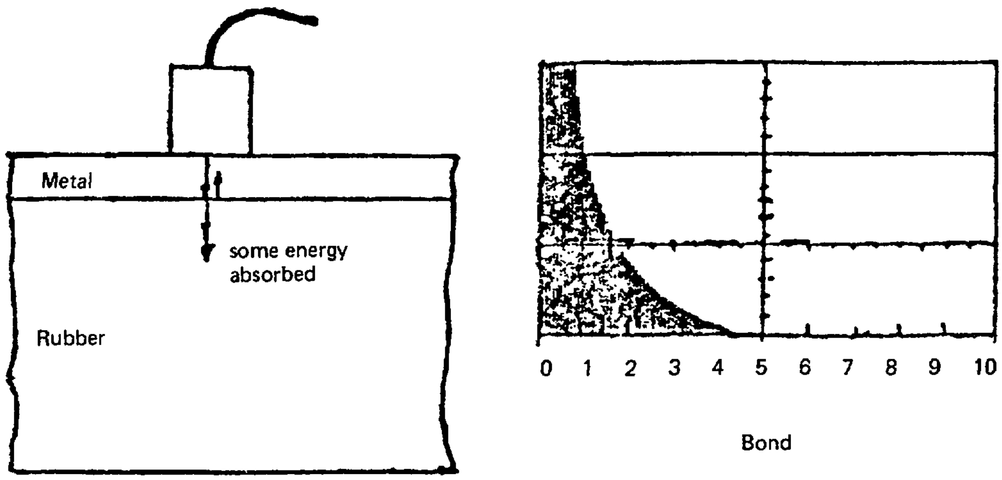


Figure 3.22

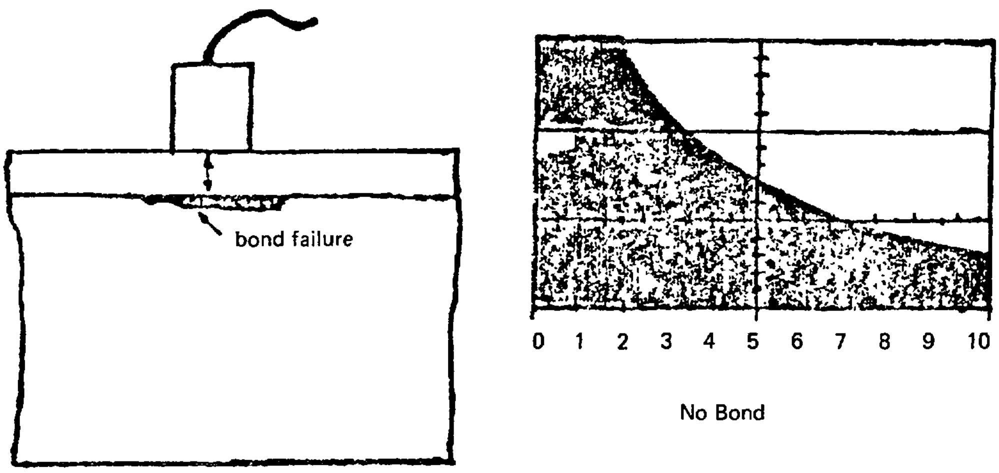


Figure 3.23

bond (Figure 3.22). 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 3.23).

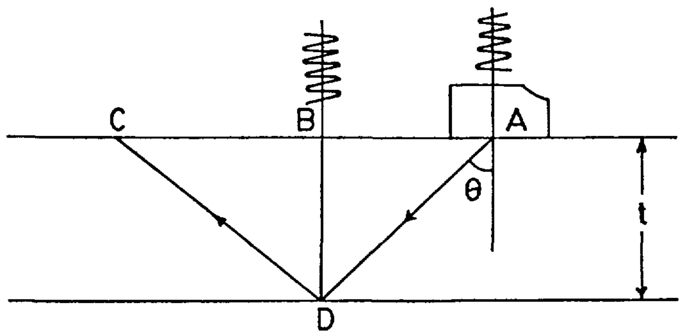
3.3.1.3 Angle Beam Techniques

The angle beam technique is used to transmit ultrasonic waves in to a test specimen at a predetermined angle to the test surface. According to the angle selected, the wave modes produced in the test specimen may be mixed longitudinal and transverse, transverse only, or surface wave modes. Usually, transverse wave probes are used in angle beam testing. Transverse waves at various angles of refraction between 35° and 80° are used to locate defects whose orientation is not suitable for detection by normal beam techniques.

3.3.1.4 Calculation of Various Distances for Angle Beam Probes

(a) Half Skip and Full Skip Distances and Beam Path Lengths

Figure 3.24 defines the half-skip-distance (HSD), full-skip-distance(FSD), half-skip-beam-path-length (HSBPL) and full-skip-beam-path-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 3.24

The relations used to calculate HSD, FSD, HSBPL and FSBPL for a specimen of thickness t, are given below:

$$HSD = t \times \tan \theta \quad (3.3)$$

$$FSD = 2 \times t \times \tan \theta \quad (3.4)$$

$$HSBPL = t/\cos \theta \quad (3.5)$$

$$FSBPL = 2t/\cos \theta \quad (3.6)$$

If the actual probe angle is exactly equal to the nominal probe angle then these distances can be calculated by the following formula :

$$\text{Distance required} = F x t \quad (3.7)$$

Where F is the appropriate factor from Table. 3.1.

Table 3.1 .

F Factor / Probe angle	35^o	45^o	60^o	70^o	80^o
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

(b) Calculation of Maximum Penetration Thickness for Thick Wall Pipes

The normal range of transverse wave angle beam probes (45 , 60 & 70), when used on thick wall pipe may not penetrate to the bore of the pipe, but cut across to the outside surface again, as shown in Figure 3.25 and miss the defect.

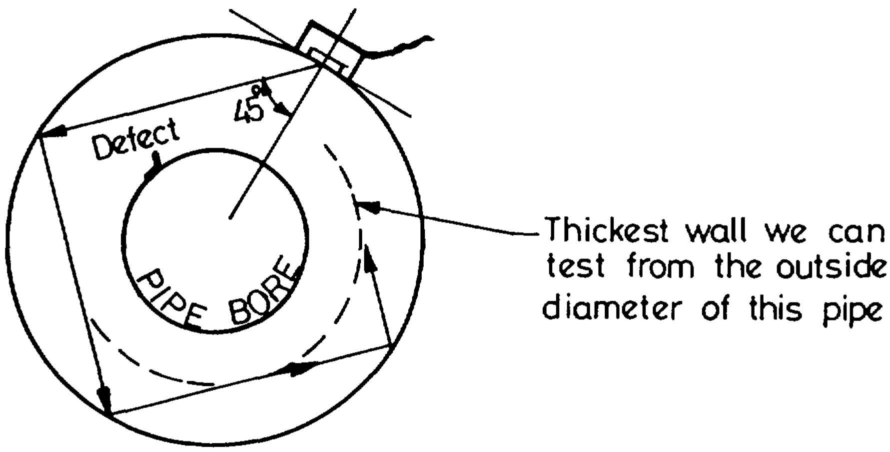


Figure 3.25

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 :

$$t = \frac{d \ (1 - \sin \theta)}{2} \qquad \text{---- (3.8)}$$

Where

t = maximum wall thickness

d = outer diameter (OD) of the pipe

θ = probe angle

Equation 3.8 can be rewritten to determine the best angle for a given wall thickness as:

$$\theta = \mathrm{Sin}^{-1} \left(1 - (2t/d) \right) \quad \text{------- (3.9)}$$

For convenience equation 3.8 can be simplified for standard angle probes as

$$t = d \times f \quad \text{----------- (3.10)}$$

Where f is the probe factor given in Table. 3.2 .

Table 3.2 .

Probe angle (θ)	35^{o}	45^{o}	60^{o}	70^{o}	80^{o}
Probes factor (f)	0.213	0.146	0.067	0.030	0.0076

Table 3.3 gives values of maximum wall thickness for various pipe sizes and probe angles.

Table 3.3

Probe angle / Pipe O.D	35^{o}	45^{o}	60^{o} Maximum Wall Thickness
4" (100 mm)	21.3 mm	14.6 mm	6.7 mm
6" (150 mm)	31.95 mm	21.9 mm	10.05
8" (200 mm)	42.6 mm	29.2 mm	13.4 mm
10" (250 mm)	53.25 mm	36.5 mm	16.75
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

3.3.1.5 Surface Wave Techniques

Surface wave techniques have been used very successfully for a great number of applications, particularly in the Aircraft Industry. However, it is not so common in the steel industry because surface finishes are often less smooth, and magnetic flaw detection will find most defects detectable by surface waves. The main advantage of surface waves is that they follow gentle contours and are reflected sharply only by sudden changes in contour, thus making it a very useful tool for the examination of complex shaped components. The main limitation of these waves is that they are almost immediately attenuated if the surface finish is rough, is covered in scale or a liquid (such as the couplant), or if any pressure is applied by another object (such as the hand of the operator).

3.3.2 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.

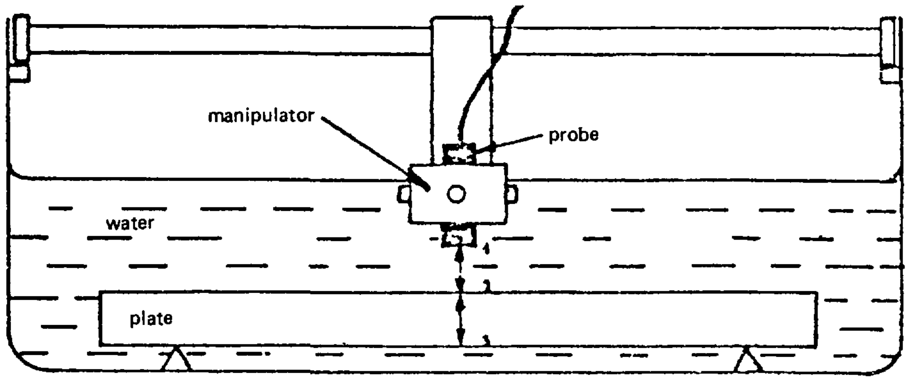
In the immersion technique both the probe and the test specimen are immersed in water. The ultrasonic beam is directed through the water in to the test specimen, using either a normal beam technique (Figure 3.26 a) for generating longitudinal waves or an angle beam technique (Figure 3.26 b) for generating transverse waves.

When the normal beam technique is being used the water path distance must always be longer than the distance S in equation (3.11).

$$S = \frac{\text{Thickness specimen x sound velocity in water}}{\text{sound velocity in specimen}} \qquad \text{----(3.11)}$$

When the specimen is steel the water path distance must be longer than 1/4 steel thickness otherwise the 1st back wall echo overlaps the 2nd surface echo and defects near the back wall may not be seen.

In the bubbler or squirter technique, the ultrasonic beam is directed through a water column in to the test specimen (Figure 3.27). This technique is usually used with an



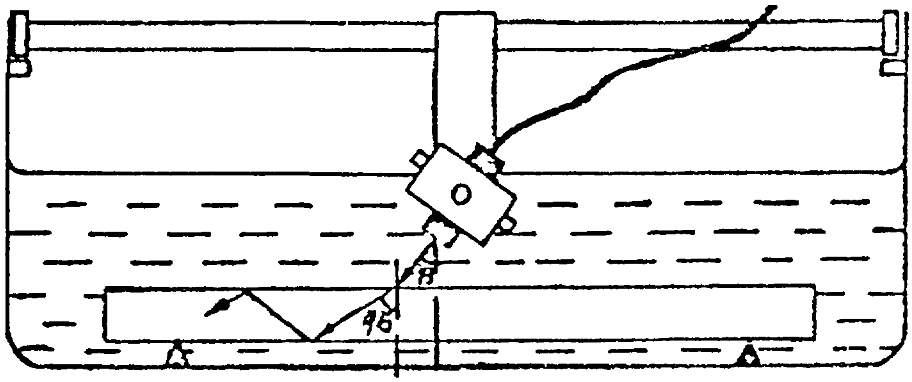


Figure 3.26

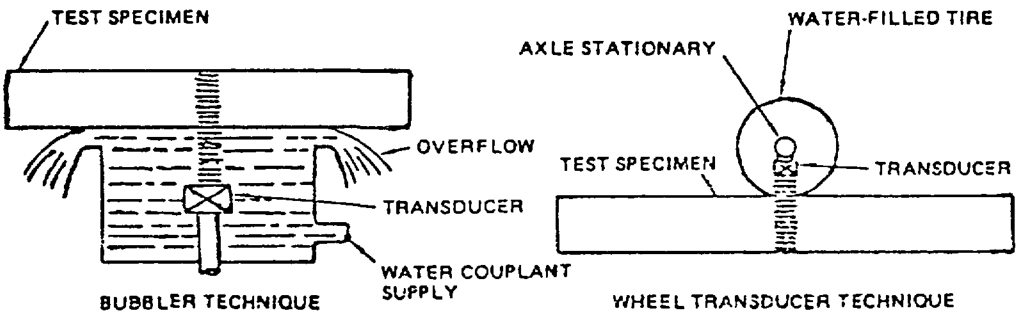


Figure 3.27 Bubbler and Wheel Transducer Techniques.

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 in to 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

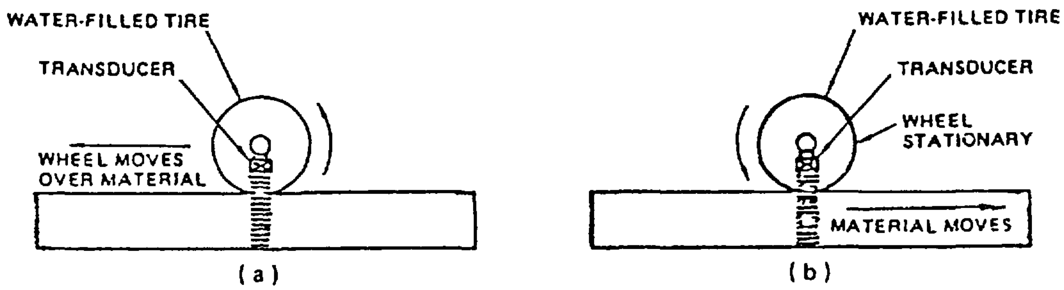


Figure 3.28 Stationary and Moving Wheel Transducers

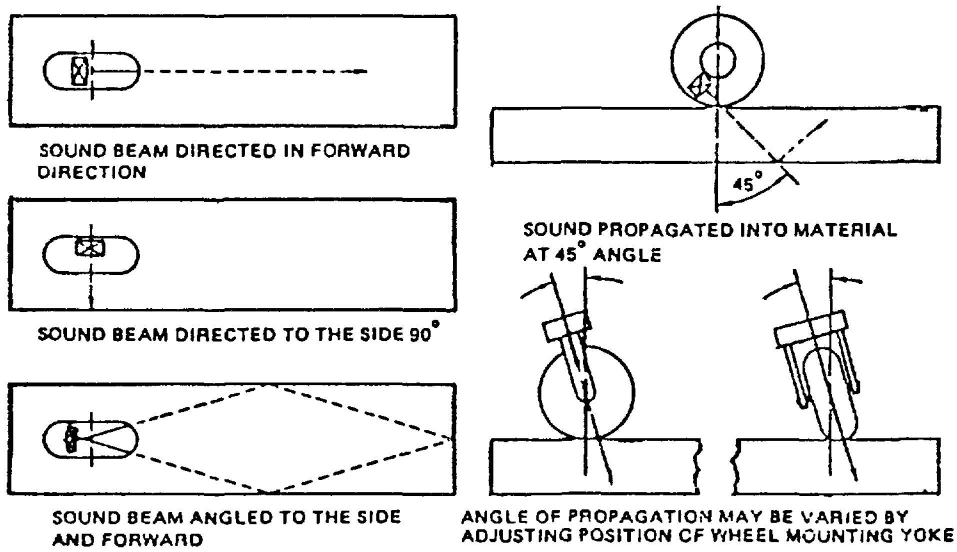


Figure 3.29 Wheel Transducer Angular Capabilities.

fixture, where the specimen is moved past it (Figure 3.28 a and b). The position and angle of the probe mounted on the wheel axle may be constructed to project normal beams, as shown in Figure 3.28 a and b or to project angled beams as shown in Figure 3.29 .

4. PULSE ECHO TYPE ULTRASONIC FLAW DETECTOR

4.1 Construction And Mode Of Operation Of A Pulse Echo Type Flaw Detector.

4.1.1 Functions Of The Electronic Elements

Figure 4.1 Shows the block diagram of a pulse echo ultrasonic flaw detector.

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 between 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 towards the CRT screen S they pass two pairs of deflecting plates X and Y . A voltage applied to the X plates deflects the electron beam horizontally while a voltage applied to the Y - plates deflects the beam vertically. The list of the CRT controls together with some of the names used by different manufacturers is given below :-

i)	Brightness control	Brightness, Brilliance, intensity.
ii)	Focus control	Focus.
iii)	Astigmatism	Astigmatism, Auxiliary focus.

This control corrects 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.

iv)	Horizontal shift	Horizontal shift, set zero, x-shift.
v)	Vertical shift	Vertical shift, Y - shift.

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 operating time (i.e the time in which the saw tooth voltage rises from zero to its maximum value) of the sawtooth voltage (Figure 4.3) .

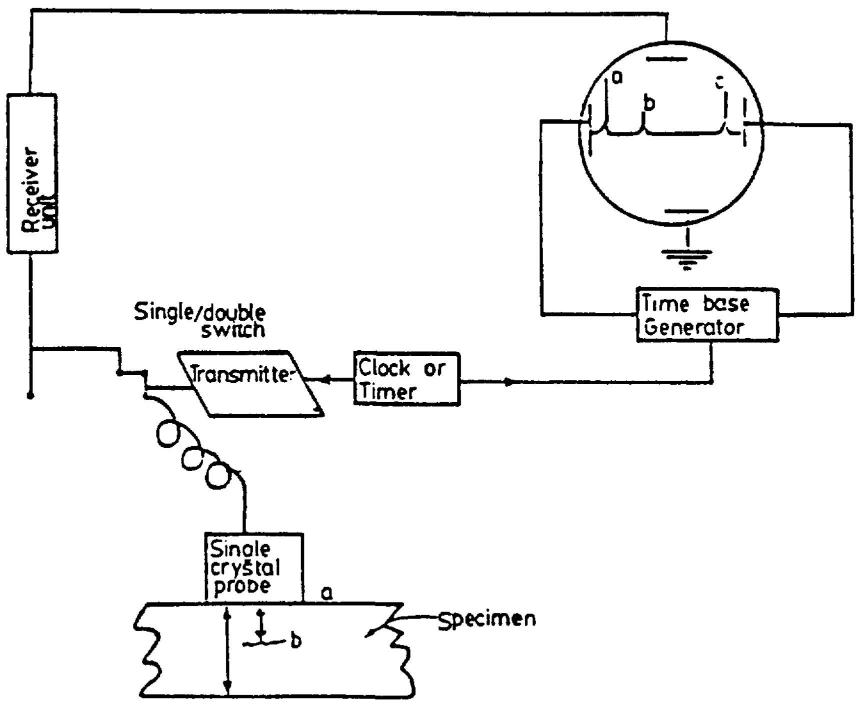


Figure 4.1

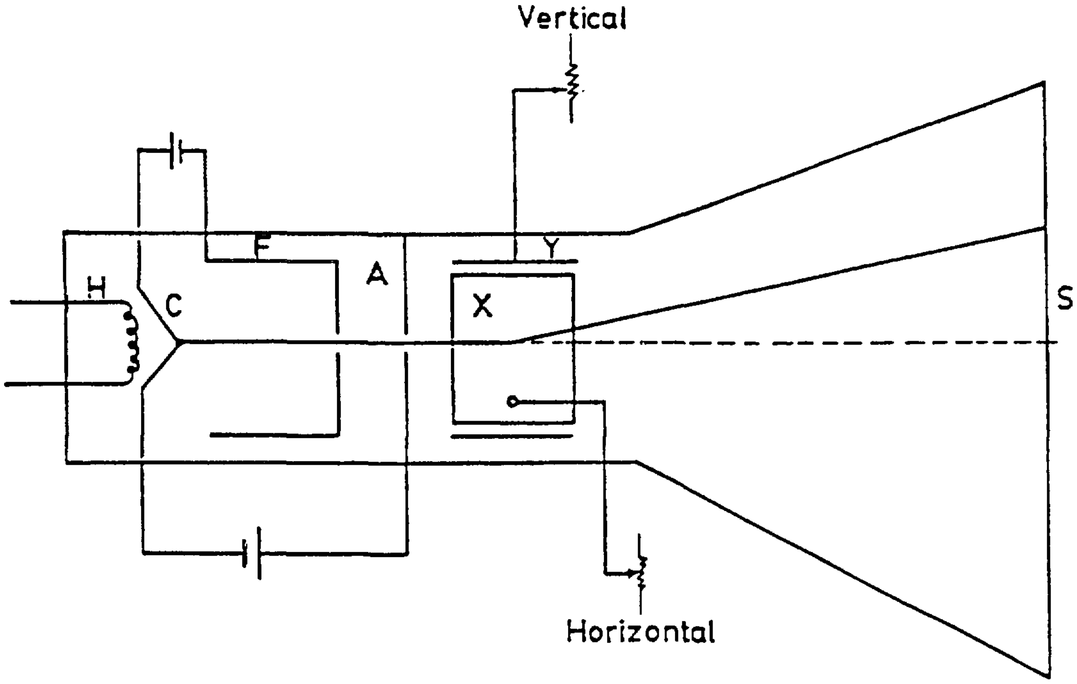


Figure 4.2

The shorter the operating time the greater is the speed of the spot. The control provided for the adjustment of the saw tooth voltage operating time and hence the speed of the spot is termed the <u>depth range</u> or <u>test range</u> control. 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 operating time of the sawtooth voltage (Figure 4.4). Sometimes it is necessary to delay the pulse which triggers the time base (see clock or timer below) compared to the

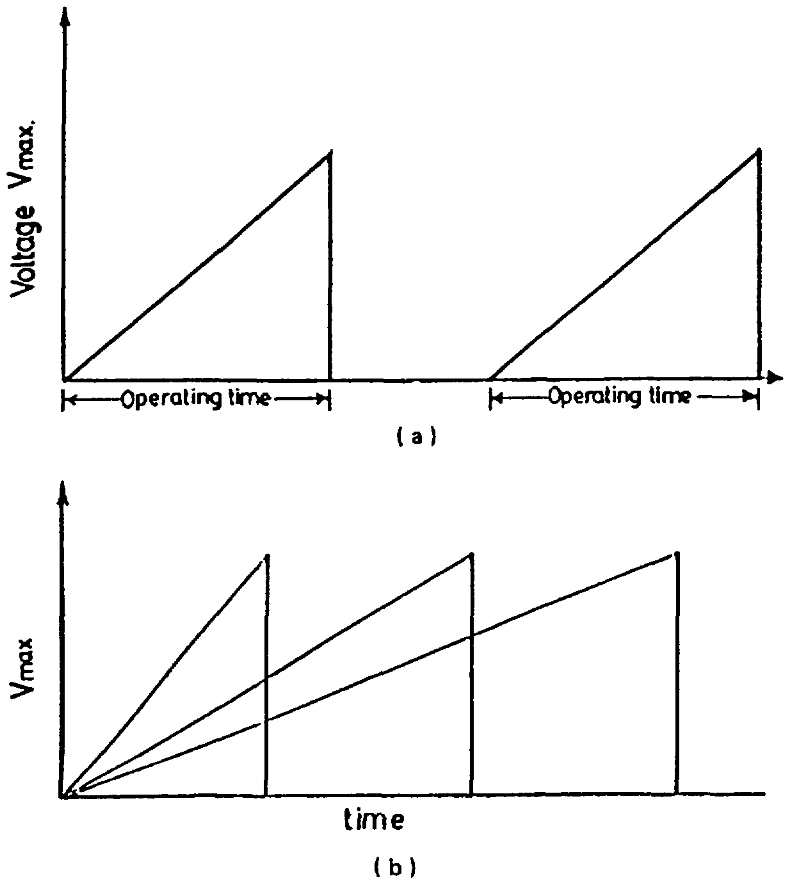


Figure 4.3 (a) SAW TOOTH VOLTAGE FOR TIME BASE.
(B) SAW TOOTH VOLTAGE WITH DIFFERENT OPERATING TIMES.

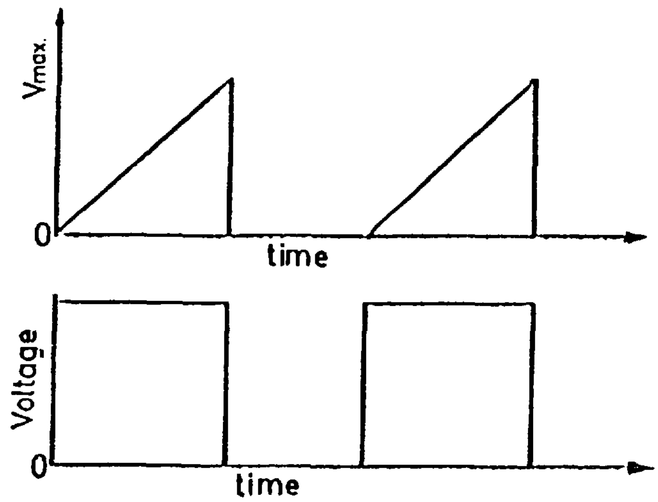


Figure 4.4 Sawtooth voltage for time base with corresponding square wave voltage for the control of brightness.

pulse which triggers the transmitter. For this purpose a control is provided. The control provided for this purpose is usually termed the delay control.

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 in to an ultrasonic wave. In some instruments controls are provided to adjust the frequency and amplitude of the 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.

The receiver unit consists of an amplifier, a rectifier and an attenuator. The amplifier amplifies any voltage pulse supplied to it from the probe. The amplification is of the order of about 10^5. In most 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 it is a narrow band type and a control is provided to tune it to the frequency of the probe. 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 the " gain control " and is calibrated in decibels or dB.

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 is 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 alteration in setting of the test range control.

A 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. This control should not be used unless its effect on the vertical linearity is known and allowed for in any subsequent evaluation of a flaw based on reflectivity.

4.1.2 Operation Of A Pulse Echo Type Flaw Detector

The simultaneous triggering of the time-base generator and transmitter by the clock, initiates an 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 ' (Figure 4.1) on the CRT screen. The indication, ' a ' is known as the " transmission echo " , " transmission pulse, " " initial pulse "or "main bang ".

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 the 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 indication 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 in figure 4.1 is a 25 mm thick steel plate, the above operation would have taken about 8 millionths of a second (8 us) to complete. The pulse repetition frequency (PRF) should, therefore, be high enough to make the pattern 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 16o micro second (us). 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 instruments, the PRF can be varied between 50 pulse per second (PPS) to 1250 PPS. This is done automatically in modern instruments with the setting of the testing range control.

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 some time before entering the test specimen. To stop the electron beam spot travelling a distance proportional to this travelling time in the perspex delay block, the delay control is used. The delay control makes the time - base generator wait for a period equal to the perspex travelling time before making the spot start from the zero position.

4.2 Scan Presentation

The ultrasonic echoes are electronically translated in to visual presentations on the CRT screen or other recording devices. The three basic presentation are known as A-scan, B-scan and C-scan.

4.2.1 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 4.5 .

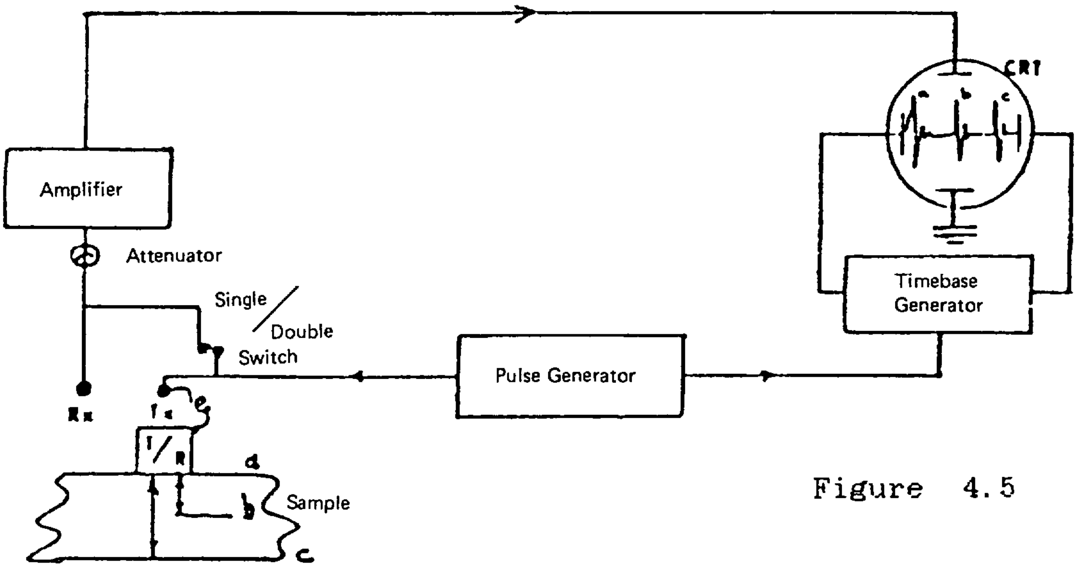


Figure 4.5

4.2.2 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 reflection of the front and back surfaces of the test material and the flaw. A typical B-scan system is shown in Figure 4.6 . The system differs from the A-scan system in the following respects :-

i) The displày is generated on a CRT screen that is a compound of a long persistance 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.

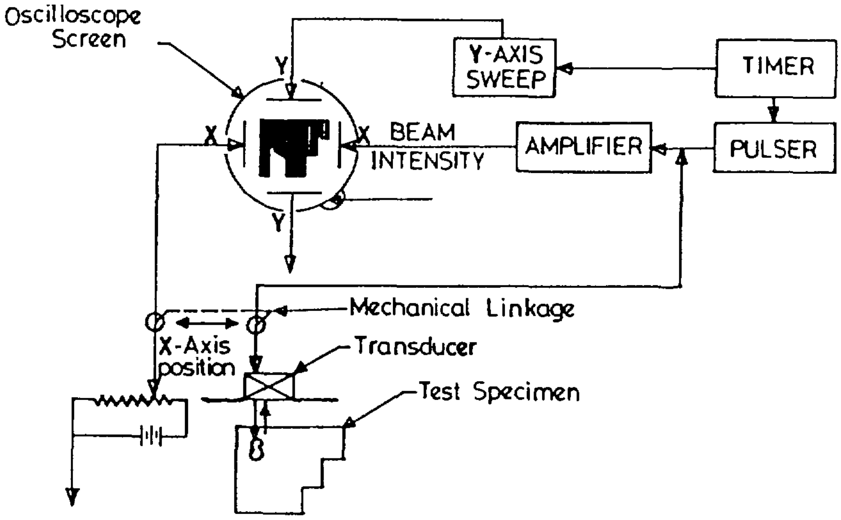


Figure 4.6 B-scan presentation.

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 brightnesses corresponding to different values of echo intensity may exhibit enough contrast to enable semiquantitative appraisal of echo intensity, with can be related to flaw size and shape.

The chief advantage of B-scan presentation is 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 cylinderical, 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.

4.2.3 C-scan Presentation

C-scan equipment is 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 4.7. 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.

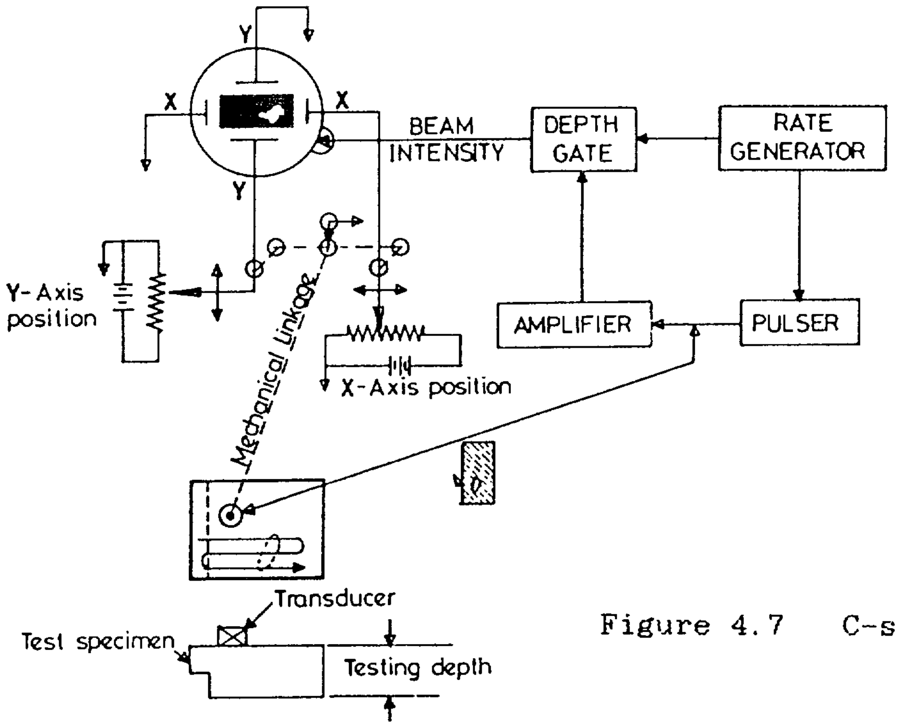


Figure 4.7 C-scan presentation.

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 of the test specimen, and the length of time the gate is open is proportional to the thickness 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.

4.2.4 Echo amplitude and its control

Most pulse echo flaw detectors have an attenuator control fitted sometimes called a calibrated gain control. By turning this control one way the echo height increases and by turning the other way the height decreases. The control is calibrated in decibel (dB) steps, usually 2dB although some flaw detectors have steps of 0.5 dB or 1dB. Because the echo height on the cathode ray tube is directly proportional to the setting on the attenuator control it is possible to compare the echo heights from two reflectors in the specimen.

4.2.4.1 Decibel (dB) Unit

The decibel unit is 1/10 of a bel which is a unit based on logariths 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 transaucer and produce elctrical signals whose power will be P_o and P_1 respectively .The ratio of these signals $\frac{I_o}{I_1}$ will will equal the electrical power ratio.

$$\text{i.e.} \quad \frac{I_o}{I_1} = \frac{P_o}{P_1}$$

Since $P \propto V^2$

$$\frac{I_o}{I_1} = \frac{P_o}{P_1} = \frac{V_o^2}{V_1}$$

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

$$\log_{10} \frac{I_o}{I_1} = \log_{10} \frac{V_o^2}{V_1} = 2 \log_{10} \frac{V_o}{V_1} \text{ Bels}$$

Since a decibel is $\frac{1}{10}$ Bel

$$2 \log_{10} \frac{V_o}{V_1} \text{ Bels} = 20 \log_{10} \frac{V_o}{V_1} \text{ decibels}$$

Since the height of the deflection on the CRT is directly proportional to the voltage applied to the Y plates which also depends on the voltage developed by the transducer:

$$20 \log \frac{V_o}{V_1} = 20 \log \frac{H_o}{H_1} \text{ decibels}$$

The advantages of the decibel unit are that :-

(a) Large echo height ratios can be given in small figures eg.

1000 : 1	=	60 dB
1000000 : 1	=	120 dB

(b) A reversal of the echo height ratio only requires a change of sign e.g.

10000 : 1	=	80 dB
1 : 10000	=	-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 echo height ratios.

Table 4.1 dB values of some echo height ratios.

dB value	Echo Height Ratio	dB value	Echo Height Ratio
1	1.12	13	4.47
2	1.26	14	5
3	1.41	15	5.62
4	1.59	16	6.31
5	1.78	17	7.8
6	2	18	7.94
7	2.24	19	8.91
8	2.51	20	10
9	2.82	21	11.2
10	3.16	22	12.59
11	3.55	23	14.85
12	3.98	24	15.85
		25	17.78

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. 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 determined as follow :

Reducing 625 to factors included in Table 4.1.

625 = 1.25 x 5 x 10 x 10

Since the dB values correspond to 1.25,5 and 10 are 2dB, 14 dB and 20 dB respectively , the dB value corresponding to echo height ratio of

625 = 2 + 14 + 20 + 20 = 56 dB.

5. CALIBRATION OF THE TEST SYSTEM

5.1 Calibration And Reference Test Blocks

In ultrasonic pulse echo testing test blocks containing notches, slots or drilled holes are used to :

(i) determine the operating chacteristics 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.

5.2 Commonly Used Test Blocks

Some of the commonly used test blocks along with their uses are as follows :

5.2.1 I.I.W (VI) Calibration Block

The most versatile calibration block is the block 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.

This block is generally used for :

(i) the calibration of the time base.

(ii) the determination of probe index.

(iii) the determination of probe angle.

(vi) the checking of performance characteristics (time base linearity, resolution, dead zone etc) of the ultrasonic flaw detector.

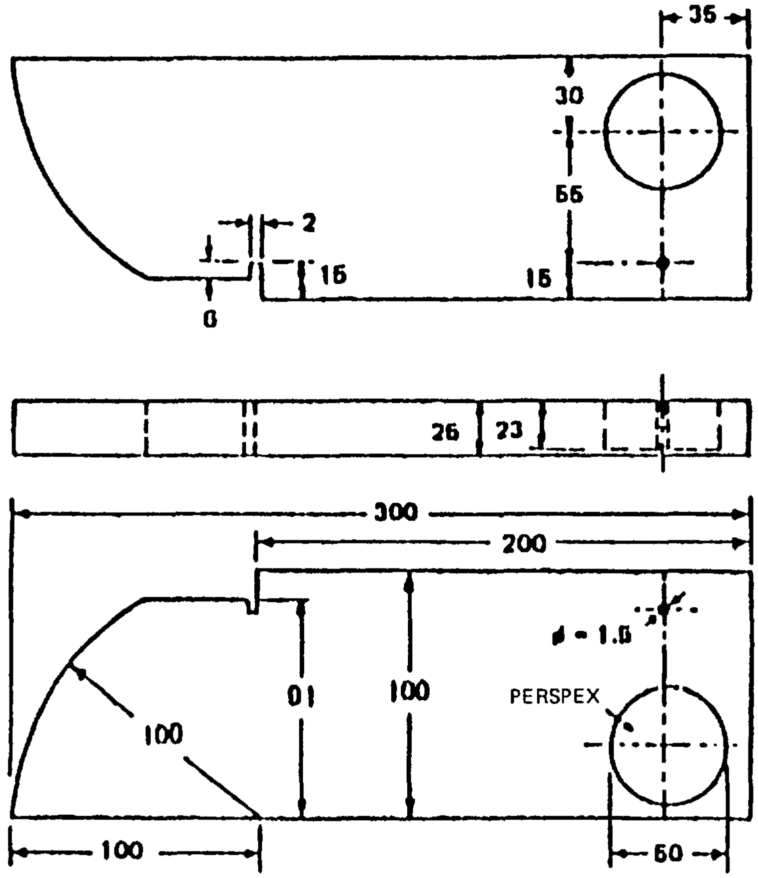


Figure 5.1

(i) <u>Calibration Of Time Base</u>

(a) **With normal beam probes**

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 5.2) and multiple back wall echoes are obtained and adjusted to the appropriate scale division of the CRT screen using the delay and fine material testing range controls. Figure 5.3 show the CRT screen display for an 100 mm calibrated CRT screen. The points where the rising back wall echoes leave the base line have beam adjusted to the appropriate scale divisions to give the time base calibrations.

For time base calibration of more than 250 mm with normal beam probe, the probe is placed at position A or B (Figure 5.2) and multiple back wall echoes are obtained and adjusted to the appropriate scale divisions. Figure 5.4 shows the CRT screen display for a one meter range.

Multiple back wall echoes are used for time base calibration because the distance between the transmission pulse and the first back wall echo is some what larger than the distance between two consecutive multiple echoes. This zero error is

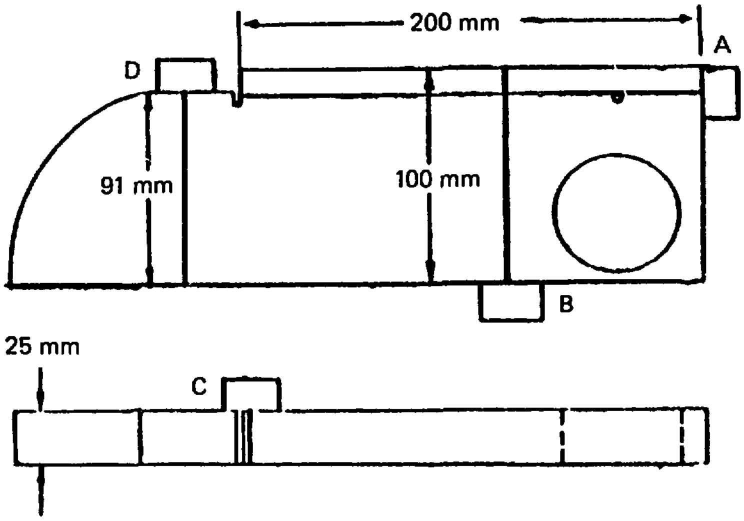


Figure 5.2

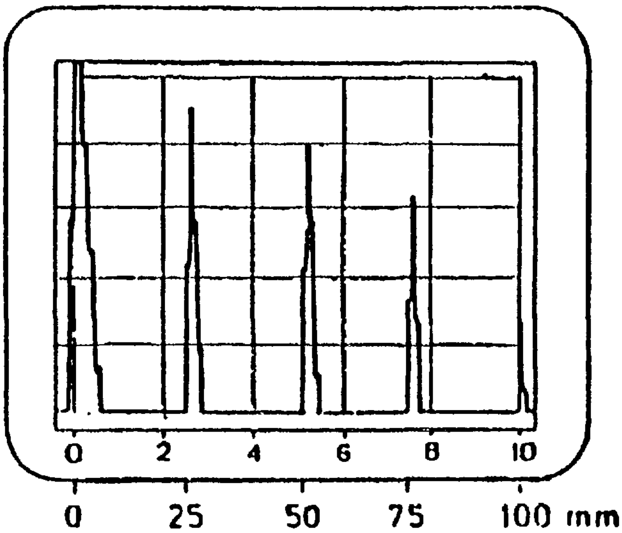


Figure 5.3

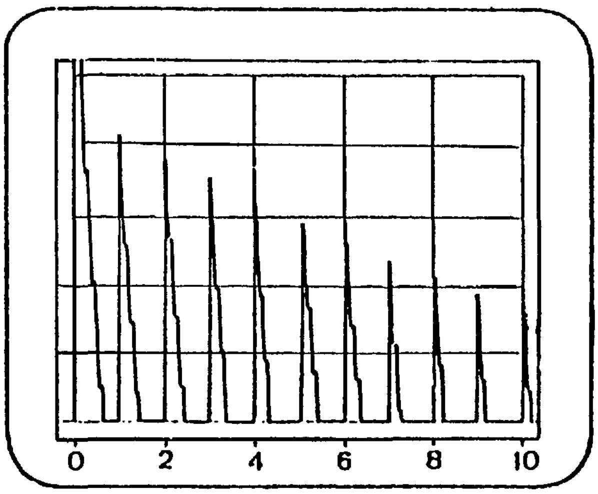


Figure 5.4

caused by the ultrasound travelling in the transducer, probe protective layer (if any) and the layer of the couplant before entering the specimen.

(b) **With angle beam probes**

For a range of 200 mm or more the most direct method is to get multiple back wall echoes from the 100 mm quadrant by placing the probe at position E (Figure 5.5 a). A CRT screen display for a range of 200 mm is shown in Figure 5.5b.

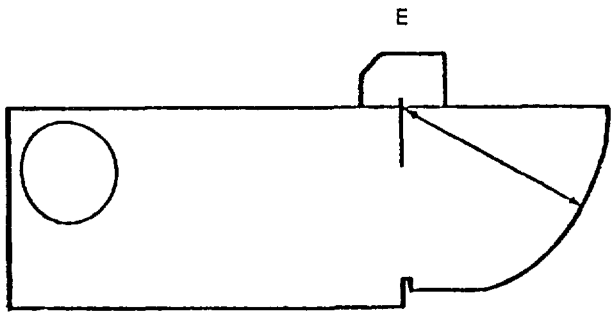


Figure 5.5 a.

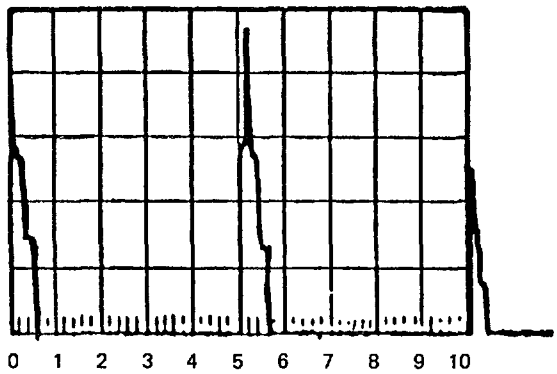


Figure 5.5.b.

Another method of calibrating the time base for angle beam probes is to position a normal wave probe at "D" in Figure 5.6(a) at which the distance of 91 mm for a longitudinal wave corresponds to 50 mm for shear waves. Figure 5.6(b) 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.

After calibrating with the normal probe replace the normal probe with an angle beam probe, position the probe at "E" so that a maximum response is obtained from the 100 mm radius and adjust the transmission point so that the echo from the 100 mm radius face coincides with the 100 mm reflection previously obtained with the normal probe thereby correcting for the delay which occurs in the probe shoe.

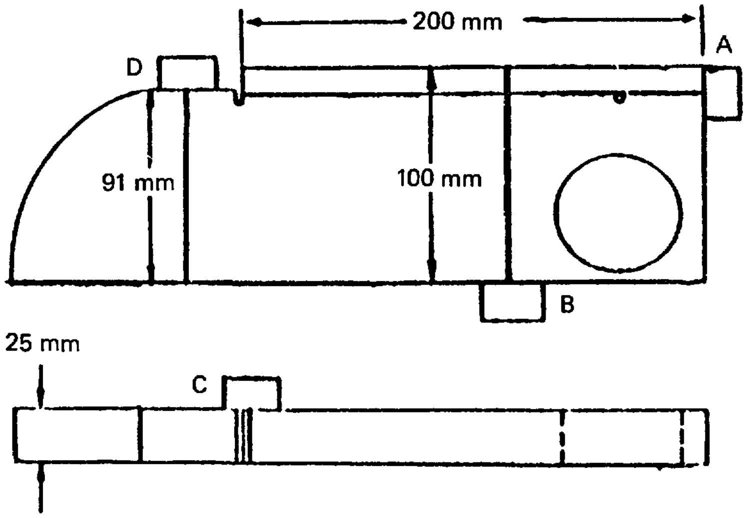


Figure 5.6(a)

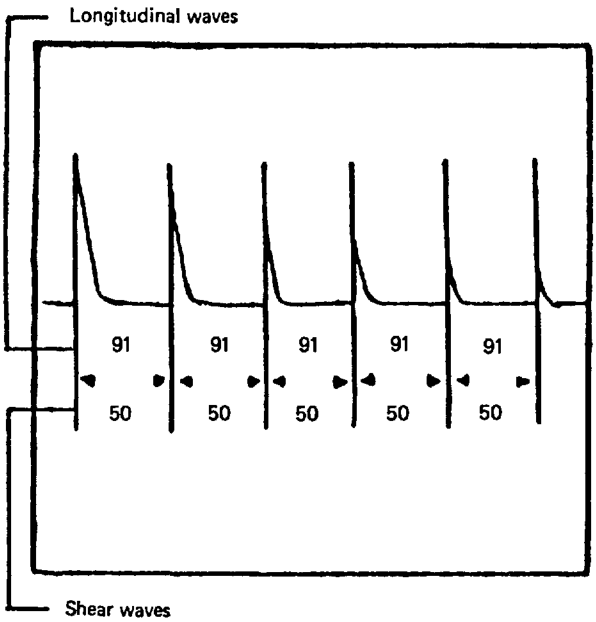


Figure 5.6 (b) Linear Scale Of 250 mm.

To calibrate the time base for a 100 mm range with an angle beam probe, the procedure used is explained in Figure 5.7 a, b & c.

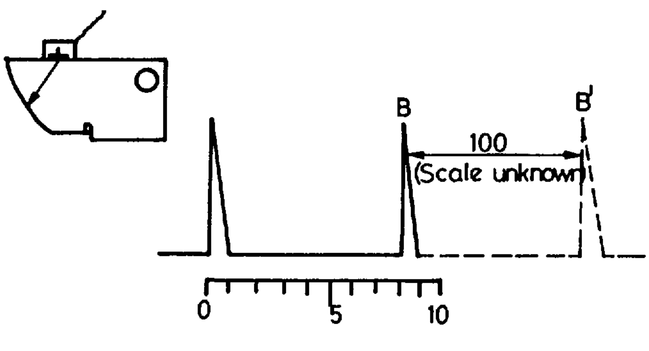


Figure 5.7 (a) B is set provisionally at or near 10 using the sweep length control

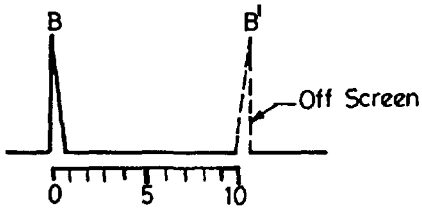


Figure 5.7 (b) Set B at 0 and B' at 10 using the delay and sweep length controls respectively.

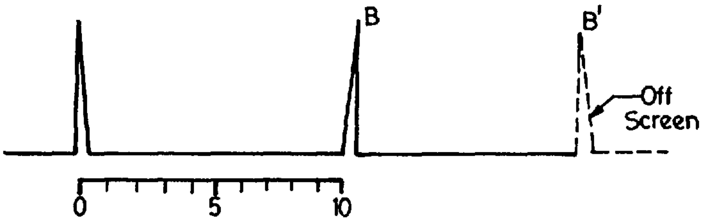


Figure 5.7 (c) Set B to 10 using the delay control. The zero is automatically correct.

(ii) **Determination of the probe index**

The probe is placed at position L on the calibration block (Figure 5.8) and a back wall echo from the 100 mm quadrant is obtained. The maximum amplitude of this back wall 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 corresponds to the point 0 on the block is the probe index.

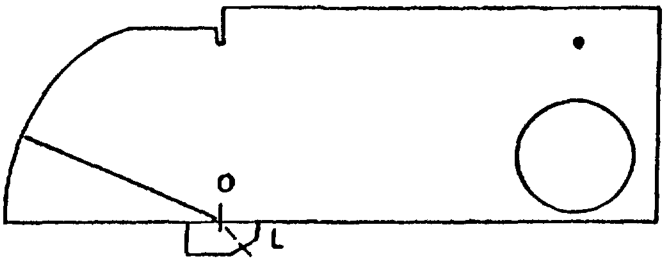


Figure 5.8

(iii) Determination and Checking the Probe Angle

To determine the probe angle, the probe is moved to and fro according its angle either at position 'a' (35° to 60°), 'b' (60° to 75°) or 'c' (75° to 80°) as shown in Figure 5.9 until the amplitude of the echo from the perspex insert or 1.5 mm diameter hole is miximum. 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.

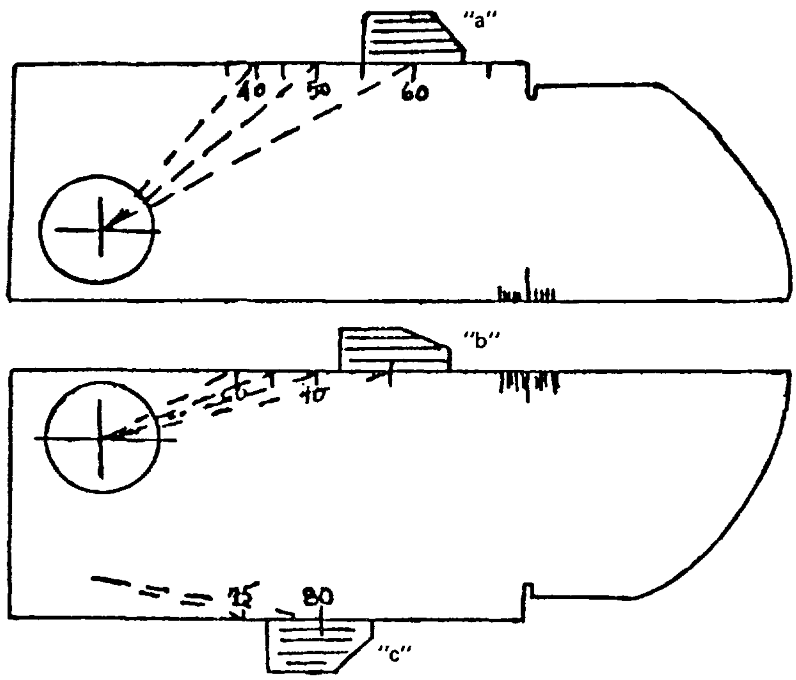


Figure 5.9 Determination of probe angle.

(iv) **Determining the pulse length**

Normal probe. On flaw detectors with a rectified display position the probe at position L (Figure 5.8) and calibrate the test range using the 6 mm step (equivalent to a 1 s 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 % 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.

