UNIT-I

INTRODUCTION

What Is Non Destructive Testing?

Non-destructive testing (NDT) is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system. In other words, when the inspection or test is completed the part can still be used.

In contrast to NDT, other tests are destructive in nature and are therefore done on a limited number of samples ("lot sampling"), rather than on the materials, components or assemblies actually being put into service.

These destructive tests are often used to determine the physical properties of materials such as impact resistance, ductility, yield and ultimate tensile strength, fracture toughness and fatigue strength, but discontinuities and differences in material characteristics are more effectively found by NDT.

Today modern non destructive tests are used in manufacturing, fabrication and in-service inspections to ensure product integrity and reliability, to control manufacturing processes, lower production costs and to maintain a uniform quality level. During construction, NDT is used to ensure the quality of materials and joining processes during the fabrication and erection phases, and in-service NDT inspections are used to ensure that the products in use continue to have the integrity necessary to ensure their usefulness and the safety of the public.

NDT Test Methods:

The six most frequently used test methods are MT, PT, RT, UT, ET and VT. Each of these test methods will be described here, followed by the other, less often used test methods.

1. Visual Testing (VT)
2. Liquid Penetrant Testing (PT),
3. Magnetic Particle Testing (MT),
4. Ultrasonic Testing (UT),
5. Radiographic Testing (RT) and
6. Electromagnetic Testing (ET).

Test method names often refer to the type of penetrating medium or the equipment used to perform that test. Current NDT methods are:

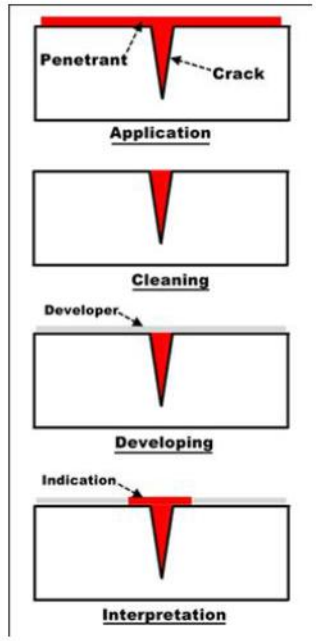
- Acoustic Emission Testing (AE),
- Electromagnetic Testing (ET),

- Guided Wave Testing (GW),
- Ground Penetrating Radar (GPR),
- Laser Testing Methods (LM),
- Leak Testing (LT),
- Magnetic Flux Leakage (MFL),
- Microwave Testing,
- Liquid Penetrant Testing (PT),
- Magnetic Particle Testing (MT),
- Neutron Radiographic Testing (NR),
- Radiographic Testing (RT),
- Thermal/Infrared Testing (IR),
- Ultrasonic Testing (UT),
- Vibration Analysis (VA) and Visual Testing (VT).

Visual Testing (VT)

Visual testing is the most commonly used test method in industry. Because most test methods require that the operator look at the surface of the part being inspected, visual inspection is inherent in most of the other test methods. As the name implies, VT involves the visual observation of the surface of a test object to evaluate the presence of surface discontinuities. VT inspections may be by Direct Viewing, using line-of sight vision, or may be enhanced with the use of optical instruments such as magnifying glasses, mirrors, boroscopes, charge-coupled devices (CCDs) and computer-assisted viewing systems (Remote Viewing). Corrosion, misalignment of parts, physical damage and cracks are just some of the discontinuities that may be detected by visual examinations.

Liquid Penetrant Testing (PT)



The basic principle of liquid penetrant testing is that when a very low viscosity (highly fluid) liquid (the penetrant) is applied to the surface of a part, it will penetrate into fissures and voids open to the surface. Once the excess penetrant is removed, the penetrant trapped in those voids will flow back out, creating an indication. Penetrant testing can be performed on magnetic and non-magnetic materials, but does not work well on porous materials. Penetrants may be "visible", meaning they can be seen in ambient light, or fluorescent, requiring the use of a "black" light. The visible dye penetrant process is shown in Figure . When performing a PT inspection, it is imperative that the surface being tested is clean and free of any foreign materials or liquids that might block the penetrant from entering voids or fissures open to the surface of the part. After applying the penetrant, it is permitted to sit on the surface for a specified period of time (the "penetrant dwell time"), then the part is carefully cleaned to remove excess penetrant from the surface. When removing the penetrant, the operator must be careful not to remove any penetrant that has flowed into voids. A light coating of developer is then be applied to the surface and given time ("developer dwell time") to allow the penetrant from any voids or fissures to seep up into the developer, creating a visible indication. Following the prescribed developer dwell time, the part is inspected visually, with the aid of a black light for fluorescent penetrants. Most developers are fine-grained, white talcum-like powders that provide a color contrast to the penetrant being used.

PT Techniques

Solvent Removable

Solvent Removable penetrants are those penetrants that require a solvent other than water to remove the excess penetrant. These penetrants are usually visible in nature, commonly dyed a bright red color that will contrast well against a white developer. The penetrant is usually sprayed or brushed onto the part, then after the penetrant dwell time has expired, the part is cleaned with a cloth dampened with penetrant cleaner after which the developer is applied. Following the developer dwell time the part is examined to detect any penetrant bleed-out showing through the developer.

Water-washable

Water-washable penetrants have an emulsifier included in the penetrant that allows the penetrant to be removed using a water spray. They are most often applied by dipping the part in a penetrant tank, but the penetrant may be applied to large parts by spraying or brushing. Once the part is fully covered with penetrant, the part is placed on a drain board for the penetrant dwell time, then taken to a rinse station where it is washed with a course water spray to remove the excess penetrant. Once the excess penetrant has been removed, the part may be placed in a warm air dryer or in front of a gentle fan until the water has been removed. The part can then be placed in a dry developer tank and coated with developer, or allowed to sit for the remaining dwell time then inspected.

Post-emulsifiable

Post-emulsifiable penetrants are penetrants that do not have an emulsifier included in its chemical make-up like water-washable penetrants. Post-emulsifiable penetrants are applied in a similar manner, but prior to the water-washing step, emulsifier is applied to the surface for a prescribed period of time (emulsifier dwell) to remove the excess penetrant. When the emulsifier dwell time has elapsed, the part is subjected to the same water wash and developing process used for water-washable penetrants. Emulsifiers can be lipophilic (oil-based) or hydrophilic (water-based).

Magnetic Particle Testing (MT):

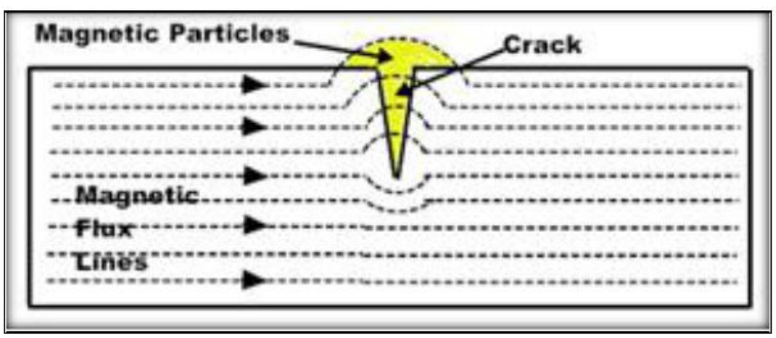
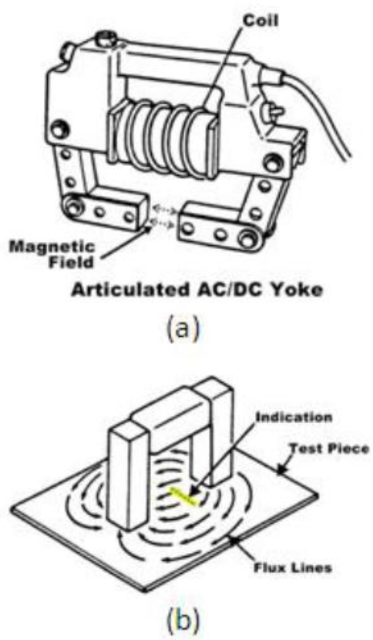


Fig : Magnetic particle testing

Magnetic Particle Testing uses one or more magnetic fields to locate surface and near-surface discontinuities in ferromagnetic materials. The magnetic field can be applied with a permanent magnet or an electromagnet. When using an electromagnet, the field is present only when the current is being applied. When the magnetic field encounters a discontinuity transverse to the direction of the magnetic field, the flux lines produce a magnetic flux leakage field of their own as shown in above figure . Because magnetic flux lines don't travel well in air, when very fine colored ferromagnetic particles ("magnetic particles") are applied to the surface of the part the particles will be drawn into the discontinuity, reducing the air gap and producing a visible indication on the surface of the part. The magnetic particles may be a dry powder or suspended in a liquid solution, and they may be colored with a visible dye or a fluorescent dye that fluoresces under an ultraviolet ("black") light.

MT Techniques:

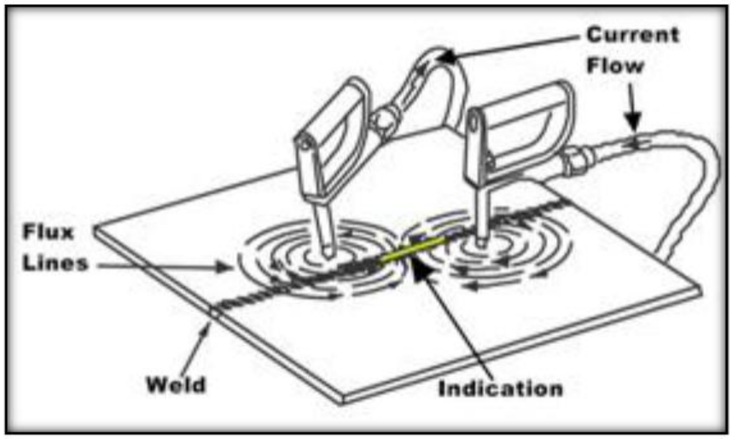
Most field inspections are performed using a Yoke, as shown at the right. As shown in Figure 2(a), an electric coil is wrapped around a central core, and when the current is applied, a magnetic field is generated that extends from the core down through the articulated legs into the part. This is known as longitudinal magnetization because the magnetic flux lines run from one leg to the other.



Yokes

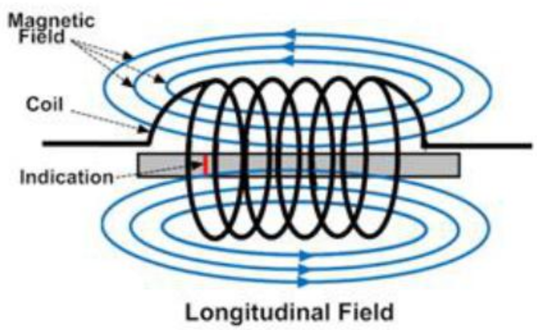
When the legs are placed on a ferromagnetic part and the yoke is energized, a magnetic field is introduced into the part as shown in (b). Because the flux lines do run from one leg to the other, discontinuities oriented perpendicular to a line drawn between the legs can be found. To ensure no indications are missed, the yoke is used once in the position shown then used again with the yoke turned 90^o so no indications are missed. Because all of the electric current is contained in the yoke and only the magnetic field penetrates the part, this type of application is known as *indirect* induction.

Prods:



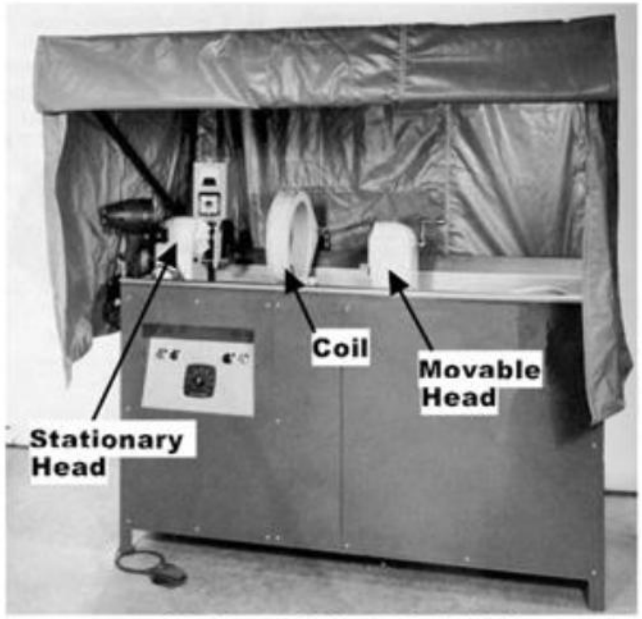
Prod units use *direct* induction, where the current runs through the part and a circular magnetic field is generated around the legs as shown in Figure 3. Because the magnetic field between the prods is travelling perpendicular to a line drawn between the prods, indications oriented parallel to a line drawn between the prods can be found. As with the yoke, two inspections are done, the second with the prods oriented 90° to the first application.

Coils:



Electric coils are used to generate a longitudinal magnetic field. When energized, the current creates a magnetic field around the wires making up the coil so that the resulting flux lines are oriented through the coil as shown at the right. Because of the longitudinal field, indications in parts placed in a coil are oriented transverse to the longitudinal field.

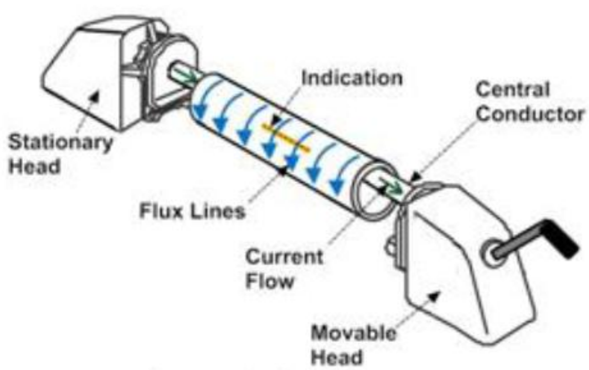
Heads:



Horizontal Wet Bath Unit

Most horizontal wet bath machines ("bench units") have both a coil and a set of heads through which electric current can be passed, generating a magnetic field. Most use fluorescent magnetic particles in a liquid solution, hence the name "wet bath." A typical bench unit is shown at the right. When testing a part between the heads, the part is placed between the heads, the moveable head is moved up so that the part being tested is held tightly between the heads, the part is wetted down with the bath solution containing the magnetic particles and the current is applied while the particle are flowing over the part. Since the current flow is from head to head and the magnetic field is oriented 90° to the current, indications oriented parallel to a line between the heads will be visible. This type of inspection is commonly called a "head shot."

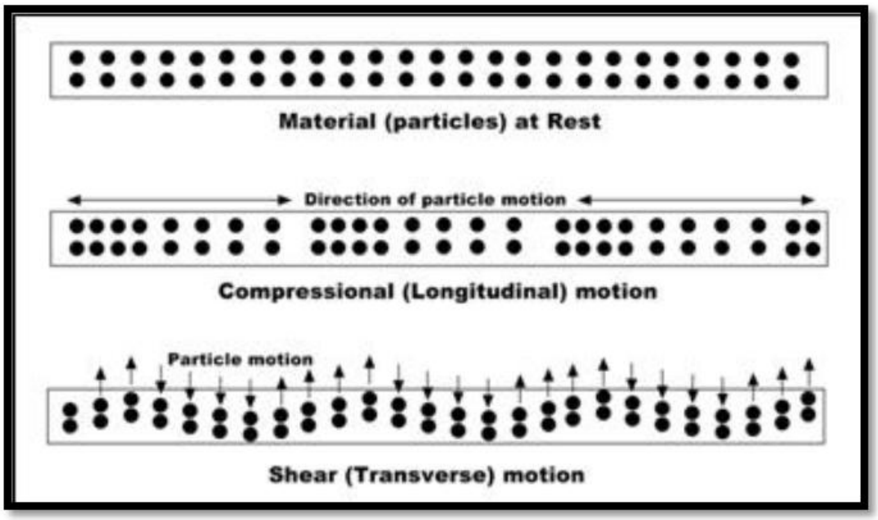
Central Conductor:



Central Conductor

When testing hollow parts such as pipes, tubes and fittings, a conductive circular bar can be placed between the heads with the part suspended on the bar (the "central conductor") as shown in Figure 6. The part is then wetted down with the bath solution and the current is applied, travelling through the central conductor rather than through the part. The ID and OD of the part can then be inspected. As with a head shot, the magnetic field is perpendicular to the current flow, wrapping around the test piece, so indications running axially down the length of the part can be found using this technique.

Ultrasonic Testing (UT):



Ultrasonic testing uses the same principle as is used in naval SONAR and fish finders. Ultra-high frequency sound is introduced into the part being inspected and if the sound hits a material with a different acoustic impedance (density and acoustic velocity), some of the sound will reflect back to the sending unit and can be presented on a visual display. By knowing the speed of the sound through the part (the acoustic velocity) and the time required for the sound to return to the sending unit, the distance to the reflector (the indication with the different acoustic impedance) can be determined. The most common sound frequencies used in UT are between 1.0 and 10.0 MHz, which are too high to be heard and do not travel through air. The lower frequencies have greater penetrating power but less sensitivity (the ability to "see" small indications), while the higher frequencies don't penetrate as deeply but can detect smaller indications.

The two most commonly used types of sound waves used in industrial inspections are the compression (longitudinal) wave and the shear (transverse) wave, as shown in above figure . Compression waves cause the atoms in a part to vibrate back and forth parallel to the sound direction and shear waves cause the atoms to vibrate perpendicularly (from side to side) to the direction of the sound. Shear waves travel at approximately half the speed of longitudinal waves.

Sound is introduced into the part using an ultrasonic transducer ("probe") that converts electrical impulses from the UT machine into sound waves, then converts returning sound back into electric impulses that can be displayed as a visual representation on a digital or LCD screen (on older machines, a CRT screen). If the machine is properly calibrated, the operator can determine the distance from the transducer to the reflector, and in many cases, an experienced operator can determine the type of discontinuity (like slag, porosity or cracks in a weld) that caused the reflector. Because ultrasound will not travel through air (the atoms in air molecules are too far apart to transmit ultrasound), a liquid or gel called "couplant" is used between the face of the transducer and the surface of the part to allow the sound to be transmitted into the part.

UT Techniques:

Straight Beam:-

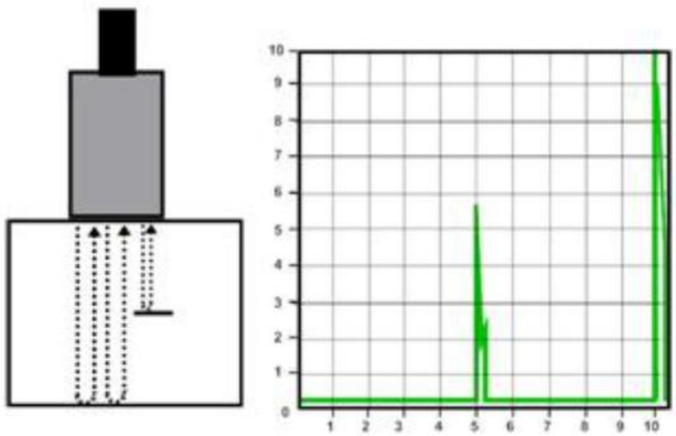
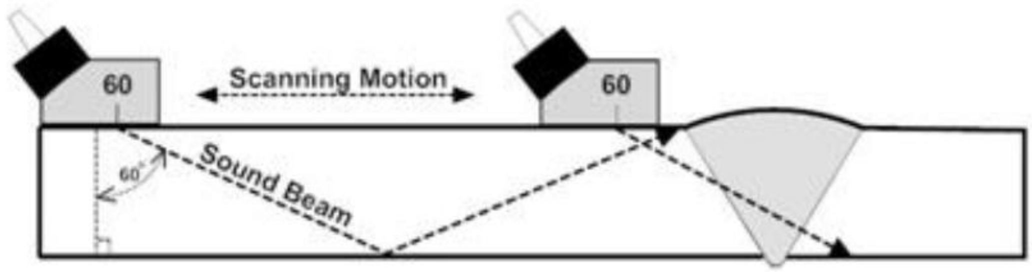


Fig: Straight Beam

Straight beam inspection uses longitudinal waves to interrogate the test piece as shown at the right. If the sound hits an internal reflector, the sound from that reflector will reflect to the transducer faster than the sound coming back from the back-wall of the part due to the shorter distance from the transducer. This results in a screen display like that shown at the right in Figure 11. Digital thickness testers use the same process, but the output is shown as a digital numeric readout rather than a screen presentation.

Angle Beam:



Angle Beam Testing

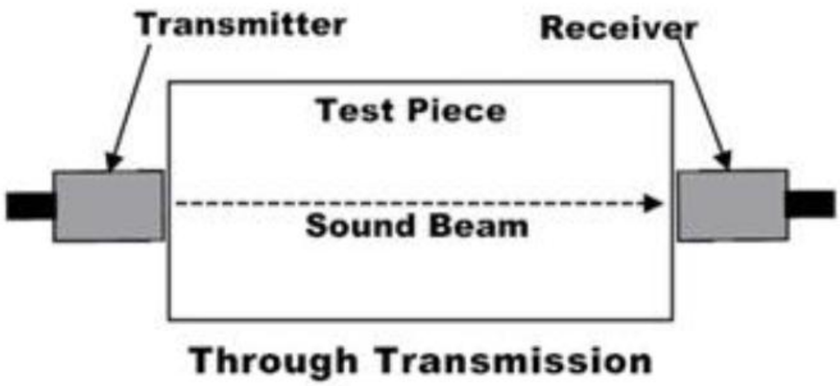
Angle beam inspection uses the same type of transducer but it is mounted on an angled wedge (also called a "probe") that is designed to transmit the sound beam into the part at a known angle. The most commonly used inspection angles are 45°, 60° and 70°, with the angle being calculated up from a line drawn through the thickness of the part (not the part surface). A 60° probe is shown in above Figure. If the frequency and wedge angle is not specified by the governing code or specification, it is up to the operator to select a combination that will adequately inspect the part being tested.

In angle beam inspections, the transducer and wedge combination (also referred to as a "probe") is moved back and forth towards the weld so that the sound beam passes through the full volume of the weld. As with straight beam inspections, reflectors aligned more or less perpendicular to the sound beam will send sound back to the transducer and are displayed on the screen.

Immersion Testing

Immersion Testing is a technique where the part is immersed in a tank of water with the water being used as the coupling medium to allow the sound beam to travel between the transducer and the part. The UT machine is mounted on a movable platform (a "bridge") on the side of the tank so it can travel down the length of the tank. The transducer is swivel-mounted on at the bottom of a waterproof tube that can be raised, lowered and moved across the tank. The bridge and tube movement permits the transducer to be moved on the X-, Y- and Z-axes. All directions of travel are gear driven so the transducer can be moved in accurate increments in all directions, and the swivel allows the transducer to be oriented so the sound beam enters the part at the required angle. Round test parts are often mounted on powered rollers so that the part can be rotated as the transducer travels down its length, allowing the full circumference to be tested. Multiple transducers can be used at the same time so that multiple scans can be performed.

Through Transmission:



Through transmission inspections are performed using two transducers, one on each side of the part as shown in Figure 13. The transmitting transducer sends sound through the part and the receiving transducer receives the sound. Reflectors in the part will cause a reduction in the amount of sound reaching the receiver so that the screen presentation will show a signal with a lower amplitude (screen height).