Angle probe Position the angle probe at position L and obtain a back echo from the 100 mm radius after calibrating the time base to a short range (10 - 25 full screen). The delay is adjusted to bring the 100 mm back

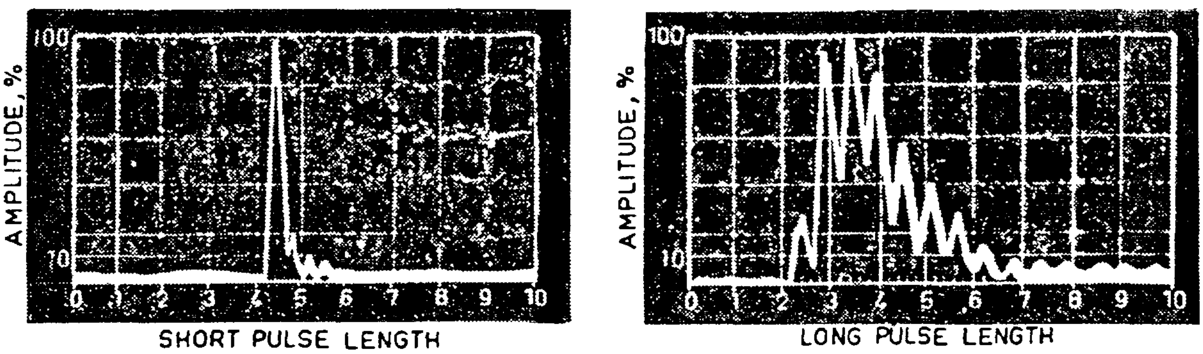


Figure 5.10 Typical pulse length display.

echo into the calibrated range. Set the back wall 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).

5.2.2 DIN 54122 (V2) Block

The latest version of this block is shown in Figure 5.11. It is particularly suitable for the time base calibration of small diameter normal and angle probes.

It can also be used to check the probe index and angle. The uses of the block are as follows :

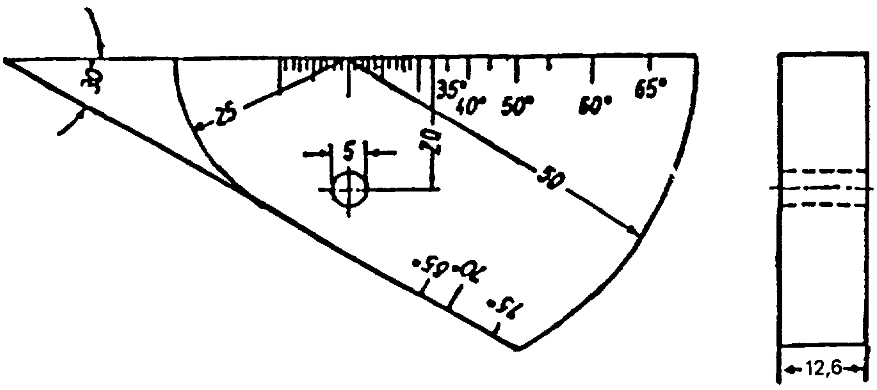


Figure 5.11 Test block V2 according to DIN 54122

(i) Time base calibration for range up to 100 mm using normal beam probe.

The probe is placed on the block as shown in Figure 5.12 a and multiple back wall echoes are obtained. These echoes are adjusted using the test range and delay controls. Figure 5.12 b shows the screen display for a 100 mm range calibration.

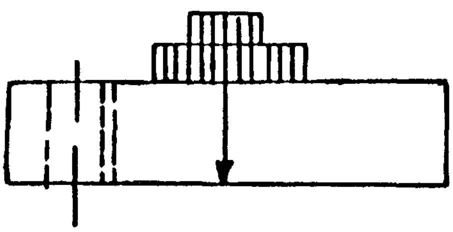


Figure 5.12 a .

Figure 5.12 b .

(ii) Time base calibration for ranges up to 250 mm with angle beam probe.

The time base calibration for an angle beam probe for ranges 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 quadrant (Figure 5.13 a). By this method the screen can be calibrated for 100 mm, 175 mm, 200 mm and 250 mm ranges. The echo pattern for a 200 mm range is as shown in Figure 5.13 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.

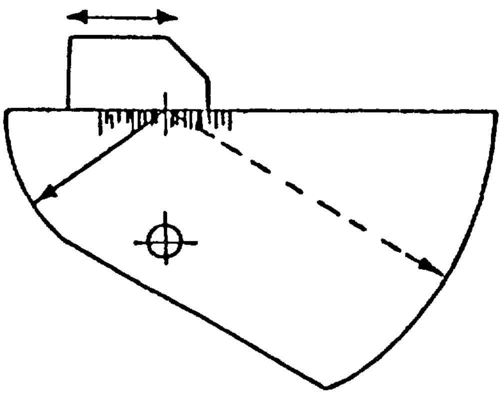


Figure 5.13 a.

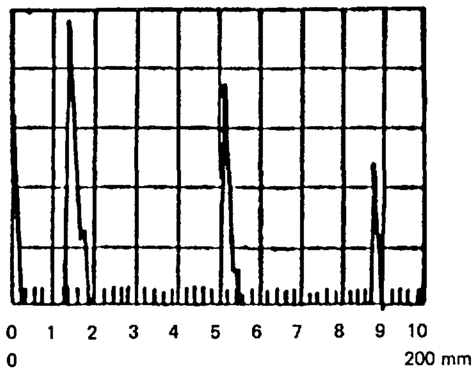


Figure 5.13 b.

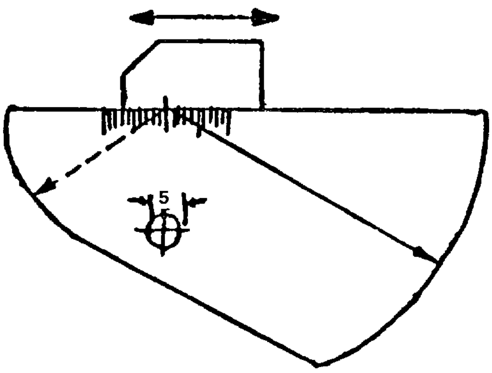


Figure 5.14 a .

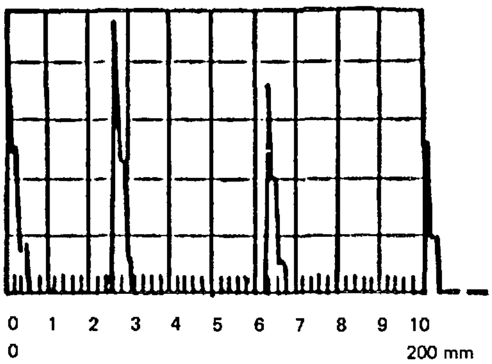


Figure 5.14 b.

In the second method the probe faces the 50 mm quadrant (Figure 5.14 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 5.14 b. The echoes appear at 50 mm, 125 mm and 200 mm.

Calibration of time base up to 200 mm using V2 block and angle probe facing the 50 mm quadrant.

(iii) Time base calibration for 50 mm

In this method the echo from the 50 mm quadrant is set at 10 using the sweep control or range control . The probe is then reversed so that the echo from the 25 mm quadrant is obtained .This echo is set at 25 using the delay control. The procedure is repeated until calibration is completed.

(iv) Determination of probe index

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 millimeter scale on the block on to the probe.

(v) Determination of the probe angle

To determine the actual probe angle use is made of the 5 mm diameter hole in the block. 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 5.15). 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.

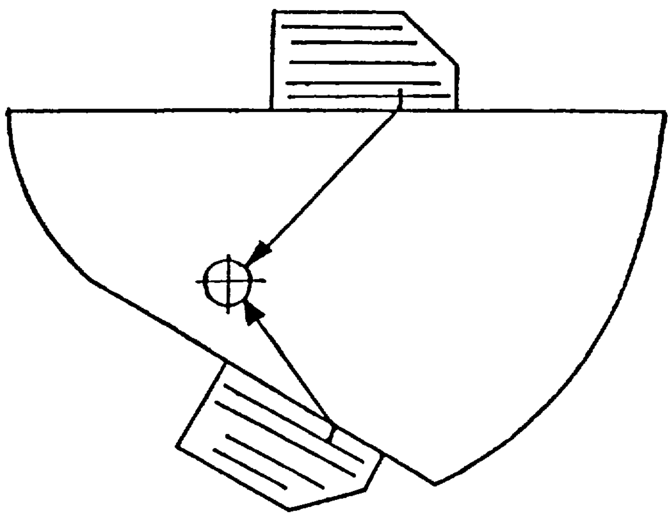


Figure 5.15 Checking probe angle using V2 block.

5.2.3 Institute of Welding (I.O.W.) Beam Profile Block

This block (Figure 5.16) is designed primarily for beam profile measurement and offers eight different direct scan approaches to the target holes for 45°, 60° and 70° probes, as shown in Figure 5.17. There are eight more approaches by indirect (one bounce) scan for 45° probes and six for 60° probes but none for 70° probes. The total number of useable probe positions in any case is determined by the size of the probe and the probe angle.

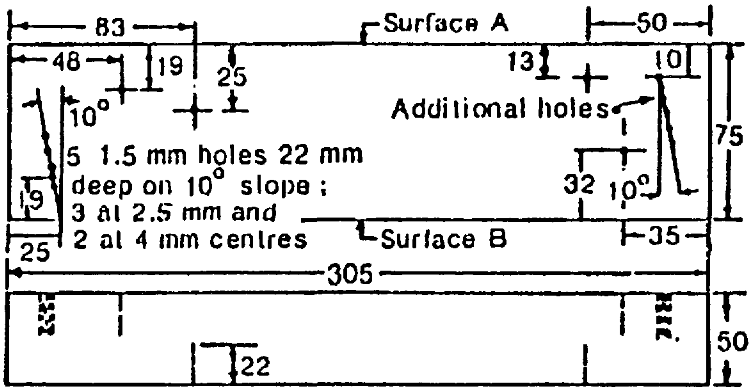


Figure 5.16.

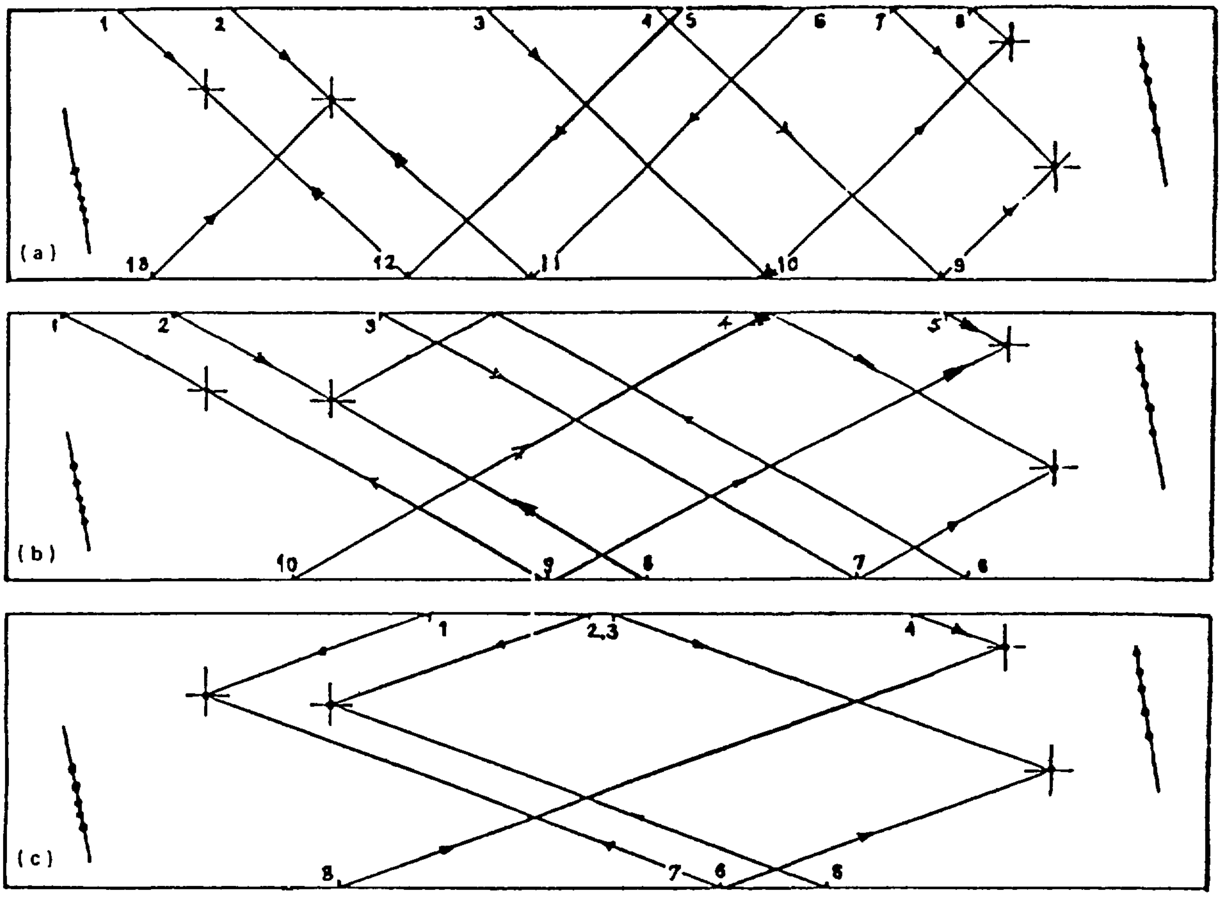


Figure 5.17

Sites for probes : (a) 45°, (b) 60° and (c) 70°

5.2.3.1 **Plotting of Beam Profile**

(a) **Vertical Plane**

The 1.5 mm target holes are sighted in succession from surfaces A and B of the 10 W block. For each case, the position of the probe index corresponding to the maximum echo amplitude is marked on the block. The probe is then moved to and fro so that the target is swept by the beam, the extremes of displacement being reached when the position of the probe index corresponds to a decrease of 20 dB, or 10 % of the original height of the echo, from the maximum echo amplitude. These positions are marked as b and c in Figure 5.18 with mark a representing the position of the probe for maximum amplitude.

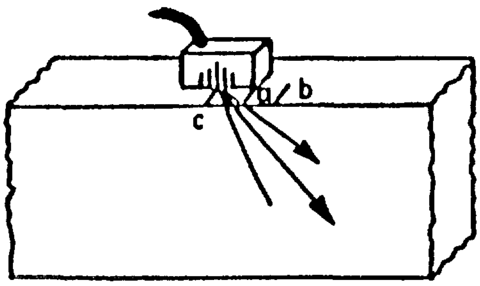


Figure 5.18 a.

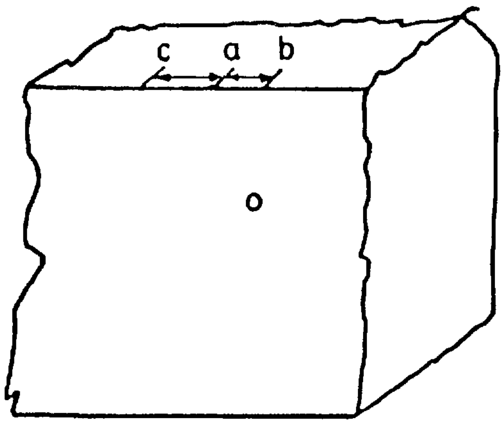


Figure 5.18 b.

With the probe in its forward position at position b the bottom edge of the beam strikes the target hole while in the backward position C the top edge of the beam strikes the target hole. The beam profile is then plotted as follows : Draw the probe angle with the probe index as its starting point. At the appropriate hole depth plot the reading ab (forward position) behind the beam axis while the reading ac (backward position) is plotted in front of the beam axis. Repeat the procedure for holes at other depths and join the points.

(b) **Horizontal Plane**

The probe is placed on surface A or B and the maximum amplitude is obtained from the selected target (Figure 5.19a). The range is noted and a reference line is drawn across the block marking the position of the rear edge of the probe. The probe is then moved away from the edge of the block and at right angles to it until the echo drops by 20 dB. The half beam spread at this particular range (X -22 in Figure 5.19 a) is found by subtracting the 22 mm drilled depth of the hole from the distance between the edge of the block and the beam axis (X in Figure 5.19 b). The

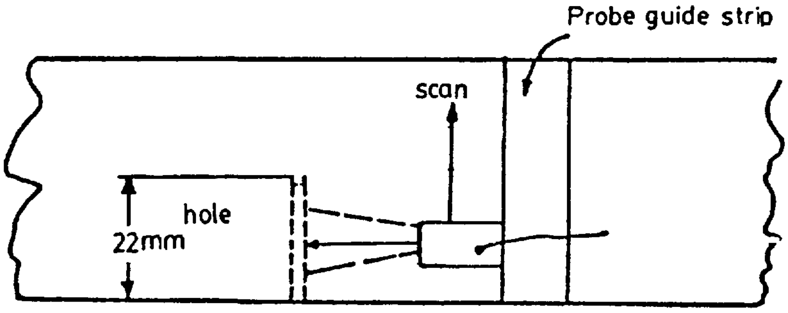


Figure 5.19 a.

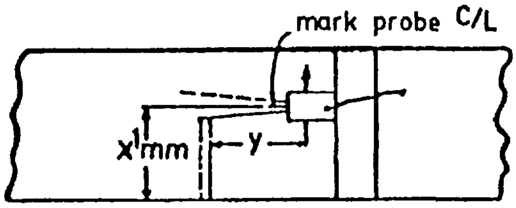


Figure 5.19 b .

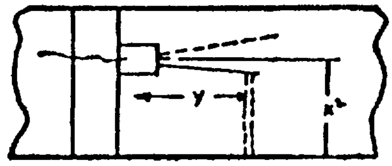


Figure 5.19 c .

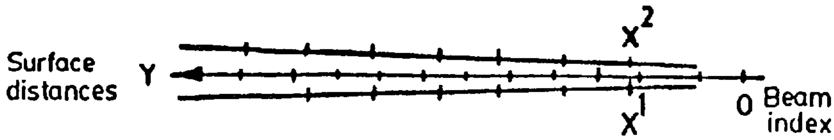


Figure 5.20 .

probe is then placed on the opposite side of the hole and the sequence is repeated to determine the other half beam spread which is equal to (X - 22) mm in Figure 5.19 c . The procedure is repeated for other holes and the beam spread against the range is plotted as shown in Figure 5.20 .

5.2.4 **ASME Reference Block**

This block is made from the same material as that of the specimen and contains a side drilled hole whose diameter depends on the thickness of the specimen. A typical ASME reference block used for the inspection of welds is shown in Figure 5.21.

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).

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 2" diameter round stock, each 3 3/4 " 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 " deep flat bottom hole drilled in the center of the bottom surface (Figure 5.22 a). The hole diameters vary from 1/64" to 8/64". The blocks are numbered to correspond with the diameter of the holes, that is block No. 1 has a 1/64" diameter hole, and so on up to No. 8, which has an 8/64" diameter hole. Similar area-amplitude blocks made from $1\frac{15}{16}$ " square stock are sometimes known as Alcoa series-A blocks.

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 high and this is also the height of the indication from a 5/64" 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.

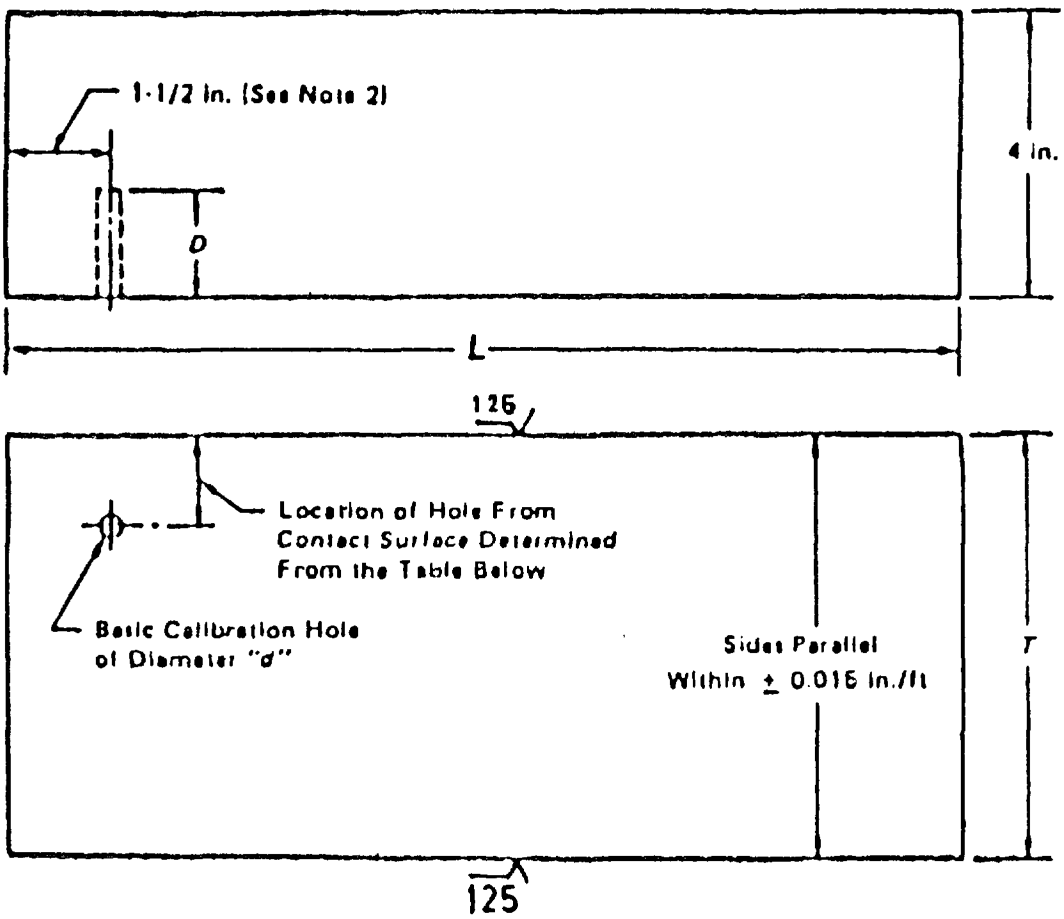


Figure 5.21 .

5.2.6 **Distance-amplitude Blocks**

Distance-amplitude blocks provide artificial flaws of a given size at various depths. 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 a 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.

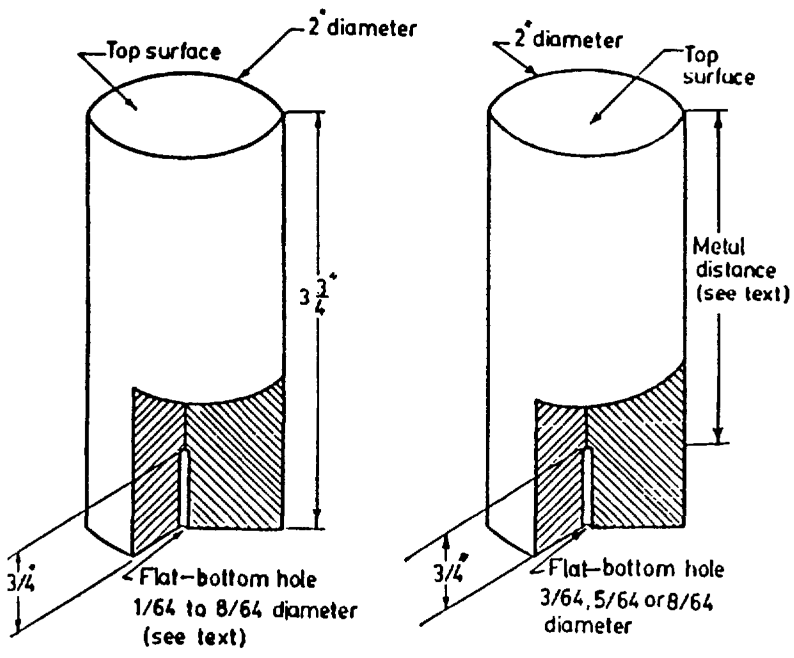
There are 19 blocks in an Alcoa series-B set. All are 2" diameter blocks of the same material as that being inspected, and all have a 3/4 " deep flat bottom hole drilled in the centre of the bottom surface (Figure 5.22). The hole diameter is the same in all the blocks of a set. Sets can be made with hole diameters of 3/64" , 5/64" and 8/64" . The blocks vary in length to provide metal distances of 1/16" , 1/8" through 1" in 1/8" increments and 1 1/4 " through 5 3/4" in 1/2" increments.

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 hundreds of an inch. For instance, a Block marked 3-0075 has a 3/64 " diameter hole and a 3/4" metal distance.

5.2.7 Blocks

ASTM blocks can be combined in to various sets of area amplitude and distance-amplitude blocks. The ASTM basic set consists of ten 2" diameter blocks, each with a 3/4" deep flat bottom hole drilled in the center of the bottom surface. One block has a 3/64" diameter hole at a 3" metal distance.

Seven blocks have 5/64" diameter holes at metal distances of 1/8" , 1/4" , 1/2" , 3/4" , 1 1/2" , 3" and 6". The remaining blocks have 8/64" diameter holes at 3" and 6" metal distances. The three blocks with a 3" metal distance and hole diameter of 3/64" , 5/64" and 8/64" form an area-amplitude set, and the set with the 5/64"



(a) (b)

Figure 5.22

Standard reference blocks for use in normal beam ultrasonic inspection :

(a) area-amplitude block, and
(b) distance-amplitude block.

diameter holes provides a distance-amplitude set. 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.

5.3 Checking Equipment Characteristics

(i) Linearity of time base

The I.I.W. , DIN 54122 or any block of similar material and finish may be used to measure time base linearity . The choice of thickness is determined by the requirements that a longitudinal wave probe placed on the block produces several back wall echoes (usually four or five) within the chosen range. For checking the linearity two of the back wall 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 and plotted in the way shown in Figure 5.23 . 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.

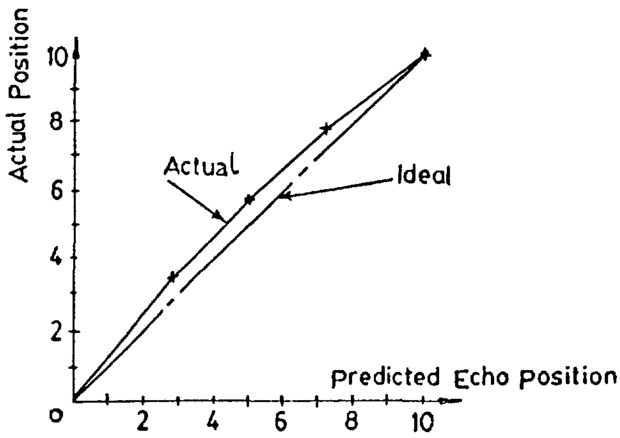


Figure 5.23 .

(ii) **Linearity Of Amplifier**

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 follow : the time base of the flaw detector is calibrated for a range of 250 mm and ten back wall echoes from 25 mm thick side of the block are obtained. 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 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 reduced to half 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 :

$$\text{Deviation} = \frac{(\text{Original amplitude of echo}) - (\text{twice the reduced amplitude})}{(\text{Original amplitude of the echo})} \times 100 \qquad (5.1)$$

The deviation from linearity as a function of amplitude can also be plotted graphically as shown in Figure 5.24 . Such a curve is only valid for particular settings of frequency, pulse energy, timebase range, and for the gain setting involved in the check.

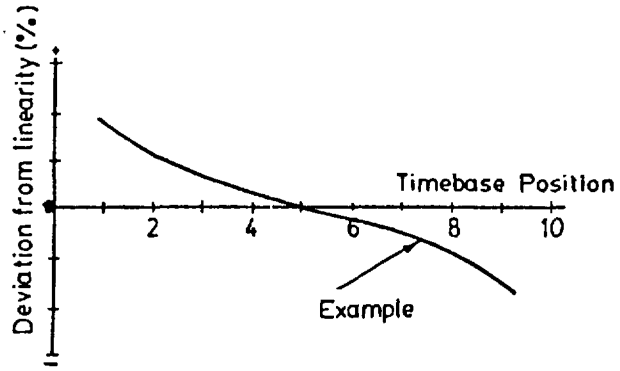


Figure 5.24

An alternative simpler method for the checking of amplifier linearity is to calibrate the time base for the 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 time 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 amplifier is linear.

(iii) Resolution of the Flaw Detector

The I.I.W. V1 block is used to determine the resolution of a flaw detector using a normal beam probe. This block has three target reflectors at ranges of 85 mm, 91 mm and 100 mm. The probe is placed on the block as shown in Figure 5.25 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. Figure 5.25 b shows the degree of resolution for flaw detectors using two different normal beam probes.

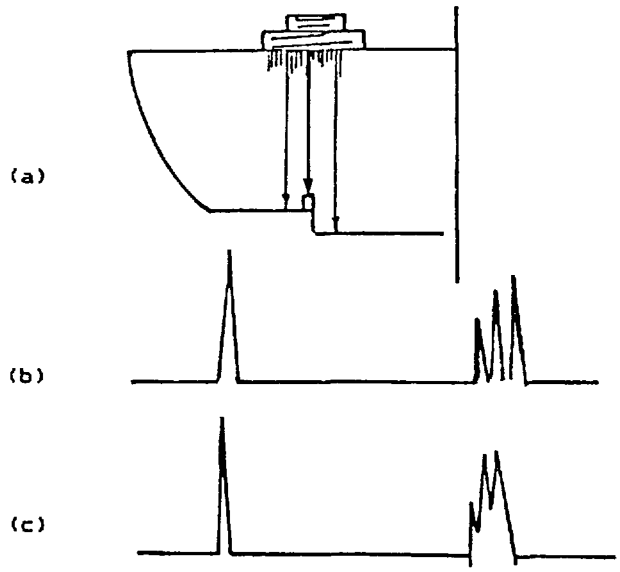


Figure 5.25 Estimating the resolving power of normal probes

Another block (described in B.S. 3923 : Part 3 : 1972)used for the determination of resolution of flaw detectors using either normal beam or angle beam probes is shown in Figure 5.26 . 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.

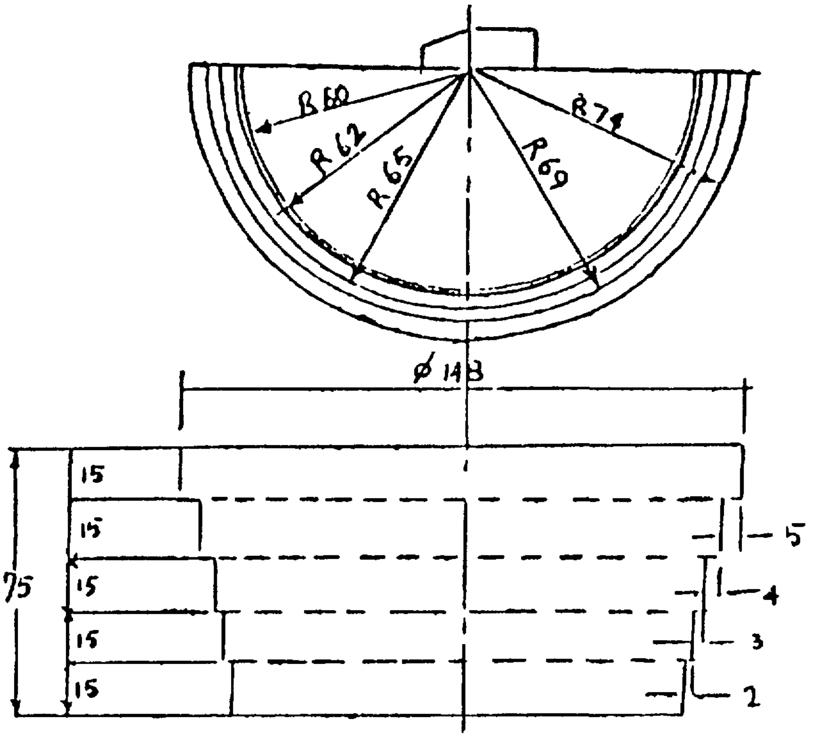


Figure 5.26 Test block for measuring probe resolution.

(iv) **Assessment of Dead Zone**

One method of determining the dead zone is to use a special block of the kind shown in Figure 5.27. The depth of the dead zone is taken as that at which the echo from the hole can be clearly distinguished from the transmission pulse of the probe at the working sensitivity.

For normal probes another method is to determine the pulse length, calibrate the time base for a known thickness of the material under test (eg. 50 mm steel), adjust the gain control to the proposed working sensitivity and place the probe on a sheet of material of thickness between 0.5 and 1 pulse length to produce a series of multiple echoes. If the dead zone is longer than the displayed transmission pulse a display similar to that shown in Figure 5.28 will result and the dead zone length can be measured on the screen.

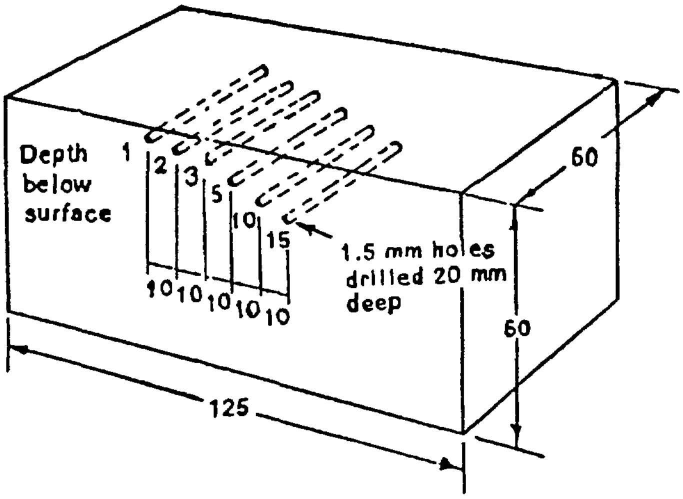
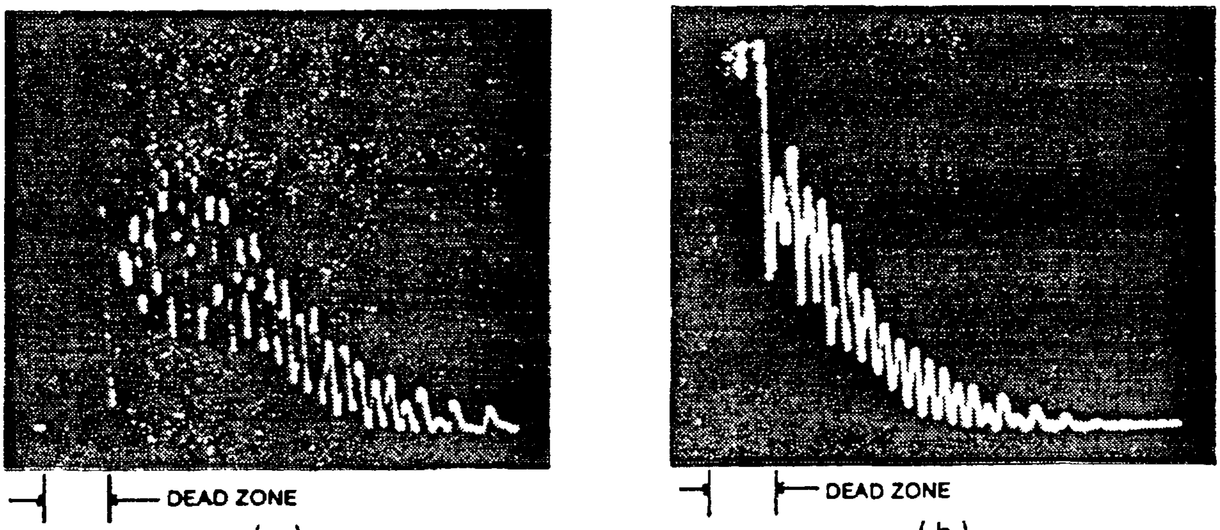
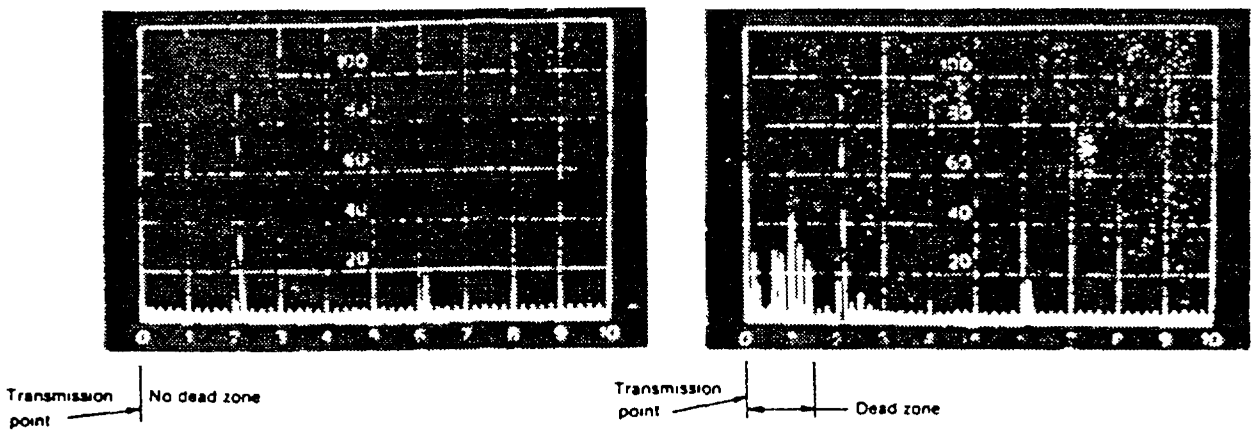


Figure 5.27



MEASUREMENT OF DEAD ZONE LENGTH USING
NORMAL PROBES

Figure 5.28.



DISPLAYS FOR SHEAR WAVE ANGLE PROBE SHOWING
TRANSMISSION POINT AND DEAD ZONE

Figure 5.29 .

For angle probes calibrate the time base for a convenient range and correct the transmission point. Adjust the gain control to the working sensitivity and note the presence of any noise on the display arising from the probe crystal backing and/or probe shoe. Measure the dead zone, if any. The dead zone is that portion of the display past the transmission point where noise interfers with interpretation. Figure 5.29 .

(V) Maximum Penetrative Power

This is the term used in British Standard BS 4331 to describe a check which is used to compare the energy out-put for a particular set and probe with its past performance or with similar equipments. The check is carried out as follows : A longitudinal wave probe is placed on the plastic insert of the I.I.W. block (Figure 5.30) and the gain of 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.

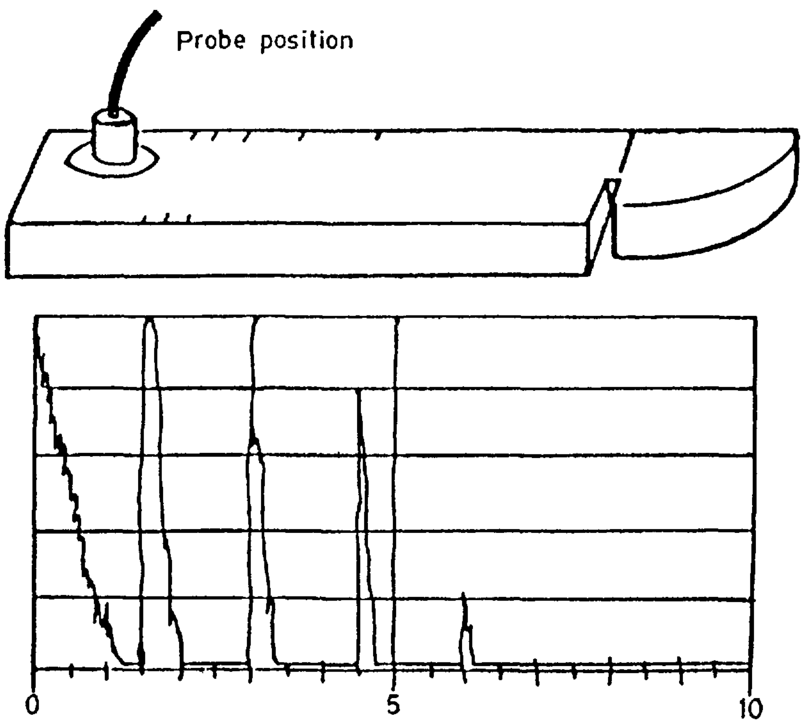


Figure 5.30 .

5.4 METHODS OF SETTING SENSITIVITY

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 principal 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.

Evaluation sensitivity (or reference sensitivity)

These are the instrument settings which produce a reproducible signal amplitude from a reference artificial reflector with which the instrument settings relating to a discontinuity echo can be compared.

The evaluation sensitivity can also be called the Primary Reference Echo (PRE) level .

Scanning Sensitivity

This 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. It is set by increasing the amplification of the instrument from the evaluation sensitivity instrument settings by a specified amount eg. 6dB.

The commonly used methods of setting evaluation sensitivity are :

i. The Distance Amplitude Correction (DAC) method which is used for instance in the ASME code in which echo heights from similar size artificial reflectors in a reference block are plotted on the CRT screen to compensate for attenuation of the signals with increasing distance from the probe.

ii. The echo height from a flaw is compared to a disc type reflector in the form of a flat bottomed hole. This method was developed by Krautkramer and is called the DGS method (D - distance, G - gain, S - size)

iii. The grain response on the time base at the maximum testing range.

iv. The echo height from a 1.5 mm drilled hole in a reference block (such as the I.O.W beam profile block).

5.4.1 Distance Amplitude Correction Curves

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 bottomed holes in a 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 or as the ASME standard specifies it not less than 3/8 V - path (i.e. 3/8 skip distance) or 2 in. which ever is less, 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 shown as position 1 in Figure 5.31 and the screen presentation is shown as Figure 5.32 . The probe is then moved to other locations (positions 2, 3 and 4 in Figure 5.31) and the signal amplitude marked on the CRT (Figure 5.32) for each position. A curve is drawn joining these points. This is the Distance Amplitude Correction 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 and is added to the DAC gain. For initial scanning the sensitivity is then set at twice (i.e + 6dB) the 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.

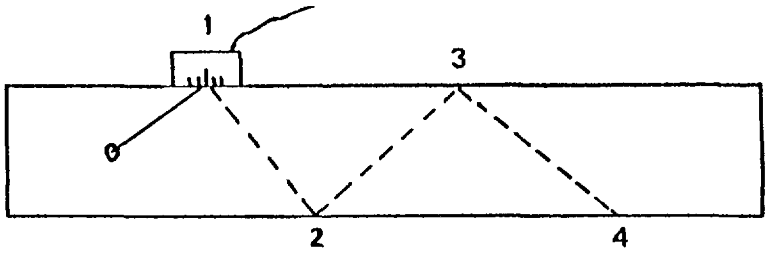


Figure 5.31

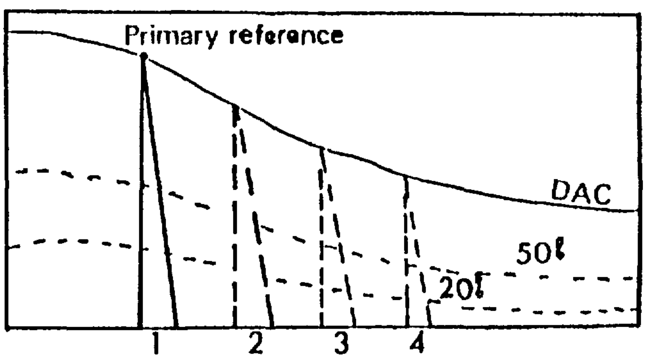


Figure 5.32

The transfer loss is determined 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.

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. 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 5.33 a). The heights of the PRE and the maximized echo at 3/4 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. (Figure 5.33 b).

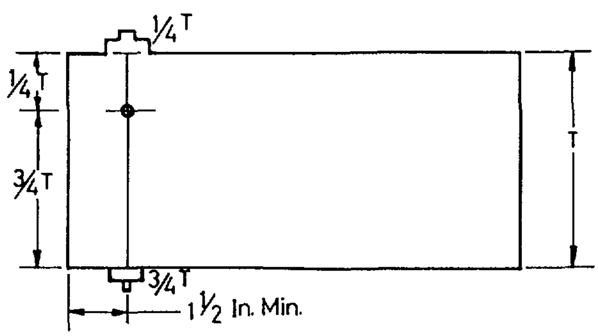


Figure 5.33 a .

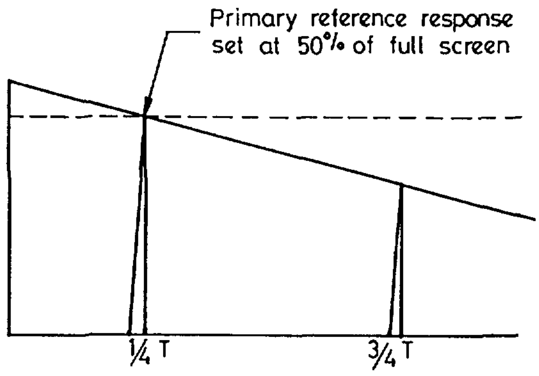


Figure 5.33 b .

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.

5.4.2 DGS (Distance-Gain-Size) Diagram Method

This method makes use of the so called DGS diagram, developed by Krautkramer in 1958 by comparing the echoes from small reflectors, namely different diameter flat bottomed 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 bottomed holes and the back wall reflector is determined in decibels i.e. dB. The universal DGS diagram for normal beam probes, which can be used for any normal beam probe irrespective of the size and frequency of the probe, is shown in Figure 5.34 .

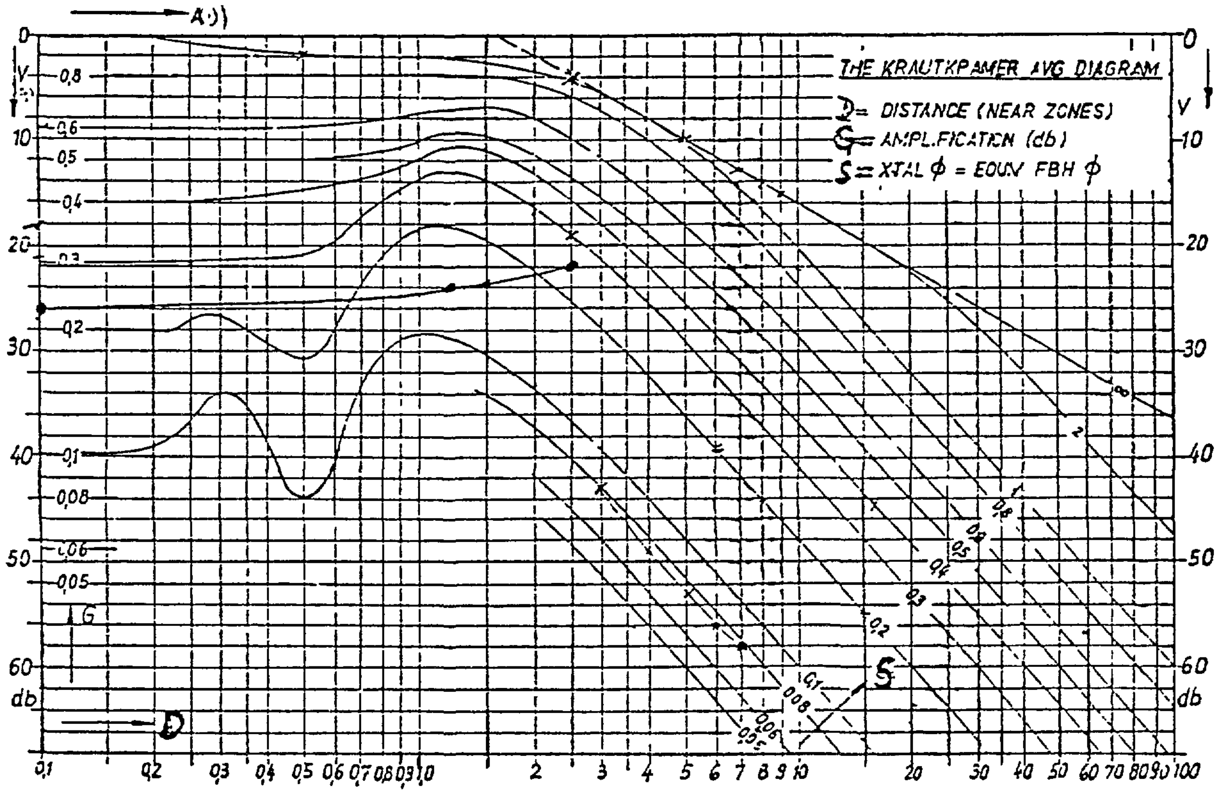


Figure 5.34 Universal DGS diagram.

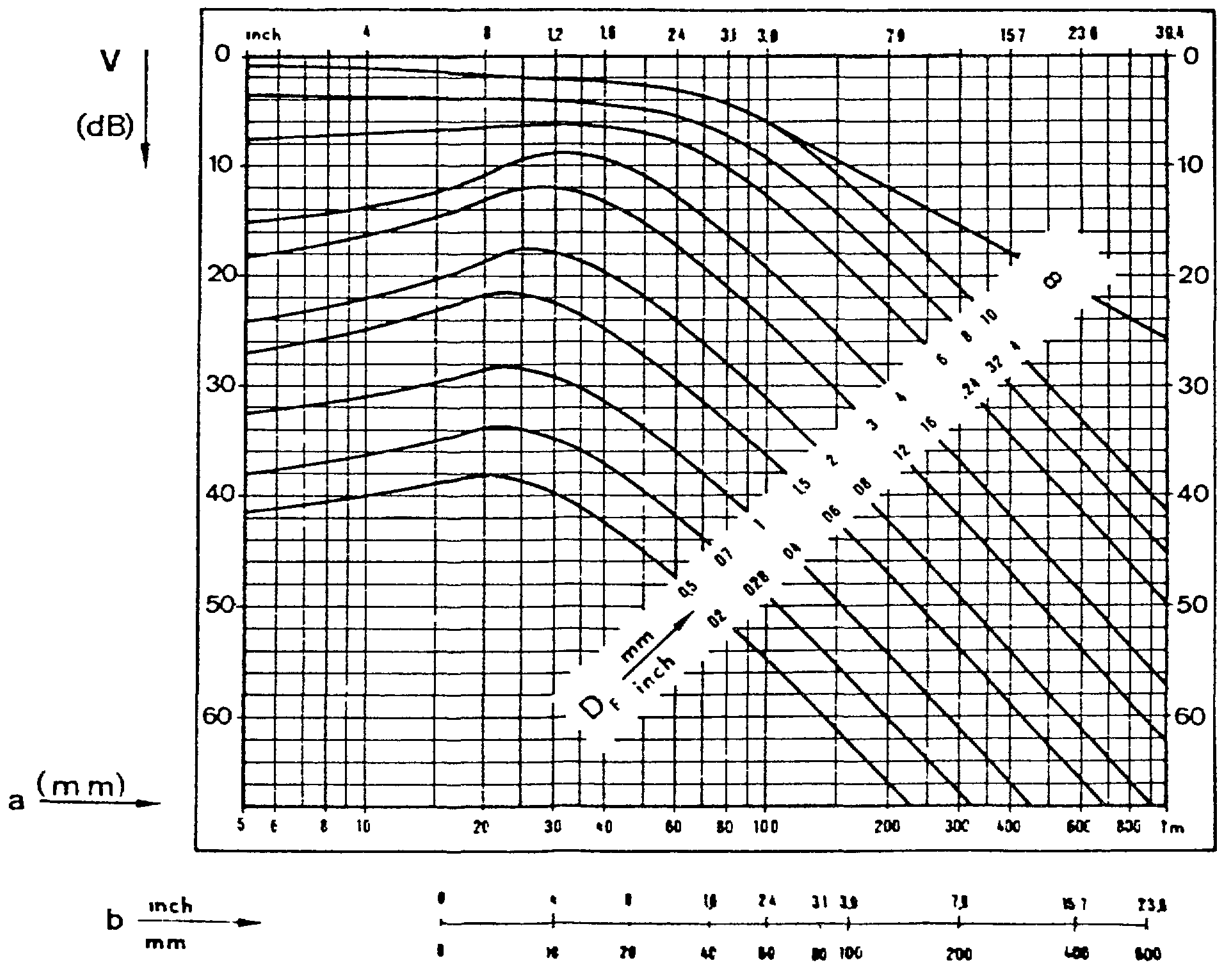


Figure 5.35. DGS diagram for an angle beam probe

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 bottomed 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.

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 5.35 shows a typical DGS diagram for a particular angle beam probe.

5.4.2.1 Setting Sensitivity For A Normal Beam Probe

The method of setting sensitivity using the DGS diagram gives the sensitivity in terms of the smallest detectable disc shape reflector which has to be detected at the maximum testing range. The procedure is as follow :

i. Determine the near field length N of the probe.

ii. Determine the maximum testing range in terms of near field length units.

iii. Specify the diameter of the smallest disc shaped reflector to be detected at the maximum testing range.

iv. Divide the diameter of disc shaped reflector specified in (iii) by the probe crystal diameter. This will determine the S line in the DGS diagram to be used.

v. Determine the point of intersection between the S line determined in (iv) and a line drawn perpendicular to the D-scale at the maximum testing range.

vi. Determine the dB value from the G scale at the point of intersection determined in (v).

vii. Determine the lowest point on the S-line up to the maximum testing range.

viii. If such a point is different from the point of intersection determined in (v), then determine the dB value corresponding to this point. Draw a line at this dB value parallel to the D-scale and extend it up to the maximum testing range. The line is called, the record level.

ix. Extend the line drawn perpendicular to the D scale at the maximum testing range in (v) to intersect the back wall echo line and note the value of G at the point of intersection.

x. Subtract the value of G obtained in (ix) from that obtained in (vi).

xi. Obtain a back wall echo from the test specimen and set it at an appropriate amplitude, say 2/5 full screen height.

xii. Increase the gain by the difference in dB obtained in (x).

The test sensitivity is now set so that any flaw with an equivalent flat bottomed hole the same as that used to set the sensitivity will give an echo of amplitude at least 2/5 full screen height. Echoes lower than 2/5 FSH are not reportable. However echoes larger than 2/5 FSH may or may not be reportable based on the depth of the flaw and the attenuation of the material.

Attenuation Curve

Since when the sensitivity was set the back wall is used as a reference, the ultrasonic pulse has been attenuated by the plate thickness $(t) \times 2 \times \alpha$ (where α is the attenuation factor in dB/mm.) in travelling out and back through the material. However at the surface of the specimen there is no attenuation so that the test sensitivity is too high by $2t\alpha$ dB and at mid thickness it is too high by $\frac{2t\alpha}{2}$ dB.

An attenuation curve can be drawn on the DGS diagram. If then a flaw echo is obtained at a particular depth which is above 2/5 FSH , the amplitude can be corrected by reducing the signal height by the difference in dB between the appropriate S line and the attenuation curve at the defect depth. If the defect is still above 2/5 FSH it is reportable.

Example

Plate thickness steel	50 mm
Probe frequency	5 MHZ
Probe diameter	10 mm normal
Near field distance	21 mm
Attenuation	0.04 dB/mm
Smallest equivalent disc	3 mm diam.
Recording level	2/5 full screen height (FSH)

i. Near field length $N = \frac{D^2}{4\lambda} = \frac{10^2 \times 5 \times 10^6}{4 \times 5.96 \times 10^6} = 21\text{mm}$

ii. Maximum testing range $= \frac{50}{21} = 2.5$ approx

iii. Smallest equivalent disc = 3 mm

iv. S line $= \frac{3}{10} = 0.3$

v. Point of intersection 0.3 line and 2.5 Near field distance is 19 dB.

vi. Lowest point on 0.3 line up to 2.5 near field distance is 22 dB.

vii. Perpendicular line at 2.5 near field distance intersects back wall line at 4dB.

viii. The difference in dB between the values determined in (vi) and (vii) is 18 dB.

ix. The reporting level on the CRT screen is 2/5 of the full screen height.

x. Place the probe on the specimen to be inspected and adjust the height of the first back wall echo to 2/5 full screen height by using the gain control of the flaw detector.

xi. Add the difference in dB determined in (viii) to the setting of the gain control determined in (x), thus setting the sensitivity of the flaw detector to give the height of the echo from an equivalent 3mm diameter disc flaw at maximum testing range at 2/5 th of full screen height.

The above procedure has not yet taken into account the losses due to attenuation of the beam in the specimen. Since 0.04 dB/mm is the attenuation of the ultrasonic beam in the specimen, then the sensitivity determined by the above procedure is not the same at the top surface and the back wall of the specimen.

The sensitivity at the top surface is high by an amount B = 0.04 x 50 x 2dB = 4 dB as compared to the sensitivity at the back wall of the specimen. Similarly the sensitivity at half way through the specimen is high by an amount C - 0.04 x 25 x 2 dB = 2 dB.

Since the record level is set according to the sensitivity at the back wall of the specimen, a flaw, occuring at a distance shorter than the maximum testing range (i.e. the back wall) and having an echo height greater than the record level (i.e. 2/5 th screen height), need not be reportable because of the greater sensitivity at shorter distances due to less attenuation.

The attenuation curve is drawn as follows :

xii. Calculate 50 mm and 25 mm in near field lengths, 2.5 and 1.25 respectively.

xiii. The three points are marked on the DGS diagram of Figure 5.34.

xiv. The attenuation curve is drawn on the DGS diagram of Figure 5.34 as shown.

xv. If a flaw is detected at 42 mm whose echo exceeds 2/5 FSH (42 = 2 NFD). The difference in dB between the attenuation curve and the S = 0.3 line curve at 2 near field distance = (22.5 - 16.5) = 6dB.

xvi. The echo height is reduced by 6 dB, if it still exceeds the 2/5 full screen height then it is reportable, otherwise not.

5.4.2.2 Setting Of Sensitivity For Angle Beam Probe

With an angle probe, because there is no back wall echo to be used as a standard reference, a separate reference echo has to be used. This reference echo can be obtained from a reference block such as the reference echo from the 100 mm radius quadrant of IIW (VI) block. This use of a reference block calls for the following allowances to be made while setting the sensitivity for an angle probe :

(a) Allowance for the transfer loss which is due to the different surface conditions of the test specimen and reference block.

(b) Allowance for the different attenuation of the ultrasonic beam in the test specimen and the reference block.

(c) Allowance for the difference, if any, between the distance of the reference reflector and the maximum testing range.

The procedure to arrive at the correct sensitivity or gain setting is as follows :

i. Measure the attenuation of the material of the test specimen and the reference block.

ii. Measure the transfer loss between the reference block and the test specimen.

iii. Specify the smallest disc shape reflector to be detected at the maximum testing range.

iv. Read the difference in dB between the reference echo from the reference block and the minimum flaw size at the worst position on the DGS diagram of the probe to be used.

v. Calculate the attenuation difference between the test range up to the reference reflector in the reference block and up to the maximum testing range in the test specimen.

vi. Set the height of the reference echo to 2/5th full screen height by adjusting the gain control of the flaw detector. Note the reading of the gain control. Let it be A dB.

vii. Now the required sensitivity is obtained when the gain determined in (iv) + transfer loss as determined in (ii) + Attenuation difference as determined in (v).

The sensitivity is thus set to give the echo height of the smallest disc shape reflector at maximum testing range at 2/5 th full screen height.

Example :

Probe frequency	=	4 MHz
Crystal dimensions	=	8 x 9 mm rectangular crystal.
Sensitivity required	=	to detect 3 mm diameter disc reflector at maximum testing range -200 mm.
Reference reflector	=	100 mm quadrant of IIW VI block.

i. Attenuation of IIW block and the test specimen is assumed to be 0.04 dB/mm and 0.08 dB/mm respectively.

ii. The transfer loss between the IIW reference block and test specimen is assumed to be equal to 6 dB.

iii. The dB difference read from the DGS diagram of Figure 5.35 between the back wall S-curve/100mm D-scale intersection and the 3mm S-curve/200mm intersection is 28 dB.

iv. The difference in attenuation between the 100 mm range of reference IIW block (0.04 x 100 = 4 dB) and the 200 mm testing range in the test specimen (0.08 x 200 = 16 dB) is 16 - 4 = 12 dB.

v. Set the height of the reference echo to 2/5th screen height and note the reading of the gain control of the flaw detector. Let it be AdB.

vi. Now the required sensitivity or gain is set by adjusting the gain control of the flaw detector to A + 28 + 6 (transfer loss) + 12 (Attenuation difference) = A + 46 dB. At this sensitivity a 3 mm diameter disc reflector will give at least an echo height of 2/5 th full screen.

To determine whether a particular flaw, occuring within the testing range and having an echo height which exceeds the 2/5 th screen height at the sensitivity determind in (vi) above , is reportable or not, the attenuation curve has to be drawn on the DGS diagram. The attenuation curve is drawn using the same procedure as outlined in section 5.3.2.1. In this example the sensitivity is high by 16 dB at the top surface and decreasing to zero at 200 mm at the rate of 0.08 dB/mm.

5.4.3 Grain Response On Time Base At Maximum Testing Range

In this method the gain controls of the flaw detector are so adjusted that "grass" (i.e. echoes caused by the metallurgical structure of the test specimen) is produced over the full testing range. For weld joints, for example, the target for setting the sensitivity using this method may be the under surface of the parent material (Figure 5.36 a). A reduction or increase in the sensitivity may now be required during the scanning to facilitate the exploration of defects. In any case, the change in gain is to be noted in decibels.

With the calibrated gain control finally set and its reading recorded (reading A), the probe is then transfered to an agreed reference block and positioned for maximum response from the target hole or a reference surface as shown in Figure 5.36 b and c. This reference or calibration block echo constitutes the primary reference echo (PRE). Its height will almost certainly not coincide with any convenient graticule division. Therefore, the gain control is adjusted to bring it to ,say, 75 % of the full screen height or to some other mark and a record is made of the difference in gain control readings. Let the new reading after adjusting the reference echo height to 75 % full screen height be B dB.

For normal beam probes, the PRE may similarly be obtained from the parallel section of the reference or calibration block.

If the examination is interupted or new equipment brought in, the sensitivity level can be reinstated by proceeding in the reverse sequence :

(a) Position the probe for maximum response from the reference target in the reference block.

(b) Set the reference echo to the predetermined graticule height, say, 75 % full screen height.

(c) Add or subtract the recorded difference between the readings A and B so as to restore the reference echo to its original height.

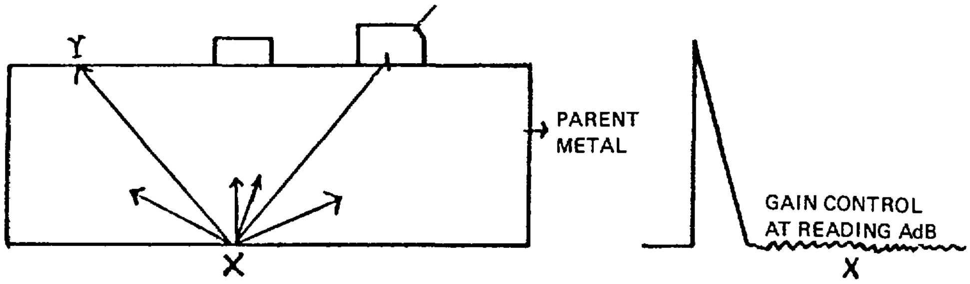


Figure 5.36 a

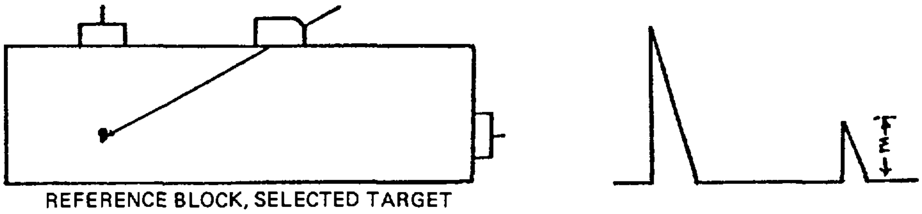


Figure 5.36 b

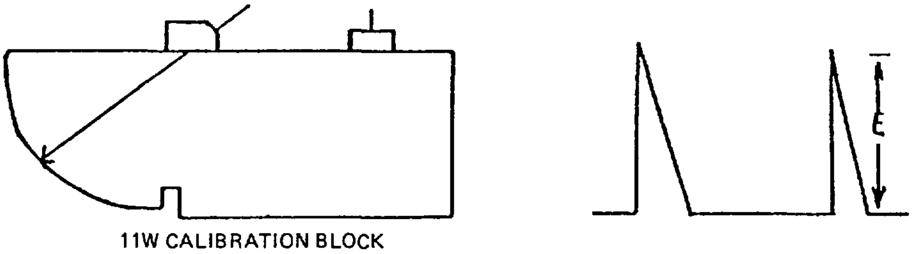


Figure 5.36 c

5.5 MEASUREMENT OF ATTENUATION

5.5.1 Longitudinal Wave Attenuation

The procedure for measurement of attenuation for longitudinal waves is based on the fact that the amplitude of reflection from an infinite reflector (i.e. back wall of the specimen) is inversely proportional to distance if the back wall is situated at a distance equal to or greater than 3 near field lengths from the probe. The procedure for measuring the attenuation of longitudinal waves in a specimen is as follows :

i. Determine the near field length N of the probe

$(N = \frac{D^2}{4\lambda}$;

D = diameter of probe crystal and λ is the wave length of the longitudinal waves).

ii. Find a distance of three near fields.

iii. Place the probe on the specimen and obtain a number of back wall echoes on a calibrated CRT screen.

iv. Choose two consecutive back wall echoes which lie beyond the 3 near field lengths.

v. Adjust the gain control of the flaw detector to bring the height of the first back wall echo, selected in (iv), to a predetermined mark on the CRT screen, say, 2/5 th full screen height and note the reading of gain control. Let it be A dB.

vi. Now bring the height of the second selected back wall echo to 2/5 th screen height and note the reading of the gain control. Let it be B dB.

vii. Find the difference C = (B - A) dB.

viii. Subtract 6 dB from the difference found in (vii) i.e. (C - 6) dB.

ix. Divide (C - 6) dB by twice the thickness of the specimen i.e. (C - 6) dB / 2T mm (where T is the thickness of the specimen). This gives the required attenuation per mm of path travelled in the specimen by the longitudinal waves.

5.5.2 **Transverse Wave Attenuation**

It is usual to express transverse wave attenuation in terms of beam path length indicated on the time base, ignoring the fact that the sound travels out and back. The procedure for the measurment of tranverse wave attenuation in a specimen is as follows :

i. Select two identical angle beam probes - one to be used as a transmitter and the other as a receiver of ultrasonic waves.

ii. Calculate the skip - distance and half-skip-beam-path-length.

iii. Calibrate the time base for sufficient range for at least one full-skip-beam-path-length.

iv. Use a guide to align the transmitter and the receiver probes.

v. Position the probes at one-skip-distance apart (Positions T and R1 in Figure 5.37.

vi. Adjust the gain-control to bring the received echo to half screen height. Note the gain-control reading. Let it be A1 dB.

vii. Move the receiver to two skip distances (Positiom R2).

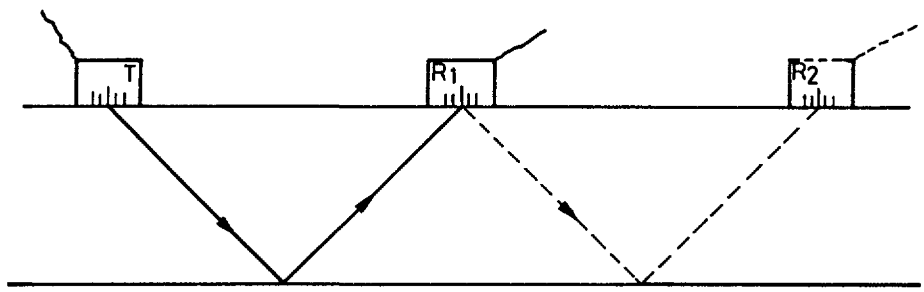


Figure 5.37

viii. Bring the height of the received echo to half screen height and note the gain-control reading. Let it be A2 dB.

ix. Calculate the difference (A2 - A1) dB.

x. Calculate the attenuation in dB/mm from

$$\text{Attenuation} \quad \frac{(A2 - A1)}{\text{Half-skip-beam-path-length}} \quad \text{dB/mm}$$

5.6 DETERMINATION OF TRANSFER LOSS FOR ANGLE BEAM PROBES

The procedure for the determination of transfer loss between the reference block and the test specimen for angle beam probes is as follows :

i. Select two identical probes having the same frequency, dimensions and refraction angle as the probe to be used in the testing of the specimen.

ii. Calculate the full-skip-distance and 1/2 skip-beam-path-length for the reference block and test specimen for the probe chosen.

iii. Using a guide to align the transmitter and receiver probe, set the probes one skip-distance apart on the reference block as shown in Figure 5.38 a.

iv. Adjust the received echo to half full screen height by using the gain-control. Note the gain-control reading. Let it be A1 dB.

v. Using the guide to align the probes, set the probes at one skip distance apart on the specimen as shown in Figure 5.38 b.

vi. Adjust the height of the received echo by using the gain-control to half full screen height. Note the reading of the gain-control. Let it be A2 dB.

viii. Calculate the gain difference A3 = (A1 - A2) dB.

ix. On the DGS diagram of the probe note the gain difference between the intersections of the reference block half-skip distance and the back wall S-curve and the intersection of the specimen half-skip-distance and the back wall S-curve. Let it be A4 dB.

x. Calculate the difference in attenuation between the half-skip-distance in the refrence block, and the half-skip-distance in the specimen. Let this difference be A 5 dB.

xi. Calculate the transfer loss in dB from :

Transfer loss = A3 - (A4 + A5) dB.

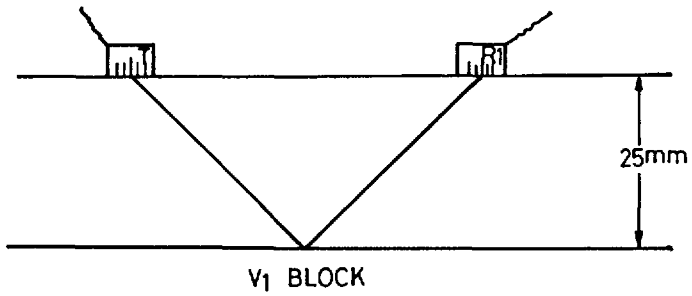


Figure 5.38 a

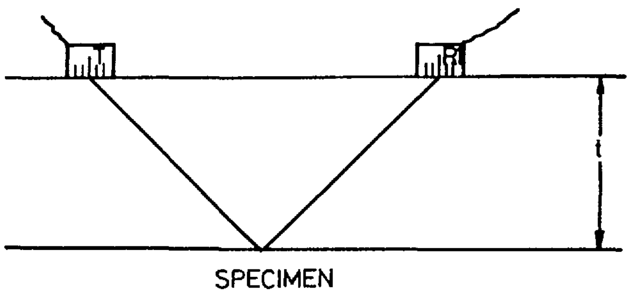


Figure 5.38 b.

5.7 COUPLANTS

In ultrasonic testing a couplant in the form of a liquid or paste is use to eliminate air between the probe and the specimen surface. If there is air between the probe and the specimen no transmission of ultrasonic waves in to the specimen will take place because of the very low acoustic impedance of air as compared to the acoustic impedances of the specimen and the probe.

Commonly used couplants in ultrasonic testing are glycerin, water, oils, petroleum greases, silicone 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. Possiblity of chemical reactions between the test specimen and the couplant.

iv. Cleaning requirement - some couplants are difficult to remove.

5.8 INFLUENCE OF THE TEST SPECIMEN ON THE ULTRASONIC BEAM

5.8.1 Surface Roughness

The surface roughness of the test specimen can affect the ultrasonic inspection in the following ways :

i. Loss of sensitivity because of scattering (Figure 5.39) due to refraction at the top surface and due to reflection at the rear surface (i.e. back wall). This is a maximum when the roughness of the surface is equal to or greater than the wavelength of the ultrasonic waves used for inspection.

ii. Loss of near surface resolution of the inspection system by a lengthening in the transmission pulse.

This lengthening is caused by the reflection of the side lobe energy back in to the probe by the roughness of the surface. The side lobe energy is not normally reflected back in to the probe.

Remedial measures to avoid or minimise this loss of sensitivity and resolution are any of the following :

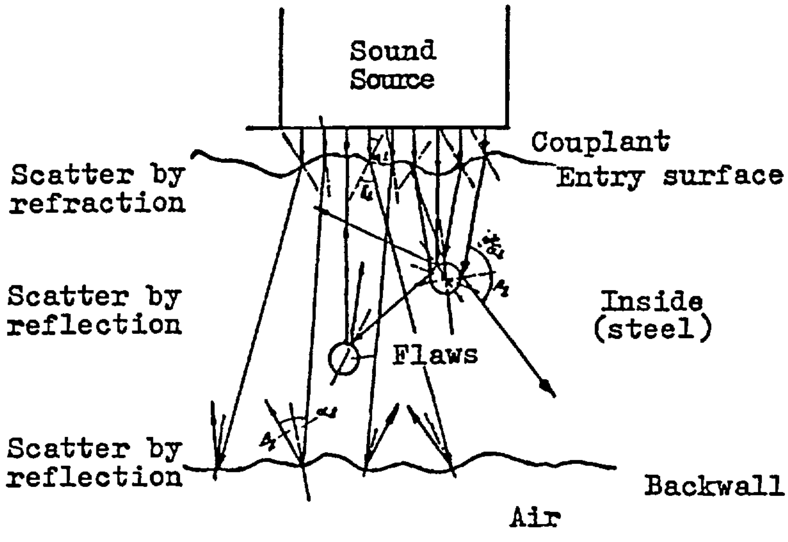
i. By smoothing the surface.

ii. By increasing the gain of the amplifier.

iii. By using a probe with a lower frequency.

iv. By using a probe with high ultrasonic output.

v. By improving the coupling of the probe to the test specimen. This can be achieved by attaching a protective plastic membrane to the front surface of the probe with some drops of couplant between the probe and the membrane. The membrane fills out the uneveness of the surface and thus facilitates the transmission of ultrasonic waves in to the test specimen. In addition the membrane also protects the probe face from mechanical damage. A part of the ultrasonic energy is obviously absorbed by the material of the membrane, but the gain caused by the improved coupling in most cases is higher than the losses in the material.

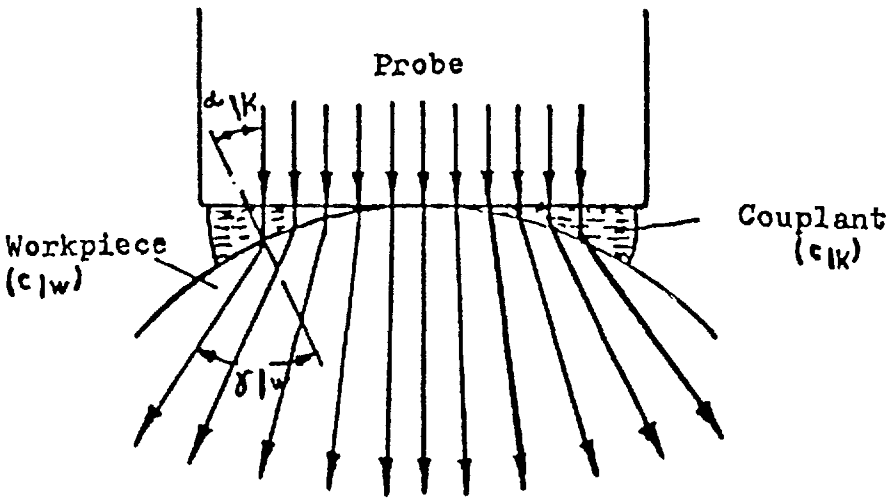


Occurrence of acoustic scatter (schematic)

Figure 5.39

5.8.2 Specimen With Curved Surface

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 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 5.40.



$$\frac{\sin \alpha|_K}{\sin \gamma|_W} = \frac{c|_K}{c|_W}$$

Figure 5.40 Additional sound beam divergence caused by refraction between couplant and workpiece surface.

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.

The skip-distances and beam-path-lengths, are increased by factors fp and fs respectively for curved surface specimens. The factors fp and fs , which depend on the probe angle θ and the ratio of wall thickness t to the out-side diameter D (i.e. t/D), can be obtained from Figures 5.41 a & b respectively.

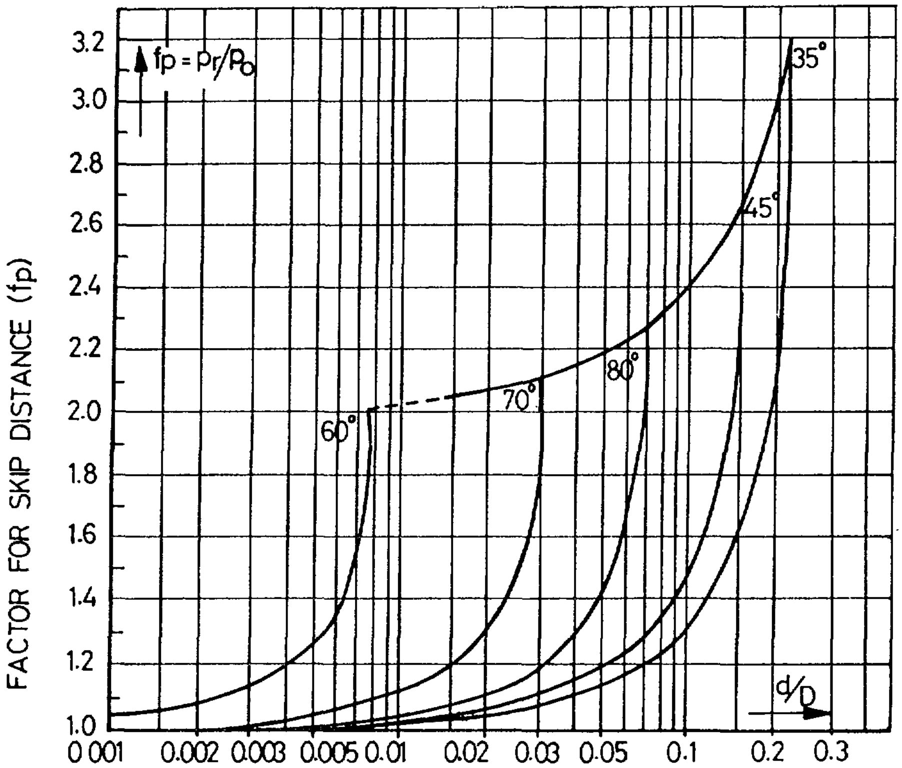


Figure 5.41a

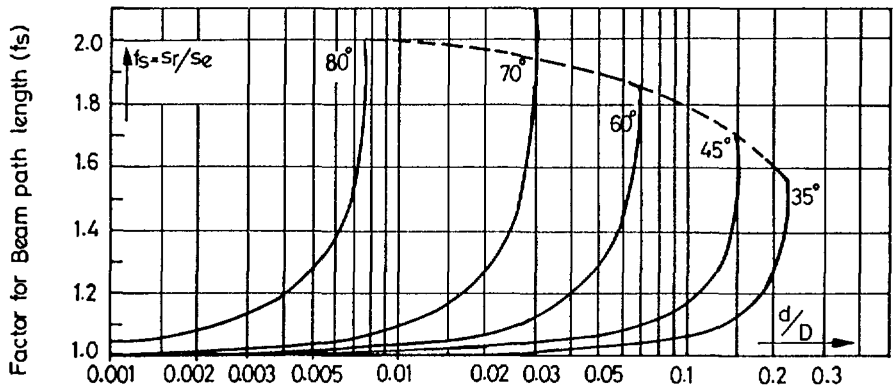


Figure 5.41b Beam-path-multiplying factor for pipes and curved surfaces.

5.8.3 Coated Surfaces

Firmly attached coatings (e.g. coats of paint, firmly attached mill scale or rust layers) will cause little or no disturbing effects. But for loose coatings, cleaning with a wire brush, file, scraper or grinder is required.

Moist or greasy surfaces are generally advantageous because of their improved coupling.

5.8.4 Mode Conversion Within The Test Specimen

When the shape or contour of the test specimen is such that the ultrasonic beam or a portion of it as in the case of beam spread, is not reflected directly back to the probe, mode conversion occurs at the boundary points contacted by the beam. If a direct reflection also occurs mode converted indications will appear after the direct reflected indication because of the longer path travelled by the mode converted longitudinal wave and slower velocity of the mode converted transverse wave. Figure 5.42 shows ultrasonic reflections within a long solid test specimen.

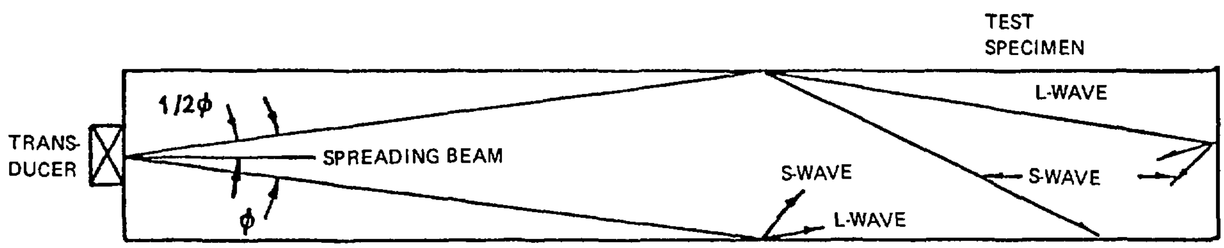


Figure 5.42 Mode Conversion Caused by Beam Spread.

5.8.5 Orientation and depth of flaw

The orientation and depth of the flaw may cause confusing indications or may result in the loss of the flaw echo. In the case of an unfavourable orientation, e.g. the flaw may lie with its long axis parallel to the ultrasonic beam, a much smaller indication is obtained than one would expect in proportion to the size of the flaw. If the flaw is angled with respect to the ultrasonic beam, the reflected beam is directed away from the probe. A sudden loss of back wall echo, while scanning, indicates the presence of such a flaw. If the decrease in amplitude of back wall echo is proportional to the flaw echo, the flaw is flat and parallel to the test surface. If the flaw echo is small, compared to the loss in back wall echo, the flaw is probably turned at an angle to the test surface.

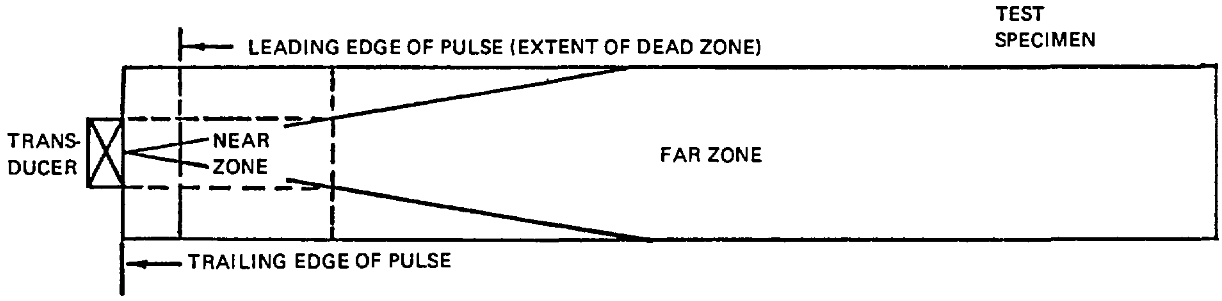


Figure 5.43 Dead Zone, Near Zone and Far Zone.

Indications are also affected by the depth of the flaw. Figure 5.43 shows the three principal zones of the ultrasonic beam : the dead zone, the near zone and the far zone. In contact testing the depth of the dead zone is determined by the length of the transmission pulse for single crystal probes. No indication from a flaw occuring in the dead zone can be obtained. The indications from flaws that occur in the near field vary considerably in amplitude as a function of the depth and positon of the flaw because of the near field affects. In the near field, the ultrasonic beam intensity is irregular and thus varying indications may be obtained from the same flaw as the probe is moved across it. Beyond the near field is the far field in which the intensity of the beam decreases exponentially as the distance increases.

5.9 Selection of Ultrasonic Probe

For pulse echo contact type ultrasonic testing the selection of a probe is made on the basis of the following factors. In order of preference the factors are :

i. Choice of ultrasonic beam direction.

ii. Choice of probe frequency.

iii. Choice of probe size.

5.9.1 Choice of Ultrasonic Beam Direction

The first thing to decide in the selection of a probe is whether a normal beam probe or an angle beam probe should be used and if an angle beam probe is to be used which angle should be selected. The choice should be such that the expected flaw offers maximum reflectivity i.e. the direction of the beam should be such that the beam strikes the flaw surface in a perpendicular direction. Other considerations that should also be taken in to account are to select such an angle : i) that will avoid indications caused by the shape and geometry of the test specimen and ii) that will give, if possible, a back wall or other reference echo which can be used for indirect flaw detection (e.g. the

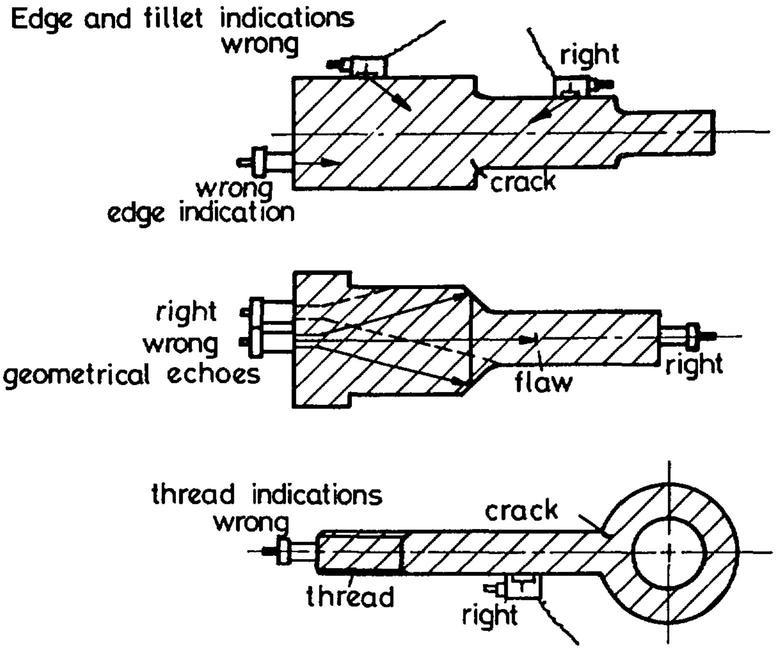


Figure 5.44 Examples of right and wrong probe arrangements.

disappearence of the back wall echo at spongy or porous structures in cast iron without any intermediate echoes) and also as an indication of correct coupling. Some examples of right and wrong probe arrangements are shown in Figure 5.44.

5.9.2 Choice Of Probe Frequency

The selection of frequency depends on three things :
the size of the smallest flaw that is to be detected ; the crystalline structure of the specimen ; and the degree of absorption the specimen offers to the ultrasonic beam. The first consideration calls for the use of as high a frequency as possible because, generally, the diameter of the smallest detectable flaw is equal to or greater than a third of the wavelength of the ultrasonic waves used. Thus the greater the frequency of the ultrasonic waves, the shorter is the wavelength and hence the smaller is the diameter of the smallest detectable flaw. In other words the sensitivity of flaw detection is better.

Another additional advantage in the use of higher frequencies is that high frequency probes emit shorter ultrasonic pulses and thus exhibit better resolution.

Two considerations require the use of low frequency probes namely if the grain size or the absorption of the specimen is large. Larger grains in the specimen cause scattering of the ultrasonic waves which results in a lower depth of penetration of the ultrasonic waves, lower flaw detection sensitivity, and also the display of considerable "grass" or "structural noise" indications on the CRT screen.

This display of grass on the CRT screen makes the differentiation of small flaw echoes from the grass, difficult if not impossible.

The absorption of ultrasonic waves in a specimen increases with increase in frequency. Using a high frequency probe to test a high absorption specimen results in a lower penetration range and lower flaw detection sensitivity.

As a result of the above discussion the following general rule for the choice of test frequency may be adopted : The frequency should be as high as possible for high flaw detection sensitivity and resolution ; but the upper limit is set by the grain size and absorption of the test specimen.

Usually forged materials are examined with frequencies between 2 and 6 MHz while cast specimens with coarser structure need frequencies between 0.5 to 2 MHz . Ceramics (e.g. for electric insulators etc) also present good ultrasonic conductivity and can be tested in most cases with frequencies between 2 to 4 MHz . Synthetic materials can be tested with frequencies from 1 to 4 MHz according to their absorption and thickness, . The test frequencies for concrete and similar materials are mostly between 50 to 200 KHz and thus need special flaw detectors.

5.9.3 Choice Of Probe Size

The third thing to decide while selecting a probe, is the probe size. For a given frequency the near field length depends only on the diameter of the probe. And as the sizing of flaws, in most cases, is done on the basis of comparison with some reference reflectors, the near field should be as short as possible. This is because the intensity variations along and across the ultrasonic beam axis are irregular and sizing of flaws occuring in the near field can not be done by comparison of its reflectivity to the reflectivity of a reference reflector. Thus for a given frequency the probe diameter should be as small as possible to have a short near field.

6. SPECIFIC APPLICATIONS

6.1 Ultrasonic Inspection of Welds

6.1.1 Types of Weld Joints

In the welding process, two pieces of metal are joined together. Molten "filler" metal from a welding rod blends with molten parent metal at the prepared fusion faces and fuses the two pieces together as the weld cools and solidifies. Most welds fall in to one of the following categories :

i. Butt weld.

ii. T-weld .

iii. Nozzle weld.

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 6.1.

Figure 6.2a 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 6.2b, showing the original preparation and the number of passes made to complete the weld.

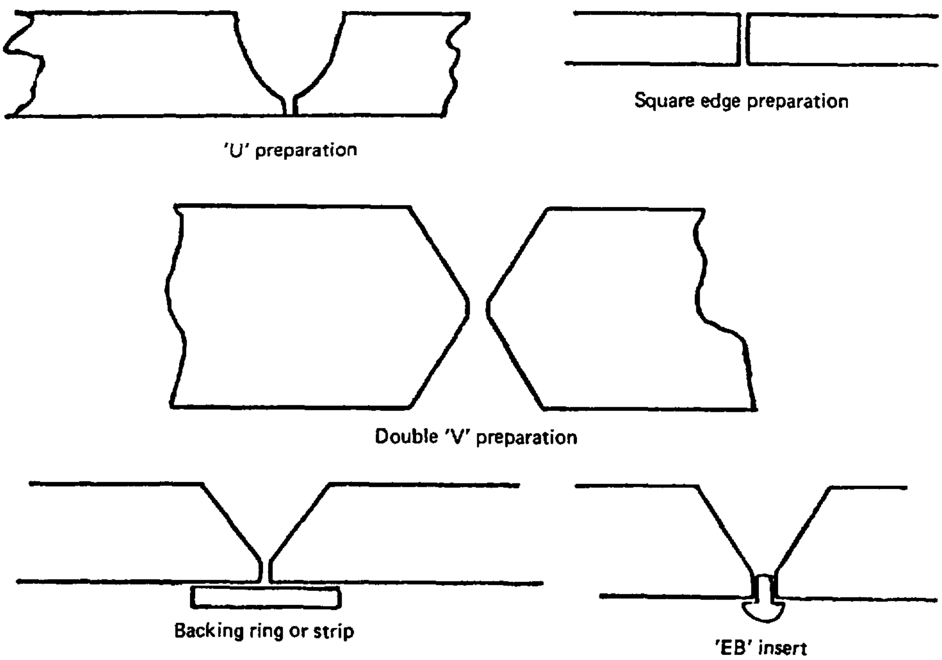


Figure 6.1.Various weld configurations

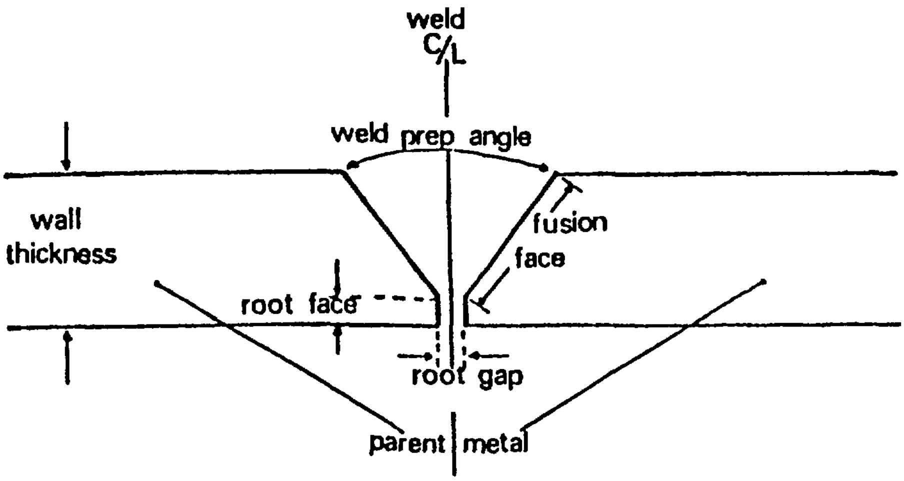


Figure 6.2a.

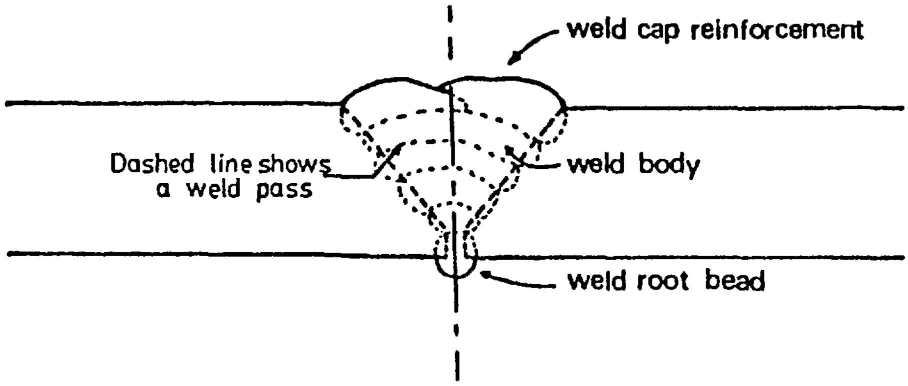


Figure 6.2b.

A T-weld is achieved when two plates are joined at right angles to each other. A T-weld may be fully penetrated (figure 6.3a) or only partially penetrated (figure 6.3b) by design.

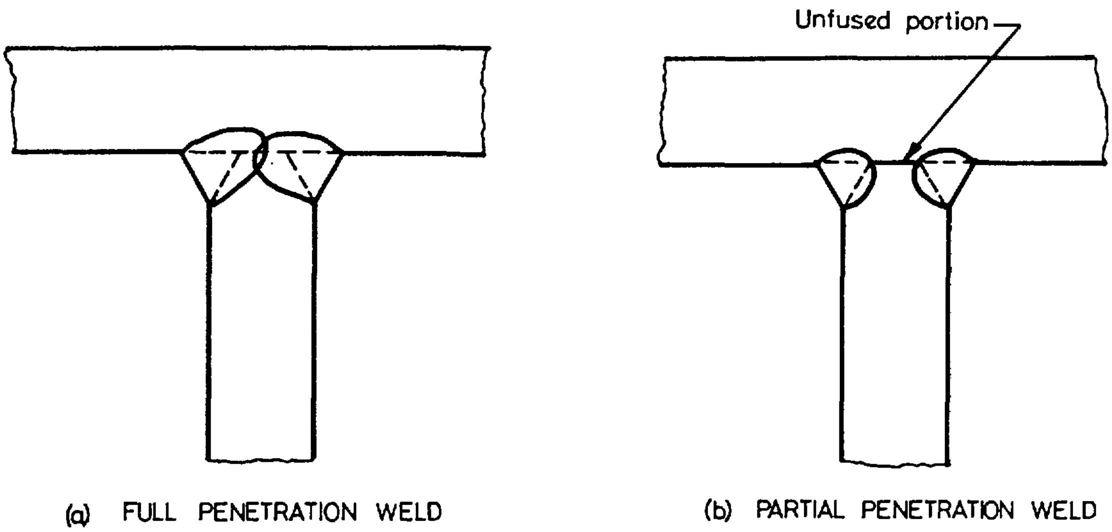


Figure 6.3.

Figure 6.4.

Nozzle welds are those in which one pipe is joined to another as a branch, either at right angles or some other angle. As with T-joints, the weld may be fully or only partially penetrated. The branch may let in to 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 6.4a and b in which the shaded portion shows the pipe wall.

Some typical weld preparations for nozzle welds are shown in figure 6.5. 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.

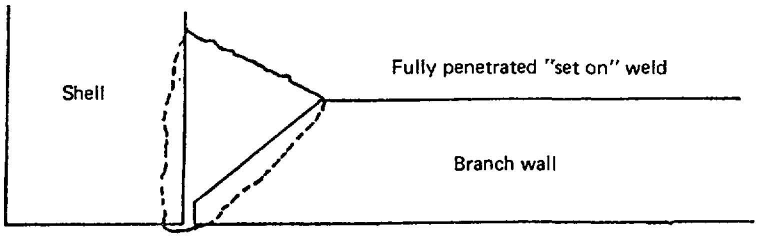


Figure 6.5a. Fully penetrated "set on " weld.

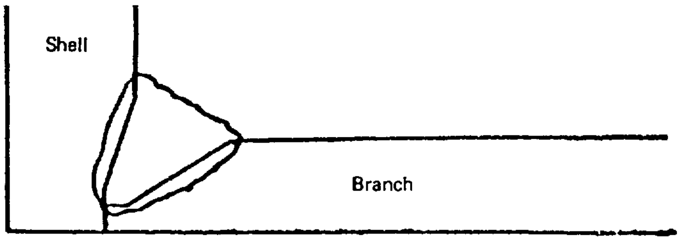


Figure 6.5b. Partial penetration weld "set in".

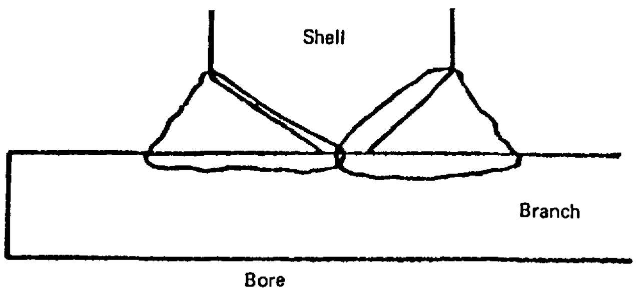


Figure 6.5c. Fully penetrated weld "set through"

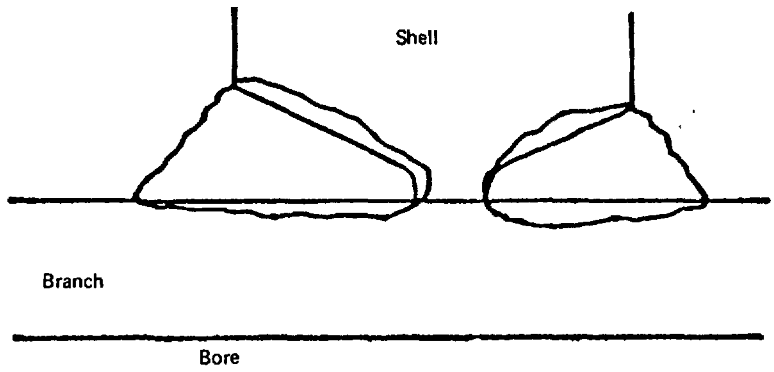


Figure 6.5d. Partial penetration weld "set through"

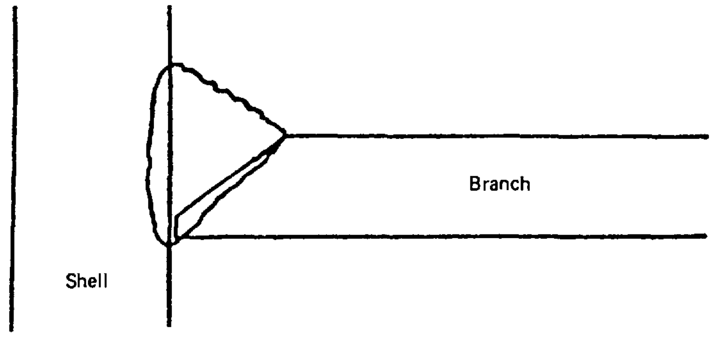


Figure 6.5e. Structural joint, fully penetrated weld.

6.1.2 Weld Defects

The defects which are commonly encountered in welds are:

6.1.2.1. Lack Of Root Penetration

In butt welding, a root gap is usually left at the bottom of the weld (single V weld) or at the centre of the weld (Double V weld). If the opening between the two pieces is narrow, it is difficult to achieve complete penetration and fusion at the root of the weld. A void remains in the root of the weld. This type of defect is called lack of root penetration or incomplete root penetration.

6.1.2.2. Lack Of Fusion

This defect is due to lack of union in a weld between the weld metal and parent metal, between parent metal and parent metal or between weld metal and weld metal. Lack of fusion can be of the following three types :

(a). **Lack of side wall fusion**

This is caused by a lack of fusion between the weld metal and the parent metal at the side of the weld outside the root.

(b). **Lack of root fusion**

This is caused by a lack of fusion between the weld metal and the parent metal or between adjacent faces of the parent metal at the root.

(c). **Lack of inter-run fusion**

This is caused by a lack of fusion between adjacent runs of weld metal in a multi-run weld.

6.1.2.3. **Slag Inclusion**

Some slag may be trapped in the deposited metal during its solidification, particulary if the metal fails to remain molten for a sufficient period to permit the slag to rise to the surface. In multi-pass welding, insufficient cleaning between weld passes can leave a portion of the slag attached to the weld metal which is then covered by subsequent passes.

6.1.2.4. **Tungsten Inclusion**

Tungsten inclusions are characteristic of the inert atmosphere welding methods. If the tungsten electrode which supports the electric arc comes in to contact with the weld metal, some tungsten particles are trapped in the deposited metal.

6.1.2.5. Porosity

Porosity is a collection of gas pores which results from the entrapment of gas in the solidifying metal. The pores are generally spherical in shape. When the pores are uniformly distributed throughout a single pass weld or throughout several passes of a multiple pass weld, the resulting porosity is called uniform scattered porosity.

A group of pores localized in an area is called cluster porosity. Pores aligned along a joint boundary, the root of the weld or an interbead boundary, result in porosity termed linear porosity.

When the pores are elongated in shape, the resultant porosity is known as piping porosity.

6.1.2.6. Cracks

Cracks occur in weld and base metal when localized stresses exceed the ultimate strength of the material. Cracks can be classified as either hot cracks or cold cracks. Hot cracks develop at elevated temperatures. They commonly form on solidification of the metal at temperatures near the melting point. Cold cracks, sometimes called delayed cracks, develop after solidification is complete.

Cracks may be termed longitudinal or transverse depending on their orientation. When a crack is parallel to the axis of the weld it is called a longitudinal crack regardless of whether it is a centerline crack in weld metal or a toe crack in the heat-affected zone of the parent metal. Transverse cracks are perpendicular to the axis of the weld. These may be limited in size and contained completely within the weld metal or they may propagate from the weld metal in to the adjacent heat-affected zone and in to the parent metal.

Cracks can be described as toe cracks,root cracks or heat affected cracks.
(a) Toe cracks generally start from the surface of the weld between the weld and parent metal.They can begin in the weld metal or heat affected zone and are often associated with restraint and the shrinkage of the last weld pass .
(b) Root cracks are associated with the first weld pass and are caused by restraint. They can occur in the weld bead or heat affected zone.
(c) Heat affected zone cracks occur in the heat affected zone and are caused by high heat affected zone hardness ,high hydrogen content in the weld metal and high restraint.

6.1.2.7. Undercut

Undercut is generally located at the junction of the weld and parent metal at the toe or root. Undercut creates a mechanical notch because of the running down of the edges of the beveled weld preparation in to the deposited metal in the weld groove. Undercut may be either continuous or intermittent with more or less sharp edges.

6.1.2.8. Excessive Penetration

In welds, sometimes, molten metal 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 the excess metal.

6.1.2.9. Concavity at the Root of the Weld

A concave surface at the root of the weld can occur especially in pipe welding(without a cover pass on the root side).

In overhead welding this conditions 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 if slag is trapped between the molten metal and the backing strip.

6.1.2.10. Lamellar tearing

Lamellar tearing is ductile tearing which occurs when a rolled plate is stressed through its thicknessby the shrinkage stresses associated with the deposition of a large volume of weld metal. Typically it occurs in full penetration T butt welds in thick plate greater than 20 mm. It often occurs outside the visible heat affected zone 5 - 10 mm below the weld. IT is characterised by first decohesion of the non-metallic inclusions in the plate and then a shearing or tearing of the plate from non-metallic inclusion to non-metallic inclusion at about 45° to form a step-like crack.

6.1.3 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 the testing a weld includes the following :

i. Parent metal specification

ii. Welding process.

iii. Weld joint preparation.

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.

(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

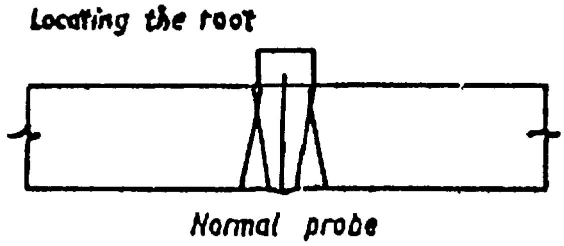


Figure 6.6a.

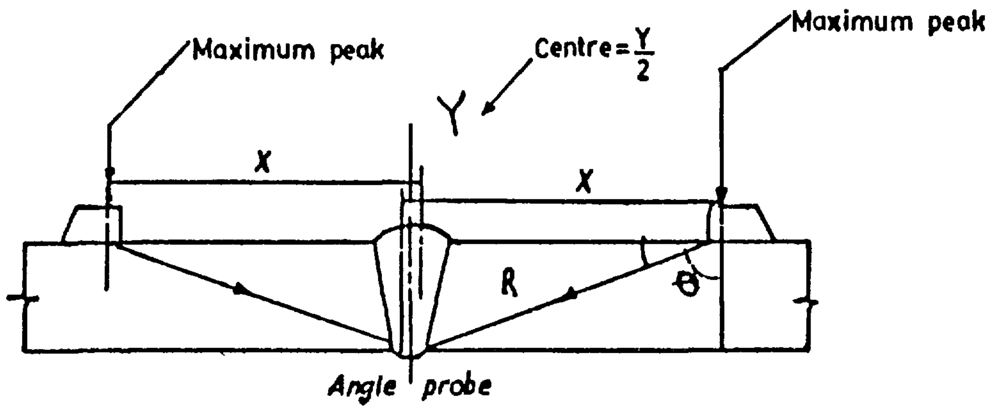


Figure 6.6b.

flush with the parent material, it may be necessary to etch the weld region to establish the weld width.