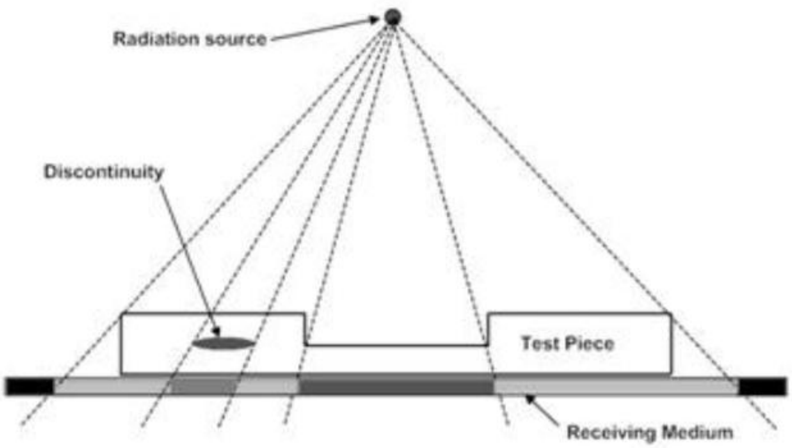
Phased Array:

Phased array inspections are done using a probe with multiple elements that can be individually activated. By varying the time when each element is activated, the resulting sound beam can be "steered", and the resulting data can be combined to form a visual image representing a slice through the part being inspected.

Time of Flight Diffraction:

Time of Flight Diffraction (TOFD) uses two transducers located on opposite sides of a weld with the transducers set at a specified distance from each other. One transducer transmits sound waves and the other transducer acting as a receiver. Unlike other angle beam inspections, the transducers are not manipulated back and forth towards the weld, but travel along the length of the weld with the transducers remaining at the same distance from the weld. Two sound waves are generated, one travelling along the part surface between the transducers, and the other travelling down through the weld at an angle then back up to the receiver. When a crack is encountered, some of the sound is diffracted from the tips of the crack, generating a low strength sound wave that can be picked up by the receiving unit. By amplifying and running these signals through a computer, defect size and location can be determined with much greater accuracy than by conventional UT methods.

Radiographic Testing (RT):



Industrial radiography involves exposing a test object to penetrating radiation so that the radiation passes through the object being inspected and a recording medium placed against the opposite side of that object. For thinner or less dense materials such as aluminum, electrically generated x-radiation (X-rays) are commonly used, and for thicker or denser materials, gamma radiation is generally used.

Gamma radiation is given off by decaying radioactive materials, with the two most commonly used sources of gamma radiation being Iridium-192 (Ir-192) and Cobalt-60 (Co-60). IR-192 is generally used for steel up to 2-1/2 - 3 inches, depending on the Curie strength of the source, and Co-60 is usually used for thicker materials due to its greater penetrating ability.

The recording media can be industrial x-ray film or one of several types of digital radiation detectors. With both, the radiation passing through the test object exposes the media, causing an end effect of having darker areas where more radiation has passed through the part and lighter areas where less radiation has penetrated. If there is a void or defect in the part, more radiation passes through, causing a darker image on the film or detector, as shown in above figure.

RT Techniques:

Film Radiography

Film radiography uses a film made up of a thin transparent plastic coated with a fine layer of silver bromide on one or both sides of the plastic. When exposed to radiation these crystals undergo a reaction that allows them, when developed, to convert to black metallic silver. That silver is then "fixed" to the plastic during the developing process, and when dried, becomes a finished radiographic film.

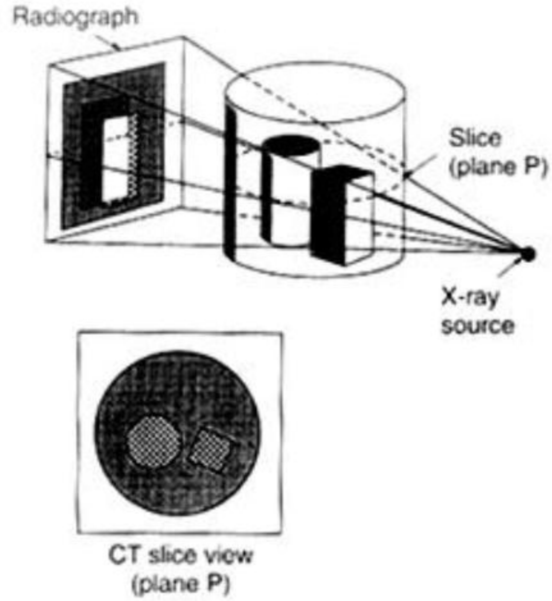
To be a usable film, the area of interest (weld area, etc.) on the film must be within a certain density (darkness) range and must show enough contrast and sensitivity so that discontinuities of interest can be seen. These items are a function of the strength of the radiation, the distance of the source from the film and the thickness of the part being inspected. If any of these parameters are not met, another exposure ("shot") must be made for that area of the part.

Computed Radiography:

Computed radiography (CR) is a transitional technology between film and direct digital radiography. This technique uses a reusable, flexible, photo-stimulated phosphor (PSP) plate which is loaded into a cassette and is exposed in a manner similar to traditional film radiography. The cassette is then placed in a laser reader where it is scanned and translated into a digital image, which take from one to five minutes. The image can then be uploaded to a computer or other electronic media for interpretation and storage.

Computed Tomography:

Computed tomography (CT) uses a computer to reconstruct an image of a cross sectional plane of an object as opposed to a conventional radiograph, as shown in Figure 9. The CT image is developed from multiple views taken at different viewing angles that are reconstructed using a computer. With traditional radiography, the position of internal discontinuities cannot be accurately determined without making exposures from several angles to locate the item by triangulation. With computed tomography, the computer triangulates using every point in the plane as viewed from many different directions.



CT image vs. a radiographic image

Digital Radiography:

Digital radiography (DR) digitizes the radiation that passes through an object directly into an image that can be displayed on a computer monitor. The three principle technologies used in direct digital imaging are amorphous silicon, charge coupled devices (CCDs), and complementary metal oxide semiconductors (CMOSs). These images are available for viewing and analysis in seconds compared to the time needed to scan in computed radiography images. The increased processing speed is a result of the unique construction of the pixels; an arrangement that also allows a superior resolution than is found in computed radiography and most film applications.

Acoustic Emission Testing (AE):

Acoustic Emission Testing is performed by applying a localized external force such as an abrupt mechanical load or rapid temperature or pressure change to the part being tested. The resulting stress waves in turn generate short-lived, high frequency elastic waves in the form of small material displacements, or plastic deformation, on the part surface that are detected by sensors that have been attached to the part surface. When multiple sensors are used, the resulting data can be evaluated to locate discontinuities in the part.

Guided Wave Testing (GW):

Guided wave testing on piping uses controlled excitation of one or more ultrasonic waveforms that travel along the length of the pipe, reflecting from changes in the pipe stiffness or cross sectional area. A transducer ring or exciter coil assembly is used to introduce the guided wave into the pipe and each transducer/exciter . The control and analysis software can be installed on a laptop computer to drive the transducer ring/exciter and to analyze the results. The transducer ring/exciter setup is designed specifically for the diameter of the pipe being tested, and the system has the advantage of being able to inspect the pipe wall volume over long distances without having to remove coatings or insulation. Guided wave testing can locate both ID and OD discontinuities but cannot differentiate between them.

Laser Testing Methods (LM);

Laser Testing includes three techniques, Holography, Shearography and Profilometry. As the method name implies, all three techniques user lasers to perform the inspections.

LM Techniques:
Holographic Testing

Holographic Testing uses a laser to detect changes to the surface of a part as it deforms under induced stress which can be applied as mechanical stress, heat, pressure, or vibrational energy. The laser beam scans across the surface of the part and reflects back to sensors that record the differences in the surface created by that stress. The resulting image will be a topographical map-like presentation that can reveal surface deformations in the order of 0.05 to 0.005 microns without damage to the part. By comparing the test results with an undamaged reference sample, holographic testing can be used to locate and evaluate cracks, delaminations, disbonds, voids and residual stresses.

Laser Profilometry:

Laser Profilometry uses a high-speed rotating laser light source, miniature optics and a computer with high-speed digital signal processing software. The ID surface of a tube is scanned in two dimensions and the reflected light is passed through a lens that focuses that light onto a photo-detector, generating a signal that is proportional to the spot's position in its image plane. As the distance from the laser to the ID surface changes, the position of the focal spot on the photo-detector changes due to parallax, generating a high resolution three-dimensional image of the part surface that represents the surface topography of the part. This technique can be used to detect corrosion, pitting, erosion and cracks in pipes and tubes.

Laser Shearography:

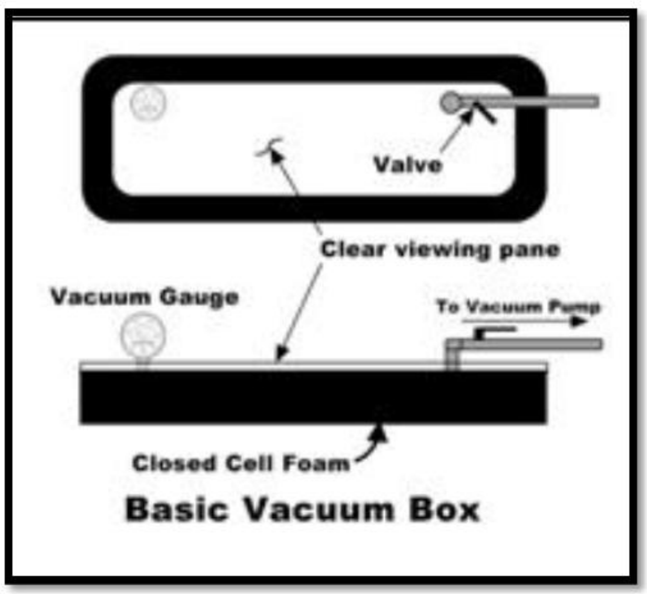
Laser Shearography applies laser light to the surface of the part being tested with the part at rest (non-stressed) and the resulting image is picked up by a charge-coupled device (CCD) and stored on a computer. The surface is then stressed and a new image is generated, recorded and stored. The computer then superimposes the two patterns and if defects such as voids or disbonds are present, the defect can be revealed by the patterns developed. Discontinuities as small as a few micrometers in size can be detected in this manner.

Leak Testing (LT):

Leak Testing, as the name implies, is used to detect through leaks using one of the four major LT techniques: Bubble, Pressure Change, Halogen Diode and Mass Spectrometer Testing. These techniques are described below.

LT Techniques

Bubble Leak Testing



Bubble Leak Testing, as the name implies, relies on the visual detection of a gas (usually air) leaking from a pressurized system. Small parts can be pressurized and immersed in a tank of liquid and larger vessels can be pressurized and inspected by spraying a soap solution that creates fine bubbles to the area being tested. For flat surfaces, the soap solution can be applied to the surface and a vacuum box can be used to create a negative pressure from the inspection side. If there are through leaks, bubbles will form, showing the location of the leak.

Pressure Change Testing:

Pressure Change Testing can be performed on closed systems only. Detection of a leak is done by either pressurizing the system or pulling a vacuum then monitoring the pressure. Loss of pressure or vacuum over a set period of time indicates that there is a leak in the system. Changes in temperature within the system can cause changes in pressure, so readings may have to be adjusted accordingly.

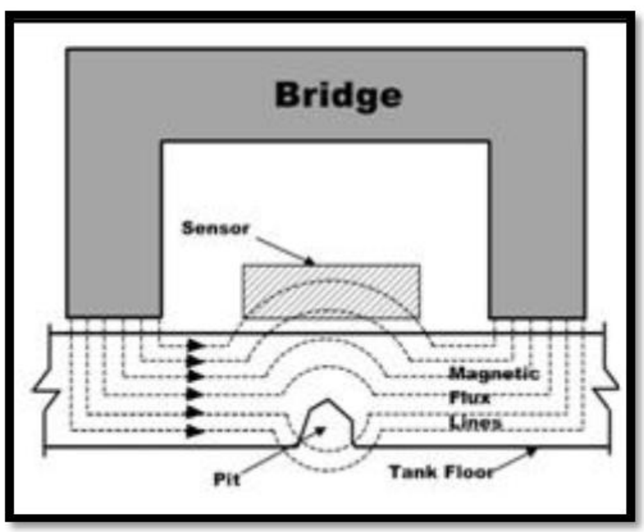
Halogen Diode Testing:

Halogen Diode Testing is done by pressurizing a system with a mixture of air and a halogen-based tracer gas. After a set period of time, a halogen diode detection unit, or "sniffer", is used to locate leaks.

Mass Spectrometer Testing:

Mass Spectrometer Testing can be done by pressurizing the test part with helium or a helium/air mixture within a test chamber then surveying the surfaces using a sniffer, which sends an air sample back to the spectrometer. Another technique creates a vacuum within the test chamber so that the gas within the pressurized system is drawn into the chamber through any leaks. The mass spectrometer is then used to sample the vacuum chamber and any helium present will be ionized, making very small amounts of helium readily detectable.

Magnetic Flux Leakage (MFL):



Magnetic flux Leakage

Magnetic Flux Leakage detects anomalies in normal flux patterns created by discontinuities in ferrous material saturated by a magnetic field. This technique can be used for piping and tubing inspection, tank floor inspection and other applications. In tubular applications, the inspection head contain is made up of drive and sensor coils and a position transducer that are connected by cable back to the power source and signal processing computer. This head is placed around the pipe or tube to be inspected and the drive coil is energized, creating a magnetic field in the part. As the head travels along the length of the part, variations in the wall thickness due to corrosion, erosion, pitting etc., will cause a change in the magnetic flux density can be picked up by the sensor and sent back to the computer. The location of this signal is sent by the position transducer so that the area detected can be marked for further evaluation. This technique can be done without removing the insulation, resulting in a fast, economic way to inspect long runs of pipe or tubing.

Tank floor inspection applies the same principle, but uses a series of magnetic field generators ("bridges") and sensors (as shown in Figure 16) located side by side across the front of a vacuum sweeper-like machine. The bridges generate a magnetic field that saturates the tank floor, and any reduction in thickness or loss of material due to pitting or corrosion will cause the field to "leak" upwards out of the floor material where it can be picked up by the sensors. On very basic machines, each sensor will be connected to an audio and/or visual display that lets the operator know there is an indication; more advanced machines can have both visual displays and recording capability so that the results can be stored, analyzed and compared to earlier results to monitor discontinuity growth.

Neutron Radiographic Testing (NR):

Neutron radiography uses an intense beam of low energy neutrons as a penetrating medium rather than the gamma- or x-radiation used in conventional radiography. Generated by linear accelerators, betatrons and other sources, neutrons penetrate most metallic materials, rendering them transparent, but are attenuated by most organic materials (including water, due to its high hydrogen content) which allows those materials to be seen within the component being inspected. When used with conventional radiography, both the structural and internal components of a test piece can be viewed.

Thermal/Infrared Testing (IR):

Thermal/Infrared Testing, or infrared thermography, is used to measure or map surface temperatures based on the infrared radiation given off by an object as heat flows through, to or from that object. The majority of infrared radiation is longer in wavelength than visible light but can be detected using thermal imaging devices, commonly called "infrared cameras." For accurate IR testing, the part(s) being investigated should be in direct line of sight with the camera, i.e., should not be done with panel covers closed as the covers will diffuse the heat and can result in false readings. Used properly, thermal imaging can be used to detect corrosion damage, delaminations, disbonds, voids, inclusions as well as many other detrimental conditions.

Vibration Analysis (VA):

Vibration analysis refers to the process of monitoring the vibration signatures specific to a piece of rotating machinery and analyzing that information to determine the condition of that equipment. Three types of sensors are commonly used: displacement sensors, velocity sensors and accelerometers.

Displacement sensors uses eddy current to detect vertical and/or horizontal motion (depending on whether one or two sensors are used) and are well suited to detect shaft motion and changes in clearance tolerances.

Basic velocity sensors use a spring-mounted magnet that moves through a coil of wire, with the outer case of the sensor attached to the part being inspected. The coil of wire moves through the magnetic field, generating an electrical signal that is sent back to a receiver and recorded for analysis. Newer model vibration sensors use time-of-flight technology and improved analysis software. Velocity sensors are commonly used in handheld sensors.

Basic accelerometers use a piezoelectric crystal (that converts sound waves to electrical impulses and back) attached to a mass that vibrates due to the motion of the part to which the sensor casing is attached. As the mass and crystal vibrate, a low voltage current is generated which is passed through a pre-amplifier and sent to the recording device. Accelerometers are very effective for detecting the high frequencies created by high speed turbine blades, gears and ball and roller bearings that travel at much greater speeds than the shafts to which they are attached.

Guided Wave Testing (GW):

Guided wave testing on piping uses controlled excitation of one or more ultrasonic waveforms that travel along the length of the pipe, reflecting from changes in the pipe stiffness or cross sectional area. A transducer ring or exciter coil assembly is used to introduce the guided wave into the pipe and each transducer/exciter. The control and analysis software can be installed on a laptop computer to drive the transducer ring/exciter and to analyze the results. The transducer ring/exciter setup is designed specifically for the diameter of the pipe being tested, and the system has the advantage of being able to inspect the pipe wall volume over long distances without having to remove coatings or insulation. Guided wave testing can locate both ID and OD discontinuities but cannot differentiate between them.

VISUAL TESTING:

Visual inspection is by far the most common nondestructive examination (NDE) technique (Ref. 1). When attempting to determine the soundness of any part or specimen for its intended application, visual inspection is normally the first step in the examination process. Generally, almost any specimen can be visually examined to determine the accuracy of its fabrication. For example, visual inspection can be used to determine whether the part was fabricated to the correct size, whether the part is complete, or whether all of the parts have been appropriately incorporated into the device

While direct visual inspection is the most common nondestructive examination technique, many other NDE methods require visual intervention to interpret images obtained while carrying out the examination. For instance, penetrant inspection using visible red or fluorescent dye relies on the inspector's ability to visually identify surface indications. Magnetic particle inspection falls into the same category of visible and fluorescent inspection techniques, and radiography relies on the interpreter's visual judgment of the radiographic image, which is either on film or on a video monitor. The remainder of this article provides a summary of the visual testing method, which at the minimum requires visual contact with the portion of the specimen that is being inspected. In arriving at a definition of visual inspection, it has been noted in the literature that experience in visual inspection and discussion with experienced visual inspectors revealed that this NDE method includes more than use of the eye, but also includes other sensory and cognitive processes used by inspectors. Thus, there is now an expanded definition of visual inspection in the literature: "Visual inspection is the process of examination and evaluation of systems and components by use of human sensory systems aided only by mechanical enhancements to sensory input such as magnifiers, dental picks, stethoscopes, and the like. The inspection process may be done using such behaviors as looking, listening, feeling, smelling, shaking, and twisting. It includes a cognitive component wherein observations are correlated with knowledge of structure and with descriptions and diagrams from service literature."

Fig: Visual inspection of a torpedo tube aboard a Navy attack submarine

Fig: An inspector at Tinker Air Force base gets a magnified view of an engine's high-pressure turbine area with a new digital fiber-optic bore scope.

Fig: Part of a routine bridge visual inspection

Fig.: Part of an in-depth bridge

Fig: Visual inspection experiment inside a Boeing 737.

Physical Principles:

The human eye is one of mankind's most fascinating tools. It has greater precision and accuracy than many of the most sophisticated cameras. It has unique focusing capabilities and has the ability to work in conjunction with the human brain so that it can be trained to find specific details or characteristics in a part or test piece. It has the ability to differentiate and distinguish between colors and hues as well. The human eye is capable of assessing many visual characteristics and identifying various types of discontinuities1. The eye can perform accurate inspections to detect size, shape, color, depth, brightness, contrast, and texture. Visual testing is essentially used to detect any visible discontinuities, and in many cases, visual testing may locate portions of a specimen that should be inspected further by other NDE techniques.

Many inspection factors have been standardized so that categorizing them as major and minor characteristics has become common. Surface finish verification of machined parts has even been developed, and classification can be performed by visual comparison to manufactured finish standards. In the fabrication industry, weld size, contour, length, and inspection for surface discontinuities are routinely specified. Many companies have mandated the need for qualified and certified visual weld inspection. This is the case particularly in the power industry, which requires documentation of training and qualification of the inspector. Forgings and castings are normally inspected for surface indications such as laps, seams, and other various surface conditions.

Inspection Requirements for visual inspection typically pertain to the vision of the inspector; the amount of light falling on the specimen, which can be measured with a light meter; and whether the area being inspected is in any way obstructed from view. In many cases, each of these requirements is detailed in a regulatory code or other inspection criteria. Mechanical and/or optical aids may be necessary to perform visual testing. Because visual inspection is so frequently used, several companies now manufacture gauges to assist visual inspection examinations. Mechanical aids include measuring rules and tapes; calipers and micrometers; squares and angle measuring devices; thread, pitch and thickness gauges; level gauges; and plumb lines. Welding fabrication uses fillet gauges to determine the width of the weld fillet, undercut gauges, angle gauges, skew fillet weld gauges, pit gauges, contour gauges, and a host of other specialty items to ensure product quality. At times, direct observation is impossible and remote viewing is necessary, which requires the use of optical aids. Optical aids for visual testing range from simple mirrors or magnifying glasses to sophisticated devices, such as closed-circuit television and coupled fiber-optic scopes. The following list includes most optical aids currently in use

- Mirrors (especially small, angled mirrors)
- Magnifying glasses, eye loupes, multilens magnifiers, measuring magnifiers
- Microscopes (optical and electron)
- Optical flats (for surface flatness measurement)
- Borescopes and fiber-optic borescopes
- Optical comparators
- Photographic records
- Closed-circuit television (CCTV) systems (alone and coupled to borescopes/microscopes)
- Machine vision systems
- Positioning and transport systems (often used with CCTV systems).

Image enhancement (computer analysis and enhancement) Before any mechanical or optical aids are used, the specimen should be well illuminated and have a clean surface. After the eyeball examination, mechanical aids help to improve the precision of an inspector's vision. As specifications and tolerances become closer, calipers and micrometers become necessary. The variety of gauges available help to determine thread sizes, gap thicknesses, angles between parts, hole depths, and weld features. As it becomes necessary to see smaller and smaller discontinuities, the human eyes require optical aids that enable inspectors to see these tiny discontinuities. However, the increased magnification limits the area that can be seen at one time, and also increases the amount of time it will take to look at the entire specimen. Mirrors let the inspector see around corners or past obstructions. Combined with lenses and placed in rigid tubes, borescopes enable the inspector to see inside specimens such as jet engines, nuclear piping and fuel bundles, and complex machinery. When the rigid borescope cannot reach the desired area, flexible bundles of optical fibers often are able to access the area. Above Figure shows visual inspection using a fiber-optic borescope. Some of the flexible borescopes have devices that permit the observation end of the scope to be moved around by a control at the eyepiece end. Some are also connected to CCTV systems so that a large picture may be examined and the inspection recorded on videotape or digitally. When the video systems are combined with computers, the images can be improved that may allow details not observable in the original to be seen.

Practical Considerations:

Visual inspection is applicable to most surfaces, but is most effective where the surfaces have been cleaned prior to examination, for example, any scale or loose paint should be removed by wire brushing, etc. Vision testing of an inspector often requires eye examinations with standard vision acuity cards such as Jaeger, Snellen, and color charts. Vision testing of inspectors has been in use for about 40 years. Although many changes in NDE methods have taken place over the years and new technologies have been developed, vision testing has changed little over time. Also, little has been done to standardize vision tests used in the industrial sector. For those seeking certification in the area of visual testing, the *ASNT Level III Study Guide and Supplement on Visual and Optical Testing* provides a useful reference.