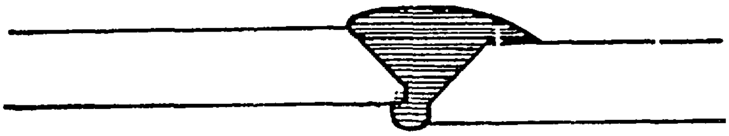
The centre line of the weld should be marked accurately on the scanning surface of the weld.

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 6.6a) 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 is not removed an angle beam probe can be used for this purpose, by placing the probe first on one side of the weld (figure 6.6 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.

(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



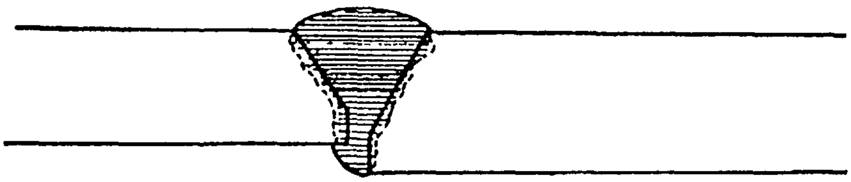


Figure 6.7.

noticed during the visual examination. If these defects are in excess of the acceptence 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 6.7). These faults may not always adversely affect weld acceptability, but they might interfere with subsequent ultrasonic inspection.

A clue to misalignment is often the widening of the weld cap because the welder tries to disguise this fault by blending the cap in with the parent metal on either side.

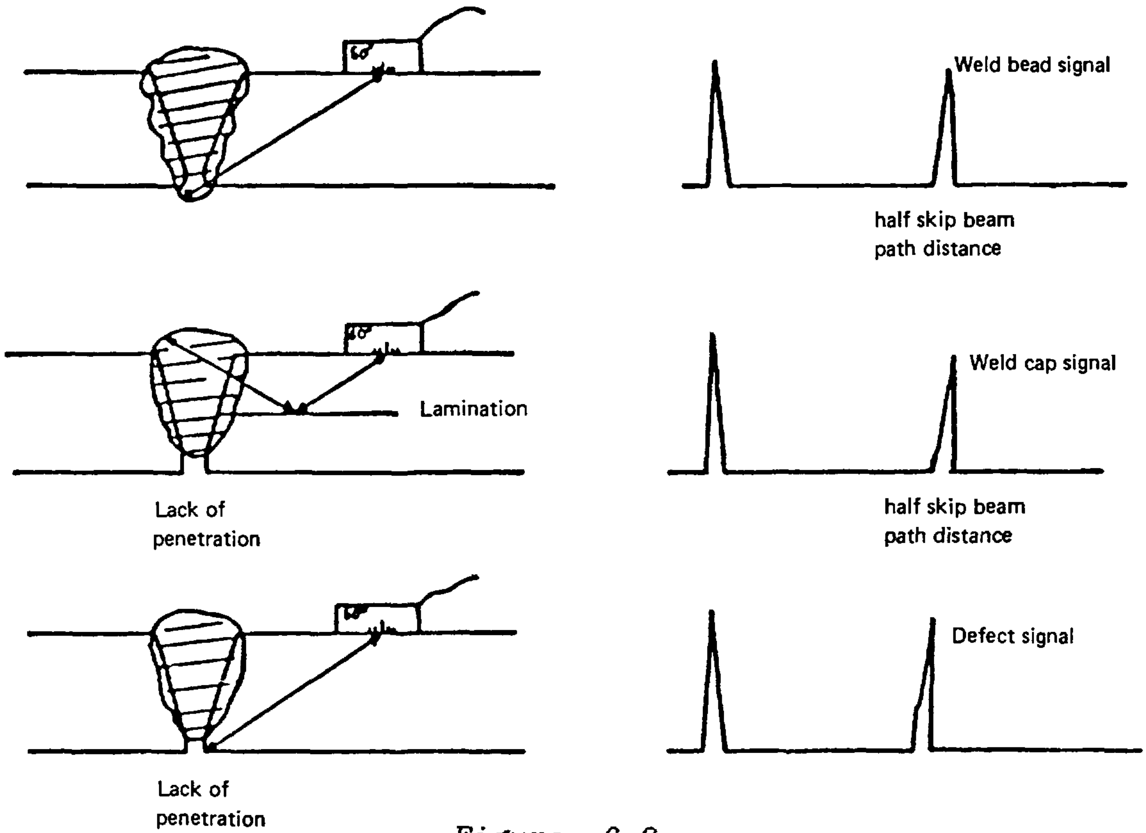


Figure 6.8.

(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 6.8 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.

The setting of sensitivity for this examinatin should be in accordance with the relevant specification or code of practice. Some of the specification requirements for sensitivity are given below. Refer to the specification for more detail.

i. ASME Specification

The method for setting sensitivity for normal beam probe examination is described in section .

ii. British Standard BS 3923 : Part 1 : 1978

In this specification, the sensitivity or gain is, whenever possible, set at a level at which the second back wall echo can be displayed at full screen height.

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 use. The highest frequency in this range is preferred.

(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 there 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 6.4 and 6.6 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.

(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 6.9, this scan is done parallel to the weld centre line alongside the weld cap with the probe inclined toward the centre as shown.

Since a crack tends to have a ragged edge, it is likely that some energy will reflected back to the transmitter. A safer technique is to use a pair of probes, one transmitting and one receiving. This is also shown in figure 6.9.

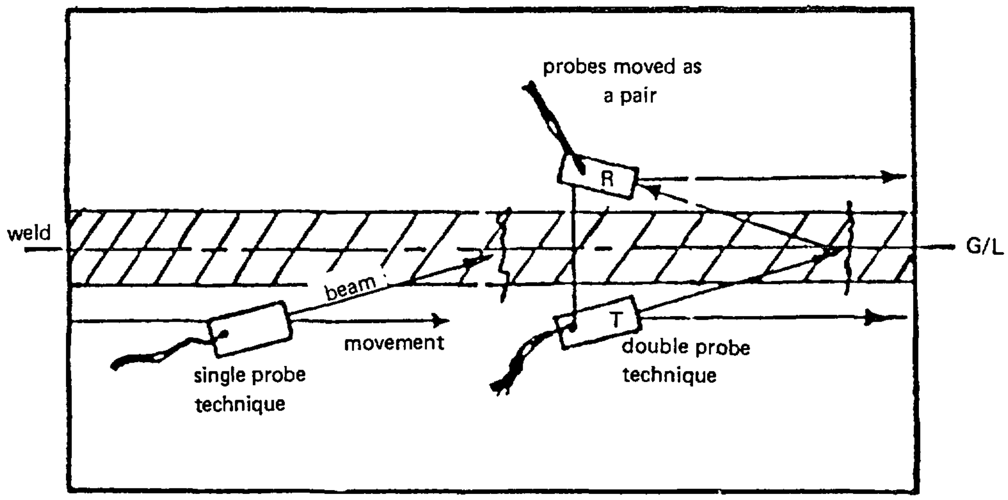


Figure 6.9.

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 for the inspector's findings to be 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.

6.1.4 Examination of Root in Single Vee Butt Welds Without Backing Strip in Plates and Pipes

6.1.4.1. 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 IIW 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 IIW V1 or V2 block.

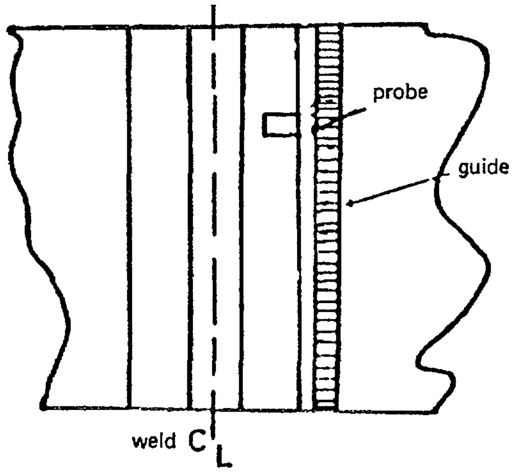
(d) Marking the probe index on the probe using IIW V1 or V2 block.

(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 + 1/2 root gap from the weld centre line on both sides of weld (figure 6.11).

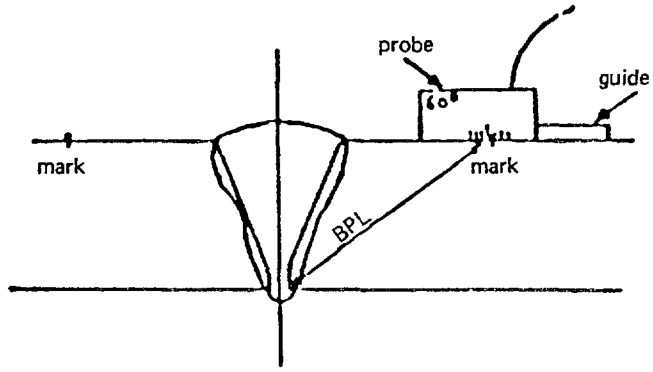
(g) Setting the gain sensitivity for scanning and evaluation.

(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



a) Plan View

Figure 6.10



b) Sectional View.

Figure 6.11.

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 6.11). 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 6.12 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 6.12 b).

(j) In addition, to determine whether an echo occuring during the root scan is due to lack of penetration, root undercut, root shrinkage, or root bead, the following points should also be taken in to 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.

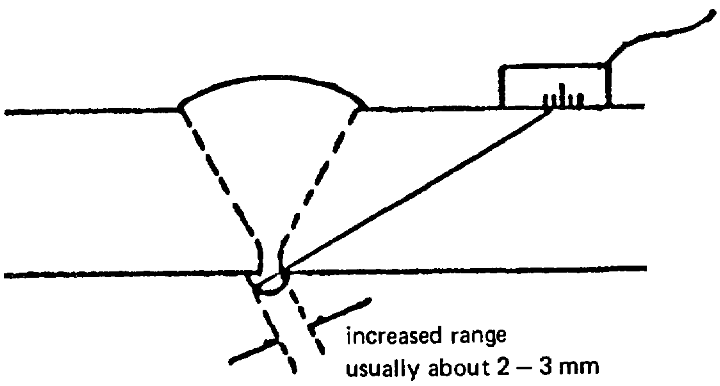


Figure 6.12 a.

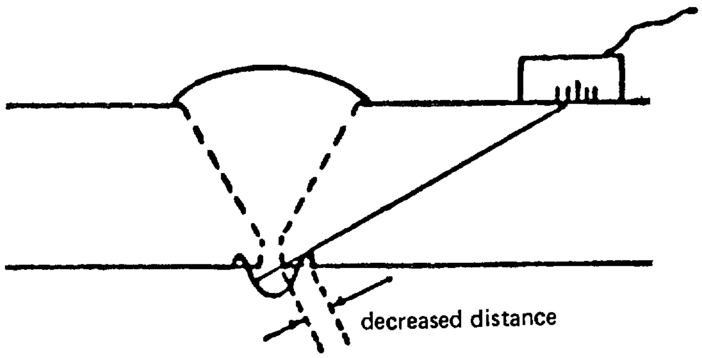


Figure 6.12 b.

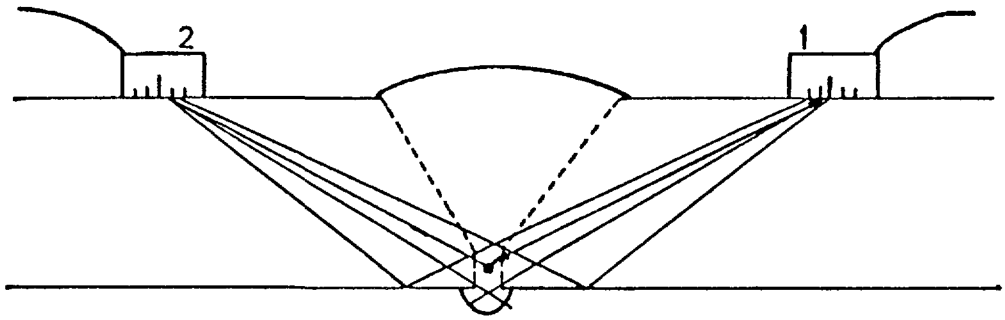
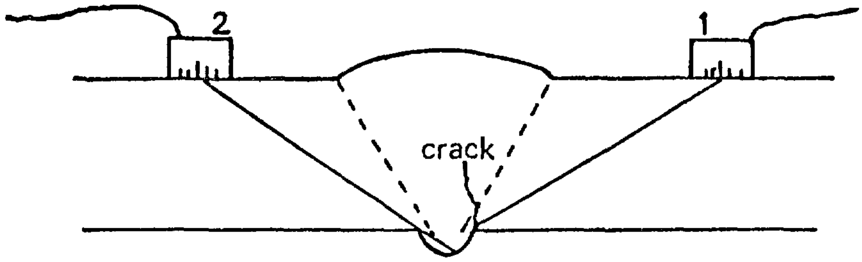


Figure 6.13

(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 defect in the root area. The first one of these is shown in figure 6.13. It is a small slag inclusion or gas pore 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 6.14.



The second defect mentioned above is shown in figure 6.14 . 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. From side 1, 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.

6.1.4.2 Selection of Probe Angle

The probe angle is normally chosen from 45°,60° or 70° and sometimes 80 probes,whichever has the shortest beam path length to the root. The choice of probe angle is limited only by the condition of the weld cap. On thin parent metals it may not be possible to position a 45° or 60° probe so that the half skip beam points at the root gap, without the toe of the probe riding up on to the weld cap.
If the weld cap has been dressed flush with the parent material, then probably a 45° probe can be used provided the material is not so thin that the critical beam path length comes in to the transmission pulse. For welds with the cap in place the following recommendations for the root scan are made for various plate thicknesses :

Parent metal thickness	Probe angle
6 - 15 mm	60° or 70°
15 - 35 mm	60° or 45°
Over 35 mm	45°

If a 60° probe is selected for the root scan, the strong mode converted longitudinal waves which occur with this probe angle if the waves strike a corner reflector such as lack of penetration can result in echoes for instance from the weld cap appearing to come from within the weld .

6.1.5 Examination of Weld Body in 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 full-skip 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.

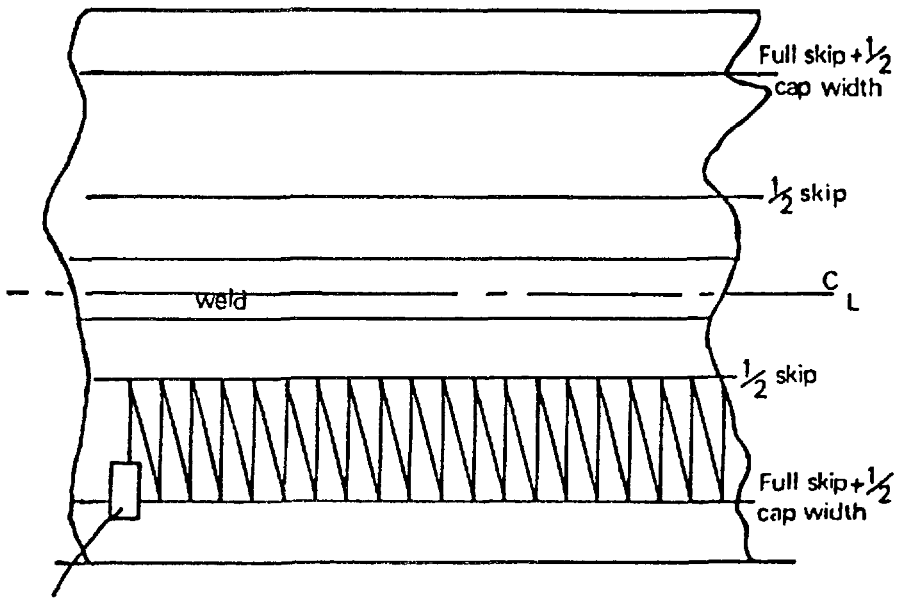


Figure 6.15.

(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 zig-zag pattern between the marked scan limits (figure 6.15). Each forward scan should be at right angles to the weld centre line, and the pitch of the zig-zag 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 defect.

6.1.5.1. Selection of Probe Angle

The initial selection of probe angle for the weld body examination depends upon the weld preparation angle.

When the cap is dressed and the scan is made directly over the dressed weld, some of the defects might be very close to the top surface. If the transmission noise of a single crystal probe lasts longer than the return time in the perspex shoe, the noise will obscure part of the timebase and mask defect echoes close to the top surface. In such cases twin crystal angle probes may be used. Measurement of beam index and angle, and timebase calibration for twin crystal probes is carried out in the same way as for single crystal angle probes. Again, if the weld is dressed, confirmation of volumetric defects can be made by scanning a compression wave probe over the weld body.

6.1.6 Inspection of Single Vee Butt Welds With Backing Strips or Inserts

The inspection procedure of 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.

6.1.6.1. 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 timebase 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 a half skip beam echo sliding up the front of the insert echo (i.e. poorly resolved), as shown in figure 6.17 (see figure 6.2a). The angle of the probe should be chosen to meet any lack of side wall fusion at right angles for maximum response. The exact angle to meet the fusion face at right angle can be calculated from the following equation :

Probe angle = 90 - $\theta/2$ .... (6.1).

Where θ = weld preparation angle.

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 6.16).

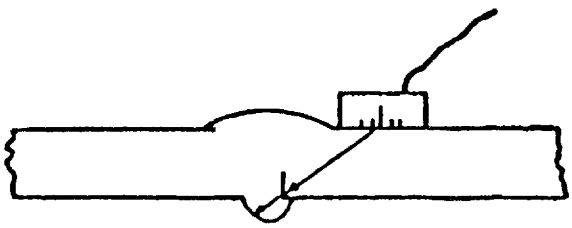


Figure 6.16.

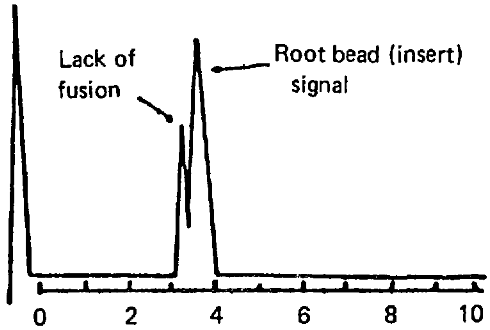


Figure 6.17.

Lack of fusion at the top of the insert (figure 6.18) 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 can not, 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.

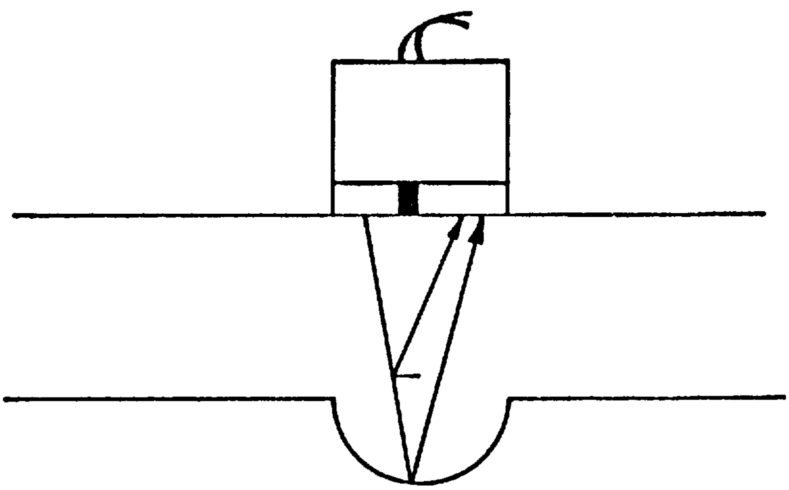


Figure 6.18.

6.1.6.2. Welds with Backing Strips

When properly fused the weld cross-section looks like the one shown in figure 6.19.

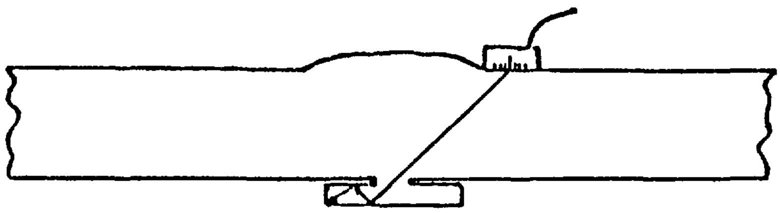


Figure 6.19.

An angle beam probe scan allows energy to pass through the root in to the backing strip. Reflection from within the strip will be shown as a pattern of echoes beyond the half skip beam path length (figure 6.20a). 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 6.20b).

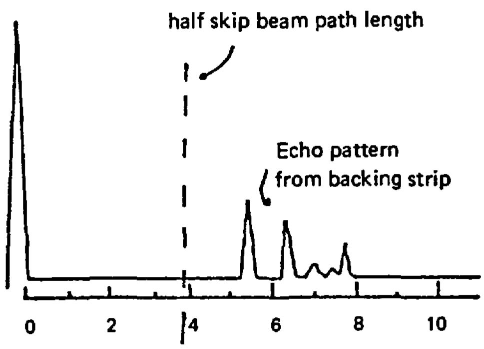


Figure 6.20a.

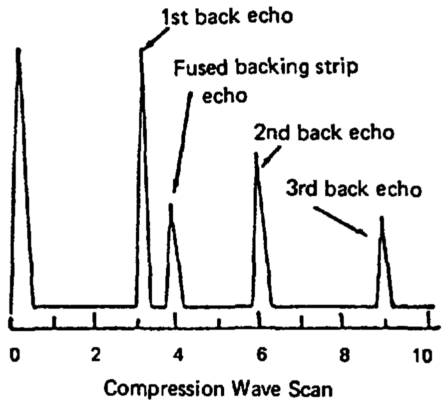


Figure 6.20b.

6.1.7 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.

6.1.7.1. Critical Root Scan for Double - Vee Welds

The typical weld preparation for a double Vee weld is shown in figure 6.1. Figure 6.21 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 planer, 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^{o} probe, positioned at 1/4 skip distance from the weld centre line, to carry out the critical root scan. The anticipated timebase range for an echo from lack of penetration can not be predicated 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 6.21.

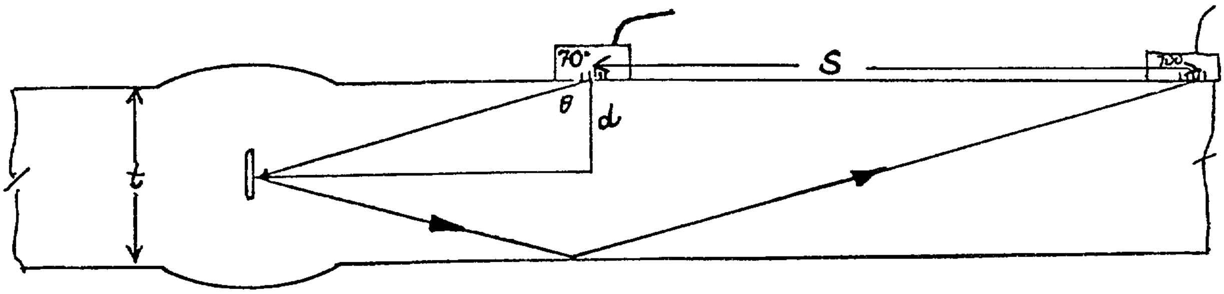


Figure 6.21.

In figure 6.21, 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

$$S = 2\ (t-d)\tan\theta \ .... \ (6.2)$$

6.1.7.2. **Weld Body Examination for Double Vee Welds**

The weld body examination 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 6.22).

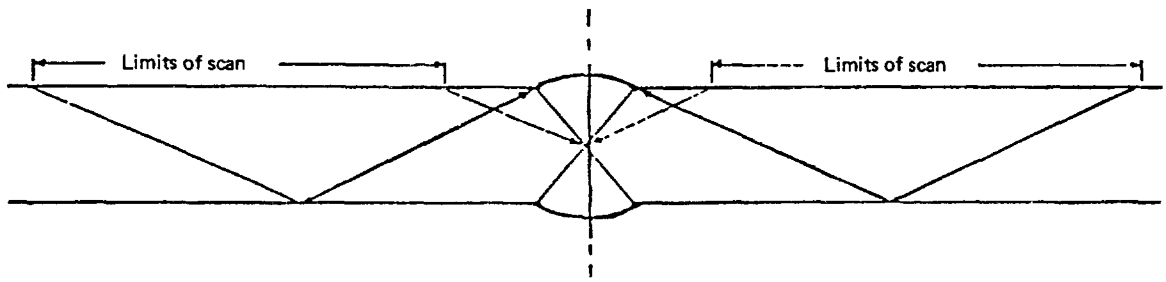


Figure 6.22.

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.

6.1.8 **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 proceduce for both partially penetrated and fully penetrated (for types of T-weld configuration see figure 6.3 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 6.23. 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 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 6.24) to reduce the tendency for confusing cap echoes.

6.1.9 **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-on nozzle welds, partially-penetrated-set-in nozzle welds, and either partially or fully penetrated set through nozzle welds.

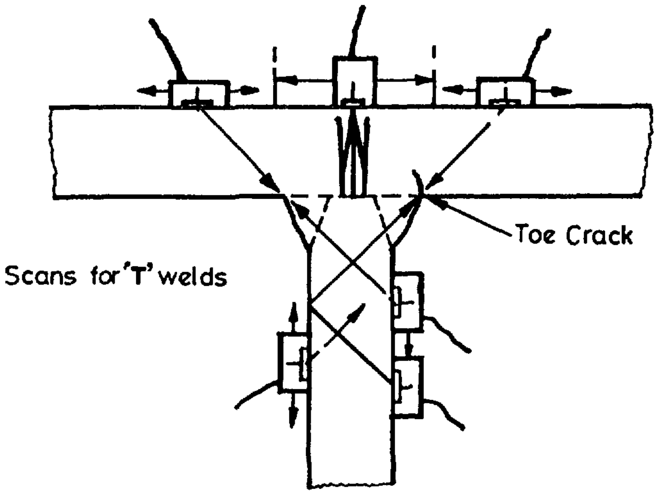


Figure 6.23.

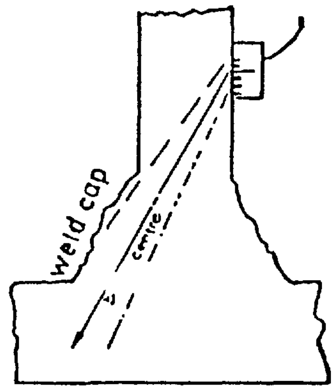


Figure 6.24.

The choice of probe angle and frequency, as discussed earlier, depends upon the particular job to be carried out.

6.1.9.1. Fully Penetrated Set on Weld

The scans to be carried out for this type of weld are shown in figure 6.25.

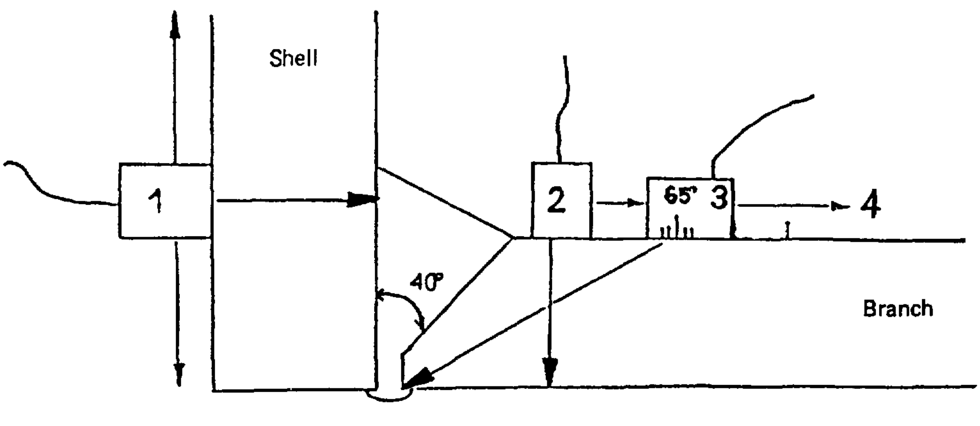


Figure 6.25.

Scans 1 and 2 are normal beam probe scans of shell and branch respectively to determine;

(a) Thickness of the shell and branch.

(b) Lamination in shell and branch.

(c) Lack of fusion of shell wall.

(d) Weld body defects.

Scan 3 is a critical root scan. For the preparation shown, 65 is the optimum probe angle.

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.

6.1.9.2. Partially Penetrated Set In Weld

The scans are similar to those shown in figure 6.25. However, in this case it is necessary to check the actual penetration achieved and to make sure that the horizontal fusion face is fused (figure 6.26 a & b).

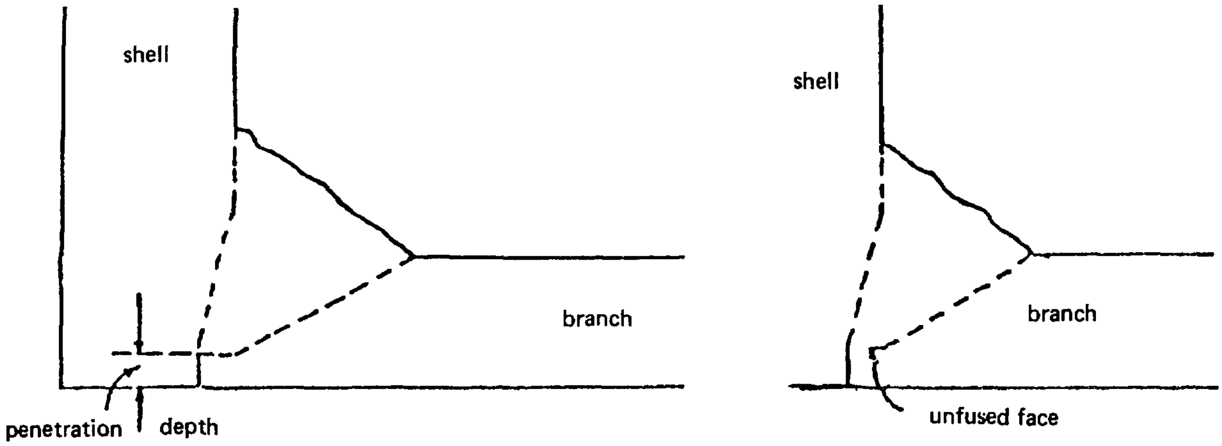


Figure 6.26 a. Intended Condition. Figure 6.26 b. Fault.

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 such as the one shown in figure 6.26 b would be suspected.

6.1.9.3. Examination of Set Through Nozzle Welds

These nozzle welds are rather like full or partial penetration T-welds and can be scanned in the same ways as shown in figure 6.23 (scans for T-welds). The main complication arises from the fact that the

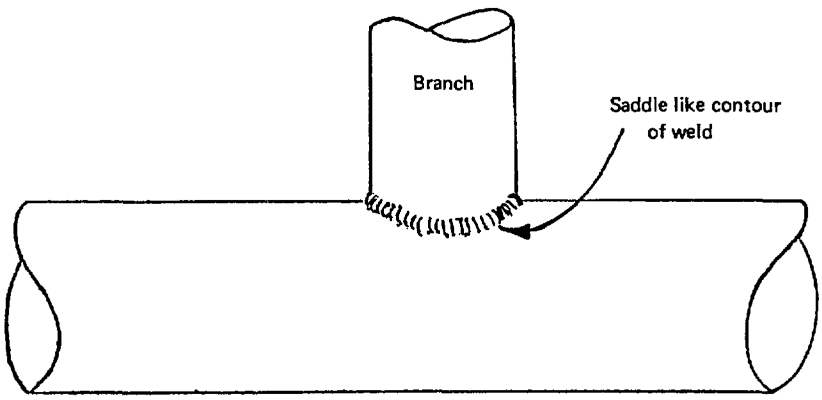


Figure 6.27.

fusion faces, when one pipe fits in to another in this way, lie along a line which looks rather like a "saddle" (figure 6.27).

The equivalent scan to scan 1 in figure 6.23 is made from the bore of the branch (compare figure 6.23 with 6.5 c&d), and to determine the weld limits, it is usual to scan the normal beam probe up and down the bore (i.e parallel to the branch axis) noting the change of echo from wall thickness to weld region and carefully marking the probe position. A series of points plotted in this way can be joined with chalk or chinagraph crayon to give the weld limits.

6.2 ULTRASONIC INSPECTION OF FORGINGS

6.2.1 Forging defects

Defects can originate during the forging operation. Forging bursts can occur as a result of insufficiently high temperature prior to forging. This means that the axis of the ingot or semifinished product is deformed when it has low ductility (or plasticity) and is unable to withstand the stresses set up by deformation and hence it bursts. Laps can also occur during the forging operation. These are caused by the squeezing of the surface metal over the top of another surface material which, because the surface is oxidised, will never completely fuse to produce a new, sound surface.

Defects can originate at the heat treatment stage. These can be hairline cracks (or flakes) and internal transverse stress cracks (or clinks). The former are due to the presence of hydrogen while the latter are due to transformation and cooling stresses which may be high enough to rupture the steel.

When mechanical work is done on a material, surface defects may appear as a result of using high machining speeds, large feed rates or local over-heating. When the material is in service, cracks may arise as a result of loading the structure. These can be due to brittleness or fatigue. Cracks due to brittleness may appear suddenly and spread very rapidly whereas fatigue cracks which are more common spread quite slowly and can often be detected even in their very early stages of propagation.

6.2.2 Testing of Semi-Finished Products: Rods and Billets

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 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 6.28), either normal or oblique to the surface. Also used are surface waves in the circumferential direction.

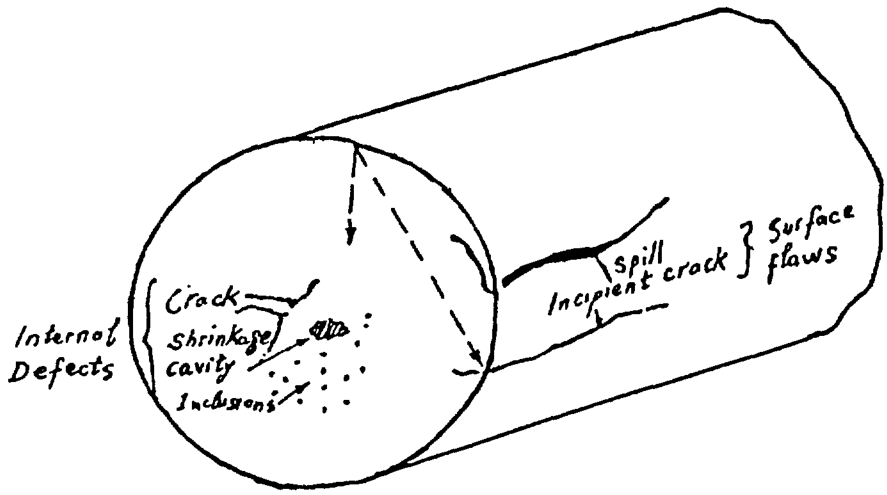


Figure 6.28 Types of defects in round stock and main directions of testing.

6.2.2.1 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 6.29 for square billets. In this test, a great part of the billet is not tested (figure 6.30) 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 with out saying that SE probes with heavily inclined

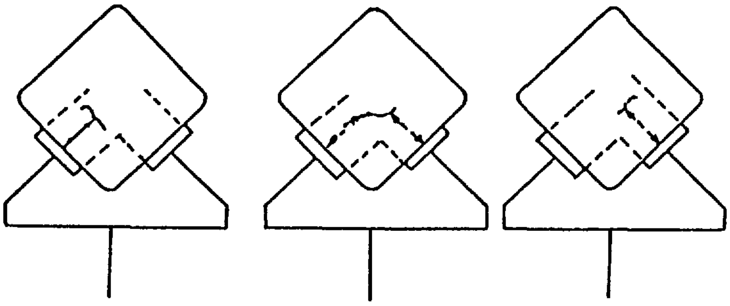


Figure 6.29 Testing billets with two probes connected in parallel.

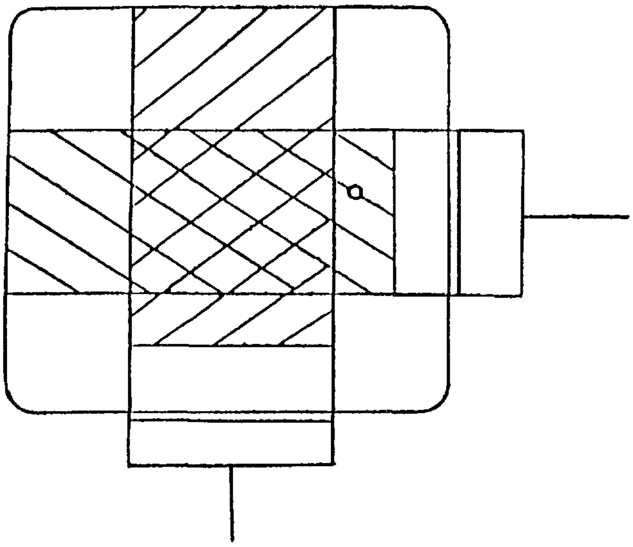


Figure 6.30 Incomplete coverage by normal probes used for testing square billets.

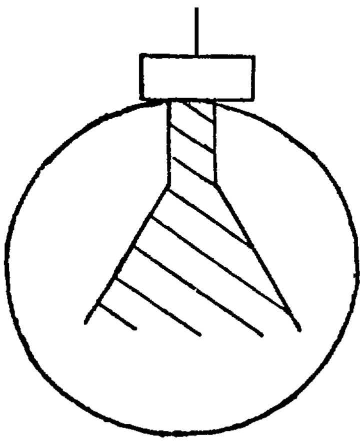


Figure 6.31. Difficulty in testing round billets with probes due to reduced contact area.

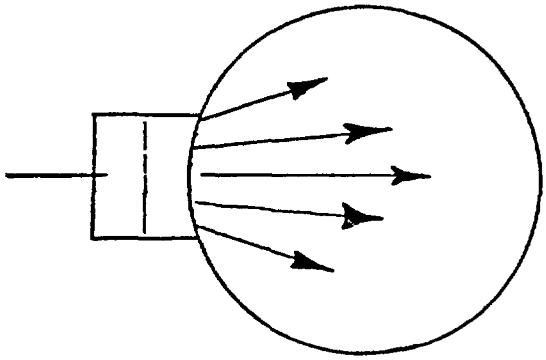


Figure 6.32 Increase in contact area by using perspex shoes.

oscillators cannot be used since their maximum sensitivity is just below the surface. Normally the so called 0 SE probes are used. Longitudinal surface flaws on square billets are practically impossible to detect with normal, SE or even angle probes.

The testing procedure with normal probes for core flaws mentioned earlier is also applicable for round billets but with more difficulty, especially when testing by hand, because of the curved surface which reduces contact area and probe sensitivity (figure 6.31).

The contact area can be increased by using a perspex shoe whose front curvature fits closely to the round billet (figure 6.32).

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.

Longitudinal surface flaws in round billets can be detected with angle probes provided the surface is not

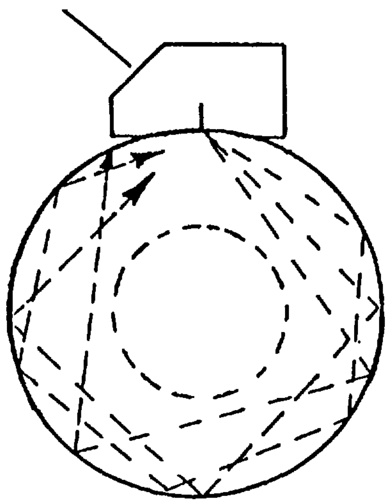


Figure 6.33. Depth of penetration of oblique transverse waves in round billets.

too rough. If a 45°or 60°angle probe with is suitably ground as shown in figure 6.33 , 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 orientated surface flaw is present (figure 6.34), 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 6.35). 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.

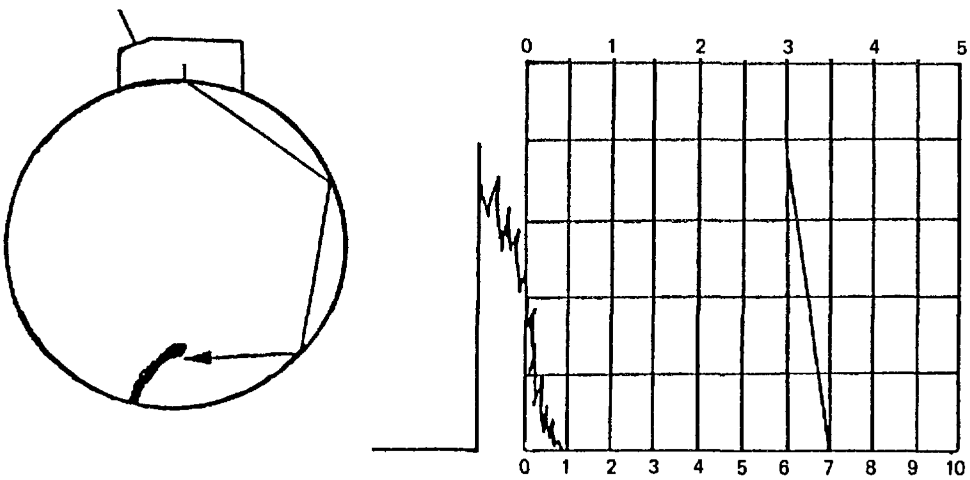


Figure 6.34 Detection of longitudinal surface flaws in round billets using angle probes.

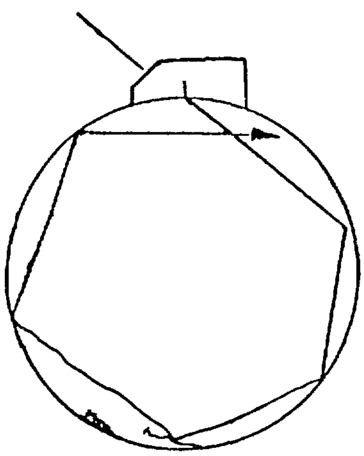


Figure 6.35 Possibility of missing longitudinal surface flaws in round billets using angle probes.

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 .

6.2.2.2. 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 in a housing, allowing a flowing water coupling, enables bars to the tested with increased speed. A bar without a surface flaw will give a large echo on the CRT screen (figure 6.36) This echo is caused by the sound beam, emitted by one oscillator, being received by the other and vice versa.

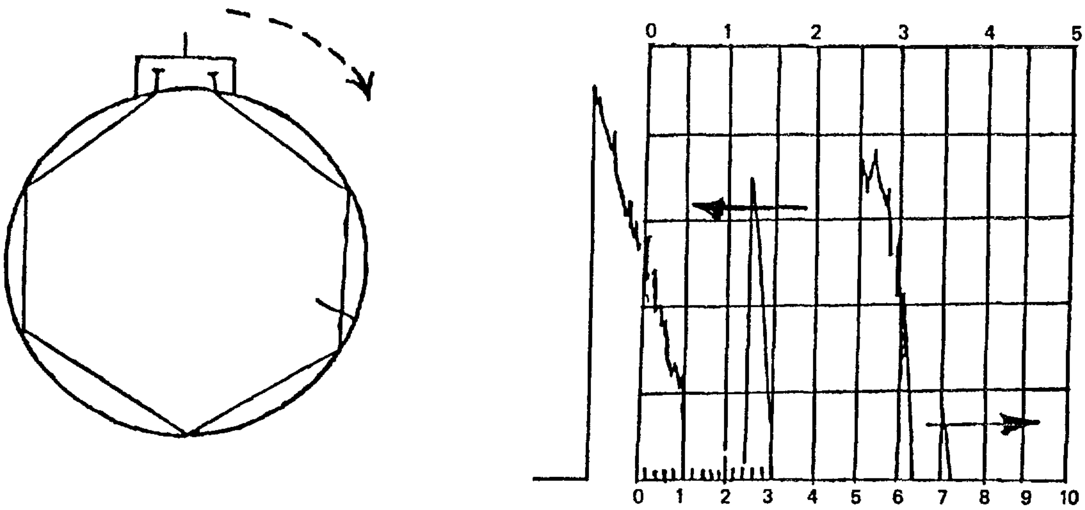
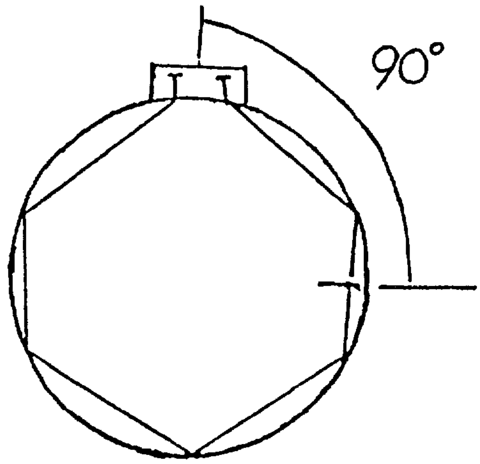


Figure 6.36 Testing of round bar with twin-angle probe.

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 paths, 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 in 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



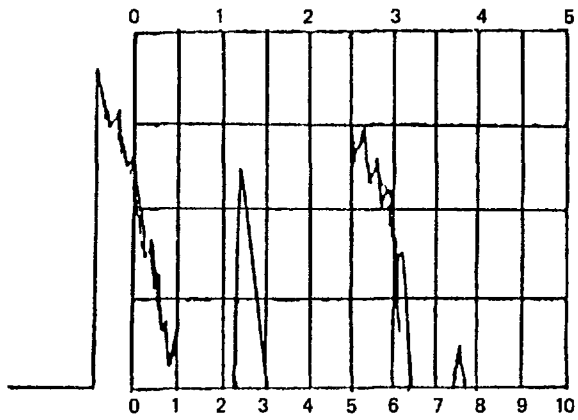


Figure 6.37 Location of surface flaw on rod using twin-angle probe.

(figure 6.36). 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 (figure 6.37).

6.2.2.3 Use of immersion technique for billet or rod materials

Test speed can be maximized by the use of the immersion technique, especially for small rod diameters. In this technique, the test specimen is immersed in water and immersion probes are used.

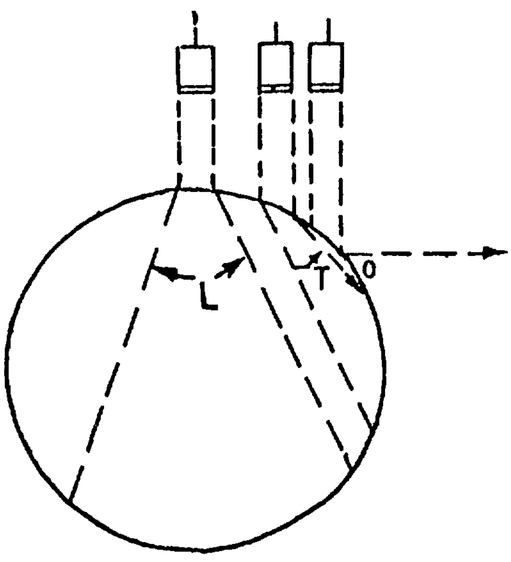


Figure 6.38. Testing of round stock by immersion technique.

When a normal probe is used, it is possible to generate all types of waves (Figure 6.38) by moving the probe position or direction. If the beam in broad, several waves can sometimes be obtained simultaneously.

If the surface is not sufficiently smooth, this may give rise to troublesome interferring echoes in a zone behind the interface echo.

These interferring 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.

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 6.39, for longitudinal defects close to the surface.

Figure 6.39 a
Rod material with no
surface flaws.

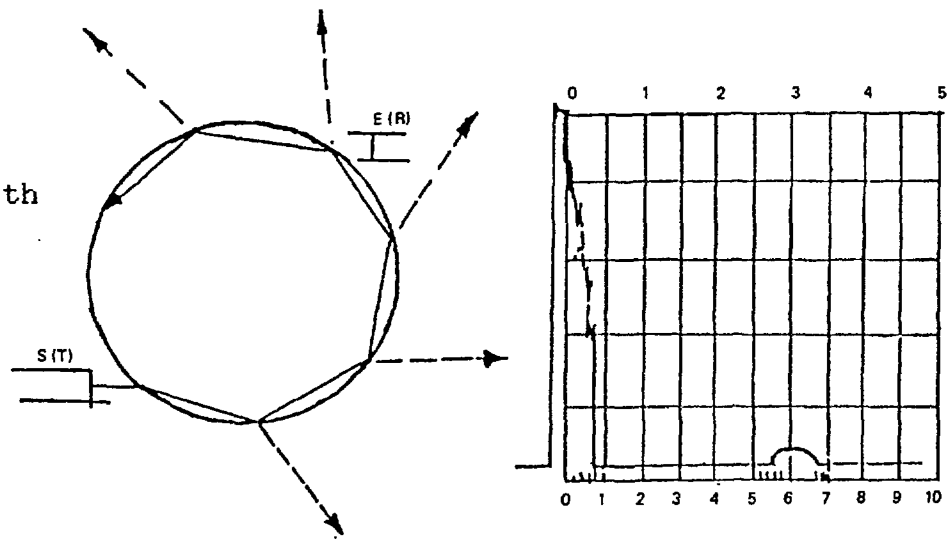
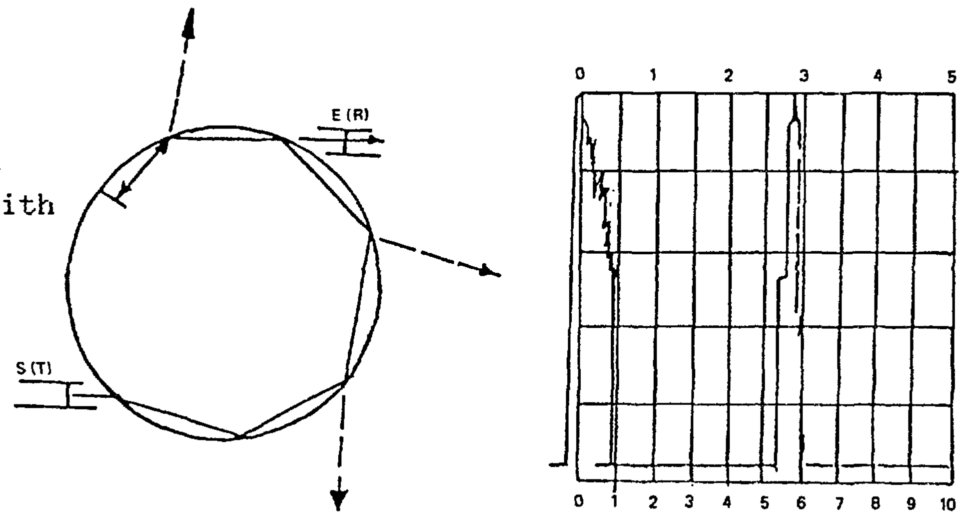


Figure 6.39 b
Rod material with surface flaws.



Figures 6.39a & 6.39b Testing method for detecting longitudinal surface defects on rod material by the immersion technique, with separate transmitting and receiving probes.

One of the normal probes acts as a transmitter and the other as a receiver. 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 6.39b), 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 6.39 a and figure 6.39 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.

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 6.40). In actual practice, the bar is spirally advanced through a water tank, the holder with its 5 probes (1 SE and 4 normal probes) sliding on the bar.

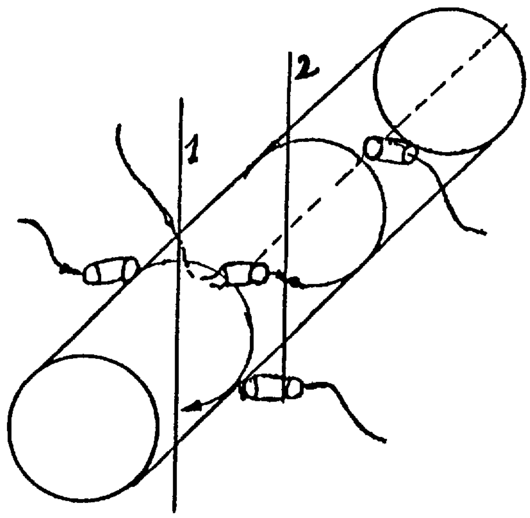


Figure 6.40. Testing method for longitudinal surface defects on rod material by the immersion technique with two pairs of TR probes.

6.2.3. Tube Testing

The same testing techniques used for round bar testing 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 tubes. In seamless and rolled pipes, the defects (figure 6.41) which are of interest are similar to those occurring in rod materials, Viz. incipient cracks and spills in the internal and external surfaces. Laminations can also appear in the wall as a result of the manufacturing process.

When an angle probe is used on a tube, the transverse wave is propagated along a zig-zag path in the tube cross-section. Flaws from both surfaces are indicated on the CRT screen by using as small an angle of incidence as possible, provided the wall thickness is not too great (figure 6.42).

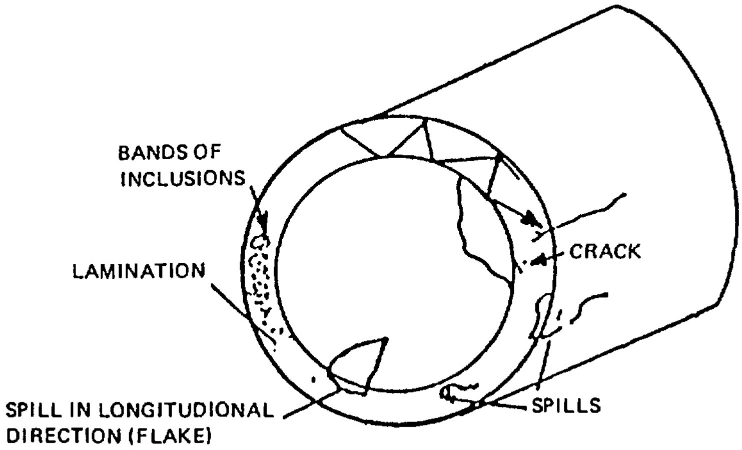


Figure 6.41 Types of defects and main direction of testing in pipes.

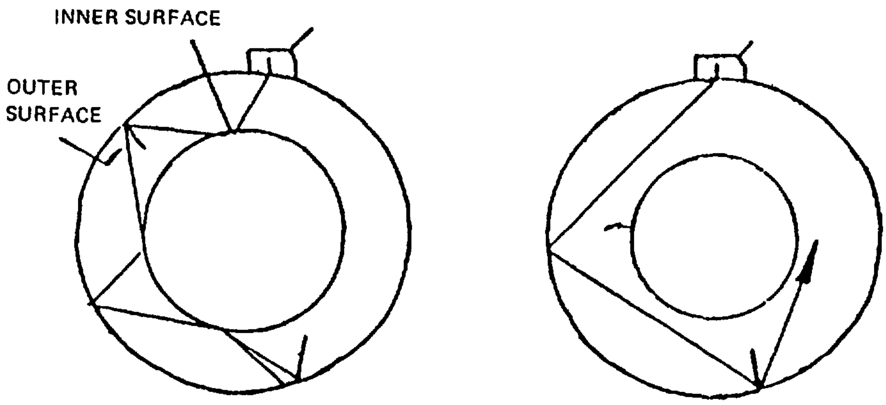


Figure 6.42 Testing of tubes using angle probes.

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 0.2. 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 6.43). Since both longitudinal and transverse waves are produced simultaneously, many interfering echoes which are not echo indications appear on the screen. Fortunately, these can be distinguished from

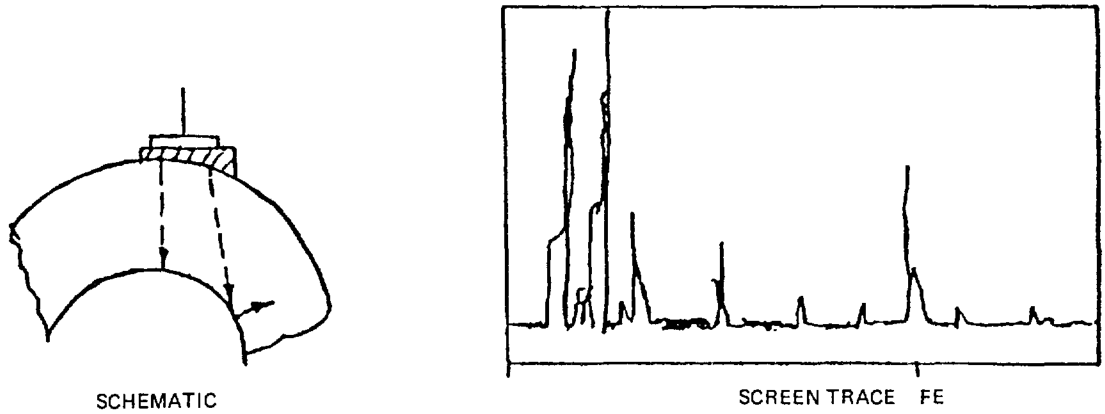


Figure 6.43 Testing method for detecting longitudinal surface defects on internal surfaces of thick-walled tubes using normal probes.

flaw echoes when the probe or the tube is rotated, since flaw echoes move across the CRT screen whereas the interfering echoes remain stationary.

6.2.4. Testing of Forgings

The testing of forgings is in many ways more straightforward 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 frequencles between 4-6 MHz and occasionally up to 10 MHz. Angled 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 prodict 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.

6.3 ULTRASONIC INSPECTION OF CASTINGS

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 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 2MHz.

Both shear and compression wave techniques are widely use 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 1/4 MHz to 2 1/2 MHz are common and occasionally it is necessary to drop to 1/2 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 1/2 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 a compression wave probe on the perspex insert of the VI 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 high penetrating power.

6.3.1. Defects in Casting

In the following, some common defects in castings along with the techniques commonly used for their detection are discussed.

6.3.1.1. Shrinkage Defects

Shrinkage defects are cavities formed during solidification and are formed through liquid to solid contraction. These defects are not normally associated with gas, but a high gas content will magnify their extent.

Shrinkage defects may occur in steel castings where there is a localised variation in section thickness. However they may also occur in parallel sections where penetration of the liquid feed metal is difficult.

Typical locations at which shrinkage cavities are most likely to occur are shown in figure 6.44. Where there is a localized change of section thickness, a hot spot will occur which can not 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.

Formation of shrinkage defects.

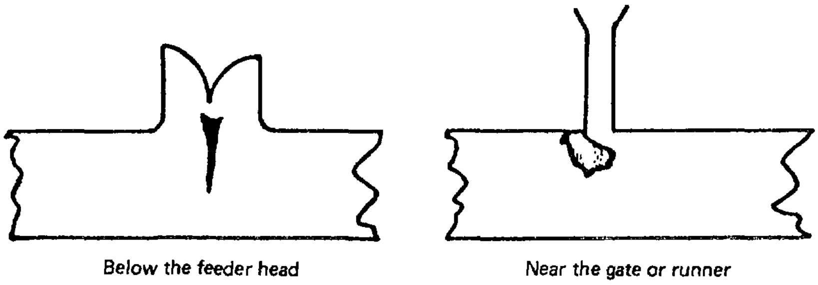


Figure 6.44 a.

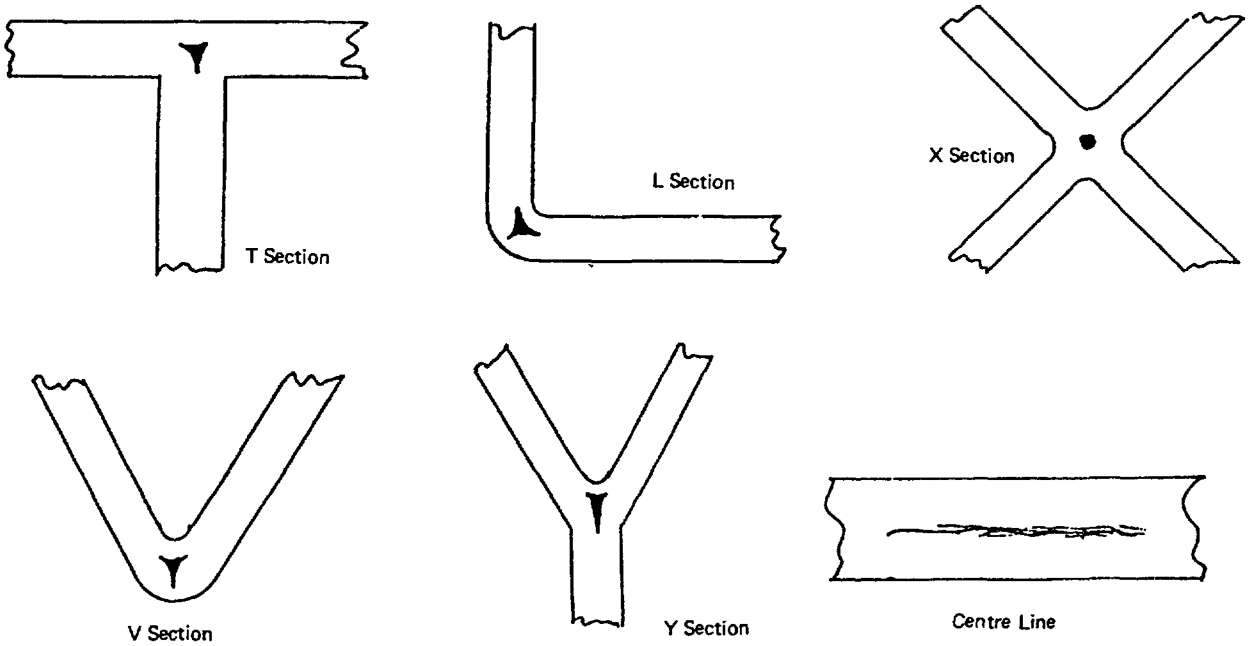


Figure 6.44 b.

Shrinkage defects in steel castings can be considered as falling in to there 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 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 use, 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

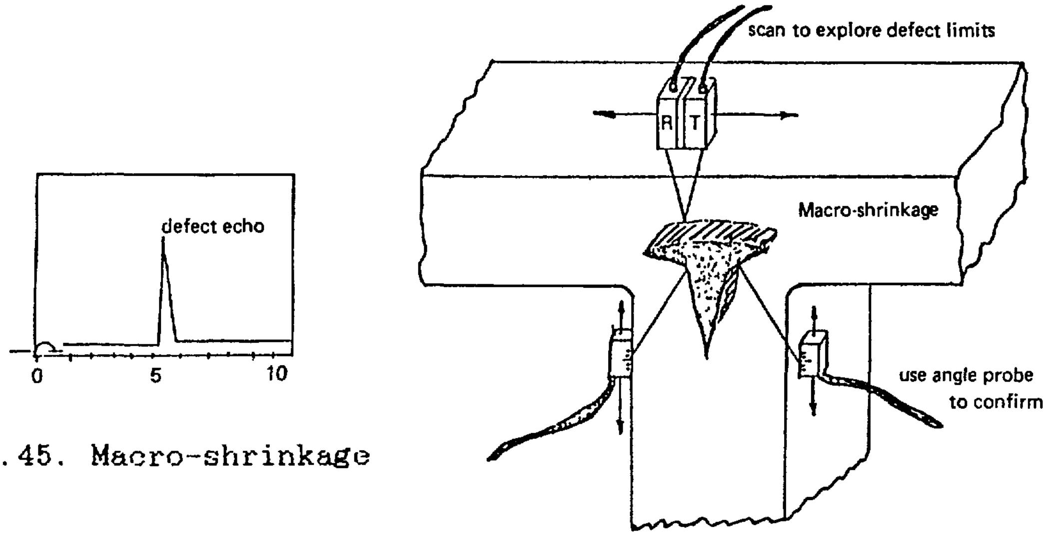


Figure 6.45. Macro-shrinkage

new defect echo. An angle probe should be used to confirm the information gained from the compression wave probe (figure 6.45).

(b) Filamentary Shrinkage

This is a coarse form of shrinkage, but of smaller physical dimension 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 worm holes. 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 (23mm) probe and the final assessment with a smaller (10-15 mm) diameter probe (figure 6.46).

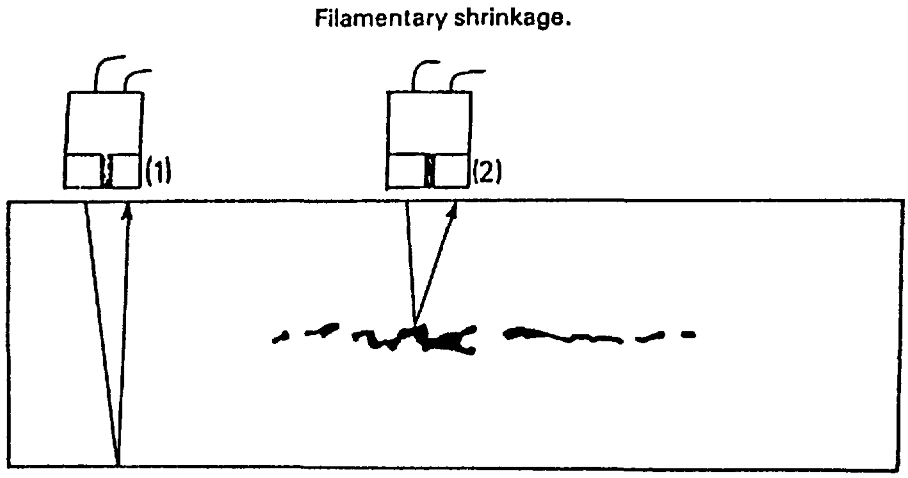


Figure 6.46.

(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).

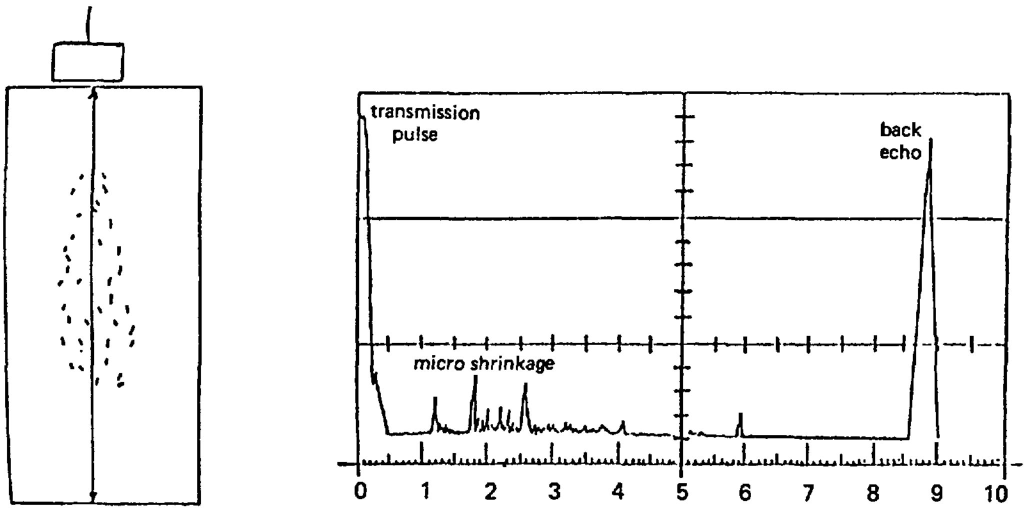


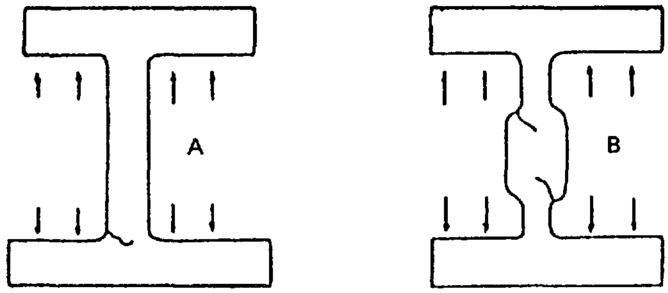
Figure 6.47 Micro -shrinkage

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 timebase (figure 6.47) . 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.

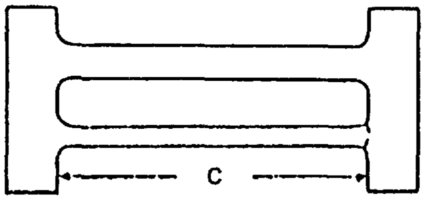
6.3.1.2 Defects Associated With Hindered Contraction During Cooling

(a) Hot Tears

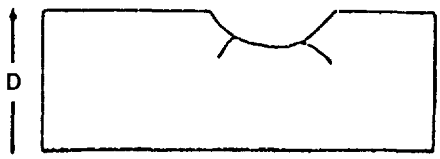
These are cracks which are discontinuous and generally of a ragged form. They are caused by stresses which develop near the solidification temperature when the metal is at its weakest. The stresses arise when the contraction of the cooling metal is restrained by a mould or core, or by an already solid thinner section. In figure 6.48 some of the causes and locations of this type of cracking are shown.



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 6.48 Hot Tears

(b) **Stress Cracks**

These are well defined, approximately straight cracks which are formed when the metal is completely solid.

The location of hot tears 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.

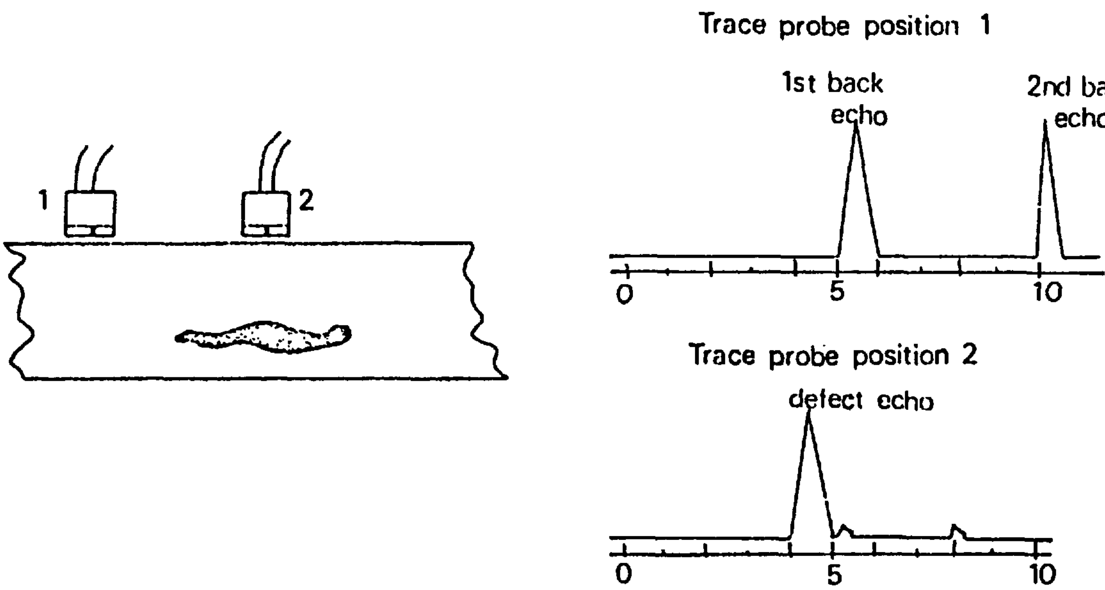


Figure 6.49 Air Locks

6.3.1.3. Defects Associated With Entrapped Gas Airlocks

When molten metal is poured in to 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 6.49).

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 "Worm hole" 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 6.50).

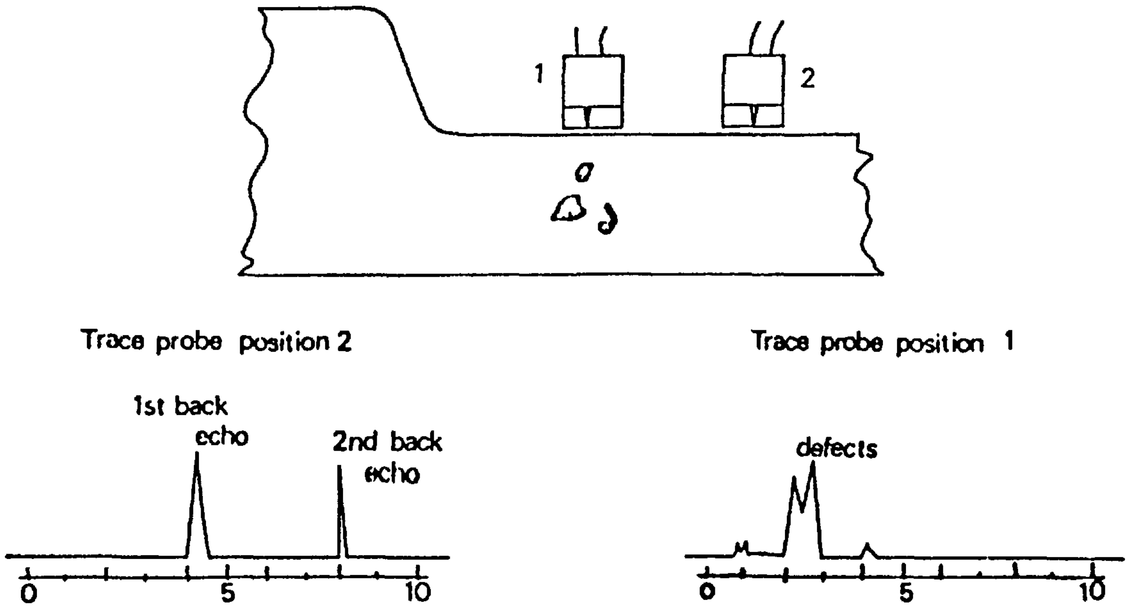


Figure 6.50 Gas Holes

7. ULTRASONIC STANDARDS

7.1 Commonly Used Ultrasonic Standards

An ultrasonic standard is a document issued by a standardizing organization to ensure reproducible results from an ultrasonic examination, no matter when, where or who conducts the examination. Some of the organizations, whose standards are commonly used in ultrasonic testing internationally, along with their addresses are listed below:

1. ASME (American Society of Mechanical Engineers)
   345 East 47th Street, New York, NY 10017, USA.

2. ASTM (American Society for Testing Materials)
   1916 Race Street,
   Philadelphia, PA 19103, USA.

3. British Standard Institution,
   2 Park Street, London W 1 A 2BS.

4. German Standard Organization (Deutscher Normenqusschuss)
   1 Berlin 30, Burggrafenstrasse 47.

The ultrasonic standards issued by the above organizations are listed along with their titles in Table 7.1. Salient features of two standards, ASME Boiler and Pressure Vessel Code and British Standard BS 3923, are given in the following sections.

7.2 ASME Boiler and Pressure Vessel Code

(a) Established Process and Features

Initial enactment of the ASME Boiler and Pressure Vessel 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 casualities 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 1986 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.

(b) Constitution of ASME Code

The following contents constitute the ASME Code, 1986 edition. Rules for nondestructive examination are collectively prescribed in Section V. Other Sections for each component (Section I, III or VIII) reference 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.

1986 ASME
BOILER AND PRESSURE VESSEL CODE

An American National Standard

Section *

I. Power Boilers

II. Material Specifications
Part A-Ferrous Materials
Part B-Nonferrous 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. Nondestructive Examination

VI. Recommended Rules for Care and Operation of Heating Boilers

VII. Recommended Rules for Care of Power Boilers

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* Available in bound and loose-leaf versions. Either version may be used for ASME Certification.

VIII. Pressure Vessels

Division 1

IX. Division 2-Alternative Rules

IX. Welding and Brazing Qualifications

X. Fiberglass-Reinforced Plastic Vessels

XI. Rules for Inservice Inspection of Nuclear Power Plant Components-Division 1

(c) **Rules Concerning Ultrasonic Examination**

In ASME Code Section V, ultrasonic examination is addressed in Articles 4,5 and 23.

Article 4 Ultrasonic Examination Methods For Inservice Inspection

This Article describes or references 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

This Article describes or references requirements which are to be used in selecting and developing ultrasonic examination procedures for welds,parts, components,materials,and thickness determinations. In all cases accept welds the Article refers to Article 23 which contains the appropiate ASTM Standards. The examination of welds is specified in considerable details since there is no appropriate ASTM Standard.

Article 23 Ultrasonic Standards

This Article 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; resonance method, straight beam method, and immersion method.

These standards are ASTM standards adopted into ASME as they are or with some modification. They are assigned the same number as ASTM with a prefix S added (ASTM A-388 -- ASME SA-388, SA-435, SA-577, SA-578, SA-609, SA-548, SE-114, SE-213, SE-214, and SE-273.

(d) **Acceptance criteria**

As already stated, acceptance criteria are not specified in Section V but each Code Section has to be consulted to find what Article of Section V is quoted there. The examination is conducted in accordance with the appropriate Article, and acceptance or rejection determined in accordance with the referencing Code Section.

As an example, acceptance criteria for welds are specified in the same way in all of,

Section I , PW-52

Section III, Subsection NB, NB-5330, and

Section VIII, Division 1, Appendix 12 (Mandatory), which are as follows;

Discontinuities are unacceptable if the amplitude exceeds the reference level, and discontinuities have lengths which exceed:

(1) 1/4 in. (6mm) for t up to 3/4 in. (19 mm), inclusive;

(2) 1/3 t for t from 3/4 in. (19 mm) to 2-1/4 in. (57 mm), inclusive;

(3) 3/4 in. (19 mm) for t over 2-1/4 in. (57 mm).

Where discontinuities are interpreted to be cracks, lack of fusion, or incomplete penetration, they are unacceptable regardless of discontinuity or signal amplitude.

7.3 BS 3923 : PART 1 : MANUAL EXAMINATION OF FUSION WELDS IN FERRITIC STEELS

Section 1. General

1. Scope

This part of BS 3923 deals with manual ultrasonic examination of fusion welded joints in ferritic steels not less than 6 mm thick.

Nozzle welds are covered in Part 3.

4. Items for agreement

The following items to be agreed between contracting parties:

(a) Size and type of the smallest flaw to be detected.

(b) Method of setting sensitivity

(c) Extent of examination

(d) Stages at which examination is to be conducted

(e) Surface condition

5. Operators

Operators shall demonstrate to the satisfaction of the contracting parties their ability in using the actual equipment to be employed for the examination.

6. Equipment

6.1 Presentation

A-scope, with permanent graticule scale markings.

6.2 Frequency within the range 1 MHz to 6 MHz.

6.3 Time base linearity to within 1% over the whole range.

6.4 Amplifier linearity to full graticule height.

6.5 Attenuator shall have steps not greater than 2dB and an accuracy of not less than 1 dB over a 20dB range. Internal 'noise' from probe shall not interfere with interpretation of results at the working sensitivity.

6.7 Resolution to block A7 in BS 2704, and the steps are resolved when their echoes are clearly separated at 6 dB below maximum echo height.

7. Information

The operator shall be given the following information before commencement of weld examination:

a. Type of ferritic steel and form (cast, forged, rolled).

b. Joint preparation.

c. Weld process; type and probable location of defects likely to occur.

d. Details of any repairs.

e. Postweld heat treatment.

f. Acceptance standard, including test sensitivity and acceptable flaw sizes.

8. **Surface**

8.1 Condition

Surface contact with probe must be satisfactory and maintain good coupling. Spatter and loose scale to be removed. Surface roughness not to exceed 6.3 um Ra or 250 C.L.A.

8.2 Profile

Weld ripples to be removed to avoid confusing surface echoes.

For critical examination, weld reinforcement shall be removed by grinding or machining to produce a smooth blending with the parent material on each side of the weld. Variations across weld not to exceed 1.5 mm in any 50 mm length.

Section 2 . Parent metal examination

9. **General**

Parent plate will be tested after welding.

a. To locate flaws, such as laminations or tears.

b. To establish material thickness.

c. To note any attenuation variations.

13. **Test sensitivity (normal probe)**

Second back wall echo to be maintained at full screen height during examination.

14. **Reporting**

A report on parent material examination shall be made describing and indicating local areas of laminations, surface flaws, areas of high attenuation.

Section 3. Weld examination procedures

15. **General**

Weld examination to consist of :

a. Parent material.

b. Weld root.

c. Fusion faces.

d. Weld body.

e. Defects lying transverse to weld.

16. Location of root

Before testing the exact location of root shall be made by a normal or transverse wave probe and accurately marked.

17.6. Test sensitivity

The size and type of the smallest flaw to be detected shall be agreed between contracting parties before testing is commenced.

The sensitivity of the flaw detector/probe combination shall be such that a clear signal will be obtained from the smallest defect to be detected throughout the scanning range.

18. Root scan with angle probes

18.1. General

A fixed root scan should be carried out from both sides using a guide strip.

18.2. Calibration

Calibration of equipment in accordance with BS 2704 and BS 4331 Part 3.

These checks must include :

a. Position of probe index.

b. Time base.

c. Angle of refraction.

d. Vertical beam spread.

e. Horizontal beam spread.

23. Evaluation of imperfections

Any significant echo signal noted shall be further investigated by the appropriate technique to :

a. Confirm the existence of flaws.

b. Determine flaw location with reference to datum points.

c. Estimate the flaw size.

d. Establish nature of flaw.

24. Presentation of results

Scale drawing are recommended indicating length of defect, depth, minimum depth below a given surface, i.e. the inner surface of a pressure vessel.

Appendix A

Guidance to probe selection.

Appendix B

Guidance on the determination of probe characteristics.

Appendix C

Note for guidance on the D.G.S. diagram.

Appendix D

Method for setting sensitivity where maximum sensitivity is required.

Appendix E

Method for determining the location, size and nature of flaws.

Table 7.1 List of Standards

Organization	Standard Number	Title
ASTM	NIL	Proposed Practice for Evaluating the Characteristics Units.
	NIL	Proposed Practice for Evaluating the Electronic Characteristics of Sections of Pulse-Echo Ultrasonic Inspection Instruments.
	NIL	Proposed Recommended Practice for the Detection and Evaluation of Discontinuities by the Immersed Pulse-Echo Ultrasonic Method Using Longitudinal Waves.
	A21	Carbon Steel Axles, Non-Heat-Treated and Heat-Treated, for Railway Use.
	A376	Specifications for Seamless Austenitic Steel for High Temperature Control Station Service.
	A388	Ultrasonic examination of Heavy Steel Forgings.
	A418	Ultrasonic Inspection of Turbine and Generator Steel Rotor Forgings.
	A435	Straigh-Beam Ultrasonic Examination of Steel Plates for Pressure Vessels.
	A450	General Requirements for Carbon, Ferrite Alloy, and Austenitic Alloy Steel Tubes.
	A503	Ultrasonic Examination of Large Forged Crankshafts.
	A531	Ultrasonic Inspection of Turbine-Generator Steel Retaining Rings.
	A556	Standard Specification for Seamless Cold-Drawn Carbon Steel Feedwater Heater Tubes.
	A557	Standard Specification for Electric-Resistance Welded Carbon Steel Feedwater Heater Tubes.
	A577	Ultrasonic, Angle-Beam Examination of Steel Plates.
	A578	Straight-Beam Wave Ultrasonic Examination of Plain and Clad Steel Plates for Special Applications.
	A609	Longitudinal Beam Ultrasonic Inspection of Carbon and Low-Alloy Steel Castings.
	A745	Ultrasonic Examination of Austenitic Steel Forgings.
	B548	Specification for Standard Method for Ultrasonic Inspection of Aluminum Alloy Plate for Pressure Vessels.

Table 7.1 List of Standards

Organization	Standard Number	Title
ASTM	B594	Ultrasonic Inspection of Aluminum-Alloy Products for Aerospace Applications.
	C597	Test Method for Pulse Velocity Through Concrete.
	D2845	Test Method for Pulse Velocities and Ultrasonic Elastic Constants of Rock, Laboratory Determination of.
	D2966	Test Method for Cavitation Erosion-Corrosion Charactericstics of Aluminum in Engine Coolants Using Ultrasonic Energy.
	E114	Recommended Practice for Ultrasonic Pulse-Echo Straight-Beam Testing by the Contact Method.
	E127	Fabricating and Checking Aluminum Alloy Ultrasonic Standard Reference Blocks.
	E164	Ultrasonic Contact Inspection of Weldments.
	E213	Ultrasonic Inspection of Metal Pipe and Tubing for Longitudinal Discontinuities.
	E214	Immersed Ultrasonic Testing by the Reflection Method Using Pulsed Longitudinal Waves.
	E273	Ultrasonic Inspection of Longitudinal and Spiral Welds of Welded Pipe and Tubing.
	E317	Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Systems Without the Use of Electronic Measurement Instruments.
	E428	Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection.
	E453	Recommended Practice for Examination of Fuel Element Cladding Including the Determination of the Mechanical Properties.
	E49	Measuring Ultrasonic Velocity in Materials.
	E500	Standard Definitions of Terms Relating to Ultrasonic Testing.
	E587	Ultrasonic Angle Beam Examination by the Contact Method.
	E588	Detection of Large Inclusions in Bearing Quality Steel by the Ultrasonic Method.
	E664	Measurement of the Apparent Attenuation of Longitudinal Ultrasonic Waves by Immercion Method.
	E797	Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method.

Table 7.1 List of Standards

Organization	Standard Number	Title
ASTM	804	Calibration of an Ultrasonic Test System by Extrapolation Between Flat-Bottom Hole Sizes.
	F600	Nondestructive Ultrasonic Evaluation of Socket and Butt Joints of Thermoplastic Piping.
	G46	Recommended Practice for Examination and Evaluation of Pitting Corrosion.
SME	Section V	Boiler and Pressur Vellel Code: Nondestructive Examination.
	B.S. 4331	Method for assessing the performance characteristics of Ultrasonic flaw detection equipment. Part 1 : overall performance Part 2 : Electrical performance Part 3 : Guidance on the inservice monitoring of probes (excluding immersion probes).
British Standard Organization	B.S. 2704	Calibration block and recommendations for their use in ultrasonic flaw detection.
	B.S. 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. Part 3 : Manual examination of nozzle welds
	B.S. 3683	Glossary of terms used in non destructive testing. Part 4: Ultrasonic flaw detection.
	DD28	Method of ultrasonic inspection of turbines and compressor discs using the AVG diagram technique.
	M36	Ultrasonic testing of special forgings by an immersion technique using flat-bottomed holes as a reference standard.
	B.S. 4408	Recommendations for non-destructive methods of test for concrete. Part 5 : 1974 Measurement of the velocity of ultrasonic pulses in concrete.
	B.S. 4336	Methods for non-destructive testing of plate material. Part 1A Ultrasonic detection of laminar imperfections in ferrous wrought plate.
	B.S. 3889	Methods for non-destructive testing of pipes and tubes. Part 1A Ultrasonic testing of ferrous pipes (excluding cast).
	DTD 936	Ultrasonic inspection of aluminium alloy inspection and hand forgings.

Table 7.1 List of Standards

Organization	Standard Number	Title
British Standard Organization	DTD 937	Ultrasonic inspection of aluminium alloy plate.
German Standard Organization	DIN 54119	Ultrasonic testing definitions.
	DIN 54120	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.

8. RECORDING AND EVALUATION OF RESULTS

8.1 Determination Of The Location, Size And Nature Of A Defect

After the initial examination, any significant echo signal is investigated to :-

(a) determine the flaw location with reference to a datum.

(b) estimate the flaw size.

(c) estimate the nature of the flaw.

8.1.1. 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 8.1 . 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.

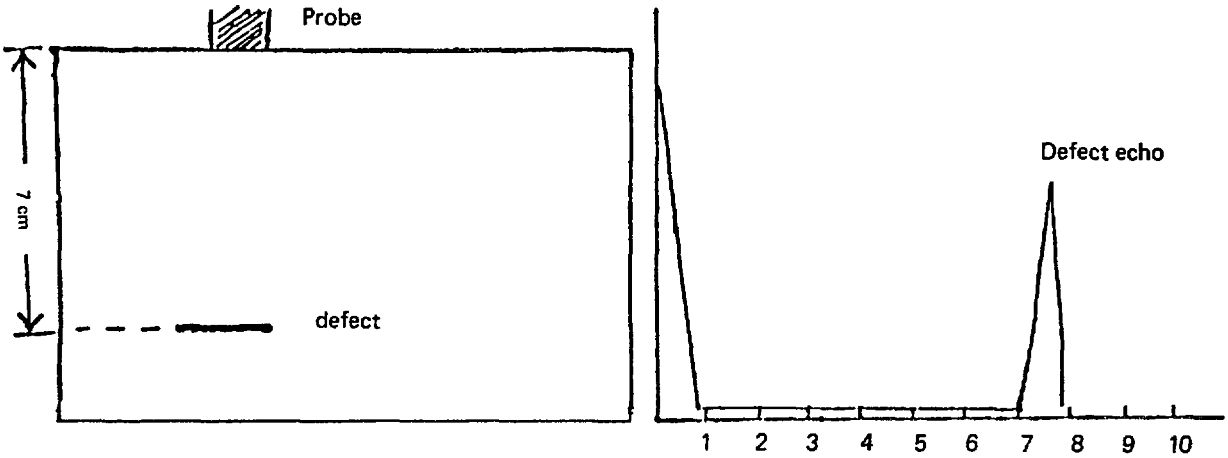


Figure 8.1

For example in Figure 8.2 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 the ultrasonic inspection of welds is often done using a Flaw Location Slide. Defect location can also be determined by producing an accurate sketch or by calculation.

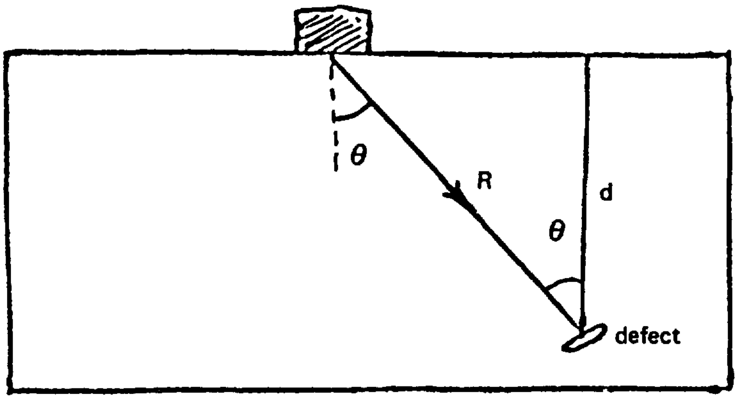


Figure 8.2

8.1.2 Methods Of Defect Sizing

The commonly used methods for flaw sizing in ultrasonic testing are :

i. 6 dB drop method.

ii. 20 dB drop method.

iii. Maximum amplitude method.

iv. DGS diagram method.

These methods are discussed below.

8.1.2.1 6 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 in to line with the edge of the flaw as illustrated in Figure 8.3. The method only works when used as described if the ultrasonic response from the flaw is essentially uniform over the whole reflecting surface.

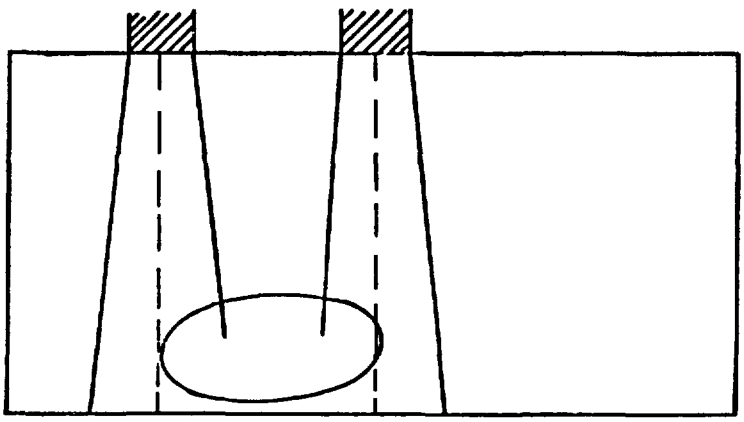


Figure 8.3

The procedure to determine the dimension of a flaw parallel to the probe movement ie. 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.

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.

8.1.2.2. 20 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.

The 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).

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.

$$\phi = D + 2 (d - Xo) \tan \quad ---- (8.1)$$

Where ϕ = beam width.

d = defect depth.

Xo = near field length.

D = probe diameter.

ix. (vii) minus (viii), as illustrated in Figure 8.4 will thus give the dimension of the flaw parallel to the movement of the ultrasonic beam.

As for the 6dB drop method if the echo amplitude varies as the probe is traversed across the flaw the 20dB drop should be carried out from the last significant echo peak.

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 2o dB drop methods 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 :

1. 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.

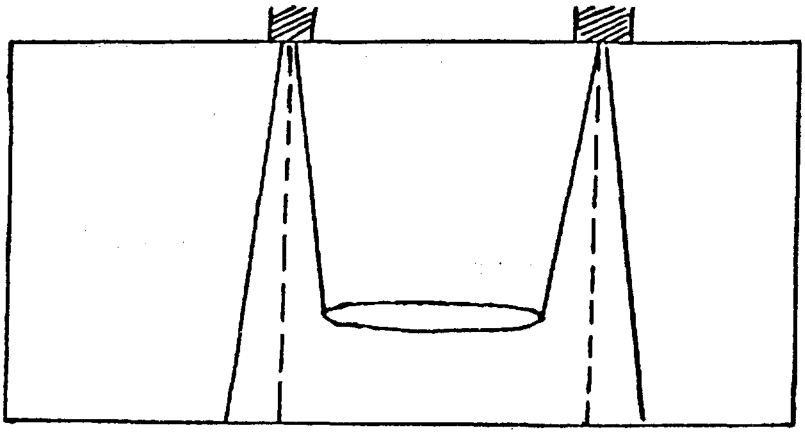
2. The orientation of the defect may change so that the probe angle is so longer giving maximum response - another probe may have to be used.

3. The defect may change its direction.

4. The probe may be twisted inadvertantly.

5. The surface roughness may change.

Figure 8.4



8.1.2.3. Flaw Location Slide

The School of Applied Non Destructive Testing (SANDT) at Cambridge, U.K., has developed a Flaw Location Slide for the location and sizing of defects in welds using the 20 dB drop method. The Flaw Location Slide consists of a beam plotting chart and a transparant cursor. Both parts of a Flaw Location Slide are shown in Figure 8.5 a and b.

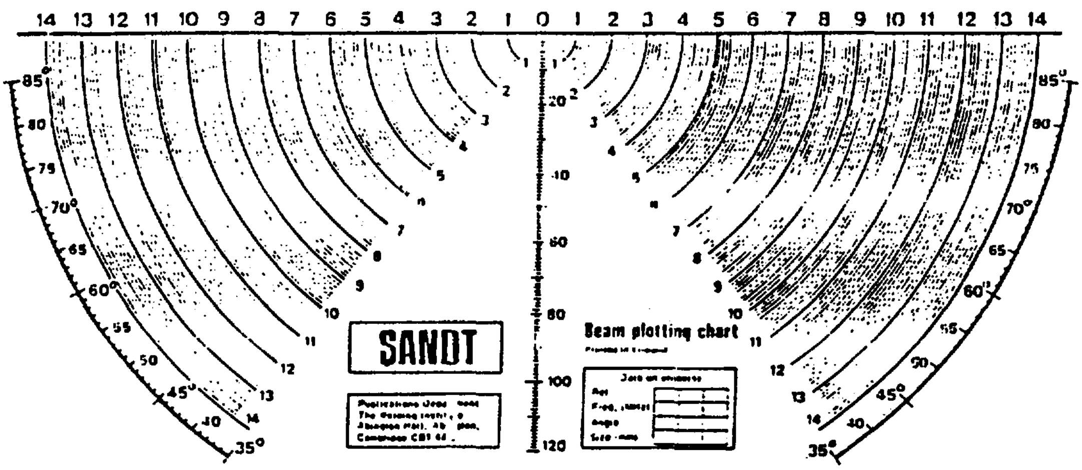


Figure 8.5 a .

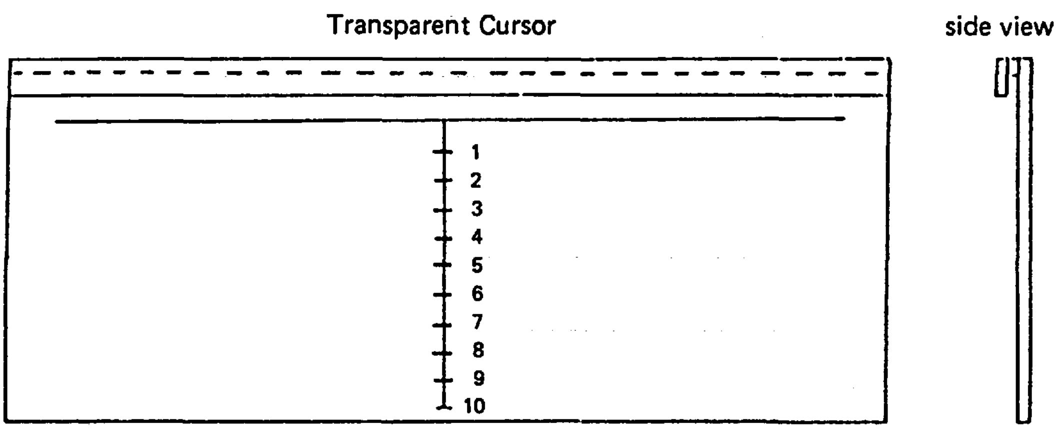


Figure 8.5 b .

8.1.2.3.1 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 8.6 .

v. Draw horizontal lines across the beam centre at depths of 13, 19, 25, 32, 43, 50, 56, and 62 mm (figure 8.6)

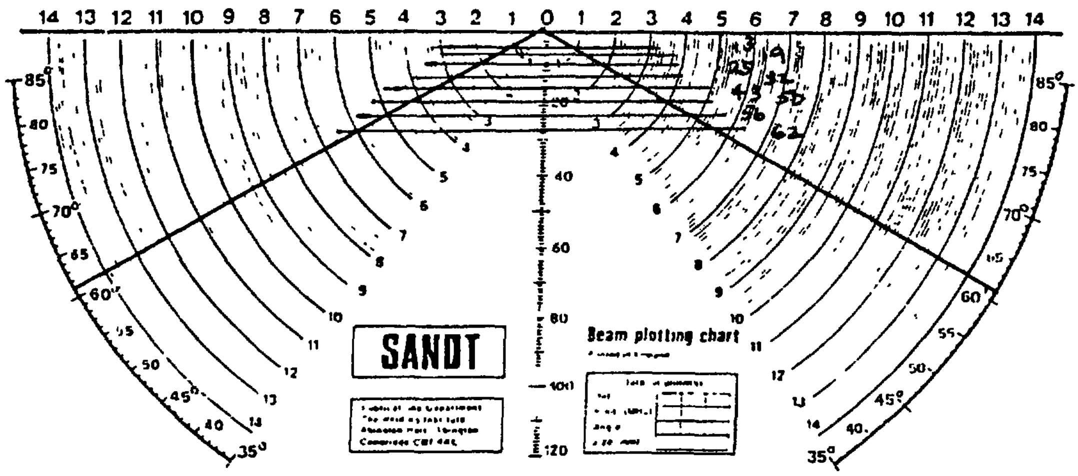


Figure 8.6 .

vi. Using the procedure outlined in section 5 determine the distances ab and ac and the corresponding beam path lengths (BPL) for each hole.

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 8.7 .

viii. Using the procedure outlined above, draw the beam profiles of 45° and 70° probe on one side of the chart and the beam profile of 60° probe on the other side of the chart.

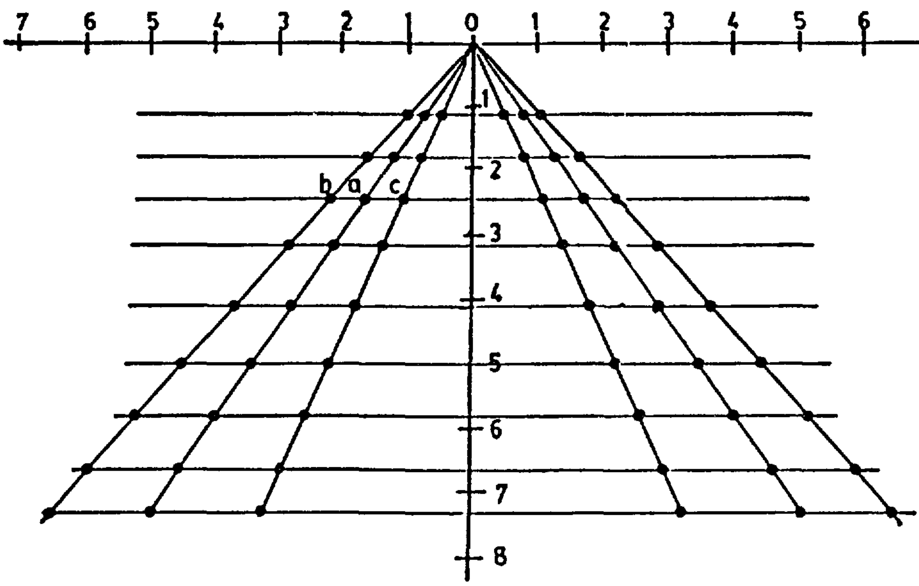


Figure 8.7 .

8.1.2.3.2. 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 8.8 .

In figure 8.8 the weld preparation of a single vee weld in 20 mm plate, and its mirror image, is drawn on the cursor.

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

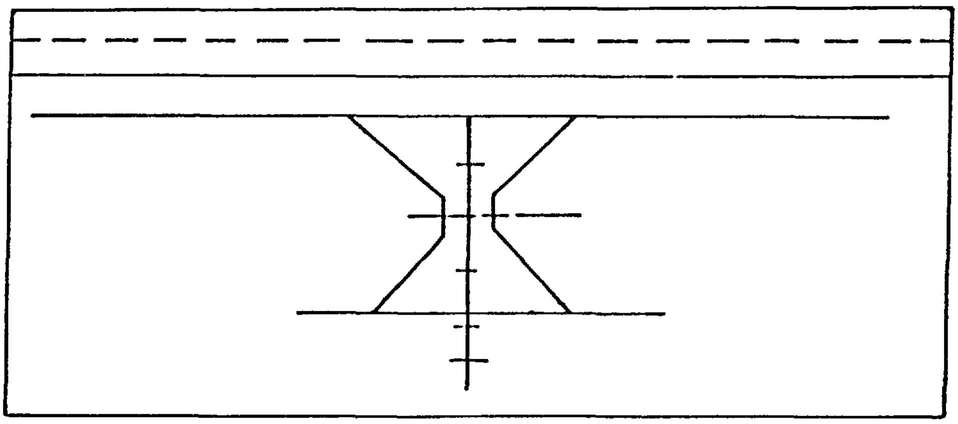


Figure 8.8

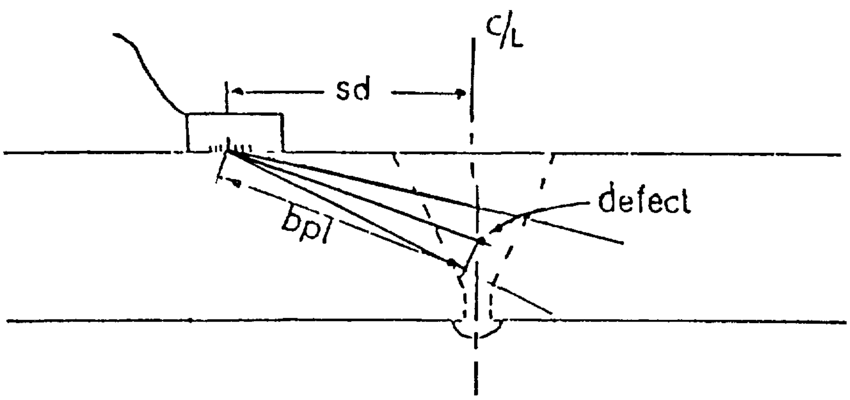


Figure 8.9 .

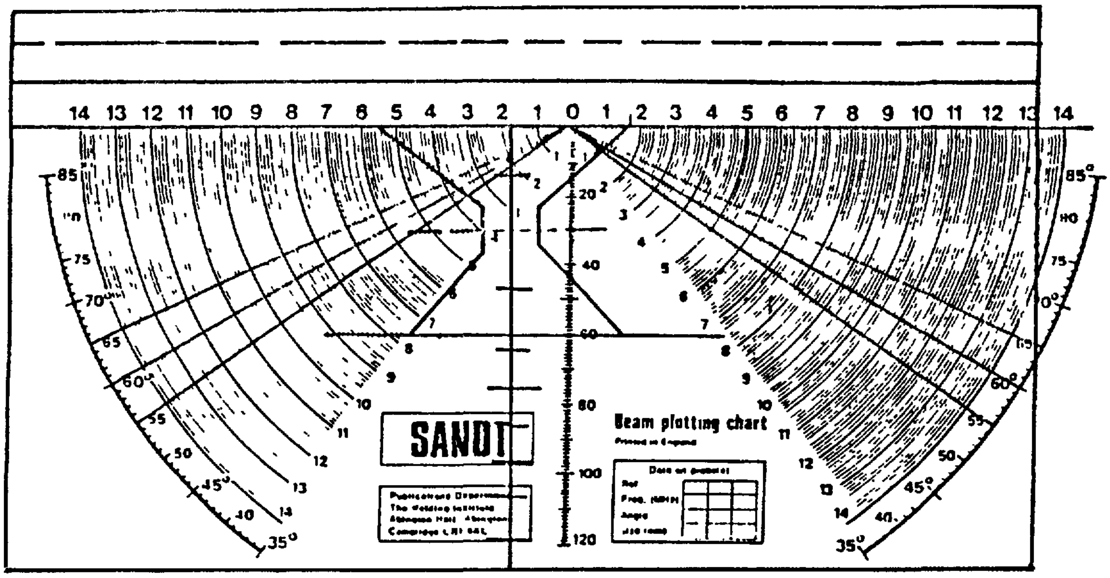


Figure 8.10 .

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 8.9 .

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 8.10.

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 8.10).

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 8.11.