Advantages of visual inspection

- It can be a very simple but effective test to perform and often does not need expensive equipment.
- Experienced operators and advanced equipment make it possible for visual inspection to be very sensitive.
- It allows discontinuities to be seen and not be just a blip on the screen.
- Many different surface-breaking discontinuities can be found.
- Training and experience times can be short.
- Virtually any component can be examined anywhere on the surface.

Disadvantages of visual inspection

- Many variables can lead to discontinuities being missed.
- At its worst, it relies totally on the human factor.
- Many organisations pay little attention to the proper training of operators.
- Sub-surface discontinuities will not be seen.

Specific applications:

Video borescopes can be used for many applications requiring remote visual testing, including the aerospace and power generation industries, engine manufacturing and marine inspections. Video borescope systems can be used to confirm questionable results of other NDT techniques, for example an indication can be located with ultrasonic inspection and then visualised with the video borescope.

A major use of video borescopes is to allow several operators or engineers to view a screen simultaneously. They are also very useful for applications requiring a critical assessment of detail or measurements, such as when checking coatings and seals, locating corrosion and pitting and burn-through of pipe weld roots. In boiler tubes, chemical deposits and oxygen pits can be located at an early stage and so help prevent tube failure.

Remote inspection can be performed in locations that would be hazardous to human operators, such as inside furnaces or high-radiation areas of nuclear power stations, where thorough use is made of visual testing during the plant shutdowns to test many critical components under high-stress, such as nozzle junctions with the vessel and cladding on nozzles.

Another important area of visual inspection is in the aerospace industry, where remote visual inspection is performed on otherwise inaccessible areas of the fuselage, where in-service problems such as fatigue cracks or corrosion can occur on aircraft integrity-critical components, such as pins joining the fuselage to the wings.

Critical visual inspection of hollow helicopter blades is carried out using video borescopes, as well as the inner surfaces of jet engines and wings. The chemical industry makes wide use of visual inspection to test furnaces, combustion chambers, heat exchangers, pressure vessels and numerous other areas within the plant. In the automotive industry, the internal condition of engines can be assessed, such as carbon deposits on valves, broken transmission gear teeth and gear wear being very easy to find.

LIQUID PENETRANT TESTING (PT)

This is a method which can be employed for the detection of open-to-surface discontinuities in any industrial product which is made from a non-porous material. 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 aswell as the location, size and nature of the discontinuity. The process is illustrated in Figure.

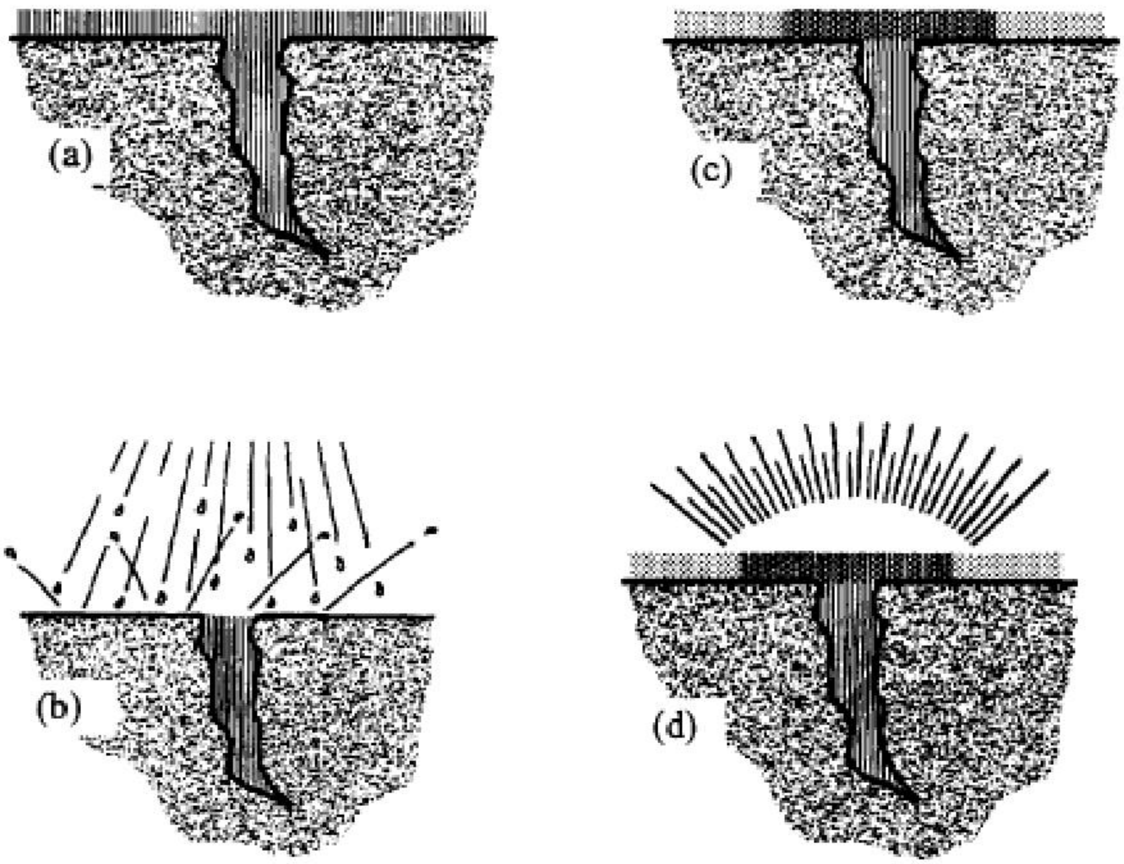


Figure: Four stages of liquid penetrant process.

(a) Penetrant application and seepage into the discontinuity.

(b) Removal of excess penetrant.

(c) Application of developer.

(d) Inspection for the presence of discontinuities.

General procedure for liquid penetrant inspection

(a) Cleaning the surface to be examined:

There should be no material such as plating, or coatings of oxide or loose dirt surface. This is to prevent false Jications and to expose hidden discontinuities to the penetrant. Solid containers such as carbon, engine varnish, paints and similar materials should be removed by vapour blast, chemical dip or other acceptable methods . Methods such as shot blasting, emery cloth, wire brushing or metal scrapping should not be used, especially for soft materials, since these cleaning methods will cover up defects by cold working the surface.

Contamination can occur due to the presence of lubricants, protective oils, metal dust polymerization, oxidation, carbonaceous deposits, protective paints, etc. Various solvents have been developed by different companies to remove them. Contamination due to inorganic corrosion products, heat treatment scale, operationally formed refractory oxides, etc. is conveniently removed by abrasive blasting with glass beads, etc. combined with a chemical cleaning. Whichever method is employed the use of trichlorethylene vapour degreasing as a final stage is strongly recommended.

(b) Drying the surface:

If, for any reason, separations are filled with liquid, they will prevent entry of penetrant, hence drying is an essential operation . It should be realized that although the surface may seem dry, separations may still be filled with liquid. With "dismountable cracks" used to evaluate penetrants, it is remarkable how long a liquid can stay in a small separation after the outer surface has become dry. The lesson is that improper drying may be worse than no cleaning, because the remaining solvent may present a barrier to the penetrant too. If penetrant liquid does reach into the separation, it will be diluted by the solvent, and this also makes the treatment less effective.

(c) Application of penetrant:

The penetrant is applied with the help of a brush or by spray or by dipping the test piece into a bath of penetrant. After this a certain residence time or 'dwell time' is allowed for the penetrant to seep into discontinuities. The residence time varies with the temperature, the type of penetrant, the nature of the discontinuity and the material of the test specimen. It usually varies between 5 and 30 minutes. In special cases it may be as long as one hour.

(d) Removal of superfluous penetrant:

The excess penetrant on the surface should be removed to obtain optimum contrast and to prevent misleading indications. The appropriate remover is usually recommended by the manufacturer of the penetrant. Some penetrants are water washable while others need application of an emulsifier before they can be removed with water. The removal method is to use a sponge or water spray. There are special penetrant removers which are essentially solvents.

It is most important that removal of the penetrant is restricted to the surface and that no penetrant is washed out of the flaws which can easily happen when the cleaning is too rigorous. When the surface is smooth washing can be less intensive than for rough surfaces; in the latter case there is a definite risk that penetrant may be washed out of small imperfections.

A general criterion for the removal operation is that it must be fast and should be prolonged long enough to make the surface almost clean. It is better to leave small traces of penetrant on the surface than to carry out excessive cleaning. When removing fluorescent penetrants, the effect of the treatment should preferably be watched under black light.

(e) Drying the surface:

The surface can be dried with a dry cloth or an air blower. Drying is generally needed to prepare the surface for the application of a powder developer, which would otherwise clot at wet places. It also decreases the adverse effect of insufficiently removed traces of penetrant. Here again excess should be avoided. Penetrant liquid left in flaws should not be allowed to dry, and this can happen when hot air is used for drying.

(f) **Application** of **developer:**

Developers are usually of two types namely dry and wet developer. Dry developer consists of a dry, light coloured powdery material. It is applied to the surface after removal of excess penetrant and drying of the part. It can be applied either by immersing the parts in a tank containing powder, or by brushing it on with a paint brush (usually not a desirable technique) or by blowing the powder onto the surface of the part.

Wet developer consists of a powdered material suspended in a suitable liquid such as water or a volatile solvent. It is applied to the parts immediately following the water washing operation. Developers should be such that they provide a white coating that contrasts with the coloured dye penetrant, and draw the penetrant from the discontinuities to the surface of the developer film, thus revealing defects. The dry developers are applied generally with fluorescent penetrants. They are applied just prior to the visual inspection process. The wet developers are also used in connection with fluorescent penetrants. They are applied after the washing operation and before the drying operation. The solvent based developers are generally used with the visible dye-penetrants. They are applied after cleaning off extra penetrant. A short time should be allowed for development of indications after the developer has been applied. This time should be approximately one half that allowed for penetration. Developer coating is removed after inspection by water stream, spray nozzle, brush, etc. The powder concentration of the liquid developer should be carefully controlled to obtain the required thin and uniform layer over the surface.

(g) Observation and interpretation of indications:

An indication in the developer will become visible after a certain lapse of time. Because all penetrant inspection methods rely upon the seeing of an indication by the inspector, the lighting provided for this visual examination is extremely important. For best results, inspection for fluorescent indications should be done in a darkened area using black light. For the interpretation of indications, it is very important to observe their characteristics at the very moment they appear. As soon 67 as the flaws have bled out the indications may run to larger spots, depending on size and depth, and at this stage it is difficult to derive characteristic information from a flaw.

The extent to which observation of developing indications can be realized in practice depends largely on the size and complexity of the surface to be examined as well as on the number of components to be tested. A brief guide to the penetrant indications is given here. A crack usually shows up as a continuous line of penetrant indication. A cold shut on the surface of a casting also appears as a continuous line, generally a relatively narrow one. A forging lap may also cause a continuous line of penetrant indication. Rounded areas of penetrant indication signify gas holes or pin holes in castings.

Deep crater cracks in welds frequently show up as rounded indications. Penetrant indications in the form of small dots result from a porous condition. These may denote small pin holes or excessively coarse grains in castings or may be caused by a shrinkage cavity. Sometimes a large area presents a diffused appearance. With fluorescent penetrants, the whole surface may glow feebly. With dye penetrants, the background may be pink instead of white. This diffused condition may result from very fine, widespread porosity, such as microshrinkage in magnesium. Depth of defects will be indicated by richness of colour and speed of bleed out. The time required for an indication to develop is inversely proportional to the volume of the discontinuity.

Penetrant processes and equipment:

Penetrants are classified depending on whether the dye fluoresces under black light or is highly contrasting under white light. A second major division of the penetrants is determined by the manner is which they can be removed from the surface. Some penetrants are water washable and can be removed from the surface by washing with ordinary tap water. Other penetrants are removed with special solvents. Some penetrants are not in themselves water washable but can be made so by applying an emulsifier as an extra step after penetration is completed. During a short emulsification period this emulsifier blends with the excess penetrant on the surface of the part after which the mixture is easily removed with a water spray.

The fluorescent penetrant water washable penetrant process uses this method. The fluorescent method is used for greater visibility; can be easily washed with water; is good for quantities of small parts; is good on rough surfaces; is good in keyways and threads; is high speed, economical of time and good for a wide range of defects. The post emulsification fluorescent process has fluorescence for greater visibility, has highest sensitivity for very fine defects; can show wide shallow defects; is easily washed with water after emulsification; has a short penetration time; high production; especially satisfactory for chromate surfaces.

The water emulsifiable visible penetrant process has greater portability; requires no black light; can be used on suspected local areas of large parts; aids in rework or repair; can be used on parts where water is not available; can be used where parts are to be repaired in ordinary light; best of all techniques on contaminated defects; sensitive to residual acidity or alkalinity; high sensitivity to very fine defects.

Fluorescent materials generally respond most actively to radiant energy of a wavelength of approximately 3650A. This is just outside the visible range on the blue or violet side but not sufficiently far removed to be in the chemically active or ultraviolet range : this is "black light". Four possible sources of black light are incandescent lamps, metallic or carbon arcs, tubular "BL" fluorescent lamps and enclosed mercury vapour arc lamps. Mercury vapour arc lamps are generally used. One of the advantages of this is that its light output can be controlled by design and manufacturing. At medium pressures (from 1 to 10 atmospheres) the light output is about evenly distributed between the visible, black light and hard ultraviolet ranges.

These medium pressure lamps are ordinarily used for inspection purposes. A red purple glass is used to filter the light not desired. Factors such as the nature of inspected surface, extraneous white light entering the booth, the amount and location of fluorescent materials near the inspector and the speed with which inspection is to be carried out have an effect on the black light intensity necessary at the inspected surface. The light level, once it is set for a practical job, should be maintained. Good eyesight is also a requisite.

Areas of application of liquid penetrants:

Liquid penetrants can be used for the inspection of all types of materials such as ferrous and non-ferrous, conductors and non-conductors, magnetic and non-magnetic and all sorts of alloys and plastics. Most common applications are in castings, forgings and welding.

Range and limitations of liquid penetrants:

All imperfections which have an opening to the surface are detectable no matter what their orientation be. Sub-surface defects which are not open to the surface will not show up and consequently will not interfere with the interpretation. No indications are produced as a consequence of differences in permeability (a weld in dissimilar steels, transition zones, etc.). There is no risk of surface damage which may occur, for example, during careless magnetization with prods in the current flow method. The equipment is also low cost.

Flaws may remain undetected by penetrant inspection if magnetic particle testing has been previously used, because the residual iron oxide may fill or bridge the defect. Similarly fluorescent penetrant will often fail to show discontinuities previously found by dye-penetrant because the dye reduces or even kills fluorescence. Reinspection should be done with the same method. Surface condition may affect the indications. Surface openings may be closed due to dirt, scale, lubrication or polishing. Rough or porous areas may retain penetrant producing irrelevant indications. Deposits on the surface may dilute the penetrant, thus reducing its effectiveness. If all the surface penetrant is not completely removed in the washing or rinse operation following the penetration time, the unremoved penetrant will be visible.

Such parts should be completely reprocessed. Degreasing is recommended. Another condition which may create false indications is where parts are press fitted to each other. The penetrant from the fit may bleed out and mask the true defect. Some of the precautions necessary for liquid penetrant inspection are briefly summarized here. Only one process should be used. Change of process is not advisable for reinspection. Contamination leads to a loss of test sensitivity and reliability. Contamination of water with penetrants should be avoided. Wet developer bath should be at the recommended concentration. The temperature should not exceed certain limits depending on materials used. The penetrant should not be heated.

Avoid contact of penetrant with skin by wearing gloves. Keep penetrants off clothes. Check for traces of luorescent penetrant on skin and clothes and inside gloves by examining under black light. Excessive mounts of dry penetrants should not be inhaled. Improperly arranged black lights may cause some eye fatigue. The materials used with visible penetrant process are flammable and should not be stored or used near heat or fire. Do not smoke while using them.

UNIT- II

ULTRASONIC TESTING

2.1 Fundamental principles:

2.1.1 *Nature and type of ultrasonic waves:*

Ultrasonic inspection is a non-destructive testing method in which high frequency sound waves are introduced into the material being inspected and the sound emerging out of the test specimen is detected and analyzed. 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. Ultrasonic waves are mechanical vibrations of the particles of the medium in which they travel. The waves are represented by a sinusoidal wave equation having a certain amplitude, frequency and velocity. Amplitude is the displacement of the particles of the medium from their mean position. Frequency is the number of cycles per second and the length of one cycle is called wavelength. The relationship between frequency, wavelength and velocity is given by $v = \lambda f$ where v is the velocity of a wave (in a medium) having frequency f and wavelength.λ.

Each medium through which sound waves travel is characterized by an acoustic impedance denoted by 'Z' which is the resistance offered by the medium to the passage of sound through it. Since the values of Z are different for different materials the velocity of sound waves is different in different materials. Velocity also depends upon the elastic properties of the medium and is given by v = (q/p)1/2 where q is the modulus of elasticity and p is the density. Also Z = pv.λ

There are two main types of ultrasonic waves. Longitudinal waves or compressional waves are those in which alternate compression and rarefaction zones are produced by the vibration of the particles. The direction of oscillation of the particles is parallel to the direction of propagation of the waves. Because of its easy generation and detection, this type of ultrasonic wave is most widely used in ultrasonic testing. Almost all of the ultrasonic energy used for the testing of materials originates in this mode and is then converted to other modes for special test applications. This type of wave can propagate in solids, liquids and gases. In transverse or shear waves the direction of particle displacement is at right angles to the direction of propagation. 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. In a particular medium the velocity of transverse waves is about half that of the longitudinal waves. Below Table gives the comparative velocities in some common materials.

2.1.2 Reflection and transmission of sound waves:

Sound energy may be reflected, refracted, scattered, absorbed or transmitted while interacting with a material. Reflection takes place in the same way as for light, i.e. angle of incidence equals angle of reflection. At any interface between two media of different acoustic impedances a mismatch occurs causing the major percentage of the wave to be reflected back, the remainder being transmitted. There are two main cases:

Material	**Longitudinal**	**Transverse**
Aluminium	6.32	3.13
Brass	4.28	2.03
Copper	4.66	2.26
Gold	3.24	1.20
Iron	5.90	3.23
Lead	2.16	0.70
Steel	5.89	3.24
Perspex	2.70	1.40
Water	1.43	-
Oil (transformer)	1.39	-
Air	0.33	-

TABLE 3.2 : VELOCITIES OF SOUND IN SOME COMMON MATERIALS

2.1.2.1 Reflection and transmission at normal incidence

The percentage of incident energy reflected from the interface between two materials depends on the ratio of acoustic impedances of the two materials and the angle of incidence. When the angle of incidence is 0 (normal incidence), the reflection coefficient (R), which is the ratio of the reflected beam intensity I_r to the incident beam intensity I;, is given by

$$= I_r/I_i = (Z_2 - Z_1)^2 /((Z_1+Z_2)^2$$

where Z\ is the acoustic impedance of medium 1, and Z2 is the acoustic impedance of medium 2. The remainder of the energy is transmitted across the interface into the second material. The transmission coefficient (T) which is the ratio of the transmitted intensity 'I t ' to the incident intensity 'I;' is given by

$$= I_r / I_t = Z_1, Z_2/(Z_1+Z_2)^2$$

Using the values of characteristic impedances, reflection and transmission coefficients can be calculated for pairs of different materials. The equations show that the transmission coefficient approaches unity and the reflection coefficient tends to zero when Z_1 and Z_2 have approximately similar values. The materials are then said to be well matched or coupled. On the other hand, when the two materials have substantially dissimilar characteristic impedances, e.g. for a solid or liquid in contact with a gas, the transmission and reflection coefficients tend to zero and 100 per cent prospectively. The materials are then said to be mismatched or poorly coupled. It is for this reason that a coupling fluid is commonly used when transmitting or receiving sound waves in solids.

3.6.1.2.2 Reflection and transmission at oblique incidence

When an ultrasonic wave is incident on the boundary of two materials at an angle other than normal, the phenomenon of mode conversion (a change in the nature of the wave motion i.e. longitudinal to transverse and vice versa) must be considered. All possible ultrasonic waves leaving the point of impingement are shown for an incident longitudinal ultrasonic wave in below figure mode conversion can also take place on the reflection side of the interface if material 1 is solid.

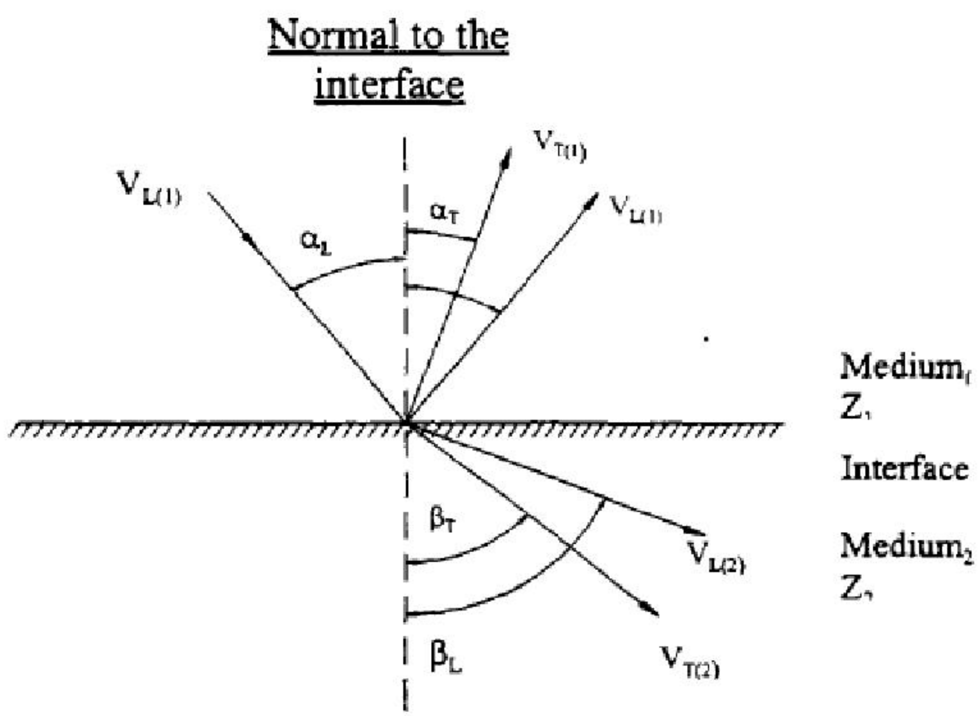


Figure: Phenomena of reflection, refraction and mode conversion for an incident wave.

2.1.2.3 First and second critical angles

If the angle of incidence cc_L is small , ultrasonic waves travelling in a medium undergo the phenomena of mode conversion and refraction on 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. The angle of incidence at which the refracted longitudinal wave emerges is called the first critical angle. If the angle of incidence a_L is further increased the angle of refraction for the transverse wave also approaches 90°. The value of a_L for which the angle of refraction of the transverse wave is exactly 90° is called the second critical, angle At the second critical angle the refracted transverse wave emerges from the medium and travels parallel to the boundary. The transverse wave has thus become a surface or Raleigh wave.