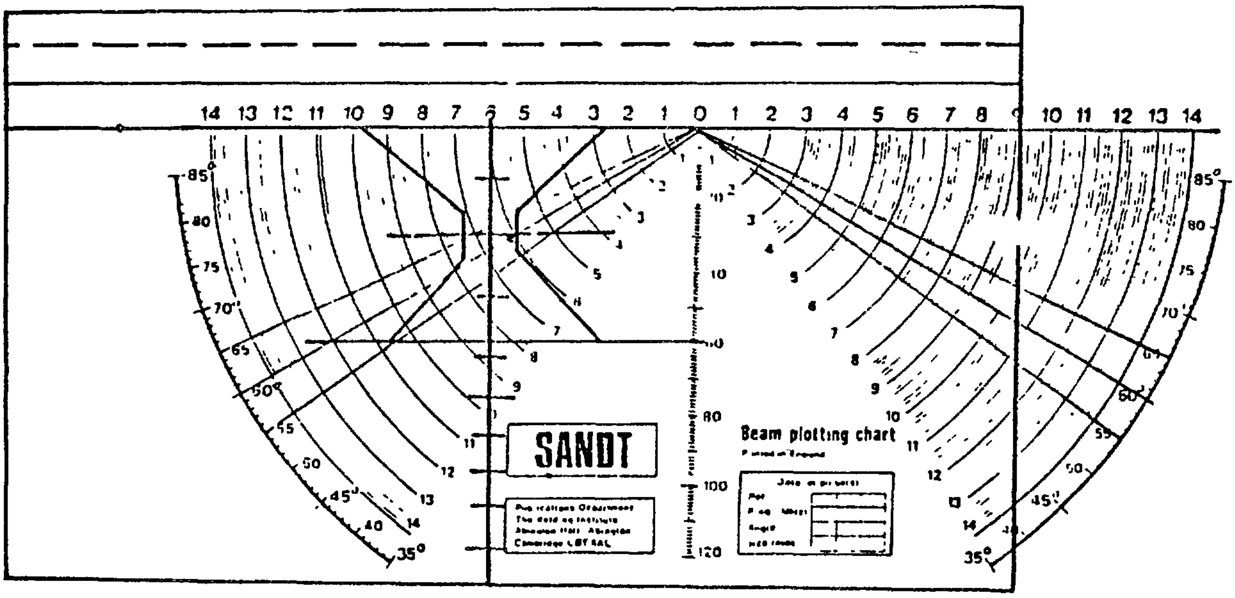


Figure 8.11 .

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 8.11).

viii. Mark the point 61 mm down the beam centre as shown in figure 8.11. This point gives the location of the flaw in the weld.

8.1.2.3.3. **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 8.1.2.3.2.

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 8.12 a, the three points on the cursor would have shown the size and orientation of the flaw as illustrated in figure 8.12 b.

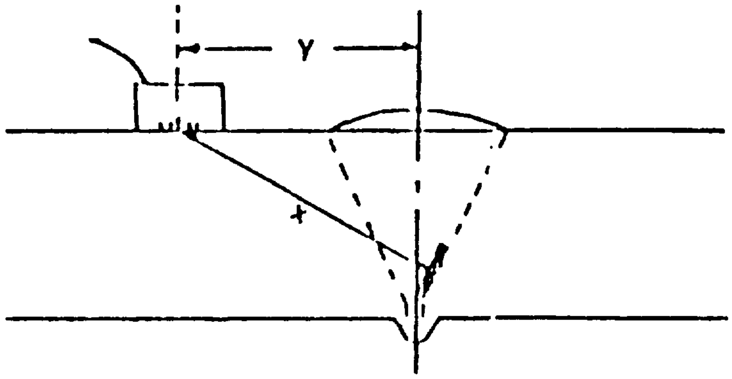


Figure 8.12a .

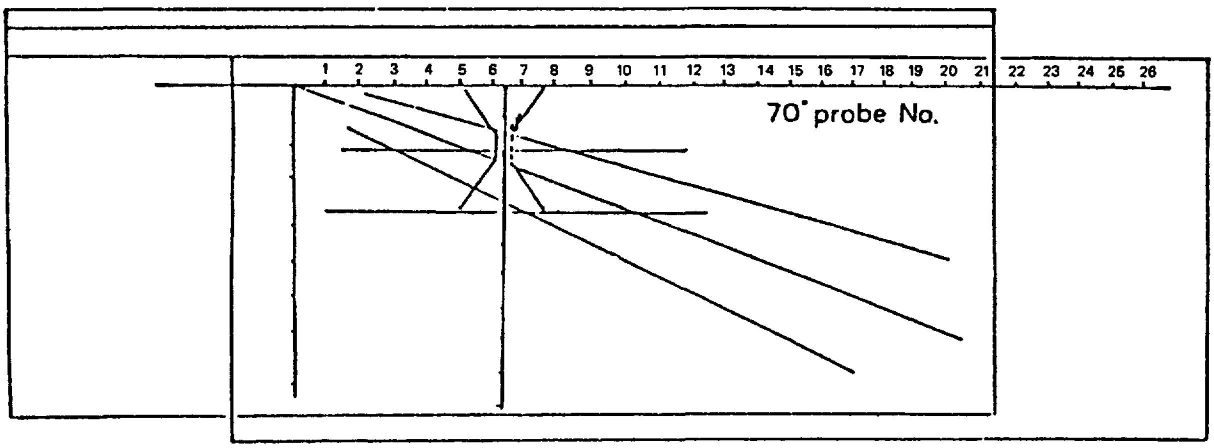


Figure 8.12 b.

8.1.2.4. Maximum Amplitude Technique

This method takes in to account that fact that most defects which occur do not present a single, polished reflecting surface, but in fact take a rather ragged path through the material with some facets of the defect surface suitably oriented to the beam and some unfavourably oriented. Figure 8.13 illustrates this, showing a crack propagating in a weld.

Each of the reflecting facets will be at a slightly different range, and although they may be too close together to resolve as separate echoes, the echo envelope can nevertheless be regarded as a series of overlapping separate echoes. In fact the envelope may look like figure 8.1 a, b, or c depending on the degree of range variation from the different facets and on the resolution of the equipment.

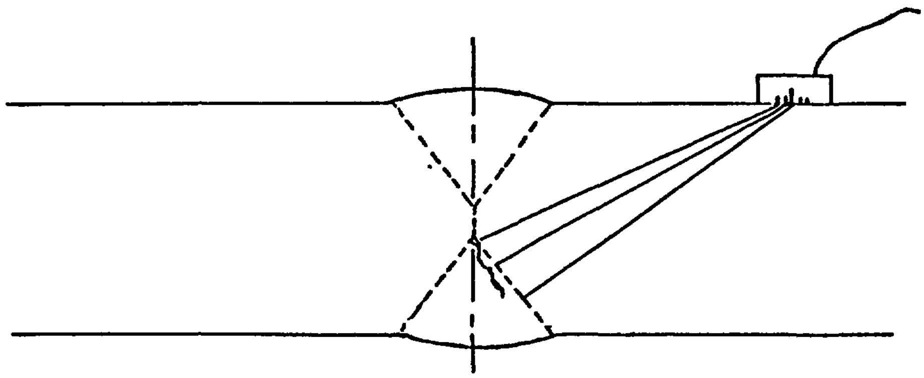


Figure 8.13.

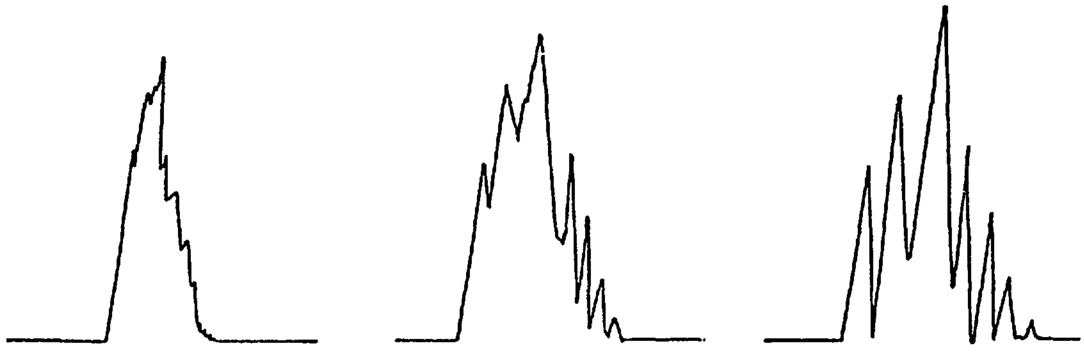


Figure 8.14.

As the beam is scanned across the surface of the defect, the beam centre will sweep each facet in turn. As it does, the echo from that facet will reach a maximum and then begin to fall, even though the main envelope may at any instant, be rising or falling in echo amplitude. The stand-off and range of the maximum echo of each facet is noted and plotted on the flaw location slide. This results in a series of points which trace out the extent of the defect. The gain is increased to follow the series of maximum echoes until the beam sweeps the last facet.

8.1.2.5. DGS Diagram Method

If after setting the sensitivity, drawing the record line and the attenuation curve on the DGS diagram of the probe used (as described in section 5.5), a flaw is detected during scanning whose echo exceeds the reporting level (i.e. 2/5th full screen height) the equivalent size of the disc type reflector for this defect is estimated as follows for both a normal beam probe and an angle beam probe :

i. Determine the flaw echo amplitude in decibels above the reporting level (i.e. above the 2/5th full screen height). Let the dB value be AdB.

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)

Probe frequency = 5MHz

Probe crystal dia = 10 mm

Sensitivity setting = as described in section 5.5.

Near field length = 21 mm

i. Echo height above the reporting level of 2/5th 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 5.34 is 1 dB.

iv. Difference between (i) and (iii) = 8 dB.

v. Point of intersection of a line draw at 2 near field lengths and line drawn at 8 dB lies close to 0.4 S-value line (DGS diagram of figure 5.34).

vi. Equivalent disc diameter = 0.4 x 10 = 4mm.

Example 2 (Angle beam probe)

Sensitivity setting = as in section 5.

i. Flaw echo amplitude above the reporting level = 40dB

ii. Flaw depth = 50 mm

iii. Difference between record level and attenuation curve at 50 mm = 12dB from DGS diagram of figure 5.35

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 5mm S-curve.

vi. Hence the diameter of equivalent disc = 5mm.

8.1.3. Determination of the Nature of a Defect

After obtaining information about the location and size of a defect, and having a knowledge of the manufacturing process, an estimation of the nature of the defect can be made. The nature of a flaw is ascertained by a series of controlled movements of the probe. Different type of probe movements are as shown in figure 8.15.

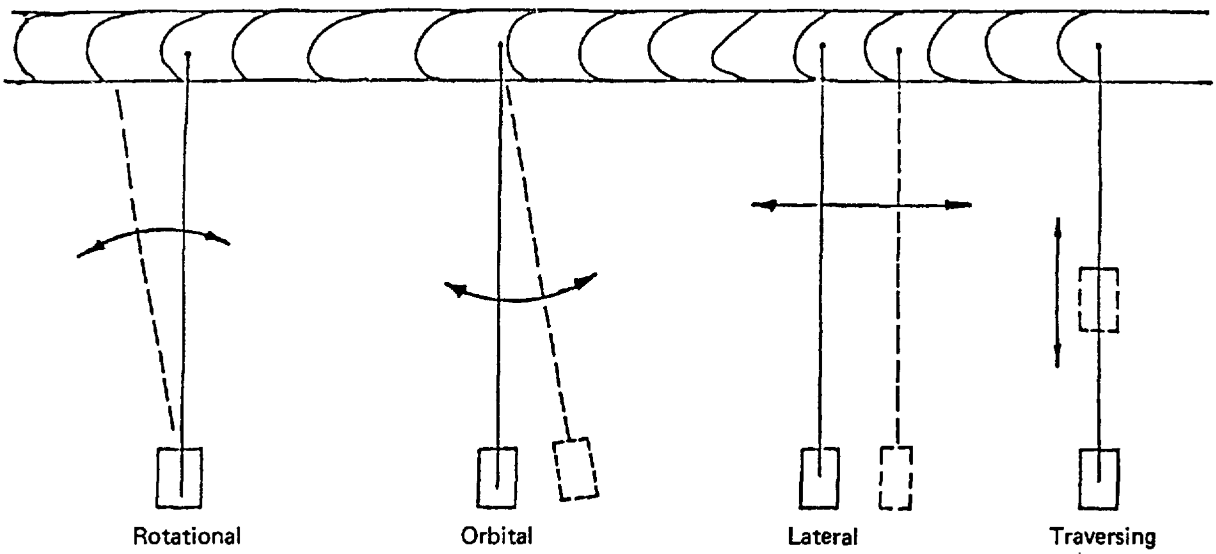


Figure 8.15 Probe movement

In general, for welds, a flaw can be differentiated as one of the following types.

(a) 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 8.16).The height and 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 8.16

During rotational, lateral and transverse scans the echo rises and falls quickly and smoothly as the beam scans through the discontinuity.

(b) **Porosity**

This gives rise to a lot of tiny echoes, depending on the number and distribution of the pores (figure 8.17).

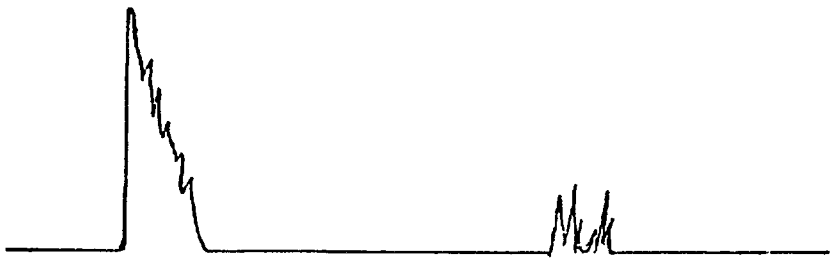


Figure 8.17

In most cases, echoes 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.

(c) **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 ragged surface, which offers many small targets at different distances, the echo rises like a pine tree from the zero line of the screen (Figure 8.18)

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 change shape and position. If the flaw is elongated parallel to the seam, a lateral scan 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

Figure 8.18.

pores, slag inclusions have no preferred location in the weld seam.

(d) **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 8.19). Therefore, it should be easy to distinguish a slag inclusion from a planar flaw.

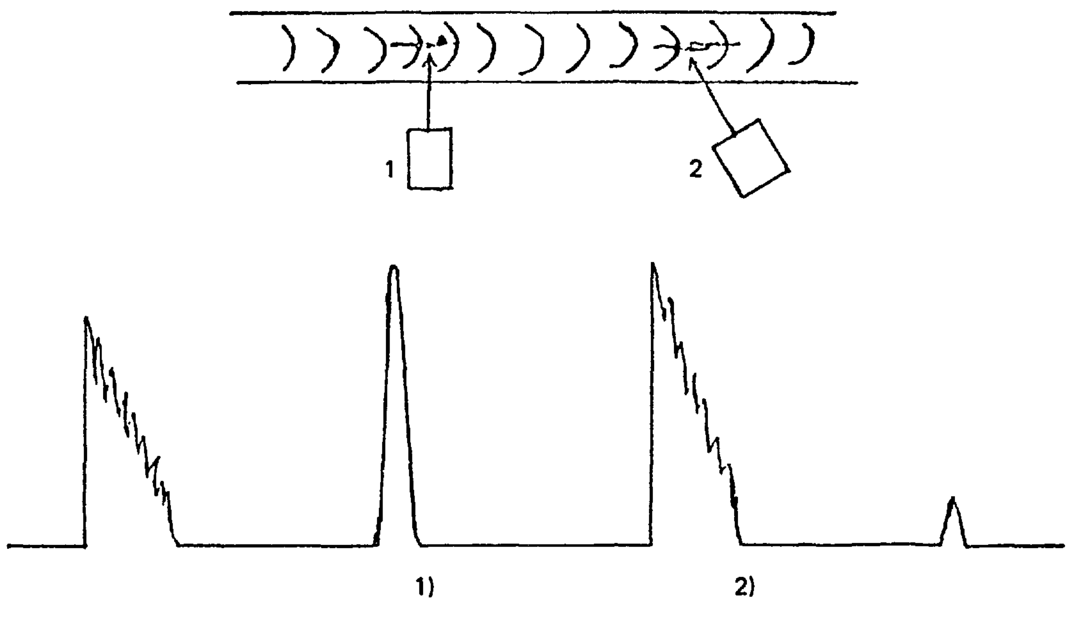


Figure 8.19.

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 radiated 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.

(e) Although it is easy to recognise 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 the flaws, 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 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 classification can be confirmed by using the flaw location slide.

8.2 ULTRASONIC TEST REPORT

In order that the results of the ultrasonic examination may be fully assessed, it is necessary for the inspectors's findings to be systematically recorded. The form of the report may be different, but, generally, it must contain, clearly and concisely, the following information :

(a) Indentification

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. Serial Number, Description, Material.

vii. Code, Specification or standards used.

(b) **Equipment**

i. Flaw Detector.

ii. Probes, Size, Frequency, Angle.

iii. Calibration and reference blocks used.

iv. Couplant.

(c) **Calibration**

i. Sensitivity for all probes used.

ii. Timebase for all probes used (a base range for)

iii. Attenuation and transfer corrections, where appropriate.

(d) **Technique**

i. Scans made (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.

(e) **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 with association with the full term, for example, "3mm diameter (3mm) , flat bottomed hole (f.b.h.)" . Results, that are shown in tabular form, or in sclae drawings, are easier to follow than long written descriptions.

Examples of two typical report forms and sketches, indicating the location of flaws, are shown in figure 8.20 and 8.21.

SINGAPORE INSTITUTE OF STANDARDS AND INDUSTRIAL RESEARCH

ULTRASONIC TEST REPORT

This is A Test Report and Not A Quality Certificate
This Report Must Not Be Used For Advertisement.

Our Ref :   Date :

Butt-Welded Plate

Client : M/s ABC Company   Site : Z - workshop

Job Identification :

Joint No. 1

Material : Type 1 steel

Thickness : 25mm nominal

Edge Psreparation : 60° double-vee

Plate Surface Preparation : As rolled

Welding Process : Manual metal arc

Stress Relieved : Yes/No

Probes used :

	Size	Frequency	Angle	Type
(a)	8 x 9mm	4mHz	60°	MWB60
(b)	8 x 9mm	4mHz	45°	MWB45
(c)	20 mm 0	4mHz	0°	SEB4H
(d)				

Welder :

Flaw Detector: Krautkramer USM2M

Sensitivity Setting :

Gain settings for evaluating discontinuitien

Test block	0	45	60
25 mm	50 dB	55 dB	60 dB

Technique : Parent metal : The parent metal was scanned with the SE probe on both sides of the seam at 1 skip distance from it.

Butt weld : The weld was scanned on both sides of the seam and on both plate surfaces, where necessary, using both angle probes. All defect lengths were estimated using the 20-dB drop method.

Results :

(a) Parent metal : No lamination was detected in the parent metal scanned.

(b) Weld : Echoes detected were below 20% of corrected PRE or each discontinuity length was less than the maximum allowed in ASME Section 8, except those detected in the areas as detailed in the following sheets.

Figure 8.20

Our Ref : Date :

Job Desoription :		Butt-welded Plate			
Weld No		1 - A	"	"	1 - B
Datum		East end of beam	"	"	"
Flaw No		1	2	3	-
Probe angle	deg.	60	60	60	60
Signal range on screen	mm	50	50	65	-
Gain setting (PRE + T.L)	db	62	62	62	-
Signal PRE	mm	X	-	-	-
PRE Signal 20% of PRE	mm	-	20	4	-
Distance from datum	cm	150	350	450	-
Defect distance from surface	mm	5	5	10	-
Defect depth	mm	4	3	3	-
Signal 20% of PRE		-	-	-	-
Defect type		Slag inolusion	Slag inclusion	Lack of Penetration	-
Compliance to ASME Section 8	Pass	-	-	-	X
	Fail	X	X	X	-

Operator : ____________

Figure 8.20 (cont.)

ULTRASONIC TEST REPORT

Defect Location In Centimetres From Datum

Job Identification :

Datum (EAST END)
(OF SCAN)

I - A

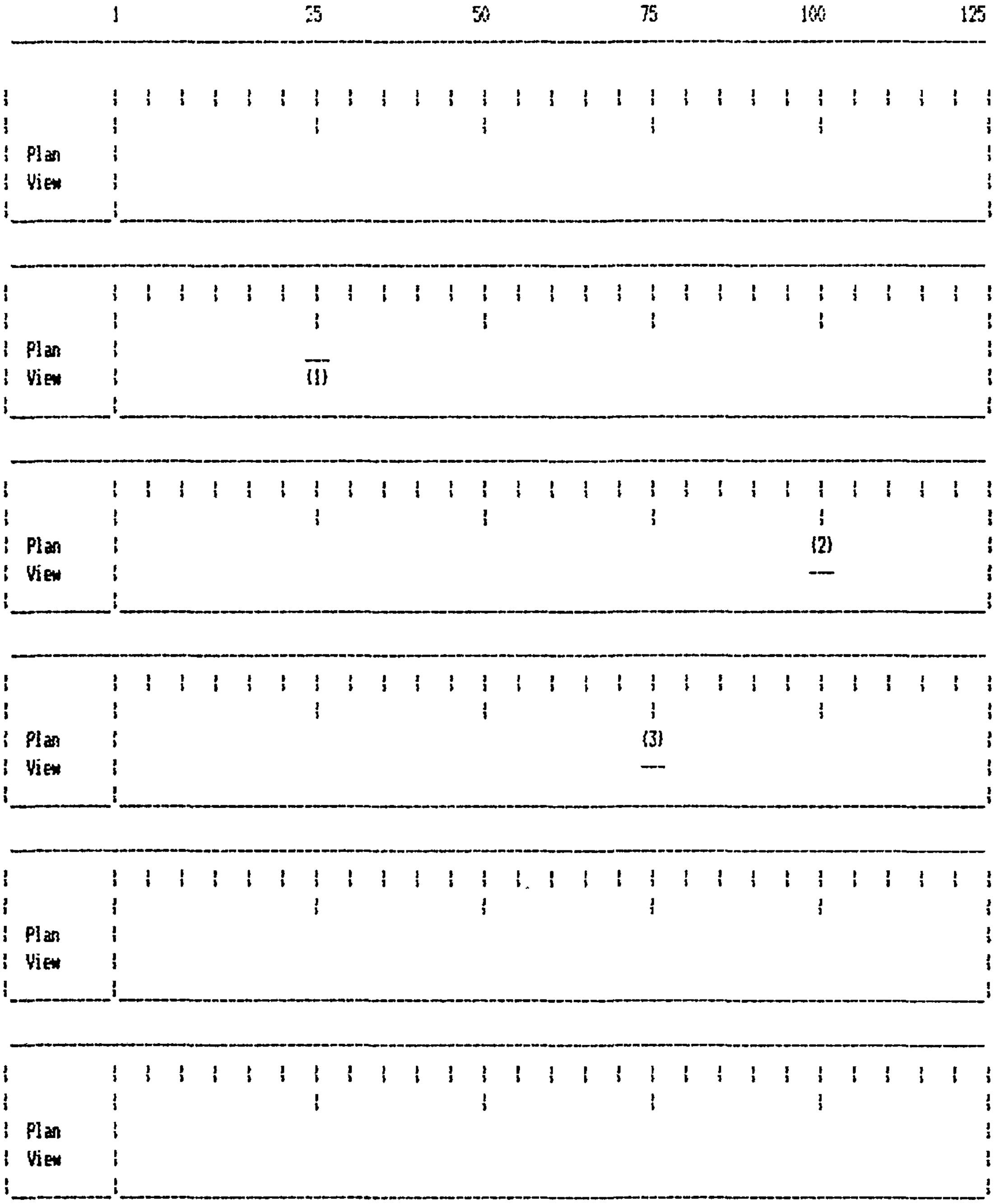


Figure 8.20 (cont.)

THE UNIT INSPECTION COMPANY LIMITED

USI

EURO

UNIT INSPECTION

Report No.

ULTRASONIC INSPECTION REPORT

Issuing Office			Date of Test
Customer: Unit Inspection	Location: Sixth Hall	Customer Order No.	Unit Job No.

Type of Work Piece: Double Vee	Identification of Work Piece: TP6

Service and Description of Work Piece	Size: 20 mm	Material: Mild steel

Welding Process: MMA	Welding Position: Downhand	Welder	Stress Relieved Yes ☐ No ☐
Inspection Specification	Acceptance Specification	Reporting Level	Couplant

Flaw Detector: Krautkramer USM2	Probe Type, Size, Angle, Frequency: 0° 10mm 5MHz MAP70° / MAP45° 4MHz	Time Base Calibration Blocks and Time Base Calibration: V2 — 0° 50mm — Angles 100mm

Sensitivity Reference Standards and Gain Adjustment

0° Probes: 2nd Back wall echo at F.S.H. Angle Probes: 1.5 mm hole in IOW block at FSH

Technique Summary	Scanning Sensitivity	0°	45°	60°	70°	°	°
Scan.		dB	dB	dB	dB	dB	dB

GENERAL REPORT	
	i) Scanned for lamination
	ii) Scanned the Root at ½ skip with 70° probe
	iii) Scanned between ½ and full skip + ½ cap with 45°
	iv) Transverse scan with 45° for transverse discontinuities
	See attached sheet

Test Restrictions or Comments	Continued on Sheet No.

Inspecting Authority	Customer	Unit Inspection Technician [signature]
Signed	Signed	U I Supervisor

Figure 8.21

THE UNIT INSPECTION COMPANY

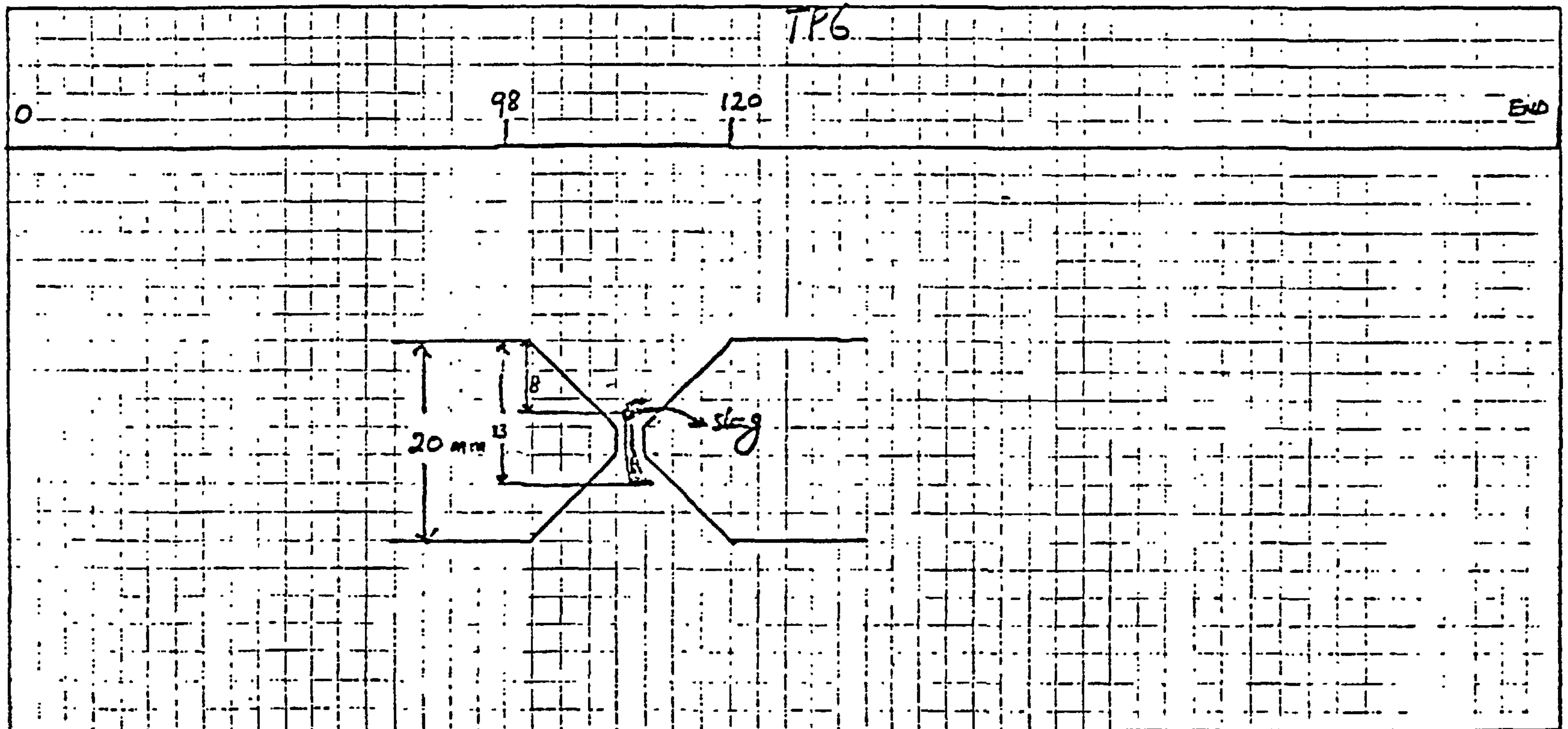
INSPECTION REPORT CONTINUATION

EUROTEST member

SKETCH 5mm Rect.

Method of Inspection			Report No. and Continuation Sheet No.
			Continued from Sheet No.
			Date of Test
Customer	Location	Customer Order No.	Unit Job No.

Description or Identification of Work Piece



Continued on Sheet No.	U.I. Technician

Figure 8.21 (cont.)

Appendix A
WELDING PROCESSES AND DEFECTS

A1.0. Welding Processes

The welding processes which are commonly used for the welding of metals can be classified as

A1.1 Electric Arc Welding Processes.

A1.2 Gas Welding Processes.

A1.3 Resistance Welding Processes.

A1.4 Brazing Processes.

A1.5 Miscellaneous Processes.

A1.1. Electric Arc Welding

Electric arc welding covers the group of welding processes wherein an electric arc furnishes the heat source for the purpose of welding. The arc is formed when a current is forced by voltage across the gap between two electrodes or between an electrode and the work (base metal) and thereby completes an electrical circuit. The arc supplies concentrated heat to melt the edges of the base metal and filler metal (when used) which intermix in a common molten pool and, upon cooling, coalesce to form a continuous weld. In electric arc welding, the higher intensity of heat source (the electric arc), as compared with a gas flame, permits a more rapid rate of heat input and higher efficiency of weld deposits. Immediately after the arc is struck, a molten pool is formed and the welding of the joint is performed by advancing the arc and adding filler metal if used.

There are two types of arc used in the application of this process. One is the direct arc, where the arc is maintained between the work piece and the electrode. The other is the indirect arc, where the arc is maintained between two non-consumable carbon or tungsten electrodes. The weld in both cases may be completed with or without the addition of filler metal.

The most widely used arc welding methods in metal working are described and their features are discussed, in the following section.

A1.1.1. Shielded Metal - Arc Welding (SMAW)

Shielded metal-arc welding, commonly called stick welding, is one of the oldest of the modern arc-welding processes. It is also the most widely used. Basically, it is a manual welding process in which the heat for

welding is generated by an arc established between a fluxcovered consumable electrode and the work. The electrode tip, weld 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. Additional shielding is provided for the molten metal in the weld puddle by a covering of slag formed by the reaction of ingredients in the flux with undesirable contaminants, such as oxides and salts. Filler material is supplied by the core of the consumable electrode typically a wire rod about 14 in. long and with certain electrodes, by metal powder included in the electrode covering.
Figure A1 illustrates the basics of the SMAW process.

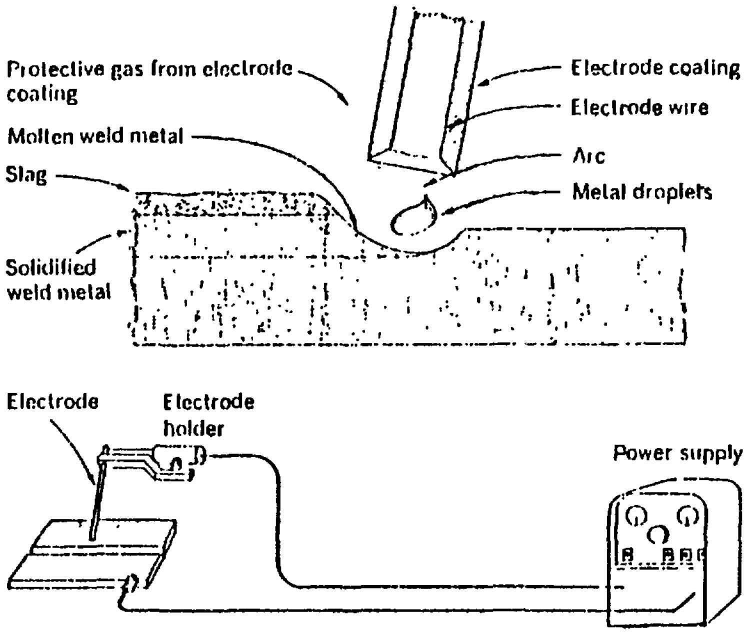


Figure A1 Typical SMAW Process

The wide use of shielded metal-arc welding stems from its versatility and the fact that the equipment needed is relatively simple, quite portable, and less expensive than other arc welding equipment. All one needs is an adequate power supply, a relatively simple electrode holder, and a set of cables. With these welding can be done indoors or out-doors on joints virtually in any position that can be reached by the electrode. That includes vertical joints and those directly over-head. With a bent electode, even joints in blind areas, which would be impossible to reach with more cumbersome welding guns associated with other equipment, can be welded.

The versatility of the process is further enhanced because power-supply leads can be extended over relatively long distances and there are no hoses for shielding gas or cooling water, as with other systems. This makes it an ideal repair process for equipment located in remote areas. Because it is well adapted to out-of-position welding and difficult locations, shielded metal-arc welding is very useful for joining the components of complex structural assemblies.

But there are limitations to this manual welding process. The deposition rates and deposition efficiency (ratio of the weight of deposited metal to the net weight of filler metal consumed exclusive of stubs) are lower than for gas metal arc and submerged arc welding and welding has to stop when the electrode has been consumed leaving a wasted stub. Another limitation of SMAW is that deslagging is necessary after each welding pass to remove the slag covering that forms on the weld surface.

Many metals can be joined by shielded metal-arc welding, but the process is most applicable to carbon and low alloy steels, stainless steels and heat resisting alloys. Cast irons and the high-strength and hardenable types of steel can also be joined by this process, but preheating, postheating or both may be necessary. Electrode selection and care are also more critical for welding hardenable steel. Copper and nickel alloys can also be welded with the SMAW process although other processes are more widely used for joining these metals. Softer metals, such as zinc, lead, and tin , which have low melting and boiling temperatures, do not lend themselves to shielded metal-arc welding.

A.1.1.2. Flux-Cored Arc Welding-FCAM

Flux-cored arc welding is a relatively new development dating back to the late 50's. It was introduced to overcome the major limitation of covered electrodes, namely, that the weld must be interrupted for electrode changing, resulting in lost time and wasted material with every welding stub. The idea was to feed electrode material, including flux, to the arc from a continuous coil. But the covering of stick electrodes cracks when wound into a coil, and , also, there is no practical way to feed electrical current to covered electrode wire.

The solution to these problems was self shielded electrodes with fluxing and shielding material inside hollow tubular filler metal that can be coiled into continuous electrode wire and fed mechanically into the arc. The availability of such flux-cored wire electrodes led to the development of semiautomatic welding with manually actuated welding "guns" and of fully automated welding with specially designed machines to manipulate a mechanized welding head and/or the material to be joined.

There are two major versions of the FCAW process; Self shielding and with auxiliary-gas shielding. The self shielding method is similar to shielded metal-arc welding in that it depends solely on the flux-core compounds for the generation of shielding gas. Auxiliary-gas shielding (usually carbon dioxide) can be combined with shielding gas from the core material by special equipment that delivers the gas to the electrode holder. Figure A.2 illustrates the two versions of the FCAW .

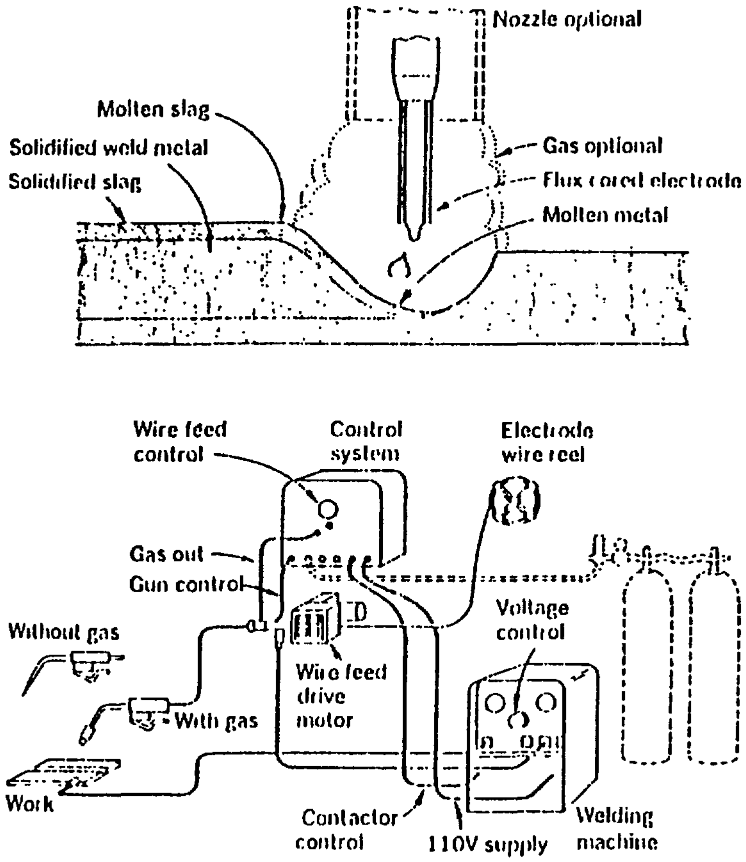


Figure A2 Typical FCAW Process.

Applications for the two flux-cored arc welding processes overlap considerably, but the self-shielding method is popular because it does not require any of the equipment associated with delivering the auxiliary shielding gas. Also, the electrode holder is simpler than that required for the auxiliary-gas shielding. The self shielding method is used mainly for welding carbon steels but also has been used successfully for welding some low alloy steels. It can be used for out-of-position welding if small diameter electrodes of suitable composition are selected. The self-shielding process does not penetrate as deeply as the auxiliary-gas shielded method and, therefore, can be used effectively where there is poor joint fitup.

Flux-cored arc welding with auxiliary-gas is used mainly for welding carbon and low-alloy steels and also has been used successfully for welding stainless steels. It is applicable to a wide range of work-metal thicknesses beginning with metal as thin as 1/16 in.

A1.1.3 Gas Metal-Arc Welding - GMAW

Gas metal-arc welding, generally still referred to as MIG (Metal Inert-gas) welding, uses a bare continuous consumable electrode wire, with arc shielding provided entirely by an externally supplied gas mixture (Figure A3). The shielding gas protects the molten metal from reacting with constituents of the atmosphere, and deoxidizers may be added as alloys in the electrode.

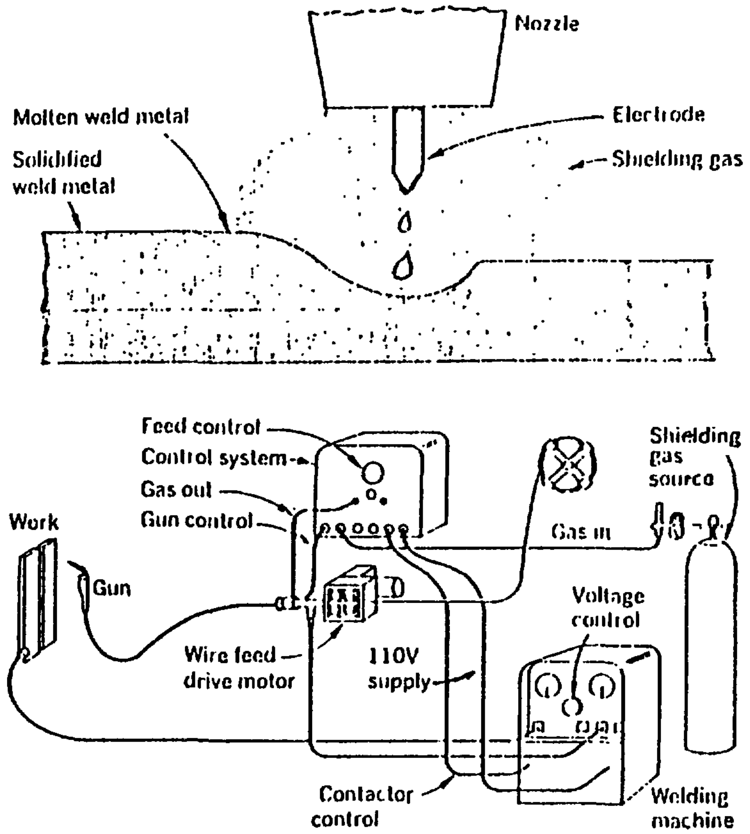


Figure A3 Typical GMAW Process.

Shielding gases may be helium, argon, carbon dioxide, or their mixtures. The equipment required is similar to that used with fluxcovered arc welding (with auxiliary gas shielding)except that the filler wire is without flux core.

The outstanding features of gas metal-arc welding are:

i. It will make top quality welds in almost all major commercial metals, including carbon, alloy and stainless steels, as well as aluminium, copper, magnesium, iron, titanium and zirconium. It is the preferred process for the welding of aluminium, magnesium, copper, and many of the alloys of these reactive metals.

ii. The absence of slag means that there is minimum postweld and interpass clean up and that no slag can be trapped in the weld.

iii. Welding can be done in all positions.

iv. It is a relatively high-speed welding process because small diameter wire can be used with high welding currents thereby providing high deposition rates.

A1.1.4 Gas Tungsten-Arc Welding - GTAW

In gas tungsten-arc welding, commonly called TIG (tungsten-inert gas) welding, the heating arc is struck between a nonconsumable tungsten electrode and the work. As with GMAW, shielding is provided entirely by an externally supplied gas mixture delivered to the weld-puddle area by the electrode holder (Figure A4). Filler metal may or may not be used, depending on the requirements of the job.

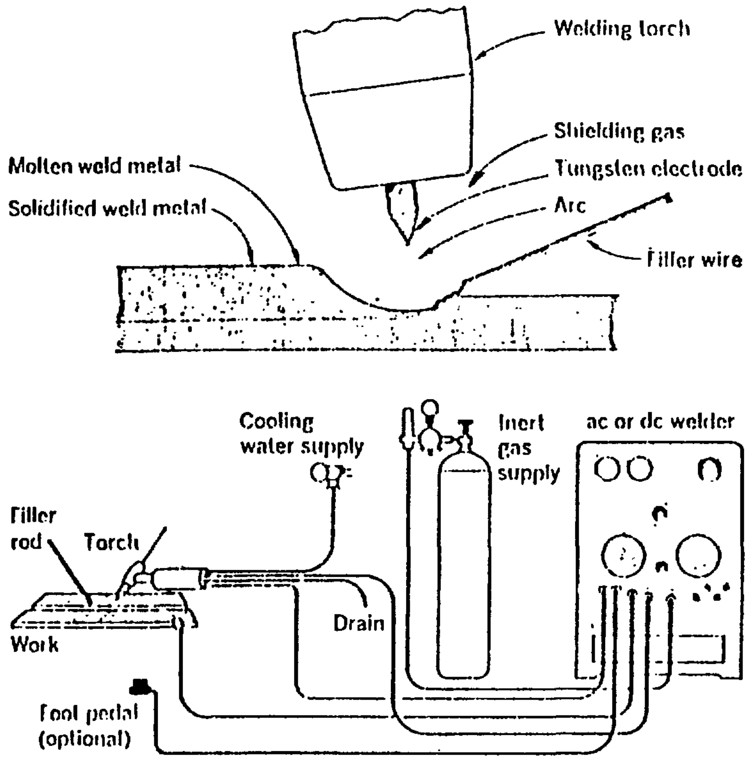


Figure A4 Typical GTAW Process.

Gas tungsten-arc welding is quite similar to gas metal-arc welding, except that the electrode is used like a torch to produce the heat necessary for coalescence of the metals to be joined. In this way, metals can be joined without the use of any filler wire. Pressure may by used to assist coalescence as the edges of the joint approach the molten state. If the work is too heavy for mere fusing of the abutting edges, and if groove joints or reinforcements are required filler metal is added separately. This is done with a filler rod fed manually or mechanically directly in to the weld puddle.

Both the tip of the electrode and the tip of the filler metal are kept under the protective gas shield at all times during the welding procedure.

The main features of gas tungsten-arc welding are :

i. It will make top-quality welds in almost all metals and alloys used in industry, including most grades of carbon, alloy and stainless steels, aluminium and most of its alloys, magnesium and most of its alloys, copper and various brasses and bronzes; high temperature alloys of various types; many hard face alloys ; and such metals as titanium, zirconium, gold and silver.

ii. Practically no post-weld cleaning is required as there is no fluxing agent.

iii. There is no weld spatter because no filler metal has to be transported across the arc stream.

iv. No slag is trapped in the weld material.

v. Welding is possible in all positions.

vi. A wide range of metal thickness can be welded. The technique is particularly well suited for welding thin materials where the requirements for quality and finish are exacting. For example it has been successful in welding various alloys in foil thicknesses, or in welding such tiny and thin-walled objects as transistor cases, instrument diaphragms etc.

A1.1.5. Plasma-Arc Welding-PAW

Plasma-arc welding is similar to tungsten-arc welding, except that the arc from a tungsten electrode is forced to pass through a restriction before reaching the work piece. This is accomplished by surrounding the electrode with a nozzle having a small orifice, and forcing an inert gas through this nozzle. The result is a jet of intensely hot and fast-moving plasma caused by the concentrated ionization of the arc. Plasma-arc torches regularly develop temperatures as high as 60,000 F.

In practice, two separate streams of gases are supplied to the welding torch. One stream surrounds the electrode within the orifice body and passes through the orifice to form the hot plasma jet. This gas must be inert and is usually argon. The other stream of gas passes between the orifice body and an outer shell of the torch to act as a shielding gas for the weld puddle and surrounding area. An inert gas such as argon can also be used for shielding, but nonoxidizing gas mixtures, such as argon with 5 % hydrogen, have often proved advantageous. As with gas tungsten-arc welding, filler metal may or may not be used, depending on the requirements of the particular joint.

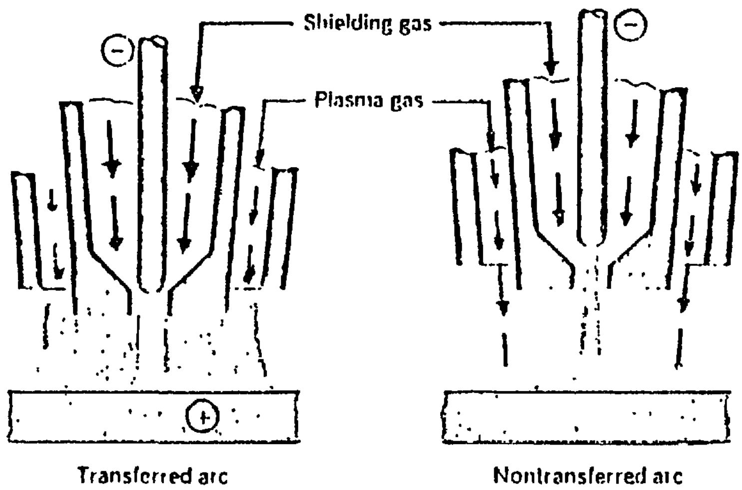


Figure A5 Arc types for PAW

Two basic arc systems (Figure A5) are used to generate the plasma : a transferred arc and a non transferred arc. In the transferred arc system, the work piece is a part of the electrical circuit, as in other arc-welding processes, and the arc "transfers" from the electrode through the orifice to the work. In the non transferred arc system, the constricting nozzle surrounding the electrode acts as an electrical terminal, and the arc is struck between it and the electrode tip. In such a system heat is delivered to the work by the hot plasma jet only. For welding, the transferred arc is used almost exclusively, because the arc delivers more heat to the work.

The main features and disadvantages of plasma-arc welding are :

i. Plasma-arc welding can be used to join carbon and alloy steels, stainless steels, heat resistant alloys, refractory metals, copper alloys and titanium alloys. Aluminium alloys have also been successfully welded with plasma arcs, but this is not a significant practice.

ii. Plasma-arc welding works extremely well for thin sections. Because of the stability and dimensional control provided by the restricted arc, foils as thin as 0.025 mm have been welded in production. Of course, welding such thin sections requires very precise fixtures and close control over the process. The practical minimum work thickness seems to be 0.075 mm. , although 0.05 mm thick stainless steel has been successfully welded for some years now. The maximum work thickness is generally a function of cost. Above about 6mm other welding processes are usually faster and more economical. Sometimes, when quality requirement is high, economical joints can be made by a combination of PAW and other less-expensive processes. Plasma-arc welding is used for the root pass; a cheaper process such as GMAW, for succeeding passes.

iii. The advantages of using the constricted arc of plasma-arc welding over the gas tungsten-arc process include greater energy concentration, improved arc stability, higher welding speed, and lower width-to-depth ratio of the weld bead for a given penetration.

iv. Some of the disadvantages of plasma-arc welding compared with conventional gas metal-arc welding include higher cost of the equipment, short life of the orifice body, the need for greater welder knowledge, and a high rate of inert-gas consumption. PAW equipment usually costs two to five times as much as that required for gas metal-arc welding. The cost of orifice-body replacement can be kept down by using a torch in which the critical area is designed as an insert that can be readily changed. Although more knowledge by the welder is required, much plasma-arc welding is performed with automatic equipment, thus requiring relatively low operator skills.

A1.1.6 Submerged-Arc Welding - SAW

In submerged-arc welding (Figure A6) a bare continuous, consumable electrode wire generates the welding arc under a protective blanket of granular fusible flux. This submerged arc is not visible to the operator and welding progresses without any of the sparks, spatter, and flash of regular open-arc welding. The process is either semiautomatic or fully automatic, although its main application today is with fully automatic systems, primarily for plate and structural fabrication work.

Regardless of the equipment, the bare consumable electrode wire, generally a low carbon steel of closely controlled chemical composition, is mechanically fed through an electrical contact tube and through the flux blanket to the joint being welded. Granular flux is deposited ahead of the arc.

In semi-automatic welding, the welding gun itself may be equipped with a flux feeding device, a small hopper atop the gun, with gravity flow through a nozzle concentric with the electrode, or a concentric nozzle connected to an air-pressurized flux tank. Flux may also be applied in advance of the welding operation or ahead of the weld, from a separate hopper run along the joint. In fully automatic systems, the flux is fed continuously to

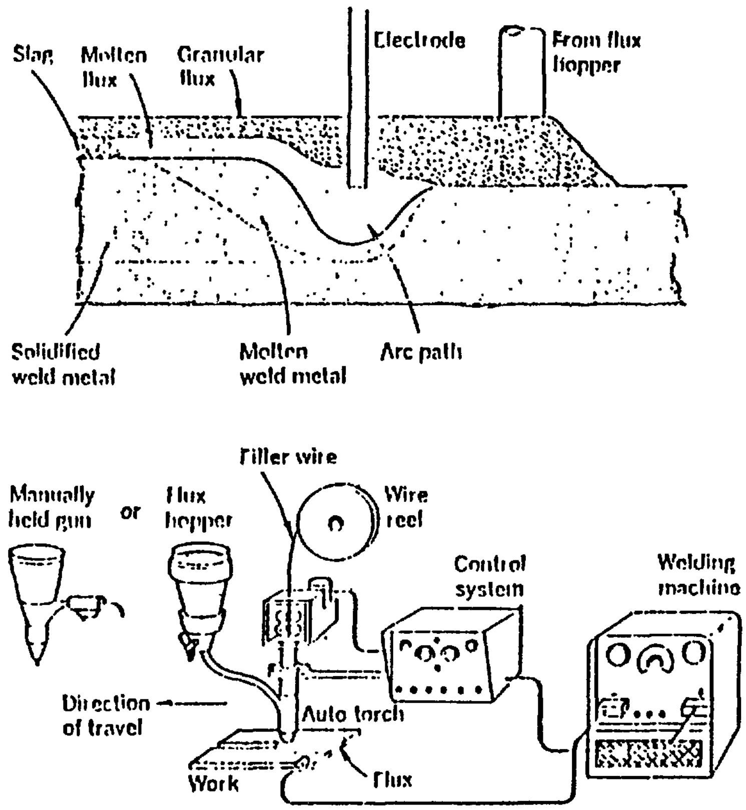


Figure A6 Typical SAW Process.

the joint ahead of or with the arc, and such installations are usually equipped with vacuum systems to pick up unused flux for reclamation.

One of the main advantages of submerged-arc welding is that it permits the use of very high currents, even on small diameter electrode wire, which results in extremely high welding heat. This is because the current can be applied to the electrode very close to its tip, reducing the problems associated with excessive resistance heating of electrode and surface flux.

Other features of SAW are :

i. Joints can be prepared with a relatively shallow V-groove, resulting in low filler metal consumption.

ii. Although eye protection for the welder is recommended, helmet-type shielding is not normally required.

iii. High welding speeds and deposition rates, up to ten times those of stick-electrode welding, can be developed.

iv. Inexpensive electrode wires can be used for welding unalloyed low carbon steels.

v. The insulating blanket of flux above the arc prevents rapid escape of heat and concentrates it in the welding zone. Not only are the electrodes and base metal melted rapidly, but the fusion is deep in to the base metal.

vi. The high welding speed possible with submerged-arc welding minimizes the total heat input of the process, and, therefore, helps to prevent problems due to heat distortion. Even relatively thick joints can be made with one pass by submerged -arc welding.

The limitations of submerged-arc welding, most of which are also common to other flux-type welding process, include the following :

i. Flux, flux handling equipment, and workholding fixtures are required. Many joints also require the use of backing plates, strips or rings.

ii. Flux is subjected to contamination that may cause weld metal porosity.

iii. To obtain a weld of good quality, the base metal must be homogeneous and essentially free of scale, rust, oil and other contaminants.

iv. The solidified residue from the fused flux must be removed from the weld bead, which is often a difficult, time consuming operation. In multi pass welding, the slag must be removed after each pass.

v. The process usually is not suitable with metal less than about 4 mm thick, because burn through is likely.

vi. Except for special applications, welding is largely restricted to the flat position for groove welds, and to flat and horizontal positions for fillet welds.

Submerged arc welding is most suitable for production welding of unalloyed low-carbon steels containing not more than 0.30 % carbon, nor more than 0.05 % phosphorous and 0.05 % sulfur. Medium-carbon steels and low-alloy structural steels are equally well suited to submerged arc welding, but they more often require preheating, post heating and special electrode wire and fluxes. SAW is also applicable to some high alloy, heat treated and stainless steels, and it is a favorite process for rebuilding and hard surfacing.

A1.1.7 Electro Slag Welding - ESW

Electro slag welding is a specialized adaptation of submerged-arc welding and it is used for joining thick materials in the vertical position (Figure A7). Strictly speaking it is not an arc welding process at

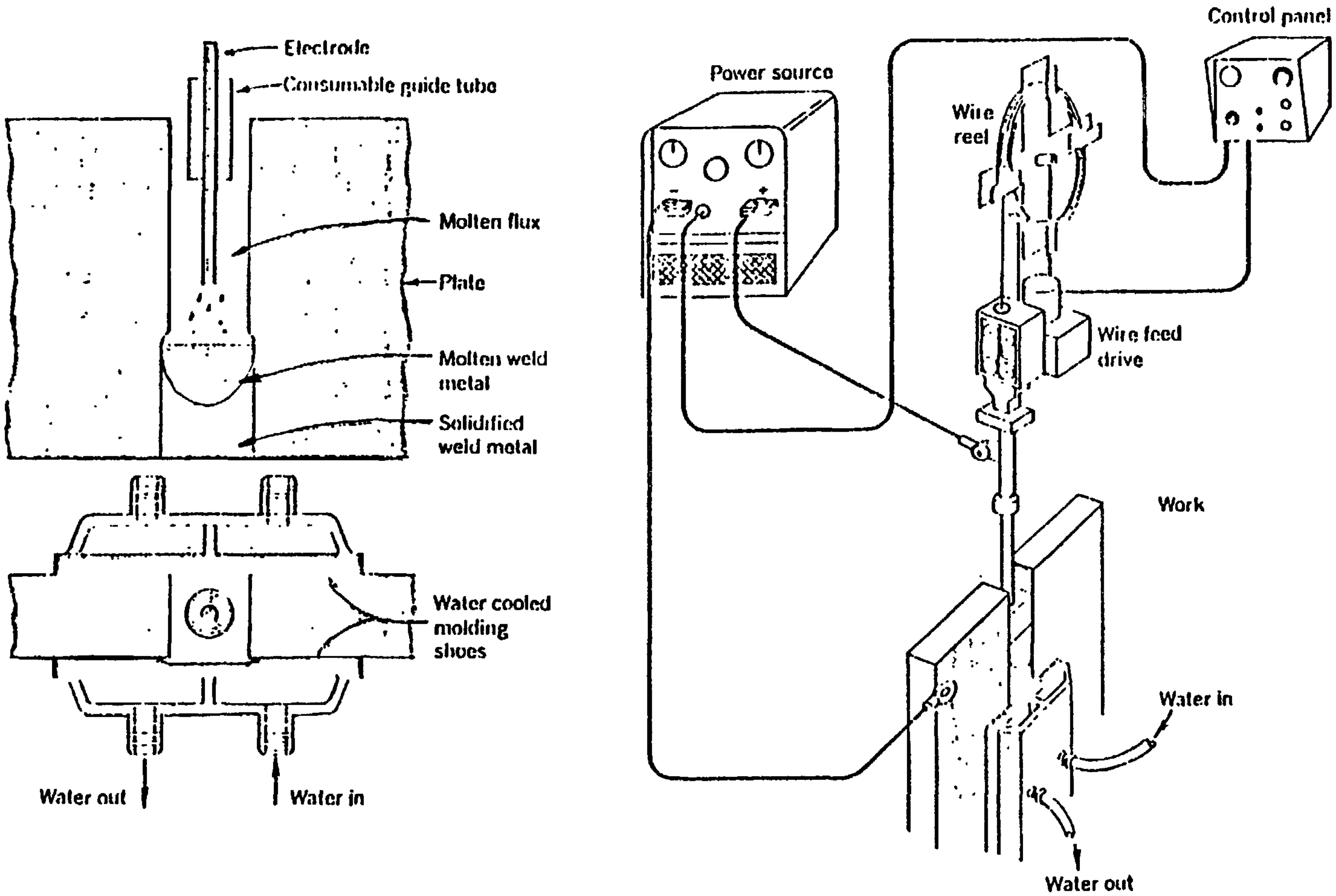


Figure A7 Typical ESW Process.

all, because it actually depends on the electrical resistivity 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 molding 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 is maintained in a molten condition by its resistance to the electric current passing through from a consumable electrode to the work.

In regular submerged-arc welding, the arc, submerged under powdered granular flux, creates the heat necessary for welding. The depth of the flux is not sufficient to block arc action. In electroslag welding, however, the flux pool is 38 to 50 mm deep and, because it is formulated to offer a conductive path for the flow of electric current, the molten flux can extinguish the arc without breaking the flow of current. Infact, ESW fluxes are compounded specially to provide the proper electrical resistivity, desired melting temperatures, and appropriate viscosity.

Electroslag welding progresses vertically along a joint, but the deposition actually takes place with the electrode being fed through a guide tube into a cavity formed by the pieces being welded and one or more dams. As the electrode is consumed, the welding head and cooling dams move up along a vertical axis. Multiple head arrangements can be used for welding extremely heavy sections.

In a variation of the basic ESW process, the consumable electrode wire is fed through a guide tube that is also consumable. This obviates the need for vertical travel of the welding head, thus simplifying the mechanical arrangement of the system. Only electrode wire need be fed, from a fixed head that hovers above the upper extreme of the weld.

The principal application of electroslag welding is welding of thick steel plates. 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.

v. Low flux consumption.

A1.1.8. Stud arc welding

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 A8). In a way it is 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.

In operation the stud is retained in a hand held or bench-mounted "gun" (Figure A9) 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 in to the molten pool created on the base plate, and the gun is withdrawn.

Typical applications of stud welding include securing special lining in tanks ; studing 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.

A1.2. Oxyfuel Gas Welding - OFW

Oxyfuel gas welding (Figure A10) is defined as a group of welding processes that produces coalescence by heating materials with an oxyfuel gas flame or flames with or without pressure. The main industrial processes in this group are oxyacetylene, airacetylene, oxyhydrogen and pressure gas welding of the various gas welding processes. Oxyacetylene welding is the most prevelant and the most important in industry. It burns with a very hot flame (about 6100-6300 F), has high heat transfer intensity and provides a protective atmosphere for the welding zone. Gas welding requires relatively simple equipment ; a fuel gas cylinder, and oxygen cylinder, regulating valves, and a torch that mixes and burns the gases. The equipment is easily portable, versatile and low cost.

Gas welding is best suited to the welding of relatively thin sections e.g. sheet metal, thin-wall tube, small pipe, and assemblies with poor fitup. Heavy sections can be gas welded, but arc welding is usually more economical. Most ferrous and nonferrous metals can be gas welded, provided the oxyfuel-gas mixture has appropriate flame characteristics such as temperature, heat-transfer intensity, and composition of flame atmosphere.

A1.3 Resistance Welding Process

Resistance welding comprises a group of welding processes in which the heat for coalescence of the two metals to be

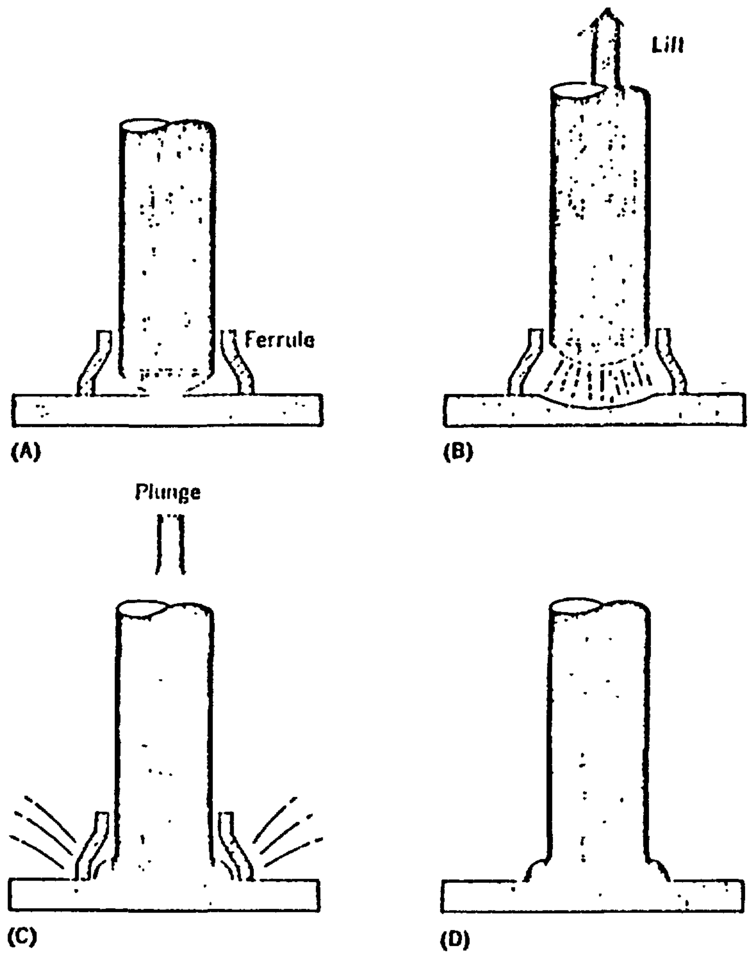


Figure A8 Typical stud welding sequence

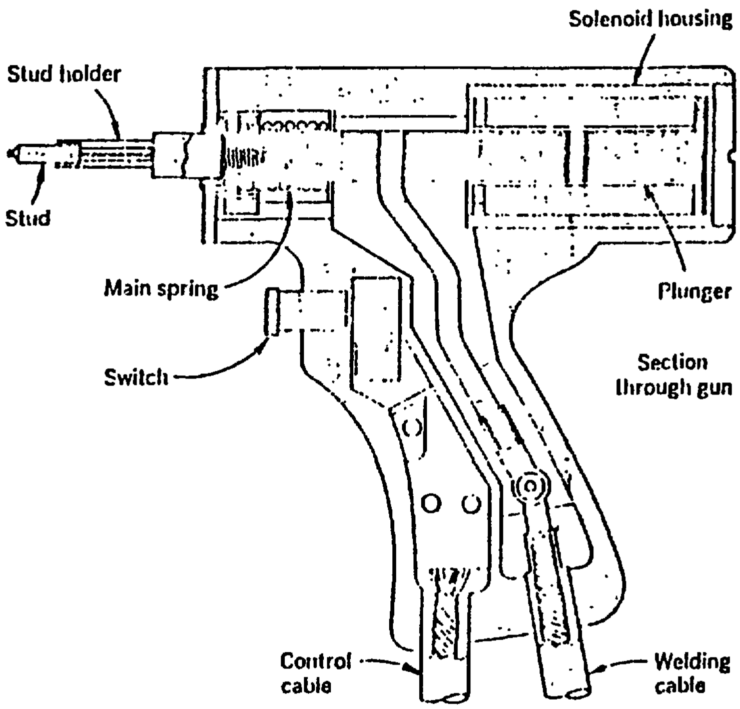
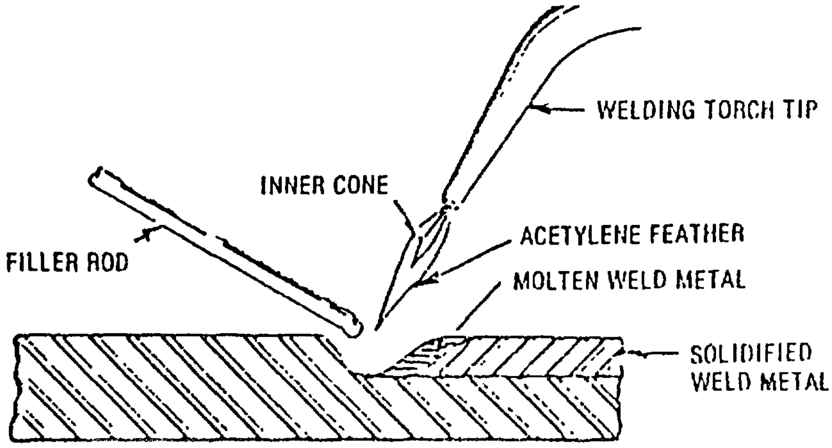


Figure A9 Typical SW gun



OFW Process

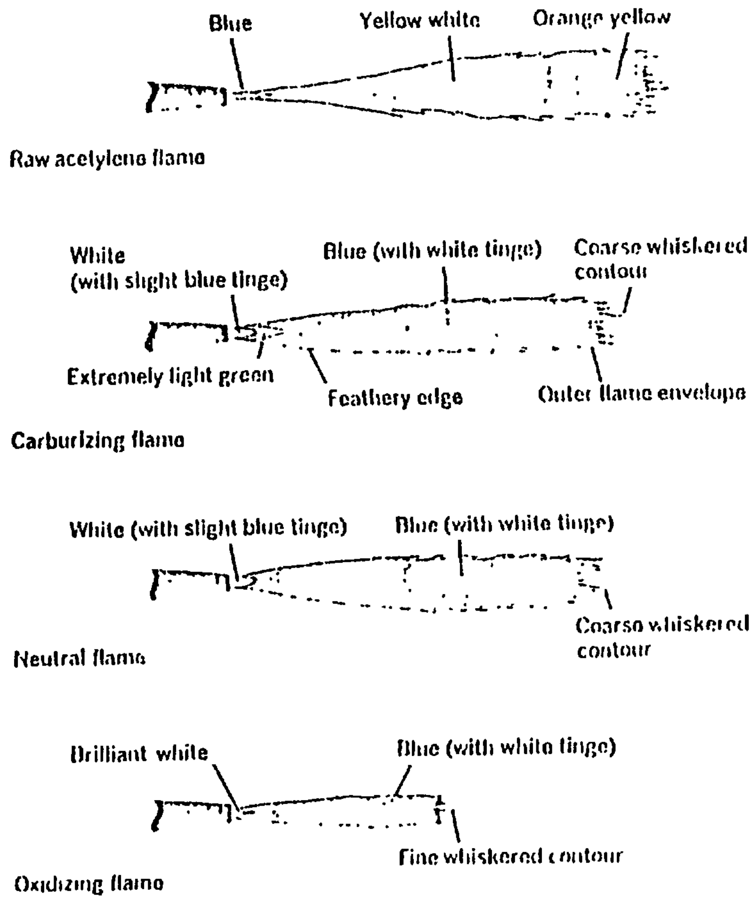


Figure A10 Acetylene flame types

joined is generated by the resistance of the joint to the passage of an electric current and the joining takes place under externally applied pressure. It differs from most other welding processes in that no extraneous material, such as filler metal or fluxes, is introduced in to the weld. Therefore, resistance welding does not alter the basic metallurgical composition of the joint. Resistance welding is used generally for sheet and light gauge metals. In this welding process the quality of fusion taking place depends upon the conditions of temperature, time and pressure. Both alternating and direct current can be used to produce resistance welds.

Two of the more common types of resistance welding processes are "spot welding" and "seam welding". In the spot welding process, the work parts are held together under pressure by cylinderical electrodes (Figure A11). The size and shape of the individually formed welds depend upon the size and contour of the electrodes. In the seam welding process, the flow of electric current is through the work parts held together under pressure by circular electrodes (Figure A11) By rotating the electrodes across the work, the result is a series of overlapping spot welds made progressively along the joint.

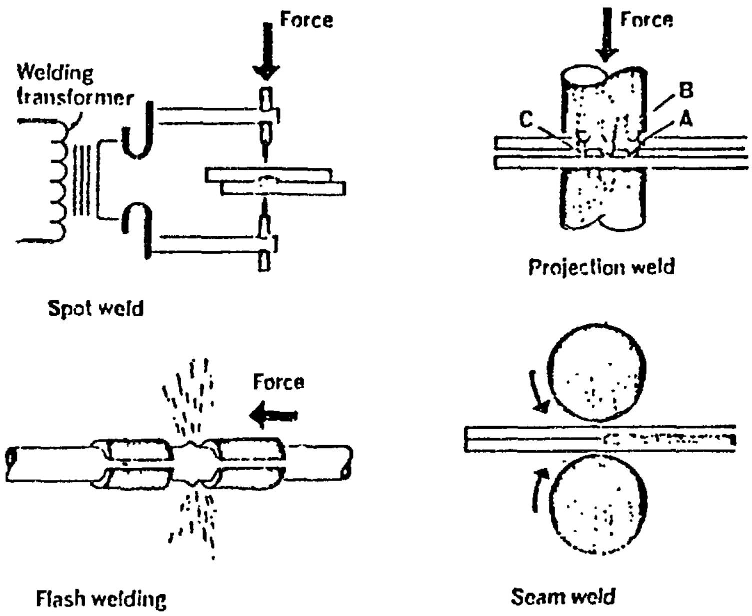


Figure A11 Basic resistance-welding methods

A1.4 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 preplaced in the form of powder, metallic rings or strips.

A1.5 Miscellaneous Processes

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

(a) 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.

Many ferrous and nonferrous alloys can be friction welded, and the method can be used to join metals of widely differing thermal and mechanical properties. Often, in fact, combinations that can not be joined by any other method because of the formation of brittle phases that would render the joint unsatisfactory, can be effectively joined with friction welding. The automatic loading and unloading of friction-welding machines make it ideal for high production work.

Some of the other advantages of friction welding are :

i) Total energy requirements are only a fraction of those needed for other welding processes.

ii) The operation is relatively clean, there is little spatter, and no arc fumes or scale.

iii) The heat-affected zone is very narrow and has a grain size that is often smaller than that in the base metal.

Of course, friction welding is limited to parts specifically designed for its unique requirements. They must be substantially round and must be able to withstand the high torques developed during welding.

(b) 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 nonferrous 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 (Figure A12). 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

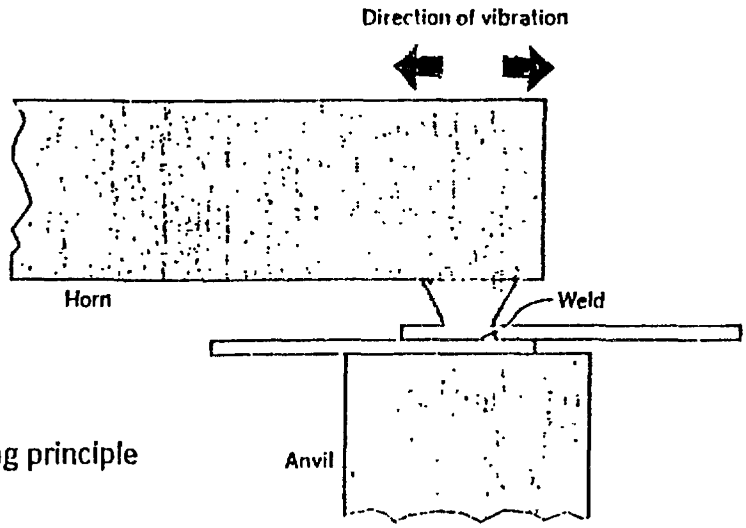


Figure A12 Ultrasonic-welding principle

oxides and other contaminants on the interface surfaces. Once they are clean the surfaces come in to 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.

(c) Electron Beam Welding

In electron-beam welding, the heat required for coalescence of the material is generated by a concentrated stream of high-velocity electrons aimed at the surface to be joined. When these electrons hit the joint, their kinetic energy is turned in to intensive heat.

The electron beam is produced by an electron gun similar in operation to that of a television tube. A heated tungsten filament provides the electrons which are than gathered and accelerated to high velocity and shaped in to a beam by electrical fields. The beam is further collimated and focused by passing through an electromagnetic focusing coil, or magnetic lens.

Electron-beam welding can be used to weld more materials or combinations of material than any other fusion process, and the weld quality in most metals in equal or superior to that of the best gas tungsten-arc welds. A main advantage of EB welding is that it is extremely fast with a minimum of heat input to the workpiece. This minimizes distortion and shrinkage in welding, reduces the effects of excessive heat on the physical characteristics of the material being joined, makes it possible to weld in close proximity to components that are sensitive to heat and makes possible the joining of dissimilar metals.

On the negative side, most EB welding equipment is relatively expensive, although small systems are now commercially available at affordable prices. Also, fitup for EB welding must be more exact than for other welding processes, because of the narrow nature of the beam.

(d) Laser-Beam Welding - LBW

Because of the higher energy levels that can be attained in the focused out-put of a laser beam, it can be used as an effective source of heat for a variety of metal work processing, including welding. A laser beam is a highly collimated, monochromatic, coherent beam of light generated by a phenomenon in physics called "Light Amplification by Stimulated Emission of Radiation - hence "laser".

When such a beam is focused on a material surface, much of the energy of this concentrated stream of photons is absorbed as heat.

The advantages of LBW include :-

i) The absence of physical contact with an electrode.

ii) The absence of flux.

iii) Localized heating and rapid cooling, due to high heat intensity and small spot size. This results in a small heat affected zone.

iv) The ability to weld many dissimilar geometries.

v) The ability to weld components in a controlled atmosphere or sealed in optically transparent material.

vi) The fact that the laser beam can be readily manipulated and shaped using optical tooling or scanning techniques, and the weld area can be located relatively far from the laser source.

On the debit side, laser systems, like EB systems, are still relativley expensive, and good part fitup is essential because of the small concentrated spot of heat.

A2.0 Weld Defects and Discontinuities

A variety of defects occur in welds. Some of these defects are discussed below :-

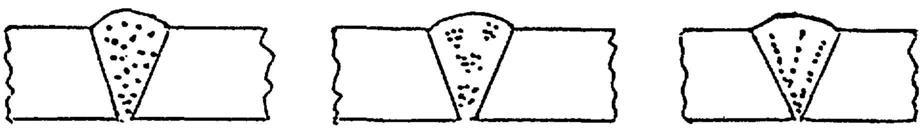
A2.1 Gas Inclusion

Gas may be formed in molten weld metal for various reasons and may be trapped if there is insufficient time for it to escape before solidification. The trapped gas is usually in the form of round holes, termed porosity or blow holes, or of an elongated shape called piping or wormholes.

Gas formation may be caused by chemical reaction during welding, high sulphur content in plate and/or electrode, excessive moisture in the electrode or on base plate edges, too short an arc, incorrect welding current, wrong polarity.

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:

(a) Uniformly scattered porosity, which is characterised by pores scattered uniformly throughout the weld (figure A13 a).



(a) (b) (c)

Figure A13

(b) Cluster porosity, which is characterized by cluster of pores that are separated by porosity-free areas (figure A13 b).

(c) Linear porosity, which is characterized by pores that are linearly distributed (figure A13 c), and which generally occur in the root pass and is associated with lack of penetration.

A2.2 Slag Inclusions

Most weld inclusions contain slag that has been trapped in the deposited metal during solidification. The slag may come from the electrode coating or flux employed. The purpose of the flux is to remove impurities from the metal. If the metal fails to remain molten for a period sufficient to allow the slag to rise to the surface some slag may be trapped within the metal. In multipass welding insufficient cleaning and brushing of the bead between passes may not remove all the slag coating. This may then be trapped in the metal by a subsequent pass. Dirty and irregular surfaces, ripple and under-cut will contribute to slag entrapment. Slag inclusions are frequently associated with lack of penetration, poor fusion, oversize root faces, too narrow a groove and faulty electrode manipulation.

A2.3 Lack of Penetration

Frequently the root of a weld will not be adequately filled with weld metal and a void is left. This inadequate penetration may be caused by too small a root opening, too large an electrode, insufficient weld current, excessive welding speed, improper groove preparation etc. In joints requiring complete penetration this type of defect is generally not acceptable and requires complete removal and rewelding.

A2.4 Lack of Fusion

Lack of fusion occurs at weld interfaces where adjacent layers of metal, or the base metal and weld metal, fail to fuse properly due to a very thin layer of oxide that forms on the metal surfaces. It is usually caused by failure to raise the temperature of the base metal or previously deposited weld metal high enough to allow any oxide layers, slag, impurities etc to rise to the surface.

A2.5 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.

Usually little deformation is apparent.

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 A14).

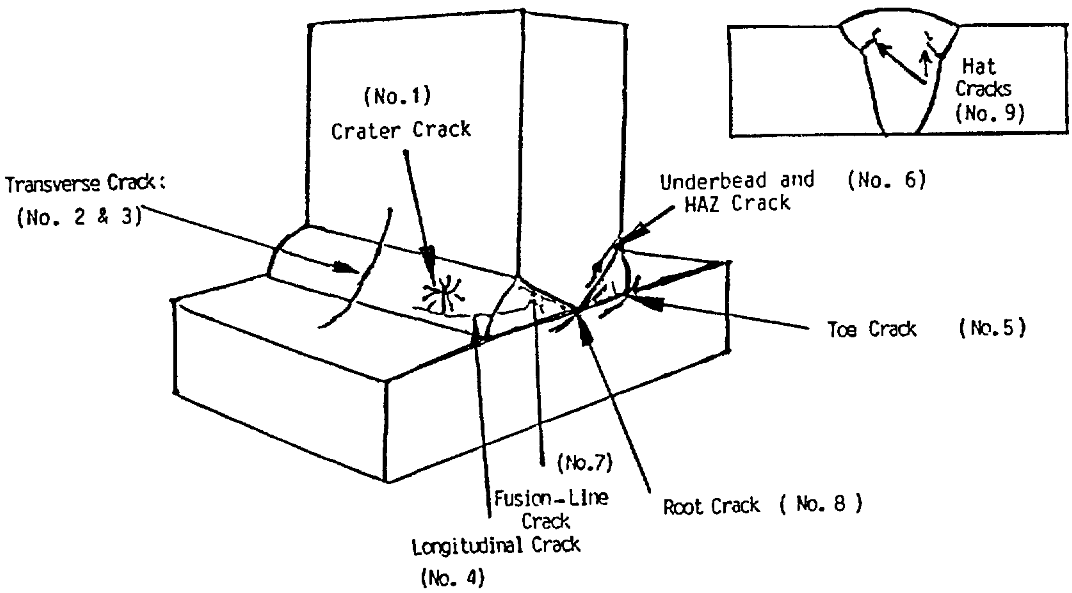


Figure A14

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 : transverse, longitudinal, crater and hat cracks. Base-metal cracks can be divided into seven categories transverse cracks, underbead cracks, toe cracks, root cracks, lamellar tearing, delaminations and fusion-line cracks.

Transverse Cracks

In weld metal (No.2 in figure A14) are formed when the predominant contraction stresses are in the direction of the weld axis. They can be hot cracks, which separate 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 A14) 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 crack propagate into the weld metal or beyond the heat affected zone into the base metal as far as in needed to relieve the residual stresses.

Underbead Cracks

(No.6 in figure A14) 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.

Longitudinal Cracks

(No.4 in figure A14) may exist in three forms, depending on their position in the weld. 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 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 results 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.

Crater Cracks

(No. 1 in figure A14). As the name implies, crater cracks occur in the weld crater formed at the end of a welding pass. 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 the 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.

Hat Cracks

(No.9 in figure A14) 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. 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.

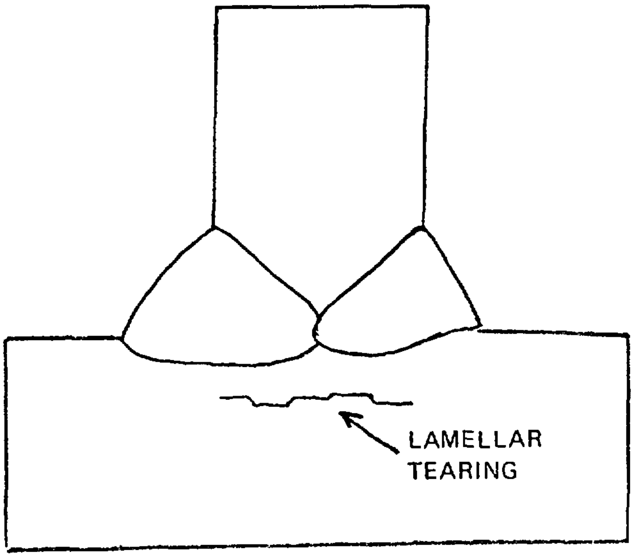
Toe and Root Cracks

(No. 5 and 8 in figure A14) can occur at the notches present at locations in the weld when high residual stresses are present. Both toe and root cracks propagate through the brittle heat affected zone before they are arrested in more ductile regions of the base metal. Characteristically, they are oriented almost perpendicular to the base-metal surface and run parallel to the weld axis.

Lamellar Tearing (Figure A15)

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 characterised by a step-like tear and is

Figure A15



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.

Fusion-line Cracks

(No. 7 in figure A14) can be classified as either weld-metal cracks or base-metal cracks, because they occur along the fusion line between the two. There are no limitations as to where along the fusion line these cracks can occur or how far around the weld they can extend.

A2.6 Root Concavity

Root concavity is commonly produced by the FC AW process. This is a groove created in the root of a butt weld welded from one side only. In overhead welding the molten metal sinks in to the weld preparation due to the force of gravity while in the flat weld position the molten metal may be pulled up by surface tension in to the weld preparation to create such a cavity.

A2.7 Under Cut

During welding of the final or cover pass, the exposed upper edges of the bevelled weld preparation tend to melt and to run down in to the deposited metal in the weld groove. Undercutting occurs when insufficient filler metal is deposited to fill the resultant grooves at the edge of the weld bead. The result is a groove that may be intermittent or continuous and parallel to the weld bead. Undercutting may be caused by excessive welding current, incorrect arc length, high speed, incorrect electrode manipulation etc.

A2.8 Burn Through

A burn through area is that portion of the weld bead where excessive penetration has caused the weld pool to be blown in to 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.

A2.9 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.

Appendix B

CASTINGS AND FORGINGS AND THEIR RELATED DISCONTINUITIES

B1.0 **Casting**

The casting of metals involves the pouring or injection of molten metal into a cavity of a particular shape where it is allowed to solidify. The cavity or mold may be of an intricate shape so that when the solidified metal is removed a part is produced which, with or without further preparation, may be used for its designed purpose. The basic steps (Figure B 1) involved in the casting process are;

a) The preparation of a pattern or die to form the final shape and size of part required.

b) The preparation of the mold cavity by use of the pattern and suitable mold material.

c) The heating and melting of the metal.

d) The insertion of the molten metal into the mold cavity.

e) The removal and when necessary the further cleaning or shaping of the part.

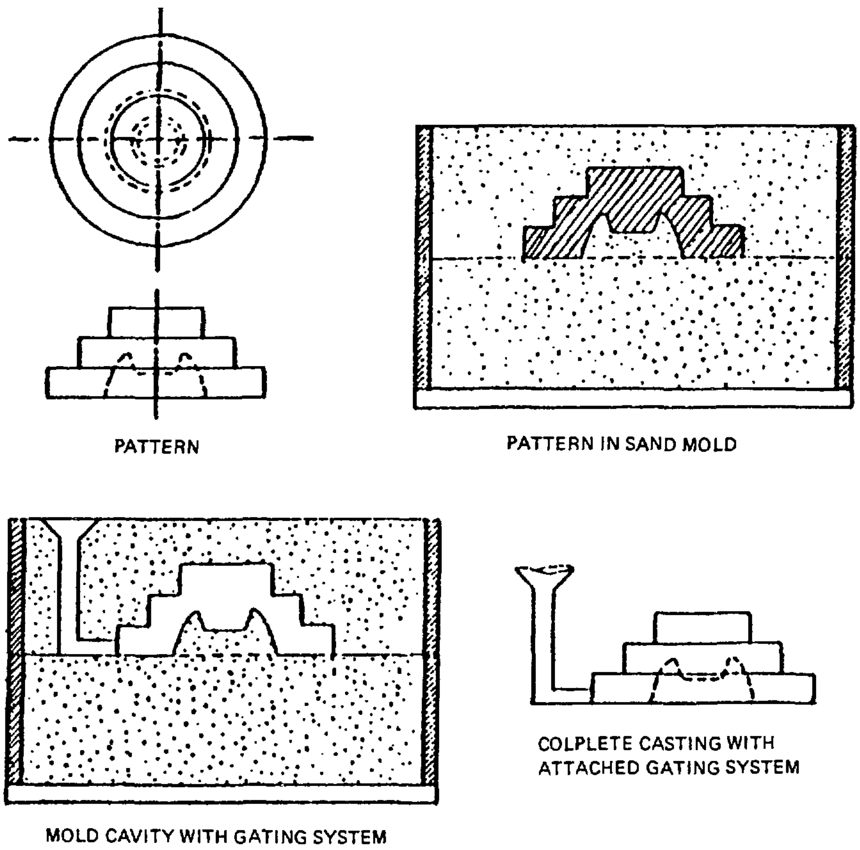


Figure B 1 Casting steps

B1.1 Methods of casting

There are many casting processes and they may be grouped into those using a non-permanent mold which is used only once, and those using permanent molds from which a number of castings may be made. Examples of non-permanent molds include:

Sand casting
Shell mold casting
Investment or precision casting

Permanent mold castings include:

Centrifugal castings
Die or pressure castings

A short summary of the principles involved in the above casting processes follows. It should be kept in mind that there are many modifications and variations of these processes which are designed for specific applications.

B1.1.1 Sand casting

The mold used for sand casting may be of the "green sand" or "dry sand " type. Silica sand is generally used as a mold material because of its refractory properties, low cost and availability. In the green sand mold the sand is given plasticity by means of a clay binder that may be present in the sand or added to it. Sufficient water is added to hold the mixture together. In a dry sand mold the sand is given plasticity in a similar fashion but the mold is dried before the metal is poured into it thus eliminating the formation of water vapour and reducing the type of casting defects that are due to gas formation. In making a mold a pattern usually of wood is placed in a flask and molding sand is rammed around it. Ordinarily the mold is made in two halves, the upper portion being called the "cope" and the lower portion the "drag".

The pattern is designed so that it can be removed without disturbing the sand, leaving a pattern shaped cavity in the sand. Cores of baked oil bonded sand are placed in the mold cavity to form internal cavities in the casting. Cores are subject to breakage due to handling and erosion from the molten metal and are dried and baked to provide the necessary strength. The cope and drag are prepared separately. Before they are placed together to complete the mold cavity, as shown in Figure B2a, a system of runners, gates and sprue are formed to allow the metal to enter the mold.

In most cases cavities for reservoirs of metal (risers) are formed in the mold (Figure B 2b). The metal rises into these reservoirs and helps to "feed" the casting as it solidifies. When the mold is closed the molten metal is poured into the pouring basin or directly into the sprue. It enters the system of runners and gates and finally fills the mold cavity and risers. After the metal has solidified and

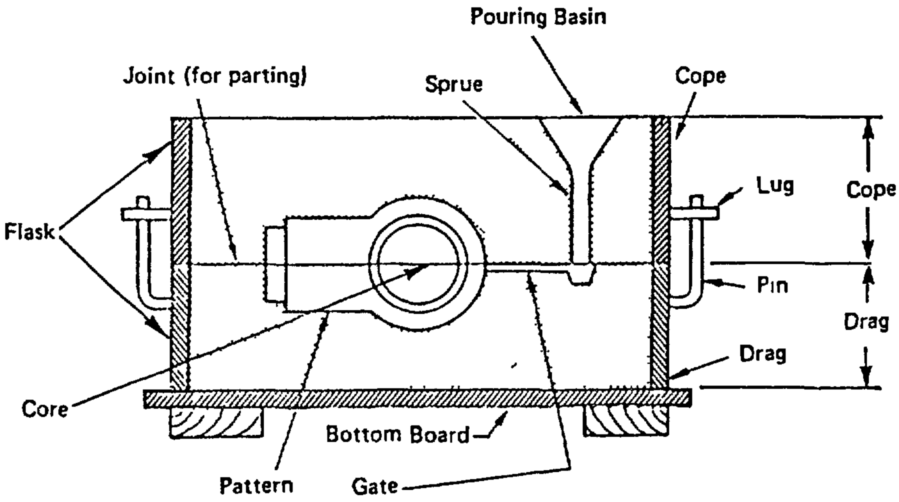


Figure B 2 a

Liquid metal supply to compensate for
liquid and solidification shrinkage

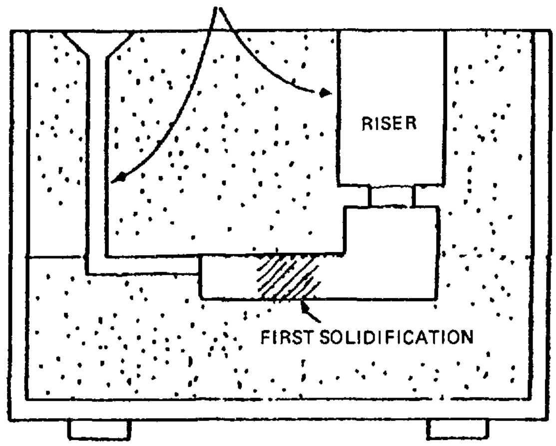


Figure B 2 b

sufficiently cooled the sand is removed and the rough casting revealed. The excess metal of gates,risers etc. are removed and the casting cleaned and finished as required.

B1.1.2 Shell molding

In this process the mold material is made of a special type of sand in which a powdered thermosetting plastic is mixed. The metal pattern used to produce the part is heated to about 200 C and it is then covered by the mixture of sand and thermosetting plastic. The heat of the pattern causes the plastic to harden and form a shell which is then heated for a short time at higher temperature. The shell is then removed from the pattern. The impressions in the shell mold will form one half of the mold cavity. A similar procedure is used to produce the other half of the mold. The mold is usually backed up with other materials ,such as loose sand ,to provide added strength before casting.

Shell molding provides a part with high dimensional accuracy and good surface finish which may eliminate subsequent machining or finishing. The production rate is relatively high and the process is suited to the production of small parts that require close tolerances.

B 1.1.3 Investment casting

This method is also called precision casting because it can produce castings with close tolerances and smooth surfaces which require little or no further machining or grinding. There are several investment casting processes developed from the "lost wax" process which is still widely used. They involve the use of a wax or plastic pattern to form the mold cavity. The wax or plastic patterns are made in quantity from metal or plaster of paris dies. THe patterns are dipped in slurry of fine refractory material and are then encased in the investment material (plaster of paris or mixtures of ceramic materials with high refractory properties). The wax is then removed from the mold by heating to liquify the wax and cause it to run out to be reclaimed. Figure B.3 illustrates the

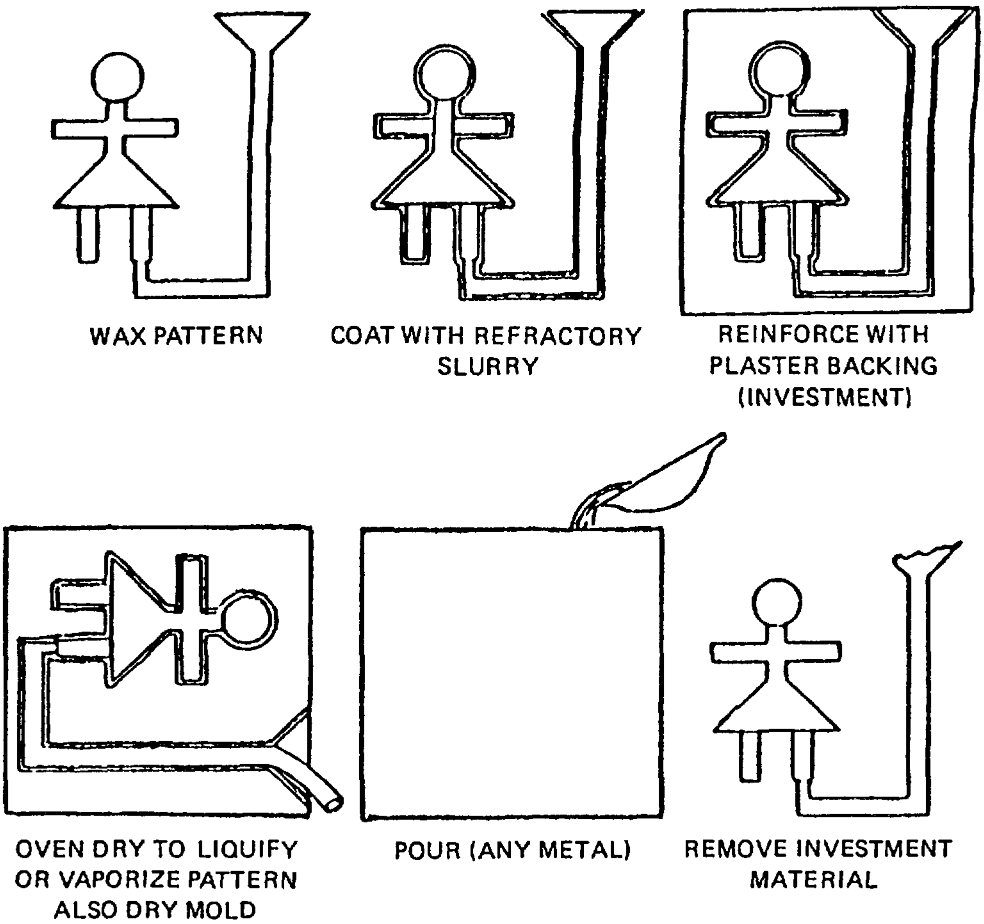


Figure B 3 Steps for investment casting

various steps involved in the investment casting process. The fine dimensional accuracy that can be obtained with the investment method makes this process ideal for complicated parts that are difficult or impossible to forge or machine. It is used generally to produce parts that weigh less than 1Kg although larger castings have been fabricated by this method.

B 1.1.4 **Die casting**

Low melting point metals and alloys may be cast under pressure in a die casting machine that uses metal molds or dies to form the metal. Liquid metal under gravity or other pressure is forced into the pair of dies which come together automatically. The metal solidifies rapidly and the resulting casting is dropped or pushed from the die when they separate.
The dies may be water cooled and the process made automatic. They are made with great care and produce parts with close dimensional tolerances and of strong, fine grained structure.

Die casting is a production operation used when a large number of similar parts are to be produced.

B 1.1.5 **Centrifugal casting**

Cylindrical shapes may be made by pouring liquid metal into a permanent cylindrical mold while it is rotating rapidly.The liquid metal is forced against the sides of the mold by centrifugal action where it solidifies to produce a tube or cylinderical shaped object such as pipe. The wall thickness of the object will depend on the amount of metal poured . When the metal has solidified ,rotation is stopped and the specimen or "inner lining " removed.
The centrifugal action on the metal while it is solidifying increases the density and strength of the part. The process is suitable for the manufacture of pipes, tubes, bushings,linings etc,although it can also be used for more complicated shapes where an entire mold complete with cores, risers,gates etc is spun about its axis.

B1.2 **Casting discontinuities**

There are certain defects and discontinuities common to cast materials and to the different casting methods. Some of the common casting discontinuities can be classified as:

i) Shrinkage discontinuities
ii) Discontinuities associated with entrapped gas
iii) Discontinuities associated with hindered contraction during cooling
iv) Inclusions
v) Segregations

vi) Cold shut
vii) Core shift
viii) Misrun

B 1.2.1 Shrinkage discontinuities

Shrinkage discontinuities are cavities formed during solidification because of liquid to solid contraction. These defects are not usually associated with gas, but a high gas content will magnify their extent. Shrinkage cavities occur usually at hot spots in the casting (Figure B 4). They may be associated with feeding heads such as risers etc and ,in such instances,are often referred to as "pipes".

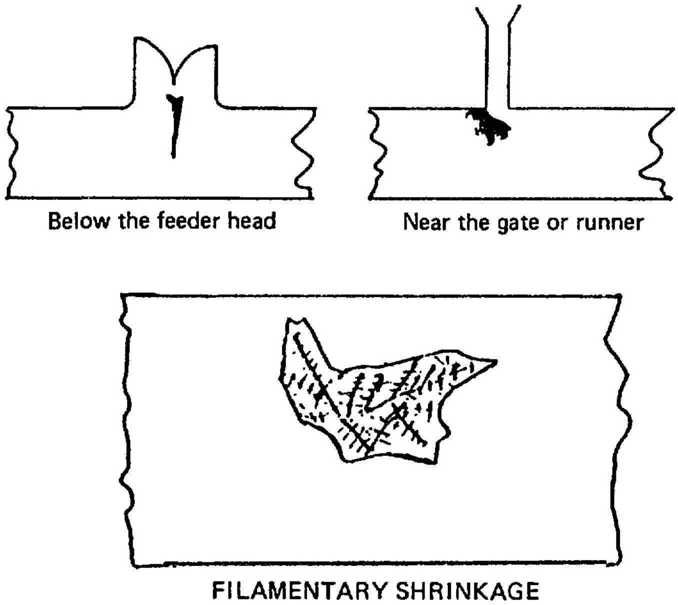


Figure B 4 Formation of shrinkage defects

A type of shrinkage discontinuity which is known as filamentary or centre line shrinkage consists of long string -like voids which run roughly parallel to each other or intertwine in a branch-like network. The network often occurs in bands within the metal near its centre (Figure B 4). It is often hard to differentiate between severe branch-like shrinkage and hot tears. Microshrinkage or Microporosity is a fine defect in castings which is due to shrinkage or gas or both in which numbers of cavities occur either round the grain boundaries (intercrystalline) or between the dendrite arms (interdendritic). A system of coarse and usually localised form of intercrystalline and interdendritic cavities is known as sponginess.

B 1.2.2 Discontinuities associated with entrapped gas.

When gas that is developed during the pouring of a metal casting can not escape through the mold itself or through the riser or other outlets ,it may be

trapped in the molten metal. The gas may be formed by release from the molten metal itself, from the green sand mold, from water vapor, or merely by turbulence caused when pouring metal.
Gas holes (or blow holes) are caused by air, mold, or core gases and water vapor being trapped in the casting, usually on the cope side, during solidification. THey occur single or in clusters and are of smooth, round, elongated, or oval shape of varying sizes. Sometimes an extremely long gas hole appears like a shrinkage cavity, although it differs from a shrink in that the ends of the gas hole are rounded and smooth.
Gas porosity is a discontinuity that is caused by dissolved gases in the molten metal which have become trapped in the solid casting. The size and amount depends on the gas content of the metal and the rate of solidification of the casting. Porosity may either occur through-out or in some localised area of the casting.
Air lock is a discontinuity arising from the entrapment of gas in the metal stream during pouring. This discontinuity may appear in the casting as a cavity or several cavities first below and parallel to the casting surface (Figure B 5).

Figure B 5 Airlock

B 1.2.3. **Crack**

This is a discontinuity which is due to the fracture of the metal during or after solidification. Hot tears are cracks which are discontinuous and generally of ragged form . They are caused by stresses which develop near the solidification temperature when the steel is at its weakest. The stresses arise when the contraction of the cooling metal is restrained by a mold or core, or by an already solid thinner section. Figure B 6 shows some of the causes and locations of this type of cracking.
Stress crack is a well defined and approximately straight rupture formed when the metal has become completely solid . Quite large stresses are required to cause such a type of crack . Distinctions are some times drawn between types of this defect depending upon the time at which fracture occured e.g. stress crack due to contraction , residual stress, shock or service.

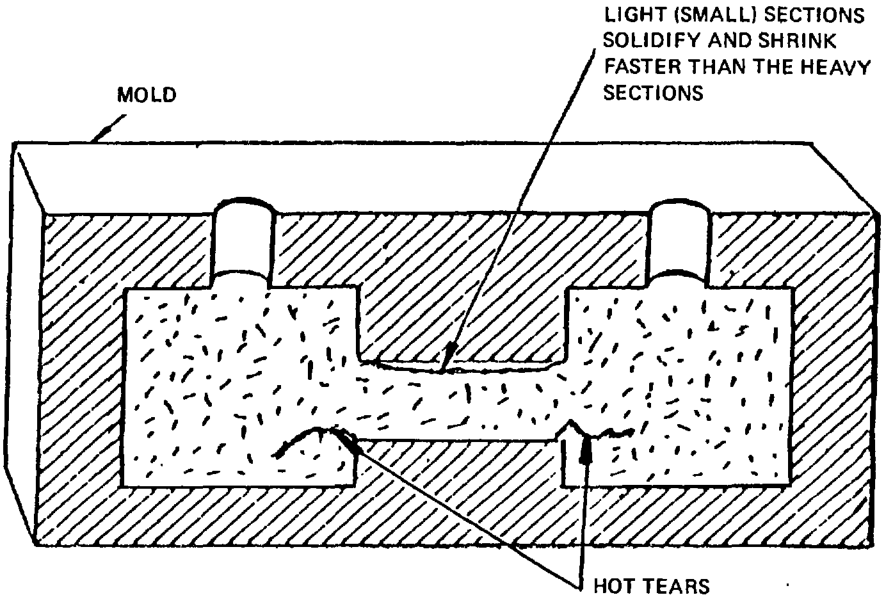


Figure B 6 Hot tears

B 1.2.4 Inclusions

Inclusions is a general term applied to sand ,slag, oxide etc. trapped in the casting. In most cases these defects occur near the surface as a "skin" effect. In some instances, however, the inclusion may occur at the centre of the casting, depending on the flow of metal.

B 1.2.5. Segregation

Segregation is a complex phenomenon that results when one or more alloying elements is not properly diffused and concentrates in certain areas. Segregation may be classified into three types ; general, localised and banded. General segregation extends over a considerable part of the casting and may take a variety of forms e.g. intercrystalline segregation. Local segregation occurs when shrinkage voids or hot tears are wholly or partially filled with a constituent of low melting point. The terms shrinkage and hot tear segregation can be applied respectively to these two conditions. Banded segregation is associated mainly with centrifugal castings but occasionally occurs in static castings. It takes the form of alternate layers of the alloy enriched in or depleted by the separating constituents.

B 1.2.6 Cold shuts

This is a discontinuity caused by the failure of the stream of molten metal to unite with a confluent stream or with solid metal such as a pouring splash, intenal chill or a chaplet. They can frequently be detected by visual inspection and look like a crack with a smooth and curved contour. If it is only a surface condition ,it is called a "cold lap".

B 1.2.7 Core shift

Castings that have internal cavities designed into them use a core usually of sand to produce the cavity. If the core is not held firmly in position it may move when the molten metal is poured around it.

B 1.2.8 Misrun

A misrun occurs when the molten metal fails to fill the mold cavity completely.

B2.0 Forgings

Forging is the working of metals 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 foging 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 properties results from;

a) A general consolidation of the metal and closing of gas and contraction cavities by means of mechanical pressure.
b) A refinement of the crystal structure.
c) A destruction of the continuity of intergranular concentrations of impurities and inclusions.

Forging is done with either a hammer or a press. A horizontal press (forging machine) is used in certain instances for forging small parts.Otherwise forging machines are of the vertical type,the lower die of which is fixed while the upper die is movable 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.With presses , force is used to raise and lower the die and the metal is worked by slow steady pressure. Forging is not only used to produce parts of a shape that can not be rolller but also for parts of simple uniform shape,round or rectangular when these are large or when the quantity required is too small to warrant a roll set-up. Tool steels are often forged with a view to improving their properties.

Forgings may be considered under two categories:

a) Where the working surface of the die is flat or of uniform curved contour and shaping is done by manipulation using tools of simple shape. This is called " open die " forging.

b) Where impression dies are used and the metal is shaped by being forced into the die impression. This is called " closed die " forging.

In the first category are forgings of simple round or rectangular cross-section and forgings of more complex shape which are so large that the "sinking" of closed dies would be impractical or too costly. Small forgings of complicated final shape may be rough forged on simple dies and machined to final forms if the number required is too small to justify the cost of an impression die. Also in this category are hollow forged parts. For these the central hole is either machined out cold (trepanned) or it is punched out hot using suitable dies on a press. The part is then forged on a mandrel which passes through the hole and is supported at both ends so that the mandrel acts as the bottom die.