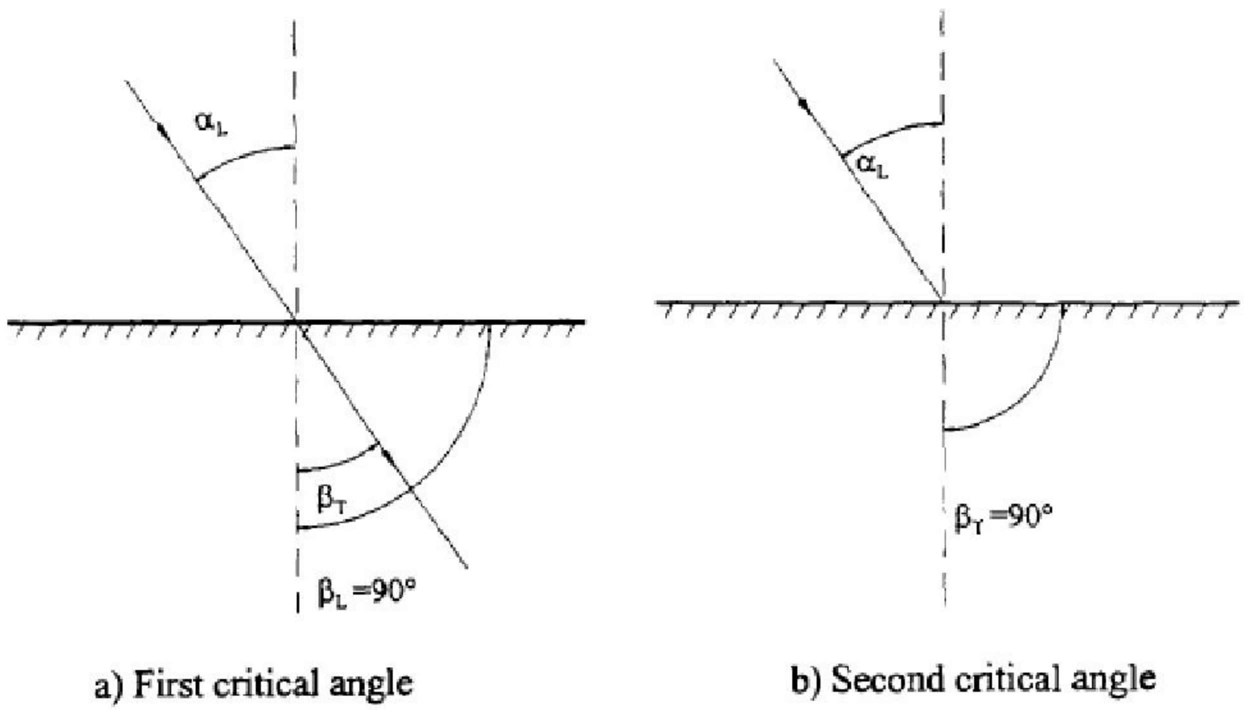


Figure : First and second critical angles.

2.2 Equipment for ultrasonic testing

The equipment for ultrasonic testing mainly consists of a flaw detector, transducers and the test or calibration blocks. These are briefly described here. Below figure shows the block diagram for a typical flaw detector. A pulse generator generates pulses of alternating voltages which excite the crystal in the probe to generate specimen by coupling the probe to it. The waves are reflected from the far boundary of the test specimen or from any discontinuities within it and reach the probe again. Here through the reverse piezoelectric effect the ultrasonic waves are converted into voltage pulses and are fed to the y-plates of a cathode ray tube through an amplifier. These then are displayed on the CRT screen as pulses of definite amplitude and can be interpreted as signals from the back wall of the test specimen or from the discontinuity present within it.

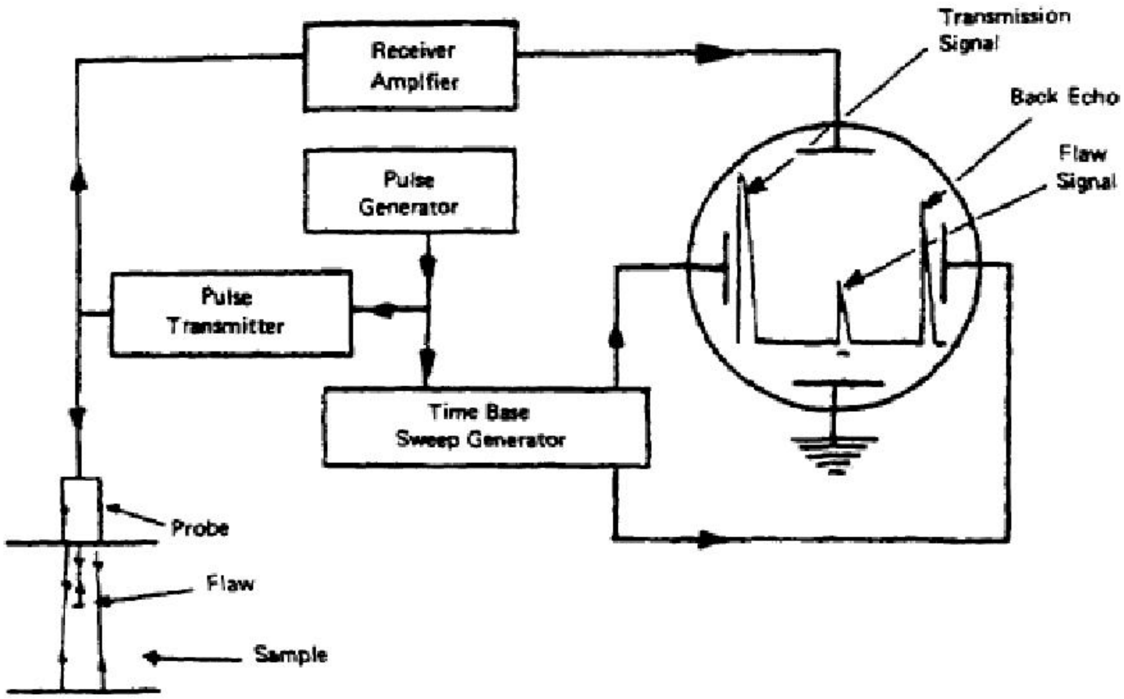


Figure: A typical ultrasonic test unit.

Ultrasound is generated in certain natural and artificially made crystals which show the effect of piezoelectricity i.e. they produce electric charges on being subjected to mechanical stresses and vice versa. Thus on the application of electric pulses of appropriate frequency these crystals produce ultrasonic pulses which are mechanical vibrations. The most commonly used materials are quartz, lithium sulphate, barium titanate and lead metaniobate. The properly cut crystal is contained in a housing, the whole assembly being termed as an ultrasonic probe. The two faces of the crystal are provided with electrical connections. On the front face of the crystal (the face which comes in contact with the test specimen) a perspex piece is provided to avoid wear and tear of the crystal. At the rear of the crystal there is damping material such as a spring or tungsten araldite. This damping material is necessary to reduce the vibration of the crystal after transmitting the ultrasonic pulse so that the crystal can be more efficient as a receiver of sound energy. Damping is necessary therefore to improve the resolution of the probe. A typical probe is shown in Figure 3.19. The probe generates ultrasound of a particular frequency which depends upon the thickness of the piezoelectric crystal. The sound comes out of the probe in the form of a cone-like beam which has two distinct regions namely the near field and the far field. Most of the testing is performed using the far field region of the beam. The probes that send the ultrasonic beams into the test specimen at right angles to the surface are called normal beam probes while those that send beams into the specimen at a certain angle are termed as angle beam probes. In angle beam probes the crystal is mounted on a perspex wedge so that the longitudinal waves fall on the surface of the test specimen obliquely. Then through the phenomenon of mode conversion and choosing a suitable angle of incidence, shear waves can be sent into the test specimen at the desired angle. These angle beam probes are used specially for the inspection of welds whose bead has not been removed.

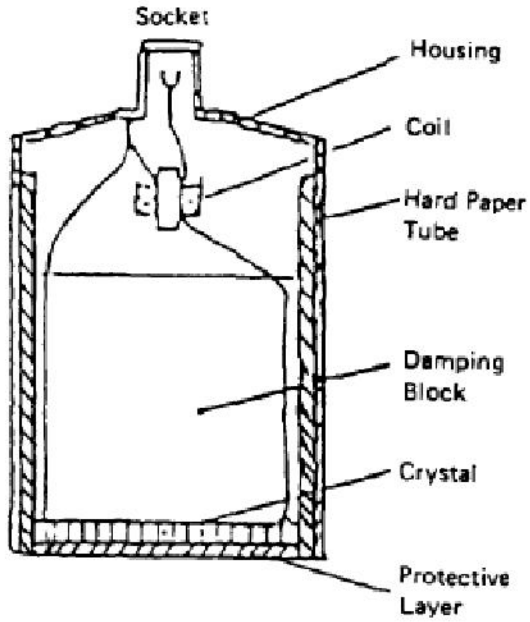


Figure: A typical normal beam single crystal ultrasonic probe.

To draw any meaningful conclusions from the indications of reflected ultrasound the flaw detector-probe system should be properly calibrated using standard calibration blocks. There is a large variety of these blocks which are in use for different types of inspection problems. Some of the most commonly used ones are briefly described here. The I.I.W test block, shown in above Figure , can be used to set test sensitivity, time base calibration, determination of shear wave probe index and angle, checking the amplifier linearity and checking the flaw detector - probe resolving power. The block is sometimes referred to as the VI block.

The V2 test block is mainly used with the miniature angle probes to calibrate the CRT screen. The block is shown in above figure along with the CRT screen appearance when the probe is placed in two different positions on the block.

Some blocks are made having flat bottom holes. These type of test blocks are made from a plate of the same material as the material under test. The ASTM area-amplitude blocks and distance-amplitude blocks are examples of this type of block

These blocks provide known-area reflectors which can be compared to reflections from unknown reflectors. They also enable reproducible levels of sensitivity to be set and therefore to approximate the magnitude of flaws in terms of reflectivity. In addition to the standard test blocks there are a number of other test blocks available. In general a test block should simulate the physical and metallurgical properties of the specimen under test. The variety of test blocks available can be found by consulting the various national standards, e.g. ASME, ASTM, BS, DIN, J1S, etc

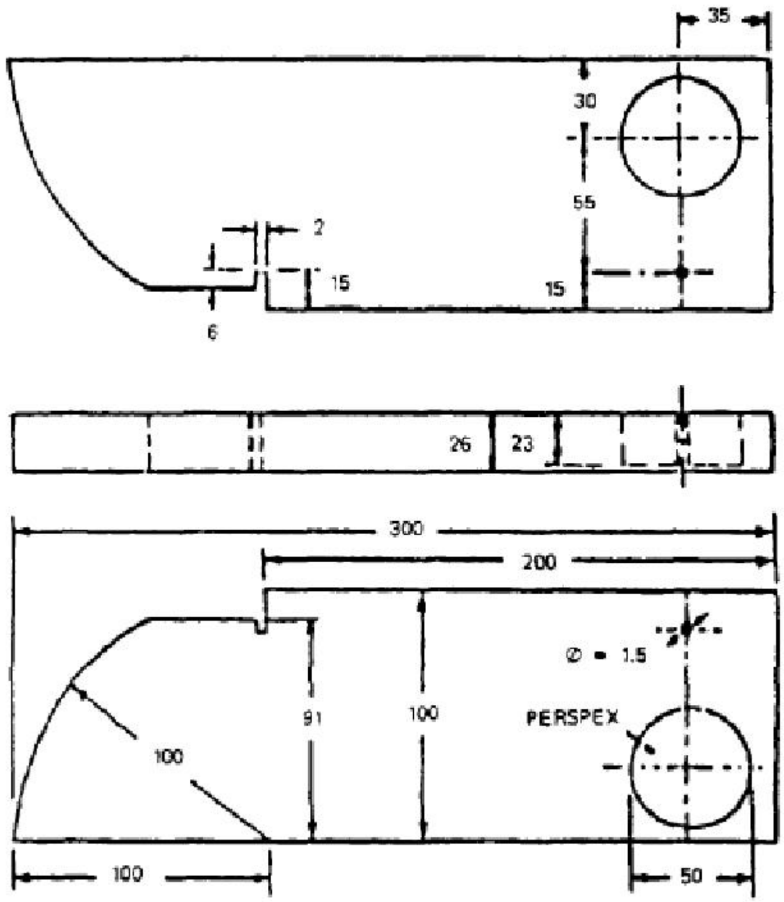


Figure : I.I.W test block.

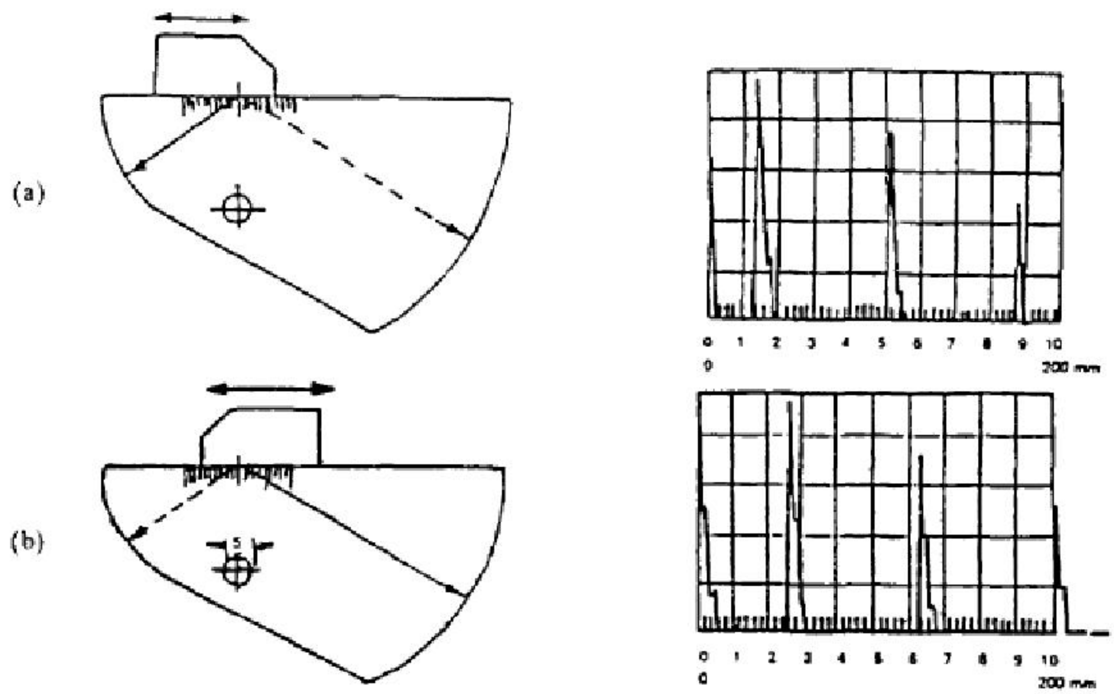


Figure : V2 test block (a) with the probe index at the zero point and directed to the 25 mm radius, (b) with the probe index at the zero point and directed to the 50 mm radius.

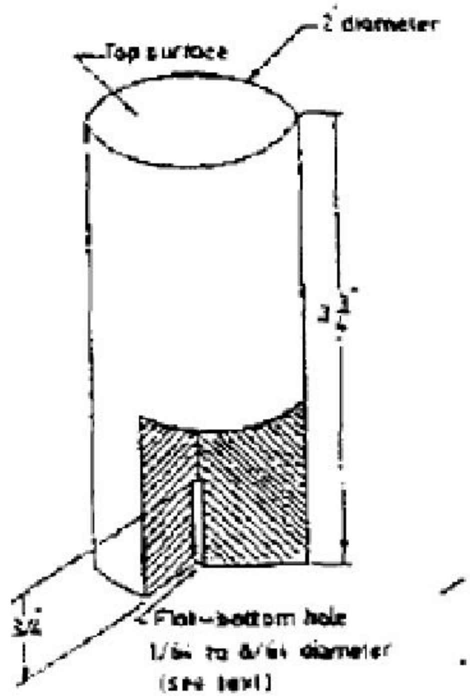


Figure : Flat bottom hole type test block.

2.3 General procedure for ultrasonic testing

The most commonly used method of ultrasonic testing is the pulse-echo or reflection method. In this case the transmitter and receiving 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 boundary or backwall signal. The CRT screen shows the separation between the time of arrival of the defect echo compared to that of the natural boundary of the specimen, therefore, location of the defect can be assessed accurately. Usually one probe acts simultaneously as a transmitter and then as a receiver and is referred to as a TR probe. The principle of the pulse echo method is illustrated in above Figure

The time base of the CRT can be calibrated either in units of time or, if the velocity of sound in the material is known, in units of distance. If "1" is the distance from the transducer to the defect and "t" the time taken for waves to travel this distance in both directions then, 1 = vt/2 where v is the sound velocity in the material.

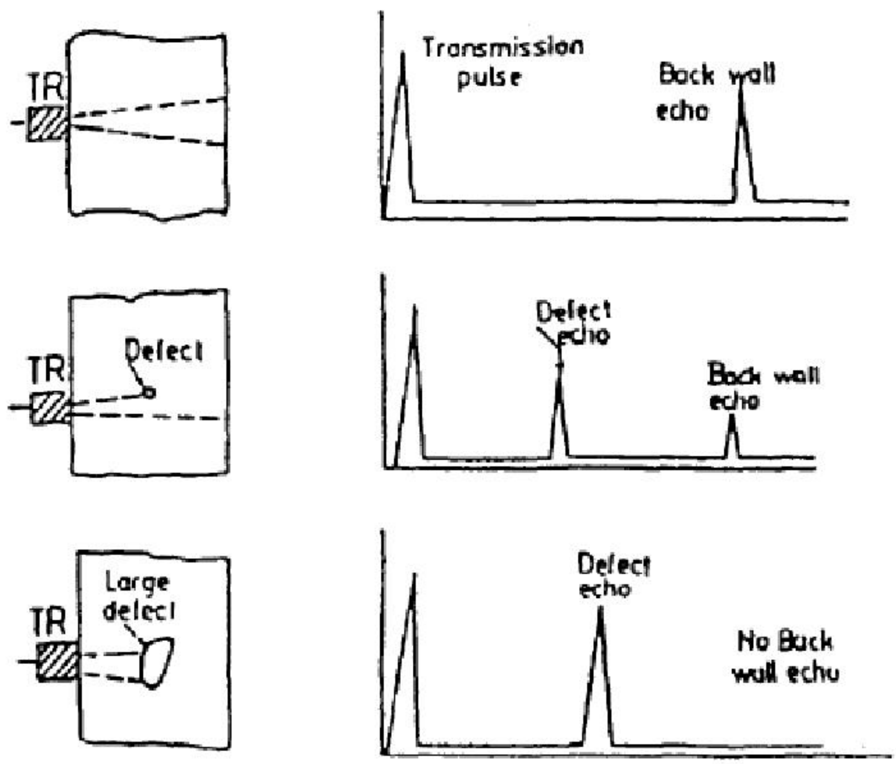


Figure: Principle of pulse echo method of ultrasonic testing (a) defect free specimen (b) specimen with small defect (c) specimen with large defect.

The procedure to conduct an ultrasonic test is influenced by a number of factors. Also the nature of the test problems in industry varies over a wide range. Therefore it is difficult to define a method which is versatile enough to work in all situations. However, it is possible to outline a general procedure which will facilitate the inspection by ultrasonics in most cases.

(i) The test specimen

Specimen characteristics such as the condition and type of surface, the geometry and the microstructure are important. Very rough surfaces may have to be made smooth by grinding, etc. Grease, dirt and loose scale or paint should be removed. The geometry of the specimen should be known since this has a bearing on the reflection of sound inside the specimen. Some reflections due to a complex geometry may be confused with those from genuine defects. The material microstructure or grain structure affects the degree of penetration of sound through it. For a fixed frequency the penetration is more in fine grained materials than in coarse grained materials.

(ii) Types of probes and equipment

The quality of ultrasonic trace depends on the probes and equipment which in turn determine the resolving power, the dead zone and the amount of sound penetration. It is difficult to construct a probe which will provide good detection and resolution qualities and at the same time provide deep penetration. For this reason, a variety of probes exist some of which are designed for special purposes. For the examination of large surface areas it is best to use probes with large transducers in order to reduce the time taken for the test. However the wide beam from such a probe will not detect a given size of flaw as easily as a narrower one. The probability of detecting flaws close to the surface depends on the type of equipment and probes used. The dead zone can be decreased in size by suitably designing the probe and also shortening the pulse length. The selection of the test frequency must depend upon previous experience or on preliminary experimental tests or on code requirements. The finer the grain structure is, the greater is the homogeneity of the material and the higher is the frequency which can be applied. The smaller the defects being looked for the higher the frequency used. Low frequencies are selected for coarse grained materials such as castings, etc. After the selection of the probe and the equipment has been finalized, its characteristics should be checked with the help of test blocks.

(iii) Nature of defects

Defect characteristics which include the type, size and location, differ in different types of materials. They are a function of the design, manufacturing process and the service conditions of the material. The detection and evaluation of large defects is not normally a difficult problem. The outline of a defect can be obtained approximately by moving the probe over the surface of the test specimen. The flaw echo increases from zero to a maximum value as the probe is moved from a region free from defects to a point where it is closest to a defect. Information as to the character of a defect can be obtained from the shape of the defect echo. For small defects, the size of the defect is estimated by comparing the flaw reflectivity with the reflectivity of standard reflectors. If the standard reflector is of the same shape and size as the unknown flaw, the reflectivity will be the same at the same beam path length. Unfortunately this is seldom the case since reference reflectors are generally flat bottomed holes or side drilled holes and have no real equivalence to real flaws. Theoretically it is possible under favourable conditions to detect flaws having dimensions of the order of half a wavelength. Indications obtained with an ultrasonic flaw detector depend to a great extent on the orientation of the defect in the material. Using the single probe method, the largest echoes are obtained when the beam strikes the surface of the specimen at right angles. On a properly calibrated time base the position of the echo from a defect indicates its location within the specimen. The determination of the type, size and location of defects which are not at right angles to the sound beam is complicated and needs deep understanding and considerable experience.

(iv) Selection of couplant

The couplant provides impedance matching between the probe and the test specimen. The degree of acoustic coupling depends on the roughness of the surface and the type of couplant used. In general the smoother the surface the better the conditions for the penetration of ultrasonic waves into the material under test. Commonly used couplants are water, oils of varying degrees of viscosity, grease, glycerine and a mixture of 1 part glycerine to 2 parts water. Special pastes such as Polycell mixed with water are also used.

(v) Test standards

Standards are used to check the performance of the flaw detector probe system. There are mainly two types of these standards. The first type of standard is used to control such parameters as amplifier gain, pulse power and time base marking and to ensure that they remain constant for the whole of the test. They are also used to verify the angle of incidence and to find the point where the beam emerges in angle probes. Another purpose of this group of standards is to calibrate the time base of the oscilloscope. The second group of standards contains those used for special purposes. They are normally used for tests which are largely dependent on the properties of the examined material and, if possible, they are made of the same materials and have the same shapes as the examined objects. These standards allow for the setting of the minimum permissible defect as well as the location of defects.

(vi) Scanning procedure

Before undertaking an ultrasonic examination, the scanning procedure should be laid down. For longitudinal probes this is simple but care must be taken with angle or shear wave probes. For instance in the inspection of welds using an angle probe scanning begins with the probe at either the half skip or full skip positions and continues with the probe being moved in a zigzag manner between the half skip and full skip positions. There are in general four scanning movements in manual scanning, rotational, orbital, lateral and traversing. The half skip position is recommended for critical flaw assessment and size estimation whenever possible. In some special applications the gap scanning method is employed. Here, an irrigated probe is held slightly away from the material surface by housing it in a recess made in a contact scanning head. Probe wear can be avoided by interposing a free running endless belt of plastic ribbon between the probe and the test surface. Acoustical coupling is obtained by enclosing the probe in an oil filled rotating cylinder in which case only the surface requires irrigation. Immersion scanning, which is most commonly used in automatic inspection, is done by holding the probe under water in a mechanical or electronic manipulator, the movement of which controls the movement of the probe.