In close die forging on a hammer or press the lower die has the impression corresponding to one half of the part to be made while the upper die has the 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 right amount of metal to fill the impression . The excess metal that is forced in to this space is referred to as "flashing " or "flash ". After forging this is trimmed off in a suitable die. The closed die business is so competative that the losses in trimmed scrap provide one of the most important areas of economy. 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. Figure B 7 shows some examples of the forging operation.

B.2.1 Rolling and forging discontinuities

Discontinuities in forgings may originate in the slab or billet modified by the rolling and forging of the material or may result from the forging process itself. The more common discontinuities are:

i) Laminations
ii) Stringers
iii) Seams
iv) Forging laps
v) Forging bursts or cracks

B 2.1.1 Laminations

Large porosity , pipes and nonmetallic inclusions in slabs or billets are flattened and spread out during

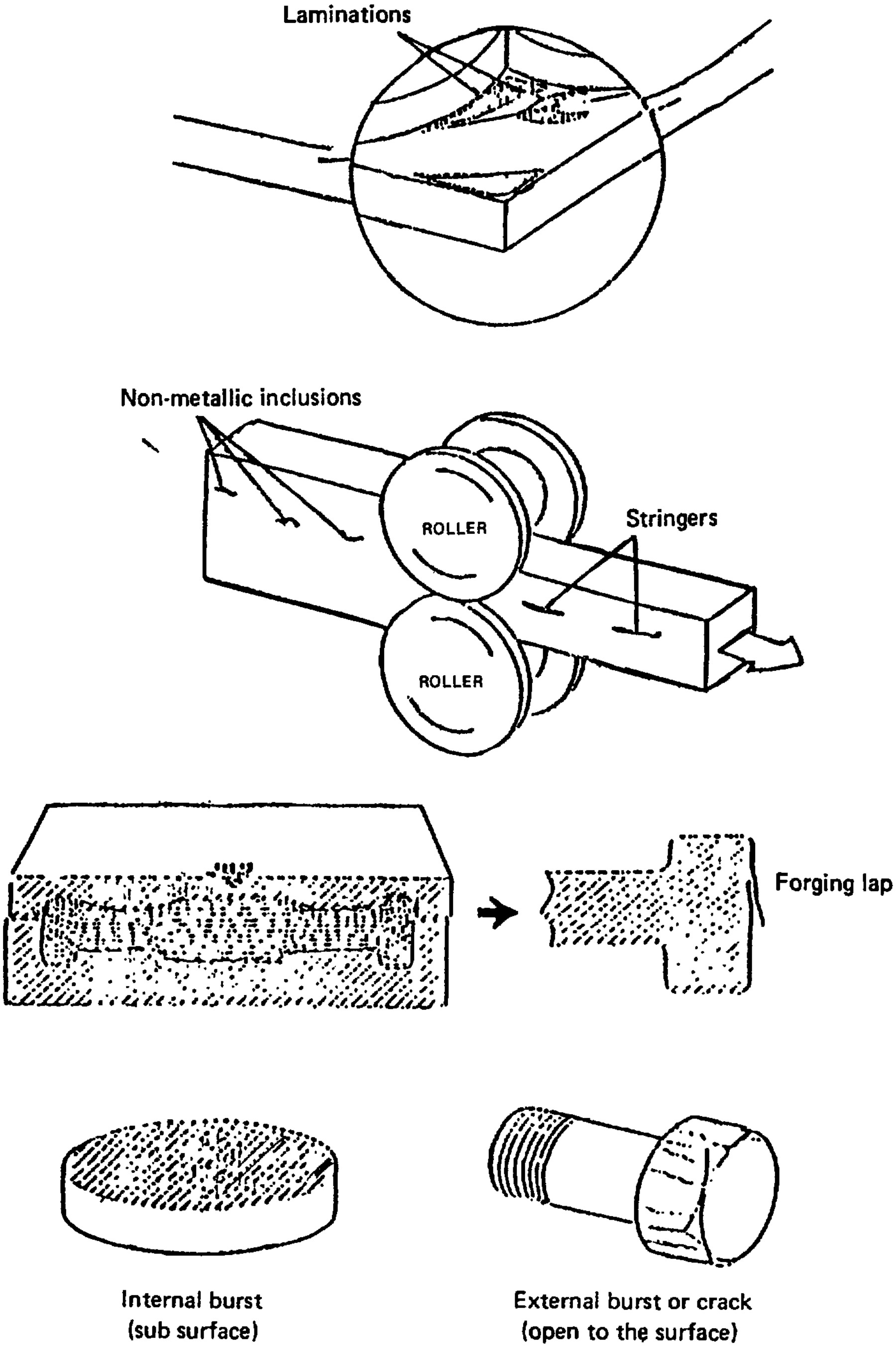


Figure B 7 Rolling and forging and their defects

the rolling and forging processes. These flattened discontinuities are known as laminations.

B 2.1.2 Stringer

Nonmetallic inclusions in slabs or billets that are thinned and lengthened in the direction of rolling by the rolling process are called stringers.

B 2.1.3 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

B 2.1.4 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.

B 2.1.5. Forging bursts or cracks

Forging bursts or cracks are ruptures caused by forging at too low a temperature. They may be internal or they may occur at the surface.

Appendix C
ULTRASONIC PRACTICALS

PRACTICAL - 1 : USE OF ULTRASONIC FLAW DETECTOR (FUNCTIONS OF VARIOUS CONTROLS ON THE FLAW DETECTOR)

1. Have the instruction manual of the flaw detector and proceed according to the procedure laid down.

2. Make a detailed sketch of the front view of the instrument showing the names and location of various control knobs.

3. Before switching on see that the instrument is adjusted for operation on battery/line voltage etc.

4. Adjust the frequency selection switch such that the reading on it matches with the frequency of the probe to be used (if control is available).

5. Adjust the transmission/reception switch. After this connect a normal probe to the flaw detector.

6. Switch on the mains switch and also switch on the instrument. Base line with transmission pulse should appear on the screen.

7. Move the base line vertically and horizontally with the help of controls on the instrument (if controls for such functions are available).

8. Adjust the 'focus' to get a sharp line and transmission pulse.

9. Apply a thin uniform layer of couplant to the test piece (V-1 test block in this case). The couplant in this case is lubricating oil or grease.

10. Apply the probe to the test block. A number of peaks should appear on the screen.

11. Adjust the 'depth range' or 'material selection switch' and see how it increases or decreases the distance between successive peaks. Select its position to get, for example, 10, 5, 3, 2, etc. peaks on the screen.

12. Operate the 'delay switch' on the instrument and see its function. It should move the spectrum of peaks as a whole without disturbing their relative separation.

13. Operate the 'gain' , 'attenuation' or 'sensitivity' switch and see its function. It should increase or decrease the amplitude of the peaks. See if there is a 'reject' switch on the flaw detector.

If so, operate it and see its function. It should clear all the grass on the base line. Switch off the reject switch. It must NOT be used unless instructed to do so.

14. There may be a 'gate' switch on the instrument. This is usually used in automatic testing and is therefore of no interest to us for the present.

15. Repeat by changing to probes of different frequencies.

16. Repeat by placing the probe on different portions and sides of the test block.

17. Record your observations in the form of a detailed report.

18. Practice with other types of flaw detectors if possible.

PRACTICAL - II : CALIBRATION AND USE OF ULTRASONIC FLAW DETECTOR WITH NORMAL PROBES

A. Calibration of time base :

1. Switch on the instrument as described in Practical - 1.
2. Apply the normal probe to the 25 mm thickness of test block V-1 as shows in Fig. 1.

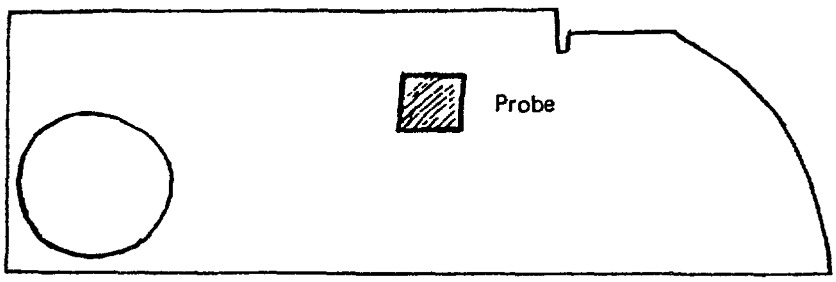


Fig. 1

3. Adjust the zero control and depth range such that four reflection peaks appear on the screen. Adjust the above delay or zero control to accurately located the leading edge of the first reflection peak with the 2.5 reading if the total screen has 10 divisions.
   Adjust the 4 th echo to the 10.0 reading using the range control. Readjust the position of the 1st echo using the delay control and then the 4th echo using the range control. Repeat until the 1st and 4th echo are located accurately. The 2nd and 3rd echo should now be at the 5 and 7.5 reading. The screen appearance would be as shown in Fig. 2 .

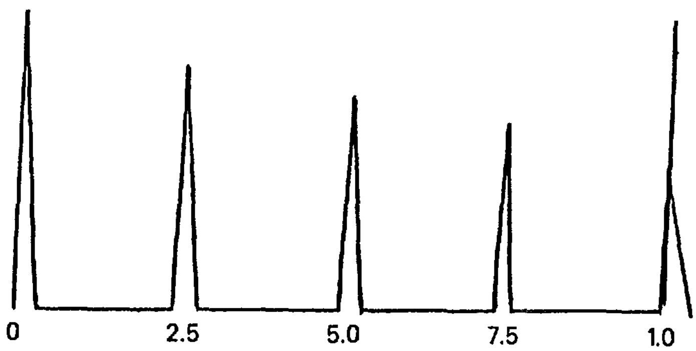


Fig. 2

   This means that the time is now linear which means that equal distances on the time base correspond to equal thickness on the test block. It is calibrated to measure thicknesses and ranges of the beam upto 100 mm.

4. Place the probe now facing the 100 mm thickness of the block as shown in Fig. 3 position (a). Only one peak should appear on the screen and it should be located at 10. Similarly place the probe at position (b) over the 91 mm thickness. The single peak should now appear at 9.1

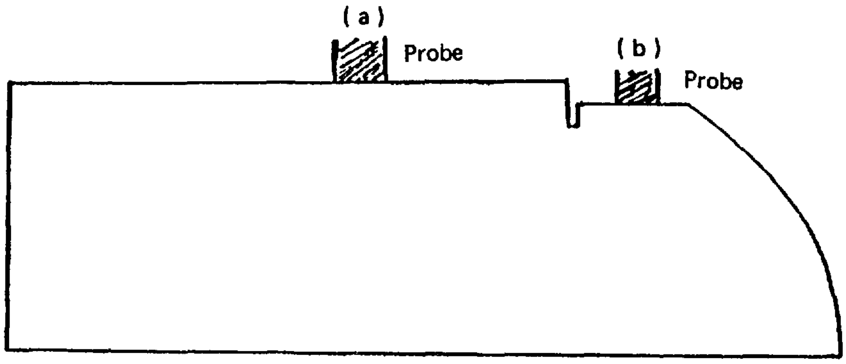


Fig. 3

reading on the screen. The corresponding screen appearance for position (a) and (b) of Fig. 3 is shown in Fig. 4.

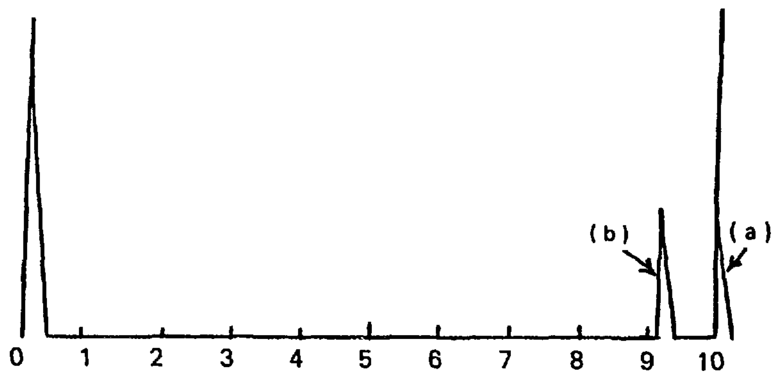


Fig. 4

5. Set the flaw detector to give a test range of 400 and 800 mm.

Caution : Always calibrate with at least two peaks on the screen to ensure proper linearity of the time base.

PRACTICAL - III : COMPARISON OF VARIOUS COUPLANTS

1. Select two normal beam probes of 2 or 4 MHz with and without a protective face plate.

2. Calibrate the time base for a 50 mm thickness range using 11W Block VI .

3. Consider the IIW Block and a plate with a rough surface as two test specimens.

4. Place the two specimen side by side and apply each couplant in turn to both the surfaces and adjust the first back-wall echo from both the specimens to 60% of full screen height.

5. Note the gain setting for each couplant and record the results.

SPECIMEN	PROTECTIVE FACE PLATE	MACHINE OIL	GLYCERIN	WATER
STANDARD BLOCK	NO YES			
PLATE	NO YES			

6. Select the best couplant.

PRACTIVAL - IV : CALIBRATION WITH ANGLE BEAM PROBE

A. **Determination of Probe Index Using VI Block.**

1. Select an angle probe.

2. Place the probe on the VI block as shown in Fig. 1 and maximise the echo from the 100 mm quadrant using to and fro movements. Set the instrument sensitivity so that the maximised echo height is 50-80% of full screen height. Care is necessary to ensure that the maximised echo is not from one of the corners of the quadrant.

3. When the maximised echo has been obtained, mark the probe index on the probe as shown in Fig. 2.

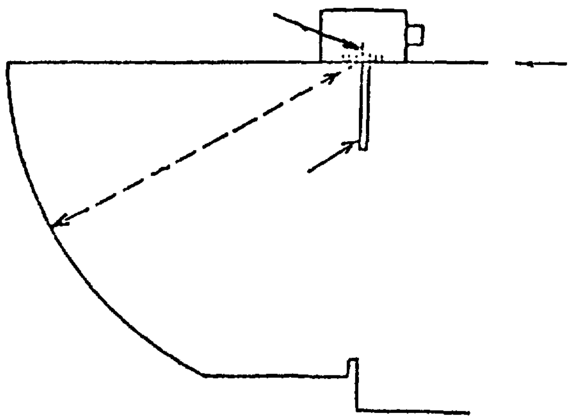


Fig. 1

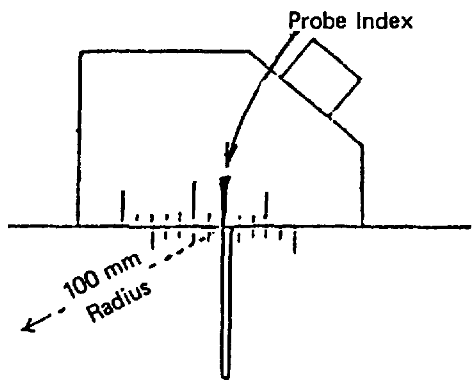


Fig. 2 .

B. **Determination of Probe Angle Using VI Block**

1. Place the probe on the 25 mm wide surface of the VI block to beam towards the 50 mm diameter perspex insert (Fig. 3) .

2. Move the probe to and fro on the test surface and maximise the signal from the insert.

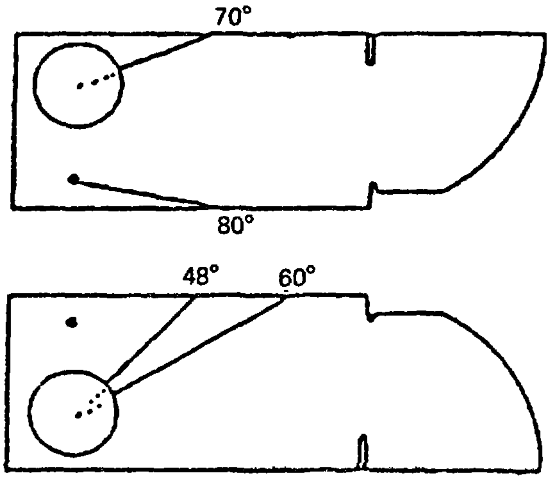


Fig. 3

3. When the maximum echo has been obtained read the angle which is marked on the side of the block and which coincides with the probe index. This is the actual refraction angle of the probe. The angle can be read to within 0.5 by interpolation. Because of the relatively large reflecting surface it is difficult to obtain a maximum echo and it is therefore recommneded that the operation be repeated two or three times to ensure that the same angle is obtained.

C. **100mm Range Calibration for Angle Beam Probe Using VI Block**

Procedure - 1

1. Place a normal probe on the step in the VI (IIW Block) to give a beam path distance of 91mm as shown in Fig. 4.

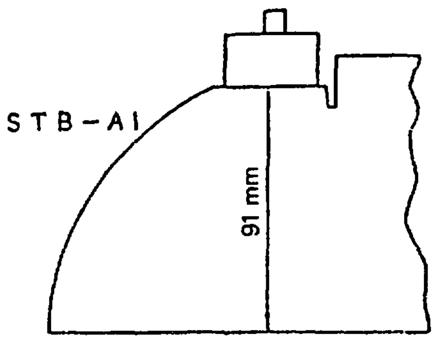


Fig. 4

2. Set the first back echo, B1 at the 4th scale division of the time base and the second back echo, B2 , at the 8th scale division as shown in Fig. 5 .

3. Change the normal probe to the angle probe.

4. Place the angle probe at the centre of the 100 mm radius quadrant as shown in Fig. 1 so that the probe index point coincides with central mark on the block.

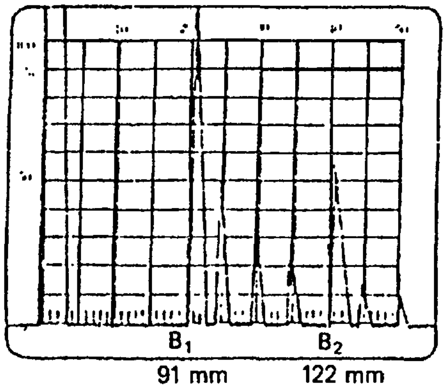


Fig. 5

The echo should be at exactly 10 scale division if the calibration is correct.

Procedure - 2

1. Obtain the maximum echo from the 100 mm quadrant and increase the instrument sensitivity (by about 20dB) to bring the second back echo to about half full screen height as shown in Fig. 6 .

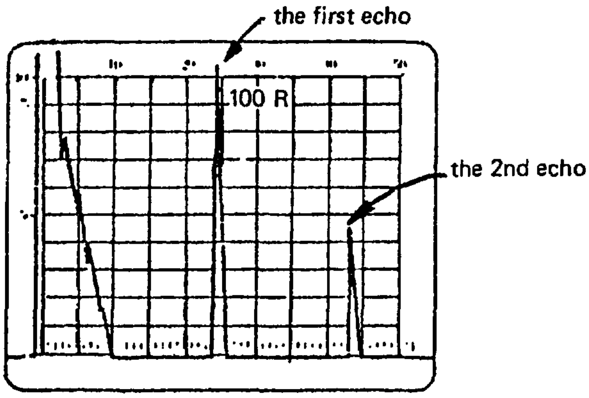


Fig. 6

2. Adjust the time base control to locate the first echo to the zero point of the time base and the second echo to the 10th scale division as shown in Fig. 7 .

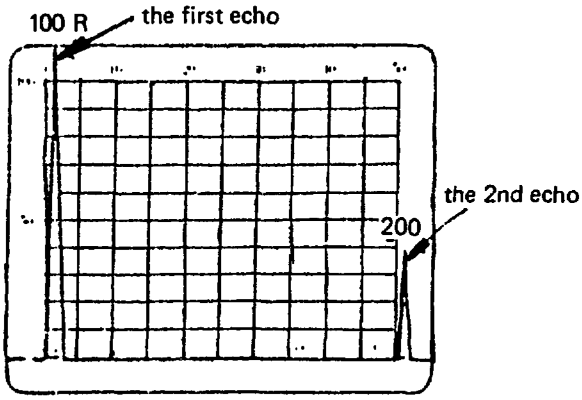
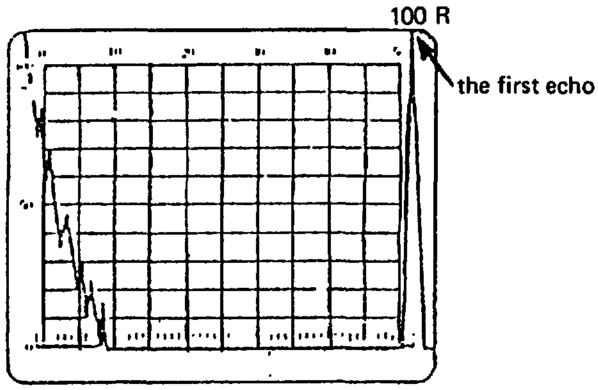


Fig. 7

Fig. 8



3. Shift the first echo to the 10th division position using the sweep delay control as shown in Fig. 8 .

The time base is now adjusted to a 100 mm test range.

D. **Calibration for Test Range 200 mm & 400 mm**

1. Place the probe on VI block as shown in Fig. 1 and obtain two back wall echoes from the 100 mm quadrant.
2. Using 'delay' and 'test range' controls set the first echo to 5th scale division and the 2nd to 10th scale division. The time base is now calibrated for 200 mm.
3. For 400 mm test range calibration, obtain four echoes from the 100 mm quadrant and set them to 2.5th, 5th, 7.5th and 10th scale divisions of the CRT screen.

E. **Calibration of Test Range of 100 mm and 125 mm Using V2 Block**

1. Determine the probe index as described in A.
2. Place the probe on the V2 block so that its crystal faces the 25mm quadrant and its probe index coincides with the central mark on the probe (Fig. 9).
3. Obtain two back wall echoes on the screen.

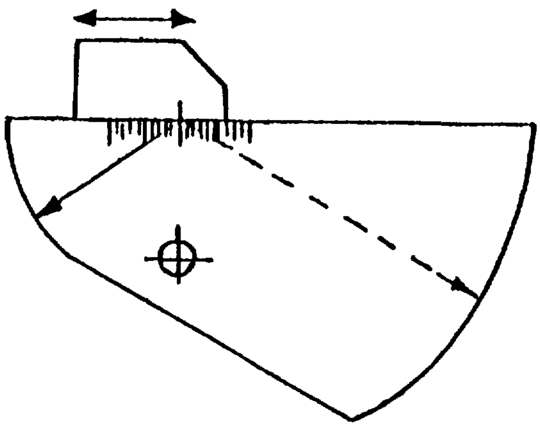


Fig. 9

4. Using the 'delay' and 'test range' controls adjust the first echo to 2.5th scale division and 2nd to 10th scale division.

5. The CRT screen is now calibrated for 100 mm test range.

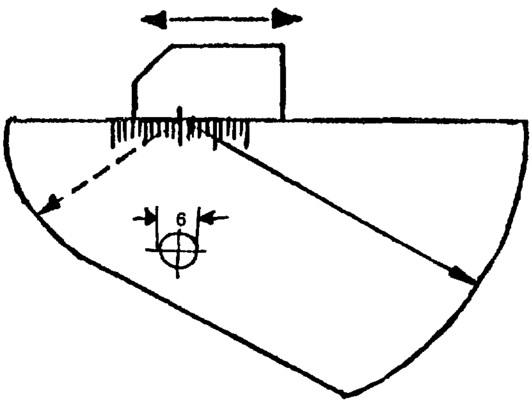


Fig. 10

6. For test calibration of 125 mm, place the probe on V2 block so that the probe index coincides with the central mark on the block and the probe's crystal faces the 50 mm quadrant (Fig. 10).

7. Obtain two back wall echoes on the screen and adjust them to 4th and 10th scale divisions of the screen. The screen is thus calibrated for 125 mm test range.

F. Determination of Probe Index Using V2 Block

1. Place the probe either facing the 25 mm or the 50 mm quadrant and obtain a back wall echo.

2. Maximize the echo by the to and fro motion of the probe.

3. Mark the point on the probe which coincides with the central mark of the block. This is the probe index.

G. Determination of the Probe Angle Using V2 Block

1. Place the probe so that its beam is directed toward the 5mm diameter hole (Fig. 11)

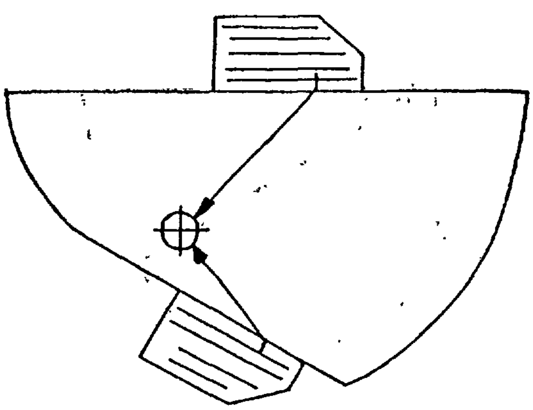


Fig. 11

2. Maximize the echo obtained from the beam reflected from the hole.

3. Estimate the probe angle by noting the probe index position with respect to the angles inscribed on the block.

H. **Measurement of the Location of a Reflector with an angle probe**

1. Place the probe as shown in Fig. 12 and obtain a maximum echo from the 1.5 mm side drilled hole in the VI block.

2. When the maximum echo is obtained, read the beam path distance, W and the distance, Y , between the probe index and the corner of the block.

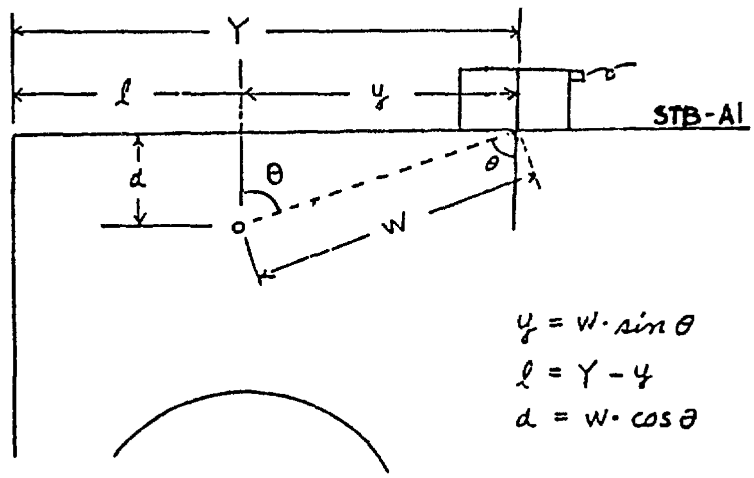


Fig. 12

3. Calculate the probe index - reflector distance.
$Y = W. \sin \theta$

4. The hole location along the test surface is given by
$= Y - y$.

5. The depth of the hole from the test surface is given by
$d = W \cos \theta$.

PRACTICAL V : THICKNESS MEASUREMENT USING THE ULTRASONIC FLAW DETECTOR

A. Thickness Measurement With Normal Beam Probes

1. Calibrate the time base for thickness range of 50 mm using a normal beam probe (MB4S-N).

2. Measure the thicknesses of steps of a stepped block and record the results.

3. Compare the result with the measurement obtained with a caliper and determine the difference.

B. Thickness Measurement with TR or Twin Crystal Probe

1. Select a TR probe (e.g. MSEB 4 H).

2. Calibrate the time base for a range of 10 mm by adjusting the sweep control and range control after placing the probe on steps with 5 mm and 10 mm thickness respectively. In case 'of 5 mm thick step, the peak should coincide with 5th graticule while for 10mm thick step the peak should coincide with 10th graticule. The time base is calibrated for 10 mm thickness range.

3. Measure the thickness of another step or plate.

4. What is the accuracy of such a measurement?

5. Place the probe on each step of stepped block and measure the thickness.

6. State the minimum thickness that can be measured with your equipment.

7. Compare the results with the measurements obtained with a vernier and calculate the error.

PRACTICAL VI : EXPERIMENT WITH MODE CONVERSION

1. Calibration the time base for a range of 200 mm by placing a normal beam probe on the narrow side of IIW block (Fig. 1). Adjust the gain control to set the second back wall echo to full screen height. Regularly spaced spikes will be seen in between the two back-wall echoes. Measure their location and explain their origin. Are these spikes seen between the transmission pulse and first back-wall echo ?

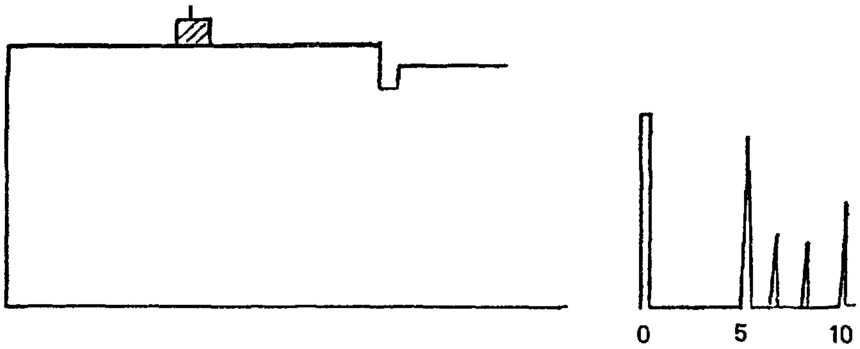


Fig. 1 IIW BLOCK

2. With the probe still on IIW, adjust the delay, range and gain controls so that four back-wall echoes are seen on the screen. Do you see the spikes between the consecutive back-wall echoes. If so what are these ?

3. Now place the same probe on a round steel bar and repeat step (1) and (2). How many echoes do you see (a) between the transmission pulse and the first back wall echo, (b) between each consecutive pair of back-wall echoes.

4. Use a 60^{o} angle probe and calibrate the time base for a range of 100 mm. Place the probe on the narrow side of IIW Block VI and direct the beam towards the 1.5 mm diameter hole. Maximize the echo height and adjust the gain control so that the echo is 80% of full screen height. Record this setting. Now place the probe on flat side of the same block. Direct the beam again towards 1.5 mm hole and record setting for the same echo height. Explain the difference between the two gain settings.

PRACTICAL IX : BEAM PROFILE IN VERTICAL AND HORIZONTAL PLANE

A. Beam Profile in Vertical Plane

1. Calibrate the time base of your flaw detector for a range of 100mm (or 200mm).

2. Determine the angle and exit point of your angle beam probe.

3. Put the probe on the IOW Block and direct the beam towards any convenient drilled hole.

4. You will most likely see a number of echoes on the CRT screen but identify the particular one coming from your selected hole. This identification can be easily achieved by comparing the position of the echo with the actual beam path (i.e the distance between the exit point and the selected drilled hole) measured by using a ruler.

5. Maximise the echo height from this drilled hole by sliding the probe forwards and backwards. Mark the position of the exit point on the block and identify it as "A" .

6. Adjust the sensitivity (gain/attenuator) control and set the echo height to, say, 80% of the full CRT screen height.

7. Move the probe forwards until the echo height drops by 20dB. Mark the new position of the exit point on the block and identify it as "B" .

8. Now move the probe backwards until the echo height again drops by 20 dB. Mark the 3rd position of the exit point on the block and identify it as "C" .

9. Measure the distances AB and AC in mm using a ruler.

10. Draw a horizontal line O' X ' on the beam profile graph paper below the X-axis at a distance equal to the depth of the selected drilled hole from the contact surface.

11. Draw a line, OZ, from the origin of the axis at an angle (as measured anticlockwise from the Y-axis) equal to the probe angle determined earlier in 2. Use the angular scale at the graph bottom for this purpose. This line will now represent the beam axis.

12. Note that AB corresponds to the distance between the beam axis and the trailing beam edge, and AC, that between the beam axis and the leading beam edge.

13. Hence, on the basis of (12), mark out two points B' & C' on O'X' at distances of AB and AC from the intersection of the beam axis, OZ , and the horizontal line, ' X ' .

B'C' is now the beam width in the vertical plane OXZY at the depth OO' .

14. Repeat steps 3 to 13 for at least six pairs of points at different depths.

15. Draw the best-fit straight line for the points on each side of the beam.

B. Beam Profile in Horizontal Plane

1. Maximize the echo obtained from a selected hole.

2. Record the surface distance, Y, between the probe index and surface position of the hole, and draw a reference line across the block marking the rear edge of the probe.

3. Move the probe away from the edge of the block at right angle to it until the echo drops by 20dB.

4. Record the distance of the probe centre from the edge of the block, say-X1 .

5. Find half the beam spread for this particular value of Y by subtracting 22 mm from X1 , where 22 mm is the hole depth in the 10Wmm block. If a different reference block is used, check the hole depth using a wire , for example a straightened paper clip.

6. Place the probe on the other side of the hole and find the other half using steps 1 to 5 .

7. Find the beam spread for other holes using the same procedure and plot the beam spread against the corresponding value of Y .

PRACTICAL X : CHECKING EQUIPMENT CHARACTERISTICS

A. Checking the Linearity of an Amplifier

There is nothing we can do to alter the characteristics of the amplifier provided in the ultrasonic instrument. Still its behaviour should be known before undertaking practical testing.

1. Apply the probe to the test block as shown in Fig. 1 and obtain the peaks shown in Fig. 2 .

2. Note the ratio of the heights of any two consecutive peaks.

3. Alter the degree of sensitivity or the reading on the attenuator.

4. Note the ratio of the height of the same peaks as in step (2) .

5. Compare the ratios in steps (2) and (4). If the ratio remains constant, the amplifier is linear.

   Another way of checking whether the amplifier is linear or not is the following :

1. Get the peak as in Fig. 2 .

2. Select any peak and bring it to the full screen height by adjusting the attenuator. Note the new attenuator reading.

3. Change the attenuator reading to bring the height of the selected peak to half screen height.Note the new reading of the attenuator.

4. The difference between the two readings in steps (2) and (3) should be 6dB. This is because we know that when the ratio of echo heights is 2, it means a 6dB change in sound pressure level.

5. Get the peaks as in Fig. 2 again. Select a peak and bring it to full screen height. Note the reading of the attenuator.

6. Change the attenuator reading to bring the echo height to 1/10th of full screen height. Note the attenuator reading.

7. The difference between the two readings in steps (5) and (6) should be 20 dB. This is because we know that when the ratio of echo heights is 10, it means a 20 dB change in sound pressure level.

   These are the famous 6dB and 20dB criteria which are used to estimate flaw size in ultrasonic testing. A good flaw detector must fulfil these criteria to help in accurate sizing of defects.

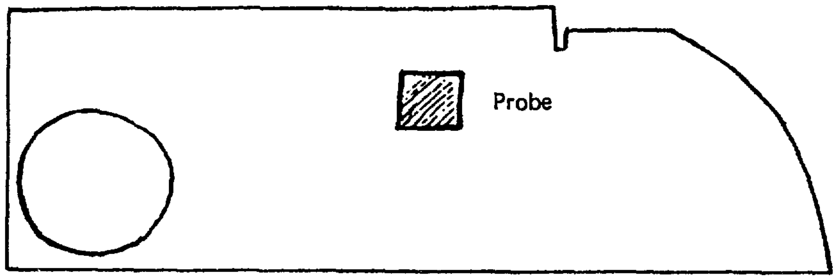


Fig. 1

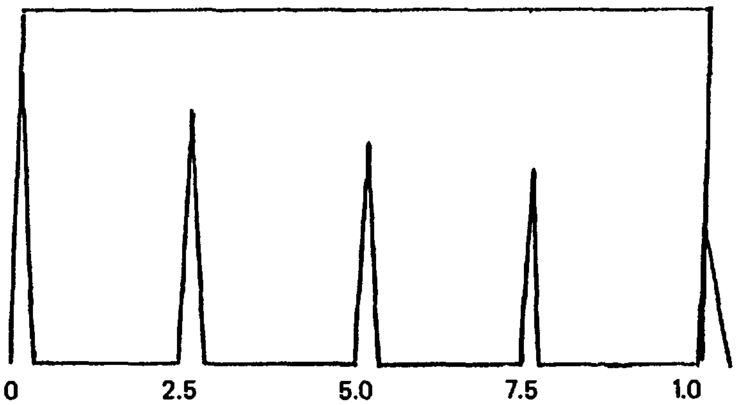


Fig. 2

Caution : Echo heights vary with the amount of pressure applied to the probes when they are coupled to the test specimen. Therefore an effort should be made to apply a uniform pressure in both the cases. This seems difficult in the beginning but comes gradually with increasing practice and experience.

B. Checking the Time Base Linearity

1. Place a normal beam probe on the 25mm thick side of the V1 block (as in Fig. 1) and obtain four back wall echoes as in Fig. 2 .
2. Set the first and fourth echo on the 2.5 and 10 scale divisions of the CRT screen.
3. Record carefully the positions of the remaining two echoes. They should be positioned at 5 and 7.5 scale divisions.
4. Determine the percentage error (if any) between the recorded and the actual screen divisions.
5. If the error is within 1% then the time base is linear otherwise it is not.

C. **Checking the Resolving Power of the Flaw Detector - Probe System**

1. Position the probe on the test block V-1 as in Fig. 3 , after the time base has been properly calibrated for 100mm.

2. Move the probe to maximise the echo heights. We should get three bottom echoes corresponding to ranges of 85,91 and 100mm, as shown in Fig. 4 .

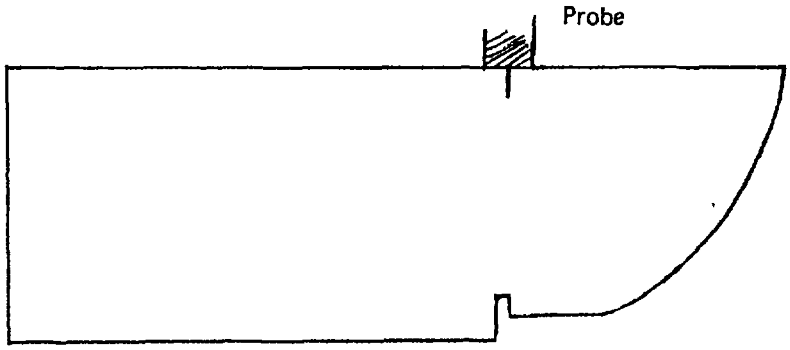


Fig. 3

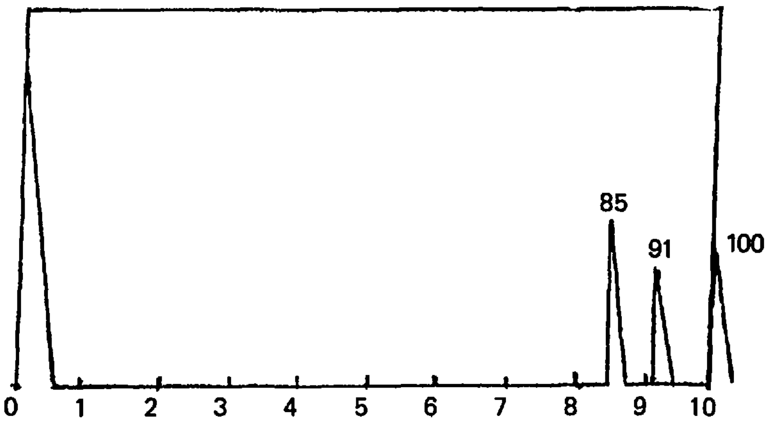


Fig. 4

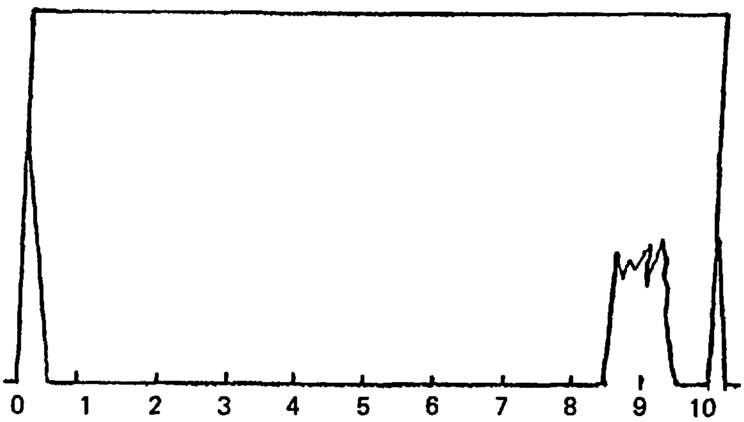


Fig 5

If the three echoes are well defined as in Fig. 4 i.e. they are separate from each other, then we say that the testing system has a good resolving power. On the other hand if the echoes are not separate but merge together to give a blurred indication such as in Fig. 5 , the equipment is said to have a poor resolution. A good resolving capability means that the flaw detector is able to show small defects such as gas pores lying close to each other as separate defects whereas for a bad or poor resolution these defects will be indicated as one.

3. Try different frequencies to see their effect on resolution.

D. **Dead Zone Check**

1. Place the probe at position A and B as shown in Fig. 5-A.

2. See whether the echoes from the 5mm and 10mm distances to the hole can be resolved from the transmission pulse. This will give an idea about the size of the dead zone of the flaw detector system.

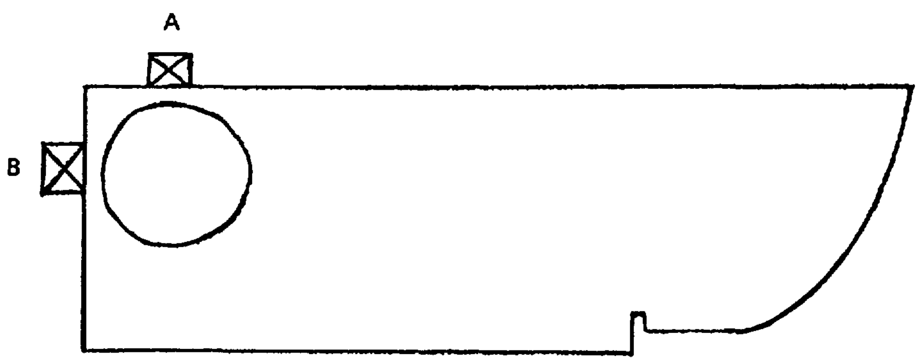


Fig. 5-A

E. **Maximum Penetrative Power**

1. Place a normal beam probe on the perspex insert of the V1 block (Fig. 6).

2. Set the gain control to the maximum value.

3. Record the number of peaks visible on the CRT screen and the height of the last echo.

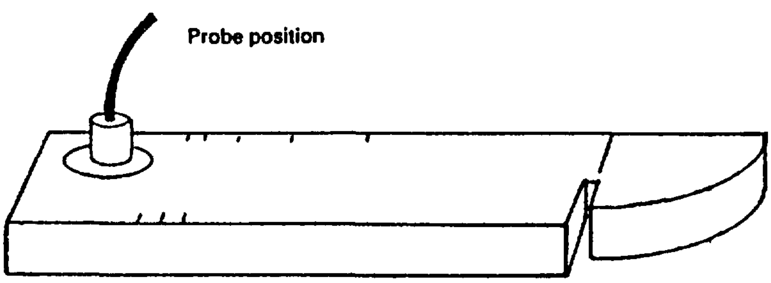


Fig 6.

4. Repeat (1) to (3) for probe with different frequencies (if possible).

5. Also repeat (1) to (3) for other flaw detectors (if possible).

PRACTICAL XI : SENSITIVITY SETTING USING AN ANGLE PROBE AND THE ASME BLOCK

1. Select an angle probe; determine its exit point and angle, and calibrate the time base for a maximum range of 200 mm.

2. Place the probe on the ASME block and find the hole which gives the maximum amplitude echo.

3. Maximise the height of this echo by moving the probe forwards and backwards (and rotating it, if necessary).

4. Check that the suppressor control is set to the minimum so that the sensitivity setting can be calibrated and made reproducible.

5. Adjust the sensitivity control until the echo height is 75% of CRT height.

6. This echo constitutes the uncorrected primary reference echo (PRE).

7. Without altering the sensitivity control, get maximized echoes for other holes and record than in percentages of the full CRT screen height as well as their location on the screen.

8. Plot each echo height vs its screen location on a transparent plastic sheet cut exactly to fit onto the CRT screen. The X and Y axis should be drawn on this sheet. Data such as time base range, probe and detector specifications, ASME block thickness and identification and the uncorrected PRE gain should be recorded on it as well.

PRACTICAL XII : DETERMINATION OF THE ATTENUATION AND SURFACE TRANSFER LOSS CORRECTION BETWEEN THE REFERENCE CALIBRATION BLOCK AND THE TEST PLATE

1. Place two identical angle probes on the broad side of the reference block (ASME block) at one skip distance apart with a weight on top of one of them. They can be kept in a line by using a straightedge.

2. Peak the signal by probe movement and adjust it to 80% full screen using the unsuppressed gain control and record the signal location on the screen.

3. Repeat the above steps for 1, 2, 3 and 4 skip distances and plot the gain settings VS echo locations on a graph paper.

4. Repeat steps 1 to 3 on the test plate.

5. The difference (Y) in gain between the two curves at the appropriate beam path on the screen is the combined attenuation and surface loss correction.

6. Plot the DAC curve on a graph paper using one of the probes.

7. Now put the two probes on the test plate at one skip distance apart and adjust the signal to the DAC curve.

8. Without changing the gain setting, put the probes at 2 skip distances and find the difference (y) in dB between the second peak and the DAC curve.

9. This difference (y) represents the attenuation loss over a beam path of one skip distance. The attenuation constant is then calculated :-

   $= \frac{Y}{X}$ dB/mm where x is the beam path distance corresponding to half the skip distance.

   The attenuation loss over any distance may be calculated using this constant.

10. The surface transfer loss correction is then calculated:-

    $$S = (Y - y) \text{ dB}$$

11. Plot the correction curve for surface transfer loss and attenuation. This correction is then added to the DAC gain to obtain the final sensitivity level for defect evaluation.

PRACTICAL XIII : FLAW SIZING PRACTICE

A. Determination of Defect Size Using a Normal Beam Probe

1. Select an appropriate normal beam (e.g MB4S-N).

2. Calibrate the time base for a 50mm range using the VI block.

4. Adjust the gain control to obtain the first back wall echo at full screen height.

3. Place the probe on the surface of the test block with machined defects.

5. Scan the surface of the test block.

6. Mark the areas where the defects are detected.

7. Using the 6dB drop method determine the size of the flaw as follows :-

   (a) Maximize the echo from the flaw and bring it to full screen height using the dB control ..

   (b) Move the probe across the flaw and mark the centre of the probe on the test specimen surface at a location where the echo drops to 50% of full screen height.

   (c) Repeat step (b) to mark all the edges of the flaw.

   (d) Draw a sketch of the test block showing all the information about the flaws.

8. Compare the size of the defects with the defect sizes shown in the radiographs of the respective test blocks.

9. Record any discrepency.

B. Determination of Defect Length With Angle Probes

1. Calibrate the time base for 100mm or 200mm thickness range using an angle probe.

2. Place the DAC curve already drawn on the screen of the flaw detector for the same time base calibration as in step (1).

3. Place the probe on the surface of the reference block IIW, VI at location, A, to scan towards the notch as shown in Figure 1.

4. Adjust the echo height from the notch to obtain a maximum echo.

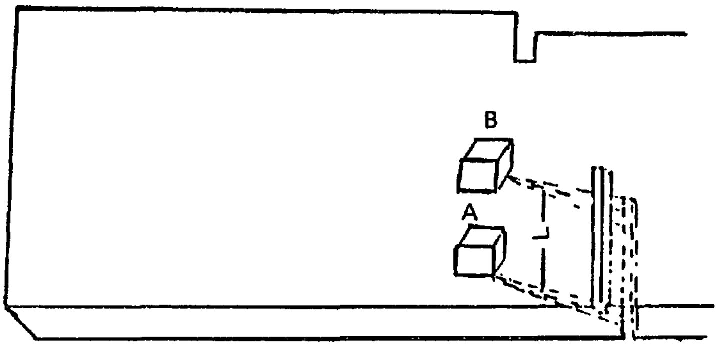


Fig 1

5. Scan the probe laterally in the direction parallel to the notch. A ruler can be used for this purpose. When the echo height drops by the specified level, L, mark the position of the centre of the probe on the block. During scanning from A to B on the test block surface in a straight line with a small to and fro movement the maximum echo height should be constantly achieved. Avoid rotational scanning.

6. The specified level can be 6dB, 10dB, 20dB or any other level specified in the code being used.

7. To find the end of the notch subtract the 1/2 beam width at the beam path distance to the notch. Use the value found in Practical 9B.

PRACTICAL XIV : PROCEDURE FOR THE EXAMINATION OF A SINGLE-VEE BUTT WELD ACCORDING TO ASME V

1. Draw to scale a section of the weld on a graph paper, showing the edge preparation.

   Draw the centre line of the weld section. Sketch a plan view of the weld seam and draw a horizontal line to indicate the seam axis.

2. Choose your probe angle according to the plate thickness, t. A frequency of 2.5MHz is recommended although any frequency between 1 to 5 MHz may be used.

   For 10 mm t 40 mm, use 70

   For 40 mm t 60 mm, use 70 or 60 and 45

   For 60 mm t 100 mm, use 60 and 45

   t 100 mm use 60 and 45

3. Use a normal or SE probe to check that the parent metal within the full skip distance from each seam edge is free of laminations or other defects. For this examination, set the sensitivity level by bringing the second back wall to full screen height. Make sure the plate surface has no weld spatter, loose scale and paint.

4. Check your equipment characteristics such as (a) linearity of time base, (b) Linearity of receiving amplifier, (c) probe index, (d) probe angle, (e) beam profile, (f) near surface and depth resolution and (g) dead zone.

   Maximum deviation in (a) + 5% & (b) 10% of 2:1 between 20% & 80% full screen.

5. Set time base range to 10mm or 200mm depending on plate thickness and put the DAC, 50% DAC, and 20% DAC curves on the screen.

6. Set the sensitivity level according to the ASME Code, with correction for transfer losses. For initial scanning, add an additional 6 dB., i.e Scanning Sensitivity = (PRE + T.L + 6) dB.

7. Draw a line to represent the weld axis over the centre of the weld seam.

8. Draw two lines on the parent metal surface at each side of the seam to mark the probe movement from half skip or full skip distances from the seam centre. Scan the weld root by moving the probe parallel to the weld seam.

9. Scan the weld for weld body flaws, moving the probe from the half skip distance to full skip distance and rotating it a bit about the direction of the main

movement. A square scan pattern with overlap is recommended. The weld must a least be scanned on both sides of the weld on the same surface. Scanning rate must not exceed 152 mm/s (6 in/s).

10. Scan the weld for transverse flaws by moving the probe over the parent metal surface along a line parallel to the weld axis with the beam slightly inclined towards the weld seam at about 10 . This scan must be done on both sides of the seam with the transducer moved in the same direction. If not possible, then scan on opposite surfaces on either side of the weld.

    NB : The scan for transverse defects is particularly important for high tensile steel especially for thick welds welded with restraint.

11. Mark out for further investigation the areas from which suspect flaw echoes are detected.

12. Transfer the screen readings (beam paths) and the probe-to-weld centre measurements to your graph after maximising the echo height on the screen. The probe-to-weld centre distance can be measured with a ruler.

13. Confirm that the echo comes from a flaw and not from some surface feature of the weld by scanning from positions on the opposite side of the weld or the opposite surfaces.

14. Work out from your scaled drawing what these locations are.

15. Determine the defect length using the 6 dB drop method with the sensitivity set at PRL with corrections for transfer losses. When the defect echo is 20% or less, it may be disregarded. All echoes above 20% must be investigated for identification, location and size.

16. Measure the length of the defect by noting the distance L1 and L2 of the defect extremities from a datum point of the weld (eg a marked end of the seam).

    L2 - L1 = defect length

17. Identify the type of defect by :-

    (a) Studying the behaviour of the echo response to probe manipulation.

    (b) Making use of knowledge of the welding process and procedure.

    (c) Defect location on your graph.

    (d) Defect orientation, location and size on a plot board or on your graph, as explained in steps 18 to 22.

18. On your graph, mark out the probe index position corresponding to maximum echo height and the defect centre using the beam path on the screen.

19. Move the probe towards the weld seam until the defect echo height is reduced by 20 dB. This is best done by setting the maximum echo height at 80% and adding 20 dB to the gain control and then move the probe until the echo is again 80% full screen.

20. On the graph, mark out the probe displacement and one extremity of the defect using the new beam path on the screen. This extremity point must be on the trailing 20 dB edge of the beam.

21. To mark out the defect extremity, draw the beam spread on a transparent paper and superimpose it over your graph.

22. Now repeat steps (23), (24) & (25) but move the probe away from the weld seam and mark the other extremity of the defect which now must be on the leading 20 dB edge of the beam.

23. From the graph, the width and inclination of the defect can be determined by joining the defect extremity points through the centre point with a straight line.

24. For single-vee butt joint (with or without backing) an additional scan, as follows, is necessary for the weld root using preferably a 45 probe. The procedure is as follows:

25. Determine the distance x (see figure below) from the weld centreline to the probe index by drawing or calculation and position the probe at this distance.

26. Put a probe guide (eg a long ruler) in front or behind the probe so that the probe can be maintained normal to the weld axis.

27. Mark on the screen the beam path distance to the centreline of the weld root.

28. Observe the echo from the weld root relative to the centreline marked on the screen as the probe is slide along the probe guide.

29. Evaluate all defect(s) detected in accordance with the ASME Code for acceptance or rejection.

30. Submit a complete report written in the manner as shown in a sample test report.