(vii) Defect sizing

After the flaws in the test specimen have been detected it is important to evaluate them in terms of their type, size and location. Whereas the type and location of the flaw may be inferred directly from the echo on the CRT screen; the size of the flaw has to be determined. The commonly used methods for flaw sizing in ultrasonic testing are 6 dB drop method, 20 dB drop method, maximum amplitude method and the DGS diagram method. The basic assumption in the 6 dB drop 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 line with the edge of the flaw. The method only works if the ultrasonic response from the flaw is essentially uniform over the whole reflecting surface. 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 to the 6 dB point as before. 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. The 20 dB drop 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 20 dB drop method gives more accurate results than the 6 dB drop method because of the greater control one has on the manipulation of the ultrasonic beam. However, size estimation using either the 6 dB or 20 dB drop method have inherent difficulties which must be considered. The main problem is that the amplitude may drop for reasons other than the beam scanning past the end of the defect due to any of the following reasons:

(a) The defect may taper in section giving a reduction in cross sectional area within the beam. If this is enough to drop the signal 20 dB or 6 dB the defect may be reported as finished while it in fact continues for an additional distance.

(b) The orientation of the defect may change so that the probe angle is no longer giving maximum response, another probe may have to be used.

(c) The defect may change its direction.

(d) The probe may be twisted inadvertently.

(e) The surface roughness may change.

The maximum amplitude method takes into account the 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 unfavorably oriented. 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.

The DGS 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 bottom holes located at various distances from the probe, with the echo of a large reflector, a back wall reflector, also at different distances from the probe (Section 7.2.4). For normal probes it relates the distance D from the probe (i.e. along the beam) in near field units, thus compensating for probes of different sizes and frequencies, to the gain G in dB for a flat bottom hole 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 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.

(viii) Test report

In order that the results of the ultrasonic examination may be fully assessed it is necessary for the tester's findings to be systematically recorded. The report should contain details of the work under inspection, the code used, the equipment used and the calibration and scanning procedures. Also the probe angles, probe positions, flaw ranges and amplitude should be recorded in case the inspection needs to be repeated. The principle is that all the information necessary to duplicate the inspection has to be recorded.

Applications of ultrasonic testing

Thickness measurements

Thickness measurements using ultrasonics can be applied using either the pulse echo or resonance techniques. Some typical applications are:

(i) Wall thickness measurement in pressure vessels, pipelines, gas holders, storage tanks for chemicals and accurate estimate of the effect of wear and corrosion without having to dismantle the plant.

(ii) Measurement of the thickness of ship hulls for corrosion control.

(iii) Control of machining operations, such as final grinding of hollow propellers.

(iv) Ultrasonic thickness gauging of materials during manufacture.

(v) Measurement of wall thickness of hollow aluminium extrusions.

(vi) Measurement of the thickness of lead sheath and insulating material extruded over a core of wire. Inspection of heat exchanger tubing in nuclear reactors. wire. Inspection of heat exchanger tubing in nuclear reactors
(viii) Measurement of the wall thickness of small bore tubing including the canning tubes for reactor fuel elements.

Flaw detection

Typical flaws encountered in industrial materials are cracks, porosity, laminations, inclusions, lack of root penetration, lack of fusion, cavities, laps, seams, corrosion, etc. Some examples of the detection of these defects are as follows:

- Examination of welded joints in pressure vessels, containers for industrial liquids and gases, pipelines, steel bridges, pipelines, steel or aluminium columns, frames and roofs (during manufacturing, pre-service and in-service).
- Inspection of steel, aluminium and other castings,
- Inspection of rolled billets, bars and sections.
- Inspection of small bore tubes including the canning tubes for nuclear fuel elements.
- Ultrasonic testing of alloy steel forgings for large turbine rotors,
- Testing of turbine rotors and blades for aircraft engines.

- Early stage inspection in the production of steel and aluminium blocks and slabs, plates, bar sections, tubes, sheets and wires.
- Detection of unbonded surfaces in ceramics, refractories, rubber, plastics and laminates.
- Detection of honeycomb bond in the aircraft industry.
- Inspection of jet engine rotors.
- Detection of caustic embrittlement failure in riveted boiler drums in the power generation industry.
- Detection of cracks in the fish plate holes in railway lines and in locomotive and bogey axles.
- Detection of hydrogen cracks in roller bearings resulting from improper heat treatment.
- In service automatic monitoring of fatigue crack growth.
- Detection of stress corrosion cracking.
- Detection of fatigue cracks in parts working under fluctuating stress.
- Inspection of fine quality wire.
- Testing of wooden components such as utility poles.
- Application of ultrasonics to monitor material characteristics in the space environment.
- Determination of lack of bonding in clad fuel elements,
- Detection of flaws in grinding wheels.
- Varieties of glass which are not sufficiently transparent to allow optical inspection can be tested ultrasonically.
- Quality control in the manufacture of rubber tyres by locating voids, etc.

- Inspection of engine crankshafts.

2.4.3 Miscellaneous applications

In addition to the applications already mentioned there are numerous others. Notable among these are those based on the measurement of acoustic velocity and the attenuation of acoustic energy in materials. Some of these applications are as follows:

1. Assessment of the density and tensile strength of ceramic products such as high tension porcelain insulators.

2. Determination of the difference between various types of alloys.

3. Detection of grain growth due to excessive heating.

4. Estimation of the values of the elastic moduli of metals over a wide range of temperature and stress.

5. Tensile strength of high grade cast iron can be estimated by measuring its coefficient of acoustical damping.

6. Crushing strength of concrete can be measured from the transit time of an ultrasonic pulse.

7. Quarrying can be made more efficient by the measurement of pulse velocity or attenuation in rock strata.

8. To find the nature of formations in geophysical surveys without having to undertake boring operations.

9. Detection of bore hole eccentricity in the exploration for mineral ores and oil.

10. Study of press fits.

11. Metallurgical structure analysis and control of case depth and hardness, precipitation of alloy constituents and grain refinement.

12. Determination of intensity and direction of residual stresses in structural metal components.

13. Detection of honeycomb debonds and the regions in which the adhesive fails to develop its nominal strength in the aerospace industry.

14. Measurement of liquid level of industrial liquids in containers.

3.6.5 Range and limitations of ultrasonic testing

Advantages

The principal advantages of ultrasonic inspection as compared to other methods for non-destructive inspection of metal parts are:

1. Superior penetrating power which allows the detection of flaws deep in the part. Ultrasonic inspection is done routinely to depths of about 20 ft in the inspection of parts such as long steel shafts and rotor forgings.

2. High sensitivity permitting the detection of extremely small flaws.

3. Greater accuracy than other non-destructive methods in determining the position of internal flaws, estimating their size and characterizing their orientation, shape and nature.

4. Only one surface needs to be accessible.

5. Operation is electronic, which provides almost instantaneous indications of flaws. This makes the method suitable for immediate interpretation, automation, rapid scanning, on-line production monitoring and process control. With most systems, a permanent record of inspection results can be made for future reference.

6. Volumetric scanning ability, enabling inspection of a volume of metal extending from the front surface to the back surface of a part.

7. Is not hazardous to operators or to nearby personnel, and has no effect on equipment and materials in the vicinity.

    a. Portability.

8. Disadvantages

9. Manual operation requires careful attention by experienced technicians.

10. Extensive technical knowledge is required for the development of inspection procedures.

11. Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.

12. Discontinuities that are present in a shallow layer immediately beneath the surface may not be detectable.

13. Couplants are needed to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected.

14. Reference standards are needed, both for calibrating the equipment and for characterizing flaws.

UNIT III

RADIOGRAPHIC TESTING

RADIOGRAPHIC TESTING

Fundamental principles

The method of radiographic testing

The method of radiographic testing involves the use of a source of radiation from which the radiations hit the test specimen, pass through it and are detected by a suitable radiation detector placed on the side opposite to that of the source. This is schematically shown in the Figure 3.11. While passing through the test specimen the radiations are absorbed in accordance with the thickness, physical density and the internal defects of the specimen and the detector system therefore receives the differential radiations from different parts of a defective specimen which are recorded onto the detector.

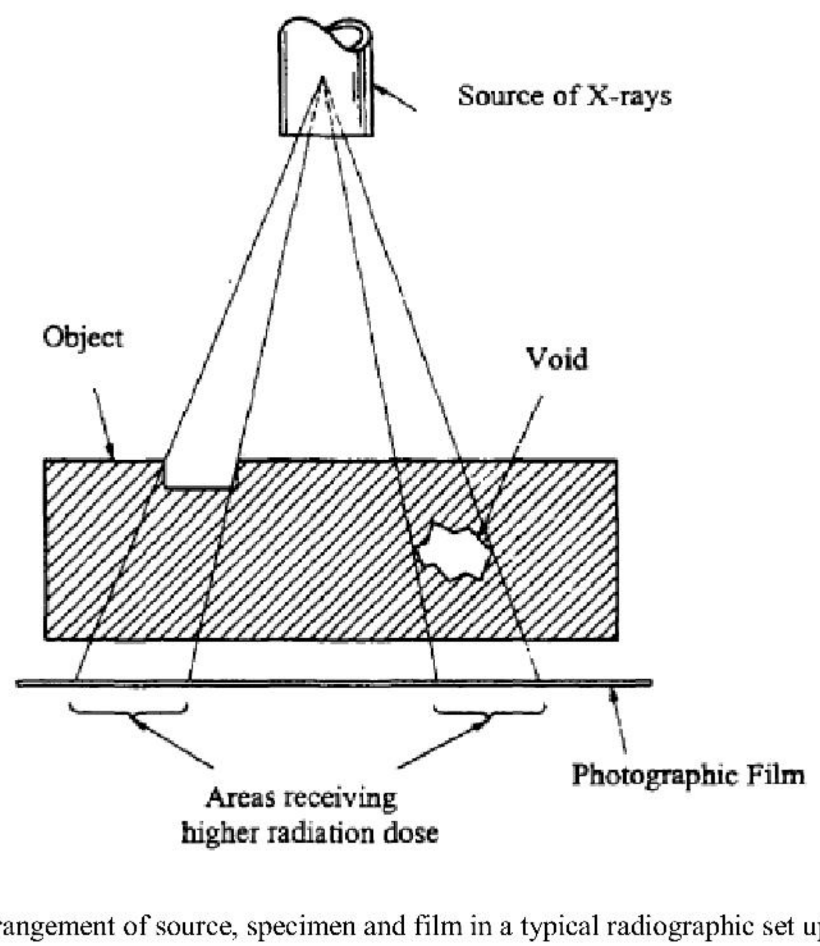


Figure : Arrangement of source, specimen and film in a typical radiographic set up

Properties of radiations

X-rays and gamma rays are electromagnetic radiations which have the following common properties.

(i) They are invisible.

(ii) They cannot be felt by human senses.

(iii) They cause materials to fluoresce. Fluorescent materials are zinc sulfide, calcium tungstate, diamond, barium platinocyanide, napthalene, anthracene, stilbene, thalium activated sodium iodide etc.

(iv) They travel at the speed of light i.e. 3×10^{10} cm/sec.

(v) They are harmful to living cells.

(vi) They can cause ionization. They can detach electrons from the atoms of a gas, producing positive and negative ions.

(vii) They travel in a straight line. Being electromagnetic waves, X-rays can also be reflected, refracted and diffracted.

(viii) They obey the inverse square law according to which intensity of X-rays at a point is inversely proportional to the square of the distance between the source and the point. Mathematically I a $1/r^2$ where I is the intensity at a point distant r from the source of radiation.

(ix) They can penetrate even the materials through which light cannot. Penetration depends upon the energy of the rays, the density and thickness of the material. A monoenergetic beam of X-rays obeys the well known absorption law, I = Io exp (-ux) where Io = the incident intensity of X-rays and I= the intensity of X-rays transmitted through a thickness x of material having attenuation coefficient u .

(x) They affect photographic emulsions.

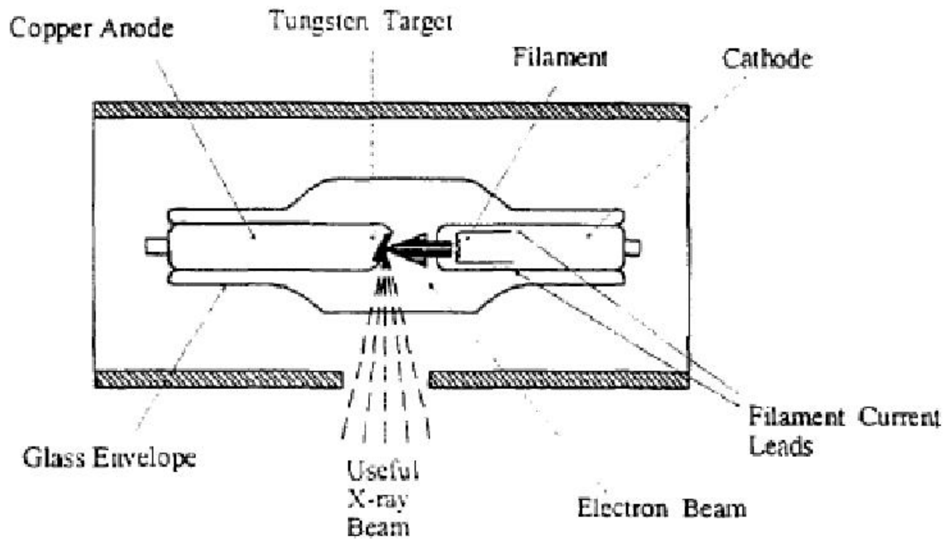
(xi) While passing through a material they are either absorbed or scattered.

Properties (vii), (viii), (ix), (x), (xi) are mostly used in industrial radiography.

Sources for radiographic testing

(i) X ray **machines**

X rays are generated whenever high energy electrons hit high atomic number materials. Such a phenomenon occurs in the case of X ray tubes, one of which is shown in above figure . The X ray tube consists of a glass envelope in which two electrodes called cathode and anode are fitted. The cathode serves as a source of electrons. The electrons are first accelerated by applying a high voltage across the cathode and the anode and then stopped suddenly by a solid target fitted in the anode. The sudden stoppage of the fast moving electrons results in the generation of X rays, These X rays are either emitted in the form of a cone or as a 360 degree beam depending upon the shape and design of the target. The output or intensity of X rays depend upon the kV and the tube current which control the number of electrons emitted and striking the target. The energy of X rays is mainly controlled by the voltage applied across the cathode and the anode which is of the order of kilovolts. The effect of a change in the tube current or the applied voltage on the production of X rays is shown in above Figure.



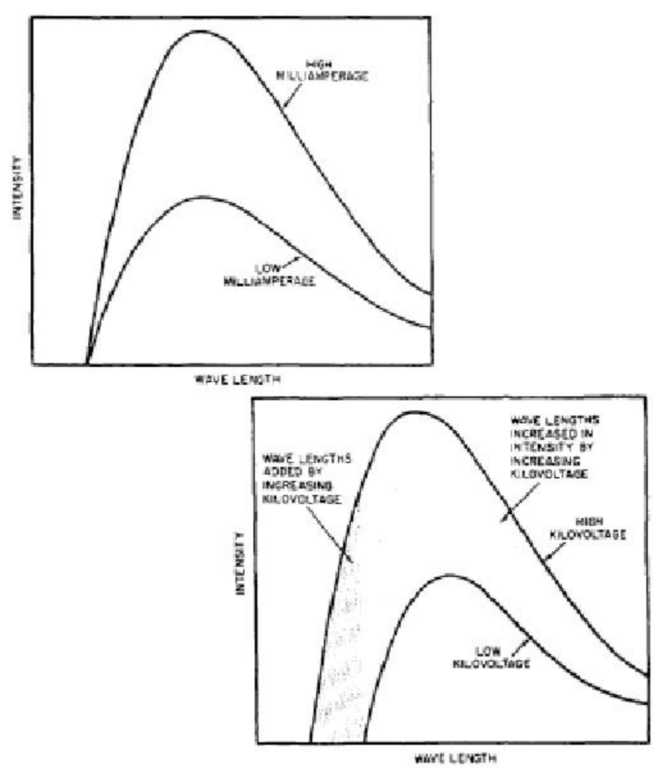


Figure : Effect of tube current (mA) and voltage (kV) on the intensity of X rays.

There is a variety of X ray machines available for commercial radiographic testing. Some of these emit X rays in a specified direction while others can give a panoramic beam. There are machines which have a very small focal spot size for high definition radiography. These are called micro focus machines. Some machines are specially designed to give very short but intense pulses of X rays. These are called flash X ray tubes and are usually used for radiography of objects at high velocity. Typically X ray machines of up to a maximum of about 450 kV are commercially available for radiographic testing.

(ii) Gamma ray sources:

These are some elements which are radioactive and emit gamma radiations. There are a number of radioisotopes which in principle can be used for radiographic testing. But of these only a few have been considered to be of practical value. The characteristics which make a particular radioisotope suitable for radiography include the energy of gamma rays, the half life, source size, specific activity and the availability of the source. In view of all these considerations the radioisotopes that are commonly used in radiography along with some of their characteristics are given in Table 3.1.

(iii) Radiographic linear accelerators:

For the radiography of thick samples, X ray energy in the MeV range is required. This has now become possible with the availability of radiographic linear accelerators. In a linear accelerator the electrons from an electron gun are injected into a series of interconnected cavities which are energized at radio frequency (RF) by a klystron or magnetron. Each cavity is cylindrical and separated from the next by a diaphragm with a central hole through which the electrons can pass. Due to the imposed RF, alternate diaphragm hole edges will be at opposite potentials at all times and the field in each cavity will accelerate or decelerate the electrons at each half cycle. This will tend to bunch the electrons and those entering every cavity when the field is accelerating them will acquire an increasing energy at each pass. The diaphragm spacing is made such as to take into account the increasing mass of electrons as their velocity increases. They impinge on a target in the usual way to produce X rays. Linear accelerators are available to cover a range of energies from about 1 MeV to about 30 MeV covering a range of steel thicknesses of up to 300 mm. The radiations output is high (of the order of 5000 Rad per minute) and the focal spot sizes usually quite reasonable to yield good quality radiographs at relatively low exposure times.

(iv) Betatron

The principle of this machine is to accelerate the electrons in a circular path by using an alternating magnetic field. The electrons are accelerated in a toroidal vacuum chamber or doughnut which is placed between the poles of a powerful electromagnet. An alternating current is fed into the energising coils of the magnet and as the resultant magnetic flux passes through its zero value, a short burst of electrons is injected into the tube. As the flux grows the electrons are accelerated and bent into a circular path. The magnetic field both accelerates the electrons and guides them into a suitable orbit and hence, in order to maintain a constant orbit,

TABLE 3.1 : TYPICAL RADIOACTIVE SOURCES FOR INDUSTRIAL RADIOGRAPHY

Characteristics / Source	Half life	Gamma ray energies (MeV)	RHM value per curie	Optimum thickness range (mm of steel)	Half value layer (mm of lead)
Thulium-170	128 Days	0.87, 0.52	0.0025	2.5 to 12	-
Cobalt-60	5.3 Years	1.17, 1.33	1.33	50 to 150	13
Iridium-192	74.4 Days	0.31, 0.47, 0.64	0.5	10 to 70	2.8
Caesium-137	30 Years	0.66	0.37	20 to 100	8.4

these two factors must be balanced so that the guiding field at the orbit grows at an appropriate rate. The acceleration continues as long as the magnetic flux is increasing, that is, until the peak of the wave is reached; at this point the electrons are moved out of orbit, either to the inner or outer circumference of the doughnut, by means of a DC pulse through a set of deflecting coils. The electrons then strike a suitable target. The electrons may make many thousands of orbits in the doughnut before striking the target, so that the path lengths are very great and the vacuum conditions required are in consequence very stringent. The radiation from betatrons is emitted in a series of short pulses. In order to increase the mean intensity some machines operate at higher than mains frequency. Most betatrons designed for industrial use are in the energy range of 6-30 MeV. Betatrons in general have a very small focal spot size typically about 0.2 mm, but the X ray output is low. Machines are built in the higher energy range in order to obtain a higher output, but this brings the disadvantages of a restricted X ray field size.

3.5.1.4 Films for radiographic testing

The detection system usually employed in radiographic testing is the photographic film usually called an X ray film. The film consists of a transparent, flexible base of clear cellulose derivative or like material. One or both sides of this base are coated with a light sensitive emulsion of silver bromide suspended in gelatin. The silver bromide is distributed throughout the emulsion as minute crystals and exposure to radiation such as X rays, gamma rays or visible light, changes its physical structure. This change is of such a nature that it cannot be detected by ordinary physical methods, and is called the latent image.

However, when the exposed film is treated with a chemical solution (called a developer) a reaction takes place causing the formation of tiny granules of black metallic silver. It is this base, that constitutes the image. Above figure is an expanded pictorial view of the general make up of afilm.

Radiographic film is manufactured by various film companies to meet a very wide diversified demand. Each type of film is designed to meet certain requirements and these are dictated by the circumstances of inspection such as (a) the part (b) the type of radiation used (c) energy of radiation (d) intensity of the radiation and (e) the level of inspection required. No single film is capable of meeting all the demands. Therefore a number of different types of films are manufactured, all with different characteristics, the choice of which is dictated by what would be the most effective combination of radiographic technique and film to obtain the desired result.

The film factors that must be considered in choosing a film are : speed, contrast, latitude and graininess. These four are closely related; that is, any one of them is roughly a function of the other three. Thus films with large grain size have higher speed than those with a relatively small grain size. Likewise, high contrast films are usually finer grained and slower than low contrast films. Graininess, it should be noted, influences definition or image detail. For the same contrast, a small grained film will be capable of resolving more detail than one having relatively large grains. The films are generally used sandwiched between metallic screens, usually of lead. These screens give an intensification of the image and thus help to reduce the exposure times besides cutting down the scattered radiation.

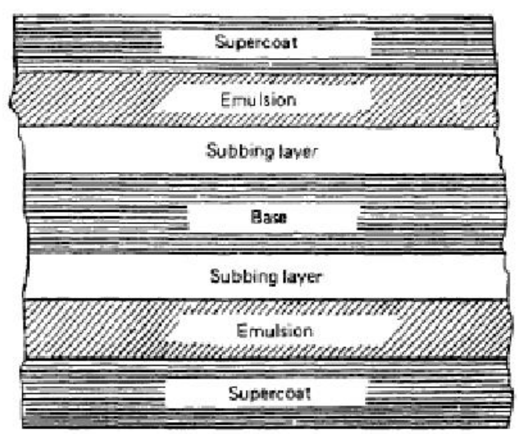


Figure : Construction of radiographic films

General procedure for radiographic testing

The test specimen is first of all properly cleaned and visually inspected and all the surface imperfections are noted. A properly selected film, usually sandwiched between intensifying screens and enclosed in a light proof cassette is prepared. The source of radiation, the test specimen and the film are arranged as shown in Figure 3.11. Image quality indicators and lead identification letters are also placed on the source side of the test specimen. From a previously prepared exposure chart for the material of the test specimen, the energy of radiations to be used and the exposure (intensity of radiations x time) to be given are determined. Then the exposure is made. After the source of radiation has been switched off or retrieved back into the shielding (in case of gamma ray source), the film cassette is removed and taken to the dark room. In the dark room, under safe light conditions, the film is removed from the cassette and the screens and processed. The processing of the film involves mainly four steps. Development reduces the exposed silver bromide crystals to black metallic silver thus making the latent image visible. Development is usually done for 5 minutes at 20°C. After development the film is fixed whereby all the unexposed and undeveloped crystals of film emulsion are removed and the exposed and image-forming emulsion is retained on the film. The fixing is done for approximately 2-6 minutes. The film is then washed preferably in running water for about 20-30 minutes and dried Finally the film is interpreted for defects and a report compiled. The report includes information about the test specimen, the technique used and the defects. It also sometime says something about acceptance or rejection of the reported defects. The report is properly signed by responsible persons.

Different forms of radiographic testing

(i) Fluoroscopy

In the general radiographic process, if the film is replaced by a fluorescent salt screen then the image of the test specimen can be visually seen. The X rays passing through the object excite the fluorescent material producing bright spots in the more heavily irradiated areas. The fluorescent screen may be viewed directly or by means of a mirror or by using a camera and a closed circuit television. The whole set-up of X ray tube, the test specimen and the fluorescent screen are encased in a protective shielding.

In many cases castings of up to about 10 mm thickness, thin metal parts, welded assemblies and coarse sandwich constructions are screened by this method and castings with obvious large defects are rejected before usual inspection using film radiography.

Plastic parts may be checked for the presence of metal particles or cavities. Other applications include inspection of electrical equipment such as switches, fuses, resistors, capacitors, radio tubes, cables and cable splices in which breaks of metal conductors, short circuiting or wrong assembly may cause troublesome electrical testing. Ceramics, fire bricks and asbestos products lend themselves perfectly to fluoroscopy. Packaged and canned foods are examined for the amount of filling and for the presence of foreign objects.

(ii) Micro radiography

Specially prepared thin samples are radiographed at extremely low energies (e.g. 5 KV) on an ultrafine grain film. The radiograph when enlarged gives the structural 92 details of the specimen. Micro-radiography is mainly applied in metallurgical studies.

(iii) Enlargement radiography

In some situations an enlarged image of an object is desired. To get the enlargement of the image the object to film distance is increased. To overcome the penumbral effects a source of an extremely small size is used.

(iv) High speed or flash radiography

For the radiography of moving objects, the exposure time should be very small and, at the same time, the intensity of the X rays should be extremely high. This is achieved by discharging huge condensers through special X ray tubes which give current of the order of thousands of amperes for a short time (of the order of a millionth of a second). This technique is normally applied in ballistics.

(v) Auto radiography

In this case the specimen itself contains the material in radioactive form. When a film is placed in contact with the specimen, an autoradiograph is obtained showing the distribution of the radioactive material within the specimen. The technique is mainly used in the field of botany and metallurgy

(vi) Electron transmission radiography

A beam of high energy X rays is used to produce photo-electrons from a lead screen. These electrons after passing through the specimen (of very low absorption like paper, etc.) expose the film and an electron radiograph is obtained.

(vii) Electron emission radiography

In this case a beam of X rays is used to produce photoelectrons from the specimen itself. These electrons expose the film which is placed in contact with the specimen. Since emission of electrons depends upon atomic number of an element, the electron emission will give the distribution of elements of different atomic numbers.

(viii) Neutron radiography

In this case a neutron beam is used to radiograph the specimen. The recording system will, therefore, not be a photosensitive film since it is insensitive to neutrons. The following methods are used to record the image:

(1) A gold foil is used which records the image, in terms of the activity produced. This image can be transferred onto

a film by taking an autoradiograph of the foil. Some other suitable materials such as indium and dysprosium can replace gold.

(2) The metallic foil upon neutron bombardment does not become radioactive but instead emits spontaneous gamma rays which expose the film placed in contact with it. Examples of metals suitable for this are lithium and gadolinium.

(3) Neutrons transmitted through the specimen are made to strike a thin neutron scintillator plate. The scintillations thus produced expose the film which is in contact with the scintillator.

In certain cases neutron radiography is advantageous as compared to X or gamma radiography, for example:

(a) If the specimen is radioactive.
(b) If the specimen contains thermal neutron absorbers or light elements.
(c) Two elements whose atomic number is not very different may be easily distinguished.

(ix) Proton radiography

For special type of studies a proton beam can also be used. The number of protons transmitted through a specimen whose thickness is close to the proton range is very sensitive to exact thickness. This helps in detecting very small local variations in density and thickness.

(x) Stereo radiography

Two radiographs of the specimen are taken from two slightly different directions. The angle between these directions is the same as the angle subtended by the human eyes while viewing these radiographs. In the stereo viewer the left eye sees one radiograph and the right eye the other. In this way a realistic three dimensional effect is obtained giving the visual assessment of the position of the defect.

(xi) Xeroradiography

This is considered as a "dry" method of radiography in which a xerographic plate takes the place of X ray film. The plate is covered with a selenium powder and charged electrostatically in the dark room. Exposure to light or radiation causes the charge to decay in proportion to the amount of radiation received and a latent image is formed.

The developing powder is sprayed on the plate in a light-tight box. The particles are charged by friction while passing through the spray nozzle. White powders have best contrast with the black selenium surface but present problems in transferring the picture to paper. Coloured powders on transfer produce negative images while fluorescent powder gives the same picture as white powder and can be viewed under black light both before and after transfer.

3.5.4 Personal safety and radiation protection

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

Somatic effects depend upon three main factors.

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

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

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

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

3.5.5 Applications of radiographic testing method

Radiographic testing is mainly applied for the detection of flaws such as cracks, porosity, inclusions, lack of root penetration, lack of fusion, laps, seams, shrinkage, corrosion, etc. in weldments and castings, in pressure vessels, containers for industrial liquids and gases, pipelines, steel bridges, steel and aluminium columns and frames and roofs, nuclear reactors and nuclear fuel cycle, boiler tubes, ships and submarines, aircraft and armaments. In most of these cases weld inspection is involved. Welds in plates are tested using an arrangement more or less similar to the one shown in above Figure 3. However, there are a number of different techniques for inspection of welds in pipes. These are illustrated in Figure 3.15. The welds in small diameter pipes are inspected usually using source-outside film-outside technique . Medium diameter pipes may also be inspected as in above Figure where source-inside-film outside technique is utilized. When the diameter of pipes becomes large enough, the circular welds may be examined using a panoramic technique. In this the source is placed at the centre inside the pipe and the film is wrapped all around the weld on the outside. Thus in this case the whole weld can be radiographed in a single exposure while for all other situations in above figure multiple exposures are required for full coverage.

Radiography is also extensively used for the inspection of castings and forgings. The regular shaped and uniformly thick specimens can be inspected as usual like welds in plates while special considerations need to be made for testing of specimens of varying thickness. Double film technique is usually employed wherein two films of different speeds are used for a single exposure. In this way correct density is obtained under the thick sections on the faster film whereas the slower films record correct images of the thin sections.

Radiography is used in inspection of explosives contained within casings, sealed boxes and equipment. In the field of electronics it is employed for the inspection of printed circuit boards and assemblies for checking adequacy of connections.

3.5.6 Range and limitations of radiographic testing

Radiographic testing method is generally applicable for the inspection of all types of materials, e.g. metallic, non-metallic and plastics, magnetic and non-magnetic, conductors and non-conductors, etc. as long as both sides of the test specimen are accessible for placement of source and the film on either side. The film needs to be placed in contact with the specimen and whenever this is not possible due to the geometry of the test specimen, radiographs of poorer quality will result.

The penetration of the radiation through the test specimen depends upon its thickness and density. For high density materials, as well as for larger thickness of the same material, higher energies are needed. Although, in principle, these higher energies are now available from betatrons and linear accelerators, these sources of radiation are extremely expensive and therefore not available for common use. Table 3.1 shows that among the commonly available radiation sources including the commercial X ray machines of up to about 420 KV, the strongest source is that of cobalt-60 which can be used for radiography of steel of thickness up to about 150 mm.

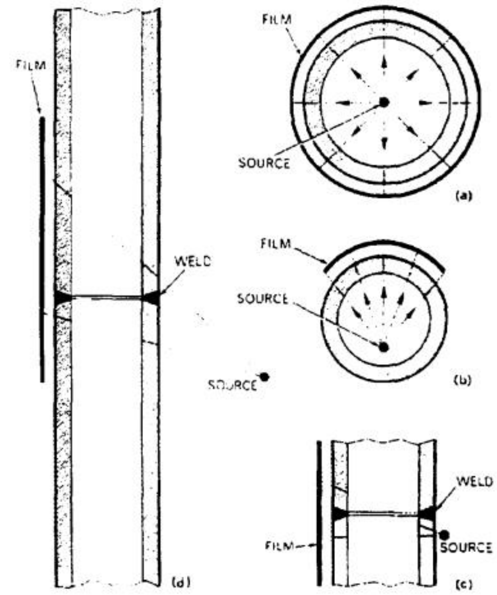


Figure 3.15: Various techniques for weld inspection.

The factors affecting radiographic quality and consequently the sensitivity of flaw detection by radiographic testing method need to be carefully considered while selecting the technique for a particular test. For example, for high sensitivity or to be able to detect smaller flaws, it is recommended that largest possible source-to film distance is used with a source of the smallest possible dimensions, the slowest and fine-grained film should be used and film processing should be done as per recommendations of the manufactures (usually for 5 minutes at 20°C). The lowest energy compatible with the thickness and density of the test specimen should be chosen. In practice a compromise has to be made between these ideal requirements to achieve an optimum level of sensitivity. But a radiograph made with a technique of poor sensitivity will need a more critical inspection, since defect images will not be so easily seen and may in fact be missed. There is a definite tendency to make a more cursory examination when defect images are only faintly seen. Similarly very small defects below the sensitivity limits of the technique employed may be missed. Such a situation can also arise due to improper viewing conditions and the training and experience of the interpreter. Sensitivity of flaw detection decreases with an increase in thickness of the test specimen.

Radiographic picture is a two-dimensional shadow of a three-dimensional defect. The orientation of the defect with respect to the direction of the beam is therefore an important consideration. Thus planar defects such as cracks, laminations, lack of fusion in welds or similar defects may not be detected if their plane is at right angles to the incident beam. Elongated defects like pipes and wormholes may show up and be misinterpreted as spherical defects. Smaller defects located behind the larger ones in the direction of the beam will not be detected.

A serious limitation with the radioisotope sources used for radiography is the fact that even unused their activity decreases with time. While they have the distinct advantage of needing no power for field radiography applications, they need special shielded enclosures to house them and the radiographic sensitivity achievable with them is usually inferior to that for X rays.

Lastly, exposure to radiations can be dangerous for human health and therefore special precautions are required which may include construction of specially shielded enclosures and cordoning off of the area where radiography is being performed. Mostly it involves either stopping of all other work and removal of the workers from the work place while carrying out radiography or to do the radiographic testing work during off hours.

UNIT –IV

ADVANCED TECHNIQUES – I

Phased array use in the industry. **Phased array** is widely used for **nondestructive testing** (**NDT**) in several industrial sectors, such as construction, pipelines, and power generation. This method is an advanced **NDT** method that is used to detect discontinuities i.e. cracks or flaws and thereby determines component quality.

Phased array ultrasonics (PA) is an advanced method of ultrasonic testing that has applications in medical imagingand industrial nondestructive testing. Common applications are to noninvasively examine the heart or to find flaws in manufactured materials such as welds. Single-element (non-phased array) probes, known technically as *monolithic* probes, emit a beam in a fixed direction. To test or interrogate a large volume of material, a conventional probe must be physically scanned (moved or turned) to sweep the beam through the area of interest. In contrast, the beam from a phased array probe can be focused and swept electronically without moving the probe. The beam is controllable because a phased array probe is made up of multiple small elements, each of which can be pulsed individually at a computer-calculated timing. The term *phased* refers to the timing, and the term *array* refers to the multiple elements. Phased array ultrasonic testing is based on principles of wave physics, which also have applications in fields such as optics and electromagnetic antennae.

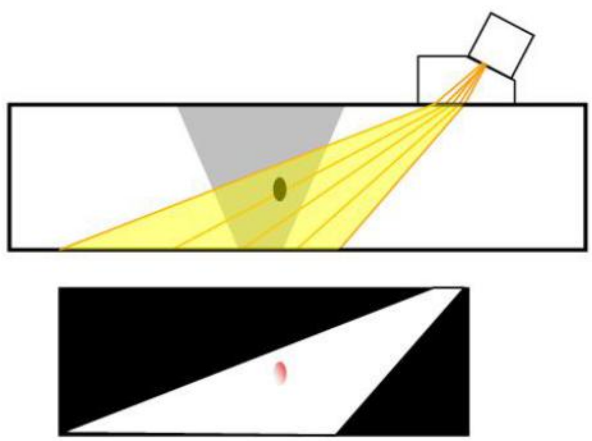


Fig: Weld examination by phased array.

Principle of operation:

The PA probe consists of many small ultrasonic transducers, each of which can be pulsed independently. By varying the timing, for instance by making the pulse from each transducer progressively delayed going up the line, a pattern of constructive interference is set up that results in radiating a quasi-plane ultrasonic beam at a set angle depending on the progressive time delay. In other words, by changing the progressive time delay the beam can be steered electronically. It can be swept like a search-light through the tissue or object being examined, and the data from multiple beams are put together to make a visual image showing a slice through the object.

Phases array use in industry:

Phased array is widely used for non destructive testing (NDT) in several industrial sectors, such as construction, pipelines, and power generation. This method is an advanced NDT method that is used to detect discontinuities i.e. cracks or flaws and thereby determine component quality. Due to the possibility to control parameters such as beam angle and focal distance, this method is very efficient regarding the defect detection and speed of testing. Apart from detecting flaws in components, phased array can also be used for wall thickness measurements in conjunction with corrosion testing. Phased array can be used for the following industrial purposes:

- Inspection of welds
- Thickness measurements
- Corrosion inspection
- PAUT Validation/Demonstration Blocks[5]
- Rolling stock inspection (wheels and axles)
- PAUT & TOFD Standard Calibration Blocks

Feature of phased array:

- The method most commonly used for medical ultrasonography.
- Multiple probe elements produce a steerable and focused beam.[6]
- Focal spot size depends on probe active aperture (A), wavelength (γ) and focal length (F).[7] Focusing is limited to the near field of the phased array probe.
- Produces an image that shows a slice through the object.
- Compared to conventional, single-element ultrasonic testing systems, PA instruments and probes are more complex and expensive.
- In industry, PA technicians require more experience and training than conventional UT technicians.

Specification of phased array:

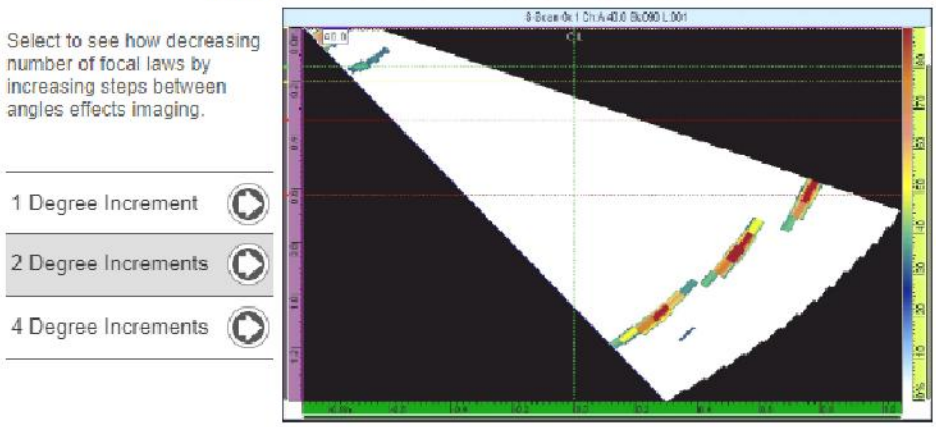
Number of Pulsers: Will define the maximum number of elements that can be grouped to form an active aperture or virtual prob aperture.

Number of Receivers: Will define the total number of elements that can be used for sequencing apertures that leads To the potential increase in coverage from a single probe footprint.

XX:YY: Naming convention used where XX = Number of pulsers and YY= Number of receiver paths. The number of receivers is always greater or equal to number of pulsers. Instruments from 16:16 to 32:128 are available in field portable packaging. Higher pulser and receiver combinations are available for in-line inspection and/or systems that Use larger element count probes.

Focal Laws: The number of focal laws that can be combined to form an image is often specified. In general, higher XX:YY configurations can support more focal laws as they support greater element apertures and/or more aperture stepping in linear scanning. Note that more focal laws does not always mean more functionality. Take the example below using a 64 element probe performing a sectorial scan of three side-drilled holes from 40 to 70 degrees, comparing steering with 1 degree (30 laws), 2 degree (15 laws), and 4 degree (7 laws) steps over a 2 inch, 50 mm metal path. While the image will be slightly better defined with finer angle increments, detection at coarser resolution is adequate. Unless beam diameter is drastically reduced with focusing, sizing from images will not dramatically change either.

5MHz Sectorial Scan, 40-70 Degrees



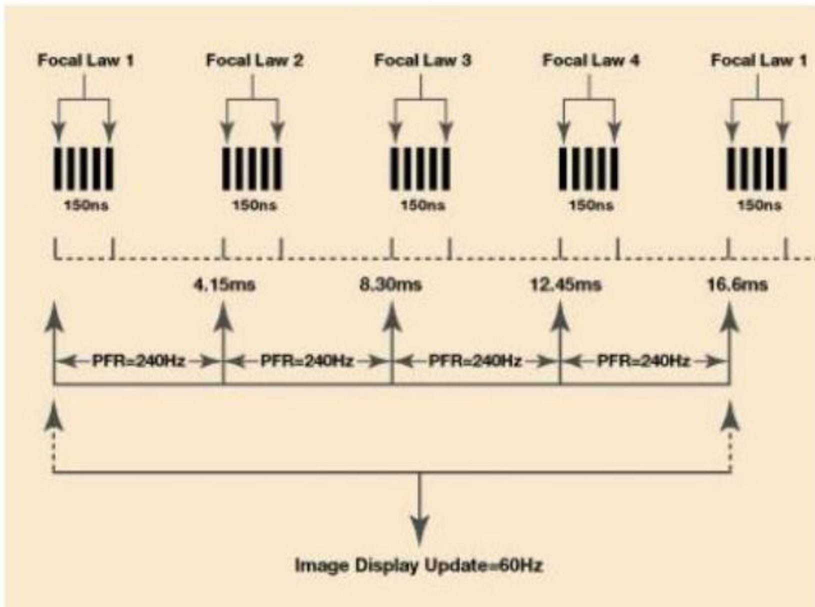
Examples for the number of focal laws required performing linear scans with varying combinations of virtual probe apertures and total element counts are shown below.

LINEAR E-SCAN

Aperture	Total Elements	Element Step	# Laws
4	16	1	13
8	16	1	9
4	32	1	29
8	32	1	25
16	32	1	17
4	64	1	61
8	64	1	57
16	64	1	49
8	128	1	121
16	128	1	113
8	256	1	249
16	256	1	241

From the above, it is readily apparent that a 16:16 configuration used with a 16 element transducers may only require 30 laws while a 16:128 or 32:128 instrument configuration used in linear scan mode with a 128 element transducer may very well require 128 focal laws.

An example of a reduced four focal law linear scan sequence with a 60 Hz image display update is shown below for conceptualization.



The actual image display rate may be affected by other parameters. The A-scan refresh rate of a single focal law will vary between instruments. In some instruments, the A-scan PRF rate is limited by the maximum image display update, whether it is shown with the phased array image or even when maximized to a full A-scan. For this reason, in some applications it may be important to verify A-scan PRF when derived from focal law sequence in various image display modes.

Probe recognition: The ability to recognize phased array probes reduces operator setup time by automatically configuring an instrument setup with proper number of elements and probe geometry.

Image types: Sectorial and linear scans are typically available in phased array instruments. The ability to stack these image modes to create amplitude and depth C-scans allows planar images to be formed and provides expanded means for sizing defects.

Waveform storage: The ability to store raw RF waveforms allows data to be reviewed off line. This is particularly useful when collecting data over a large area.

Multi-Group support: More capable phased array instruments allow multiple focal law groups to be sequenced on one or more connected transducers. This is especially useful in cases where it is important to collect volumetric data which will be analyzed off line. For example, a 5 MHz, 64 element probe can be programmed to use elements 1-16 for a 40 to 70 degree sector scan, while a second group can be used to perform a 60 degree linear scan with an aperture of 16 elements, stepping by one element over the entire 64 element length.

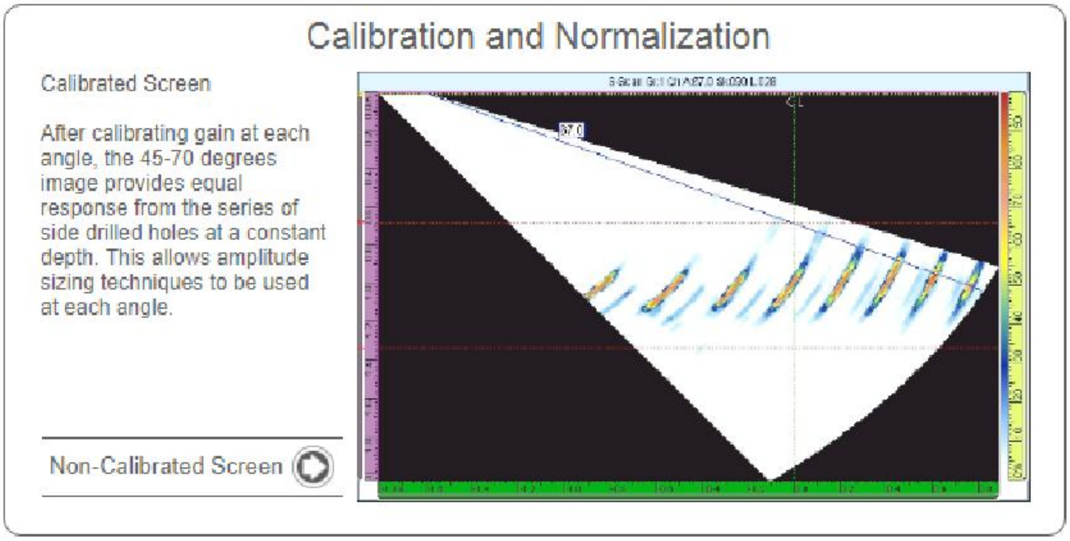
Encoding: There are two classes of instruments generally available: manual and encoded.

A manual phased array instrument works much like a conventional flaw detector as it provides real time data. Along with an A-scan, the instrument also shows real time S-scan or linear scan images which can aid in detection and discontinuity analysis. The ability to use and visualize more than one angle at a time in a test would be the main reason for using this type of instrument. In some cases like crack sizing, the image can be used as a tool to help size crack depth.

A phased instrument with encoder interface merges probe positional data, probe geometry, and programmed focal law sequences to allow top, end and side view images of test specimen. In instruments that also store full waveform data, images can be reconstructed to provide cross sectional views along the length of the scan or regenerate planar C-scans at various levels. These encoded images allow for planar sizing of defects.

Reference Cursors: Instruments will provide various cursors that can be used on an image for direct sizing. In a sectorial scan, it is possible to use cursors for measurement of crack height. Approximate defect size can be measured in encoded linear C-scans as well.

Calibration Method: The method of calibration for phased array transducers can be varied. As beam formation relies on variant element delays and groups, it is important to normalize the response from each focal law, to compensate both for element-to-element sensitivity variations in the array transducer and for varying wedge attenuation and energy transfer efficiency at different refracted angles. Calibration of wedge delay and sensitivity over the entire inspection sequence not only provides clearer image visualization, but also allows measurement and sizing from any focal law. While Olympus NDT instruments allow full calibration, many instruments will only allow calibration of one focal law at any one time.



TVG/DAC for phased array: For sizing defects, A-scan amplitude techniques using DAC curves or time corrected gain are common. These methods account for material attenuation effects and beam spreading by compensating gain levels (TCG) or drawing a reference curve based on same size reflector response as a function of distance. As in sensitivity calibrations, some instruments allows a TCG to be built at multiple points over all defined focal laws. In these instruments, the view can be switched from TCG to DAC curve at any time. This allows use of sizing curves at multiple angles for sectorial scans or at any virtual aperture in linear scans.

Some phased array instruments also provide a conventional ultrasonic channel to support inspections with single element transducers. It is important to know how this conventional channel functions.

Pulser: Because of the small size of phased array elements, and leveraging the fact that constructive interference effects between elements results in higher sensitivity, phased array pulsers are typically limited to 100 volts. Often vendors use this limited phased array pulser as the conventional transducer pulser. This can become very limiting in applications involving long sound paths or highly attenuating materials, especially when using frequencies at or below 2.25MHz.

Image Support: While the phased array portion of the instrument supports A-scan, B-scan, C-scan, and sectorial scans, this does not mean the conventional UT portion of the instrument will necessarily incorporate any imaging. More capable instruments do allow cross sectional B-scans on a timed basis with waveform storage on the conventional side. Some also include the ability to interface with conventional transducers attached to one or two axis encoded scanners to generate actual position related B-scans and C-scans respectively. Of course sectorial scanning is unique to phased array.

In the image below, a combined phased array/conventional instrument is working in conventional mode. performing a

B-scan of a corroded pipe with a dual element transducer in an encoded hand scanner.

Fig : phased array Testing

Anatomy of Phased Array Display

This section provides further insight into how phased array images are constructed. In particular, it will further explain required inputs, and the relationships of the various phased array display types with respect to the actual probe assembly and part being inspected. We will also explain the typically available A-scan views associated with the phased array image.

Required Considerations for Proper Inspection

As discussed previously, there are many factors that need to be identified in order to properly perform any ultrasonic inspection. In summary, there are material specific characteristics and transducer characteristics needed for calibrating the instrument for a proper inspection.

Material:

1. Velocity of the material being inspected needs to be set in order to properly measure depth. Care must be taken to select the proper velocity mode (longitudinal or shear). As you may recall, compressional straight beam testing typically uses longitudinal waves while angle beam inspection most often uses shear wave propagation.
2. Part thickness information is typically entered. This is particularly useful in angle beam inspection. It allows proper depth measurement relative to the leg number in angle beam applications.
3. Radius of curvature should be set considered when inspecting non-flat parts. This curvature can be algorithmically accounted for to make more accurate depth measurements.

Transducer:

1. Frequency must be known to allow for proper pulser parameters and receiver filter settings.
2. Zero Offset must be established in order to offset electrical and mechanical delays resulting from coupling, matching layer, cabling and electronic induced delays for proper thickness readings.
3. Amplitude response from known reflectors must be set and available for reference in order to use common amplitude sizing techniques.
4. Angle of sound beam entry into the material being inspected.
5. For phased array probes, the number elements and pitch need to be known.

Wedge:

1. Velocity of sound propagation through the wedge
2. Incident angle of the wedge.
3. Beam index point or front of probe reference.
4. First element height offset for phased array.

In conventional ultrasonic testing, all of the above steps must be taken prior to inspection to achieve proper results. Since a single element probe has a fixed aperture, the entry angle selection, zero offset, and amplitude calibration are specific to a single transducer or transducer/wedge combination. Each time a transducer or its wedge is changed, a new calibration must be performed.

Using phased array probes, the user must follow these same principles. The main advantage of phased array testing is the ability to change aperture, focus, and/or angle dynamically, essentially allowing the use of several probes at one time. This imparts the additional requirement of extending calibration and setup requirements to each phased array transducer state (commonly referred to as a focal law). This not only allows accurate measurements of amplitude and depth across the entire programmed focal sequence, but also provides accurate and enhanced visualization via the natural images that phase array instruments produce.

One of the major differences between conventional and phased array inspections occurs in angle beam inspection. With conventional UT, input of an improper wedge angle or material velocity will cause errors in locating the defect, but basic wave propagation (and hence the resultant A-scan) is not influenced, as it relies solely on mechanical refraction. For phased array however, proper material and wedge velocities along with probe and wedge parameter inputs are required to arrive at the proper focal laws to electronically steer across the desired refracted angles and to create sensible images. In more capable instruments, probe recognition utilities automatically transfer critical phased array probe information and use well-organized libraries to manage the selection of wedge parameters.

The following values must normally be entered in order to program a phased array scan:

Probe Parameters

Frequency

Bandwidth

Size

Number of elements

Element pitch

Wedge Parameters:

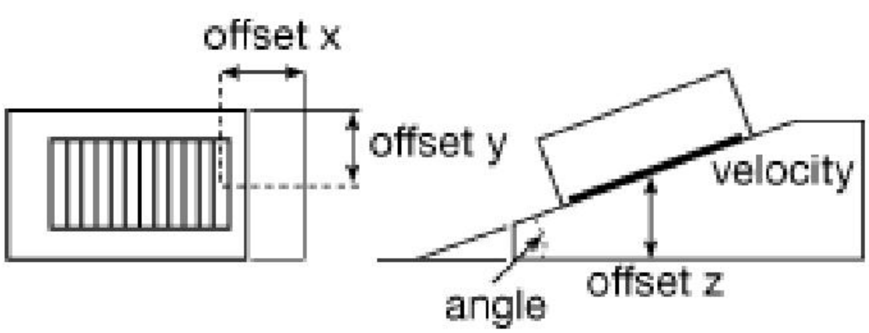
Incident angle of the wedge

Nominal velocity of the wedge

Offset Z = Height to center of first element

Index offset X = distance from front of wedge to first element

Scan offset Y = distance from side of wedge to center of elements

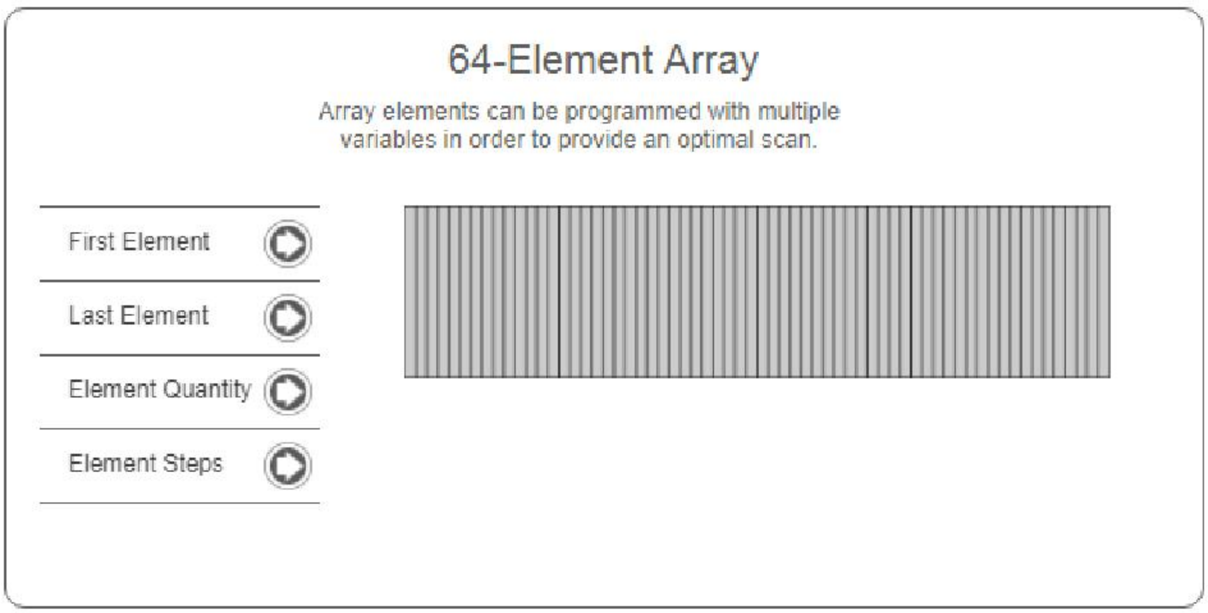


Focal Law Setup:

To gain the full advantages of linear array scanning, typically a minimum of 32 elements are used. It is even more common to use 64 elements. More elements allow larger apertures to be stepped across the probe, providing greater sensitivity, increased capacity of focusing and wider area of inspection. The instrument must have the basic probe and wedge characteristics entered, either manually or via automatic probe recognition. Along with typical UT settings for the pulser, receiver and measurement gate setup, the user must also set transducer beam and electronic steering (focal law) characteristics.

Required User inputs:

- Material Velocity
- Element Quantity (the number of elements used to form the aperture of the probe)
- First element to be used for scan
- The last element in the electronic raster
- Element step (defines how defined aperture moves across the probe)
- Desired focus depth, which must be set less than near field length (N) to effectively cerate a focus
- Angle of inspection



Straight Beam Linear scans:

Straight beam linear scans are usually easy to conceptualize on a display because the scan image typically represents a simple cross-sectional view of the test piece. As described in Section 3.7, a phased array system uses electronic scanning along the length of a linear array probe to create a cross-sectional profile without moving the transducer. As each focal law is sequenced, the associated A-scan is digitized and plotted. Successive apertures are "stacked", creating a live cross sectional view. The effect is similar to a B-scan presentation created by moving a conventional single element transducer across a test piece and storing data at selected intervals.

In practice, this electronic sweeping is done in real time so a live part cross section can be continually viewed as the transducer is physically moved. The actual cross section represents the true depth of reflectors in the material as well as the actual position typically relative to the front of the probe assembly. Below is an image of holes in a test block made with a 5L64-A2, 64-element 5 MHz linear phased array probe. The probe has a 0.6mm pitch.

In this example, the user programmed the focal law to use 16 elements to form an aperture and sequenced the starting element increments by one. So aperture 1 consists of elements 1 through16, aperture 2 from elements 2 through 17, aperture 3 from elements 3 through18, and so on. This results in 49 individual waveforms that are stacked to create the real time cross-sectional view across the transducer's length.

The result is an image that clearly shows the relative position of the holes within the scan area, along with the A-scan waveform from a single selected aperture, in this case the 29th aperture out of 49, formed from elements 29-45, is represented by the user-controlled blue cursor. This is the point at which the beam intersects the second hole

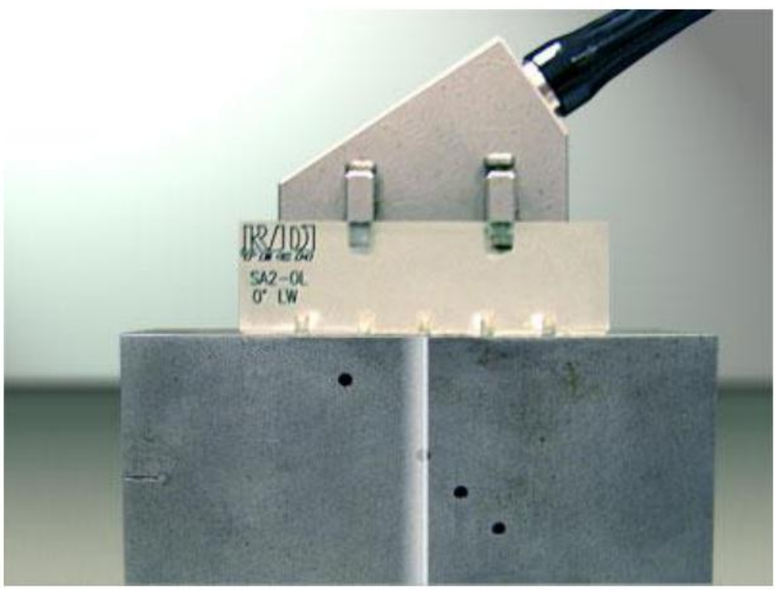
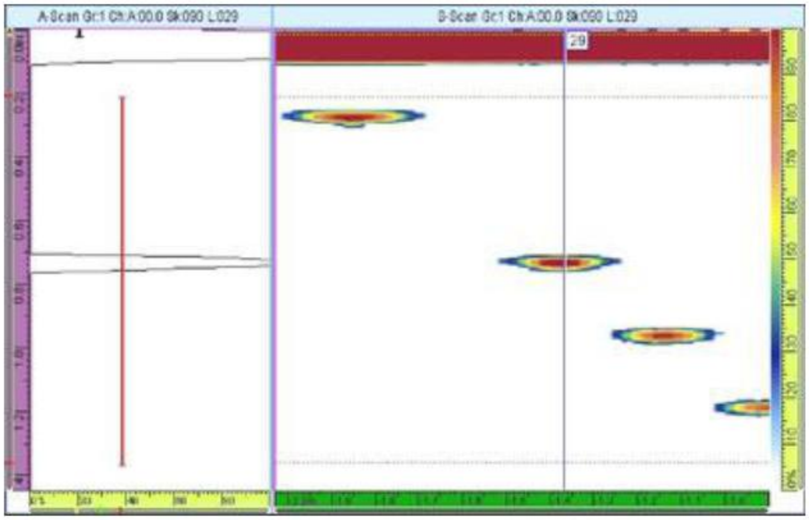
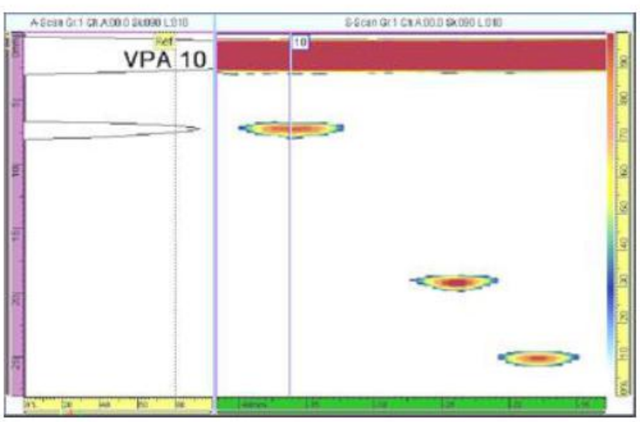


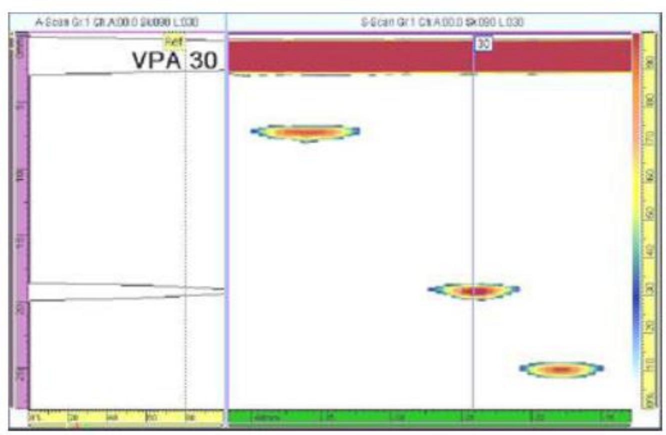
Fig : Straight Beam Linear scans



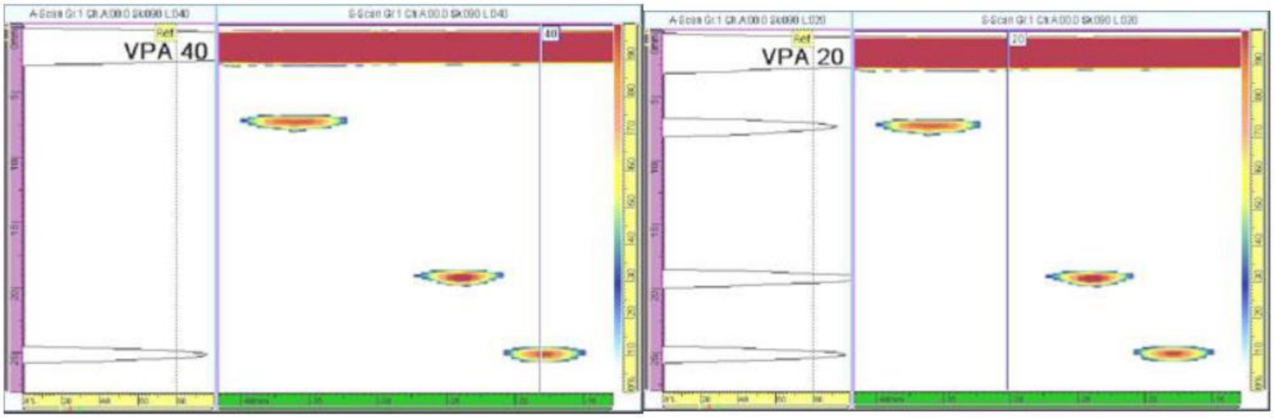
The vertical scale at the left edge of the screen indicates the depth or distance to the reflector represented by a given peak in the A-scan. The horizontal scale of the A-scan indicates relative echo amplitude. The horizontal scale under the scan image shows reflector position with respect to the leading edge of the probe, while the color scale on the right edge of the screen relates image color to signal amplitude.

Alternately, the instrument can be set to display an "all laws" A-scan, which is a composite image of the waveforms from all apertures. In this case, the A-scan includes the indications from all four holes within the gated region. This is particularly useful mode in zero degree inspections, although it can also be confusing when working with complex geometries that produce numerous echoes. In the example below, the first three screens show views in which the A-scan display depicts the waveform from a single virtual probe aperture in the scan, each of which is centered over one of the reference holes.





This fourth screen shows an all laws A-scan in which the signals from all apertures is summed, thus showing all three hole indications simultaneously.



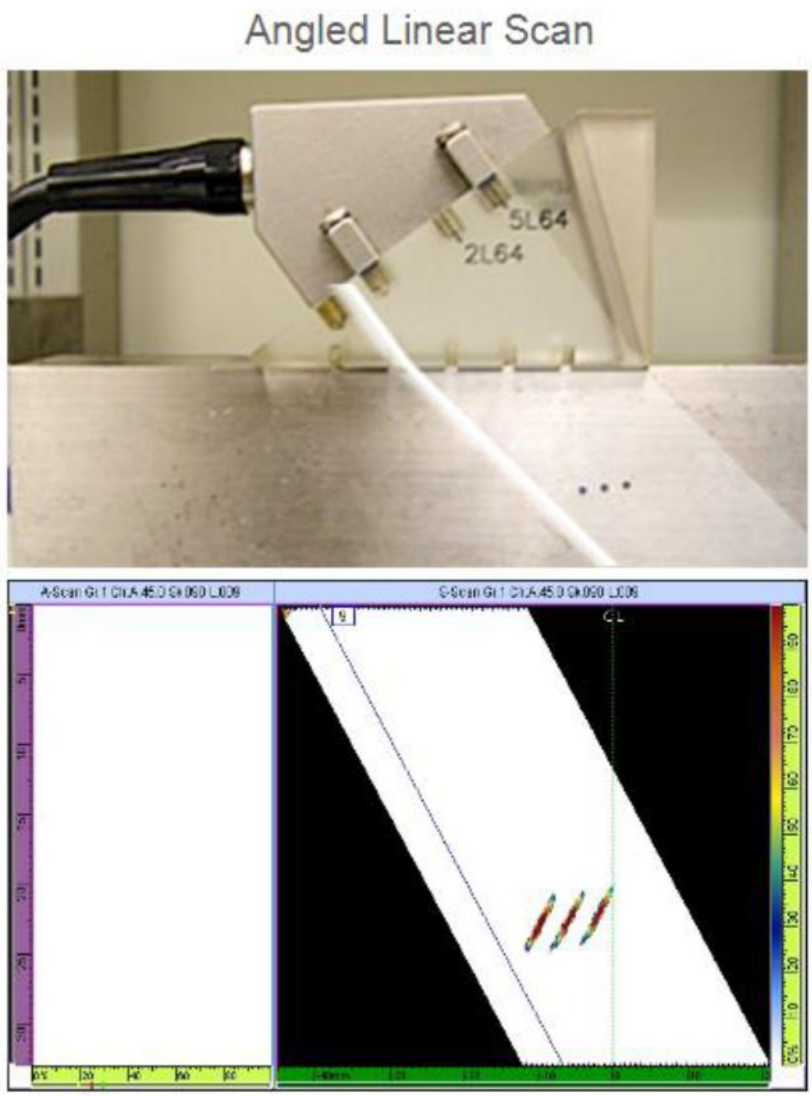
A-scan source mode on some more advanced instruments allows the A-scan to be sourced from the first or maximum signal within the gated region.

Leak testing:

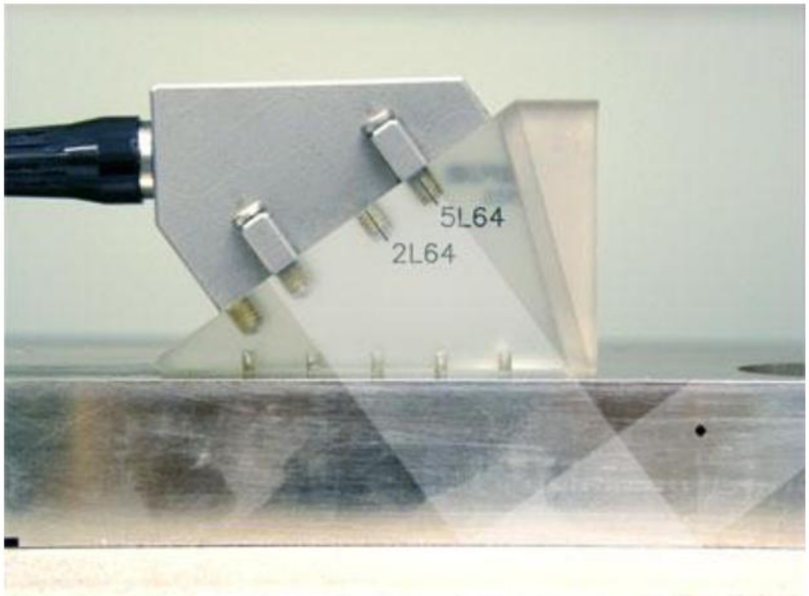
It is conventional to use the term "leak" to refer to an actual discontinuity or passage through which a fluid flows or permeates. "Leakage" refers to the fluid that has flown through a leak. "Leak rate" refers to the rate of fluid per unit of time under a given set of conditions, and is properly expressed in units of mass per unit time. Modern leak testing is thus based on the notion that all containment systems leak, the only rational requirement that can be imposed is that such systems leak at a rate no greater than some finite maximum allowable rate, however small that may be as long as it is within the range of sensitivity of a measuring system.

Angled Linear Scans:

A linear scan can also be programmed at a single fixed angle, much like the beam from a conventional single element angle beam transducer. This single-angle beam will scan across the length of the probe, allowing the user to test a larger width of material without moving the probe. This can cut inspection time, especially in weld scanning applications.



In the example above, the beam is sweeping across the test piece at a 45 degree angle, intercepting each of three holes as it moves. The beam index point, the point at which the sound energy exits the wedge, also moves from left to right in each scan sequence. The A-scan display at any given moment represents the echo pattern from a given aperture. In any angle scan not involving very thick materials, it is also necessary to consider the actual position of reflectors that fall beyond the first leg, the point at which the beam first reflects from the bottom of the test piece. This is usually a factor in tests involving typical pipes or plates. In the case below, as the beam scans from left to right, the beam component from the center of the probe is reflecting off the bottom of the steel plate and hitting the reference hole in the second leg.



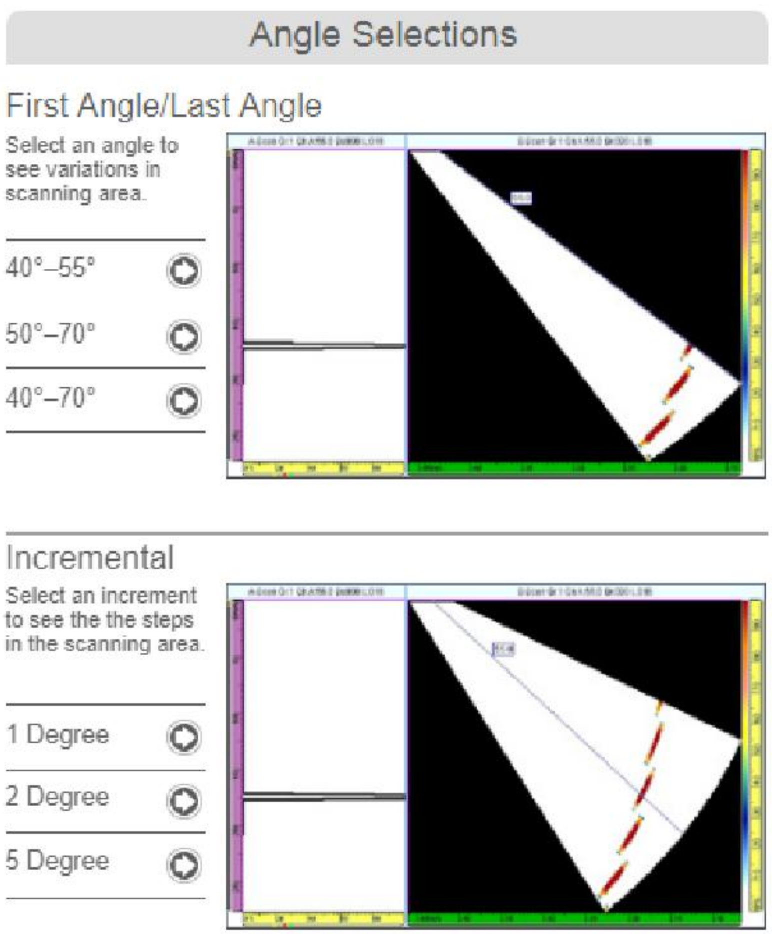
The screen display has been set up to show by means of the dotted horizontal cursors the relative positions of the end of the first leg and the end of the second leg on the image. Thus, this hole indication, which falls between the two horizontal cursors, is identified as being in the second beam leg. Note that the depth scale on the left edge of the screen is accurate only for the first leg. To use the scale beyond that, a correction must be applied. In the second leg, it is necessary to subtract the apparent depth as read off the scale from twice the thickness of the test piece to get the true depth of an indication. For example, in this case the actual depth of the second leg indication in the 25 mm thick plate is 38 - (2 x 25), or 12 mm. In the third leg, it is necessary to subtract twice the thickness of the test piece from the apparent depth of the indication to obtain true depth.

Focal Law Sequence:

This is very similar to the linear scan setup described in Section 5.1 in that the parameters listed there must be entered, except that a range of angles must also be selected. All of the other considerations listed in section 5.1 apply. Along with typical UT settings for pulser, receiver and measurement gate setup, the user must also set transducer beam and electronic steering (focal law) characteristics.

Required User inputs:

- Material Velocity
- Element Quantity (the number of elements used to form the aperture of the probe)
- First element to be used for scan
- The last element in the electronic raster
- Element step (defines how defined aperture moves across the probe)
- The first angle of the scan.
- The last angle of the scan.
- The increment at which angles are to be stepped.
- Desired focus depth, which must be set less than near field length (N) to effectively cerate a focus



Interpreting Sector Scans

In the case of swept angle sector scans, interpretation can be more complex because of the possibility of multiple leg signals that have reflected off the bottom and top of the test piece. In the first leg (the portion of the sound path up through the first bounce off the bottom of the part), the display is a simple cross-sectional view of a wedge-shaped segment of the test piece. However beyond the first leg, the display requires more careful interpretation, as it also does when using a conventional flaw detector.

A conventional flaw detector used with common angle beam assemblies displays a single-angle A-scan. Modern digital instruments will use trigonometric calculation based on measured sound path length and programmed part thickness to calculate the reflector depth and surface distance. Part geometry may create simultaneous first leg and second leg indications on the screen, as seen here in the case below with a 5 MHz transducer and a 45 degree wedge, where a portion of the beam reflects off the notch on the bottom of the part and a portion reflects upward and off the upper right corner of the block. Leg indicators and distance calculators can then be used to confirm the position of a reflector.

The first leg indication is a large reflection from the notch on the bottom of the test block, The depth indicator (upper left of screen image) shows a value corresponding to the bottom of a 25 mm thick block, and the leg indicator (lower right of screen image) shows that this is a first leg signal.

The second leg indication is a small reflection from the upper corner of the block. The depth indicator shows a value corresponding to the top of a 25 mm thick block, and the leg indicator shows that this is a second leg signal. (The slight variation in depth and surface distance measurements from the expected nominal values of 0 and 50 mm respectively is due to beam spreading effects).

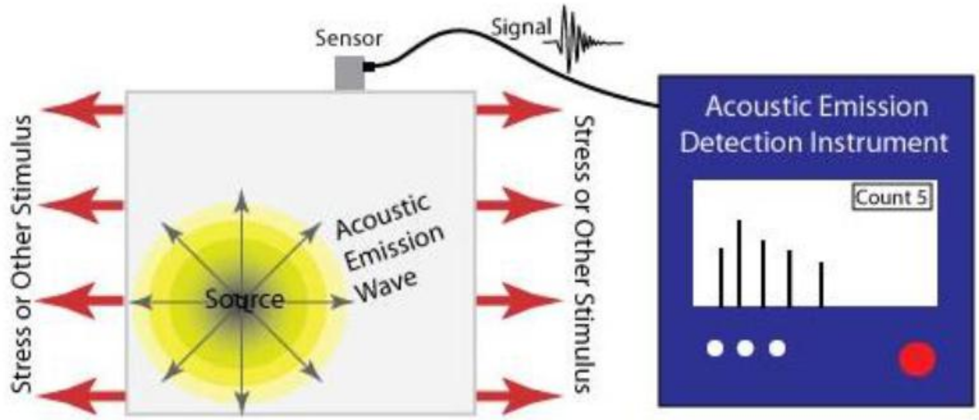
When the same test is performed with a 5 MHz phased array probe assembly, scanning from 40 to 70 degrees, the display shows a sector scan that is plotted from the range of angles, while the accompanying A-scan typically represents one selected angular component of the scan. Trigonometric calculation uses the measured sound path length and programmed part thickness to calculate the reflector depth and surface distance at each angle. In this type of test, part geometry may create simultaneous first leg and second leg indications on the screen as well as multiple reflectors from a single angle. Leg indicators in the form of horizontal lines overlayed on the waveform and image segment the screen into first, second, and third leg regions, while distance calculators help confirm the position of a reflector. Those distances are typically presented as follows:

FIG: Three indications from a single probe position as the beam sweeps through a 40 degree to 70 degree scan.

UNIT – V

ADVANCED NDE TECHNIQUES-II

Introduction to Acoustic Emission Testing:



Acoustic Emission (AE) refers to the generation of transient elastic waves produced by a sudden redistribution of stress in a material. When a structure is subjected to an external stimulus (change in pressure, load, or temperature), localized sources trigger the release of energy, in the form of stress waves, which propagate to the surface and are recorded by sensors. With the right equipment and setup, motions on the order of picometers (10 -12 m) can be identified. Sources of AE vary from natural events like earthquakes and rockbursts to the initiation and growth of cracks, slip and dislocation movements, melting, twinning, and phase transformations in metals. In composites, matrix cracking and fiber breakage and debonding contribute to acoustic emissions. AE's have also been measured and recorded in polymers, wood, and concrete, among other materials.

Detection and analysis of AE signals can supply valuable information regarding the origin and importance of a discontinuity in a material. Because of the versatility of Acoustic Emission Testing (AET), it has many industrial applications (e.g. assessing structural integrity, detecting flaws, testing for leaks, or monitoring weld quality) and is used extensively as a research tool.

Acoustic Emission is unlike most other non destructive testing (NDT) techniques in two regards. The first difference pertains to the origin of the signal. Instead of supplying energy to the object under examination, AET simply listens for the energy released by the object. AE tests are often performed on structures while in operation, as this provides adequate loading for propagating defects and triggering acoustic emissions.

The second difference is that AET deals with dynamic processes, or changes, in a material. This is particularly meaningful because only active features (e.g. crack growth) are highlighted. The ability to discern between developing and stagnant defects is significant. However, it is possible for flaws to go undetected altogether if the loading is not high enough to cause an acoustic event. Furthermore, AE testing usually provides an immediate indication relating to the strength or risk of failure of a component. Other advantages of AET include fast and complete volumetric inspection using multiple sensors, permanent sensor mounting for process control, and no need to disassemble and clean a specimen.

Unfortunately, AE systems can only qualitatively gauge how much damage is contained in a structure. In order to obtain quantitative results about size, depth, and overall acceptability of a part, other NDT methods (often ultrasonic testing) are necessary. Another drawback of AE stems from loud service environments which contribute extraneous noise to the signals. For successful applications, signal discrimination and noise reduction are crucial.

A Brief History of AE Testing

Although acoustic emissions can be created in a controlled environment, they can also occur naturally. Therefore, as a means of quality control, the origin of AE is hard to pinpoint. As early as 6,500 BC, potters were known to listen for audible sounds during the cooling of their ceramics, signifying structural failure. In metal working, the term "tin cry" (audible emissions produced by the mechanical twinning of pure tin during plastic deformation) was coined around 3,700 BC by tin smelters in Asia Minor. The first documented observations of AE appear to have been made in the 8th century by Arabian alchemist Jabir ibn Hayyan. In a book, Hayyan wrote that Jupiter (tin) gives off a 'harsh sound' when worked, while Mars (iron) 'sounds much' during forging.

Many texts in the late 19th century referred to the audible emissions made by materials such as tin, iron, cadmium and zinc. One noteworthy correlation between different metals and their acoustic emissions came from Czochralski, who witnessed the relationship between tin and zinc cry and twinning. Later, Albert Portevin and Francois Le Chatelier observed AE emissions from a stressed Al-Cu-Mn (Aluminum-Copper-Manganese) alloy.

Fig: Modern Tensile Testing Machine (H. Cross Company)

The next 20 years brought further verification with the work of Robert Anderson (tensile testing of an aluminum alloy beyond its yield point), Erich Scheil (linked the formation of martensite in steel to audible noise), and Friedrich Forster, who with Scheil related an audible noise to the formation of martensite in high-nickel steel. Experimentation continued throughout the mid-1900's, culminating in the PhD thesis written by Joseph Kaiser entitled "Results and Conclusions from Measurements of Sound in Metallic Materials under Tensile Stress." Soon after becoming aware of Kaiser's efforts, Bradford Schofield initiated the first research program in the United States to look at the materials engineering applications of AE. Fittingly, Kaiser's research is generally recognized as the beginning of modern day acoustic emission testing.

AE Sources:

As mentioned in the Introduction, acoustic emissions can result from the initiation and growth of cracks, slip and dislocation movements, twinning, or phase transformations in metals. In any case, AE's originate with stress. When a stress is exerted on a material, a strain is induced in the material as well. Depending on the magnitude of the stress and the properties of the material, an object may return to its original dimensions or be permanently deformed after the stress is removed. These two conditions are known as elastic and plastic deformation, respectively.

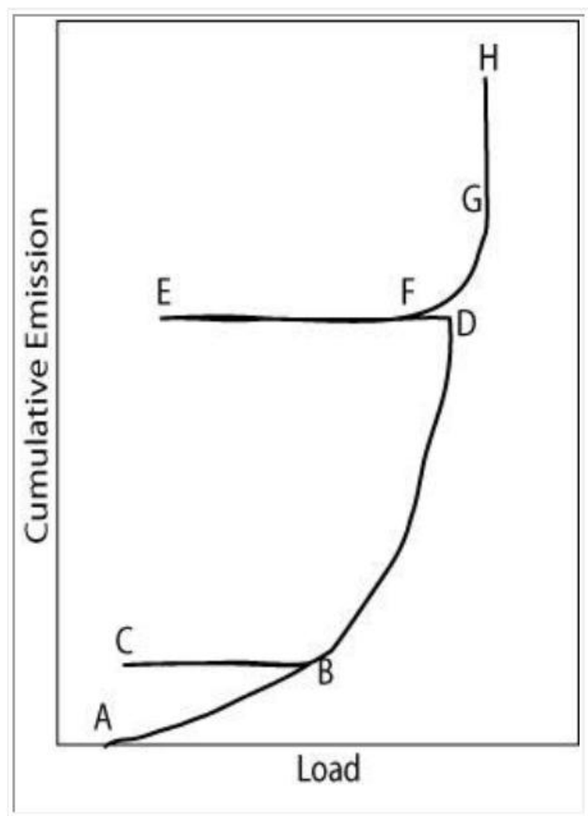
The most detectible acoustic emissions take place when a loaded material undergoes plastic deformation or when a material is loaded at or near its yield stress. On the microscopic level, as plastic deformation occurs, atomic planes slip past each other through the movement of dislocations. These atomic-scale deformations release energy in the form of elastic waves which "can be thought of as naturally generated ultrasound" traveling through the object. When cracks exist in a metal, the stress levels present in front of the crack tip can be several times higher than the surrounding area. Therefore, AE activity will also be observed when the material ahead of the crack tip undergoes plastic deformation (micro-yielding).

Two sources of fatigue cracks also cause AE's. The first source is emissive particles (e.g. nonmetallic inclusions) at the origin of the crack tip. Since these particles are less ductile than the surrounding material, they tend to break more easily when the metal is strained, resulting in an AE signal. The second source is the propagation of the crack tip that occurs through the movement of dislocations and small-scale cleavage produced by triaxial stresses.

The amount of energy released by an acoustic emission and the amplitude of the waveform are related to the magnitude and velocity of the source event. The amplitude of the emission is proportional to the velocity of crack propagation and the amount of surface area created. Large, discrete crack jumps will produce larger AE signals than cracks that propagate slowly over the same distance.

Detection and conversion of these elastic waves to electrical signals is the basis of AE testing. Analysis of these signals yield valuable information regarding the origin and importance of a discontinuity in a material. As discussed in the following section, specialized equipment is necessary to detect the wave energy and decipher which signals are meaningful.

Activity of AE Sources in Structural Loading:



AE signals generated under different loading patterns can provide valuable information concerning the structural integrity of a material. Load levels that have been previously exerted on a material do not produce AE activity. In other words, discontinuities created in a material do not expand or move until that former stress is exceeded. This phenomenon, known as the Kaiser Effect, can be seen in the load versus AE plot to the right. As the object is loaded, acoustic emission events accumulate (segment AB). When the load is removed and reapplied (segment BCB), AE events do not occur again until the load at point B is exceeded. As the load exerted on the material is increased again (BD), AE's are generated and stop when the load is removed. However, at point F, the applied load is high enough to cause significant emissions even though the previous maximum load (D) was not reached. This phenomenon is known as the Felicity Effect. This effect can be quantified using the Felicity Ratio, which is the load where considerable AE resumes, divided by the maximum applied load (F/D).

Basic AE history plot showing Kaiser effect (BCB), Felicity effect (DEF), and emission during hold (GH) 2

Knowledge of the Kaiser Effect and Felicity Effect can be used to determine if major structural defects are present. This can be achieved by applying constant loads (relative to the design loads exerted on the material) and "listening" to see if emissions continue to occur while the load is held. As shown in the figure, if AE signals continue to be detected during the holding of these loads (GH), it is likely that substantial structural defects are present. In addition, a material may contain critical defects if an identical load is reapplied and AE signals continue to be detected. Another guideline governing AE's is the Dunegan corollary, which states that if acoustic emissions are observed prior to a previous maximum load, some type of new damage must have occurred. (Note: Time dependent processes like corrosion and hydrogen embrittlement tend to render the Kaiser Effect useless)Noise.

The sensitivity of an acoustic emission system is often limited by the amount of background noise nearby. Noise in AE testing refers to any undesirable signals detected by the sensors. Examples of these signals include frictional sources (e.g. loose bolts or movable connectors that shift when exposed to wind loads) and impact sources (e.g. rain, flying objects or wind-driven dust) in bridges. Sources of noise may also be present in applications where the area being tested may be disturbed by mechanical vibrations (e.g. pumps).

To compensate for the effects of background noise, various procedures can be implemented. Some possible approaches involve fabricating special sensors with electronic gates for noise blocking, taking precautions to place sensors as far away as possible from noise sources, and electronic filtering (either using signal arrival times or differences in the spectral content of true AE signals and background noise).

Pseudo Sources

In addition to the AE source mechanisms described above, pseudo source mechanisms produce AE signals that are detected by AE equipment. Examples include liquefaction and solidification, friction in rotating bearings, solid-solid phase transformations, leaks, cavitation, and the realignment or growth of magnetic domains (See Barkhausen Effect).

Wave Propagation

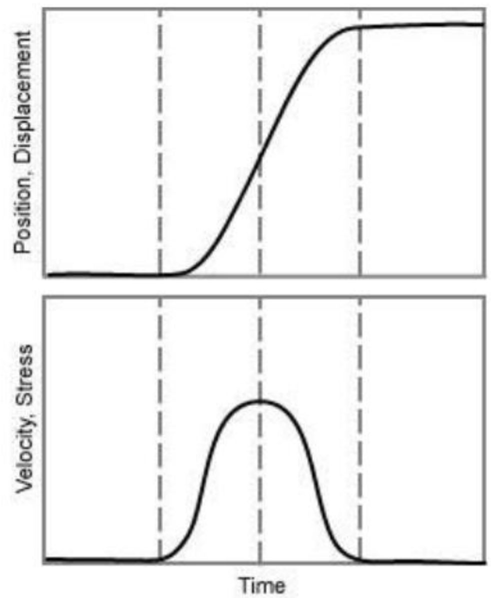
A primitive wave released at the AE source is illustrated in the figure right. The displacement waveform is a step-like function corresponding to the permanent change associated with the source process. The analogous velocity and stress waveforms are essentially pulse-like. The width and height of the primitive pulse depend on the dynamics of the source process. Source processes such as microscopic crack jumps and precipitate fractures are usually completed in a fraction of a microsecond or a few microseconds, which explains why the pulse is short in duration. The amplitude and energy of the primitive pulse vary over an enormous range from submicroscopic dislocation movements to gross crack jumps.

Waves radiates from the source in all directions, often having a strong directionality depending on the nature of the source process, as shown in the second figure. Rapid movement is necessary if a sizeable amount of the elastic energy liberated during deformation is to appear as an acoustic emission.

As these primitive waves travel through a material, their form is changed considerably. Elastic wave source and elastic wave motion theories are being investigated to determine the complicated relationship between the AE source pulse and the corresponding movement at the detection site. The ultimate goal of studies of the interaction between elastic waves and material structure is to accurately develop a description of the source event from the output signal of a distant sensor.

However, most materials-oriented researchers and NDT inspectors are not concerned with the intricate knowledge of each source event. Instead, they are primarily interested in the broader, statistical aspects of AE. Because of this, they prefer to use narrow band (resonant) sensors which detect only a small portion of the broadband of frequencies emitted by an AE. These sensors are capable of measuring hundreds of signals each second, in contrast to the more expensive high-fidelity sensors used in source function analysis. More information on sensors will be discussed later in the Equipment section.

The signal that is detected by a sensor is a combination of many parts of the waveform initially emitted. Acoustic emission source motion is completed in a few millionths of a second. As the AE leaves the source, the waveform travels in a spherically spreading pattern and is reflected off the boundaries of the object. Signals that are in phase with each other as they reach the sensor produce constructive interference which usually results in the highest peak of the waveform being detected. The typical time interval from when an AE wave reflects around the test piece (repeatedly exciting the sensor) until it decays, ranges from the order of 100 microseconds in a highly damped, nonmetallic material to tens of milliseconds in a lightly damped metallic material.

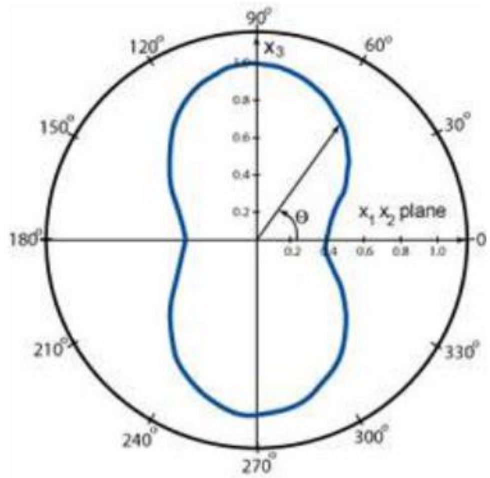


Primitive AE wave released at a source. The primitive wave is essentially a stress pulse corresponding to a permanent displacement of the material. The ordinate quantities refer to a point in the material.

Attenuation

The intensity of an AE signal detected by a sensor is considerably lower than the intensity that would have been observed in the close proximity of the source. This is due to attenuation. There are three main causes of attenuation, beginning with geometric spreading. As an AE spreads from its source in a plate-like material, its amplitude decays by 30% every time it doubles its distance from the source. In three-dimensional structures, the signal decays on the order of 50%. This can be traced back to the simple conservation of energy. Another cause of attenuation is material damping, as alluded to in the previous paragraph. While an AE wave passes through a material, its elastic and kinetic energies are absorbed and converted into heat. The third cause of attenuation is wave scattering. Geometric discontinuities (e.g. twin boundaries, nonmetallic inclusions, or grain boundaries) and structural boundaries both reflect some of the wave energy that was initially transmitted.

Measurements of the effects of attenuation on an AE signal can be performed with a simple apparatus known as a Hsu-Nielson Source. This consists of a mechanical pencil with either 0.3 or 0.5 mm 2H lead that is passed through a cone-shaped Teflon shoe designed to place the lead in contact with the surface of a material at a 30 degree angle. When the pencil lead is pressed and broken against the material, it creates a small, local deformation that is relieved in the form of a stress wave, similar to the type of AE signal produced by a crack. By using this method, simulated AE sources can be created at various sites on a structure to determine the optimal position for the placement of sensors and to ensure that all areas of interest are within the detection range of the sensor or sensors.

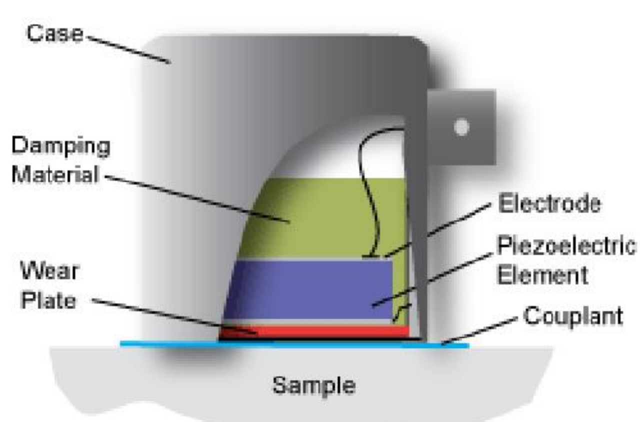


Angular dependence of acoustic emission radiated from a growing microcrack. Most of the energy is directed in the 90 and 270°directions, perpendicular to the crack surfaces.

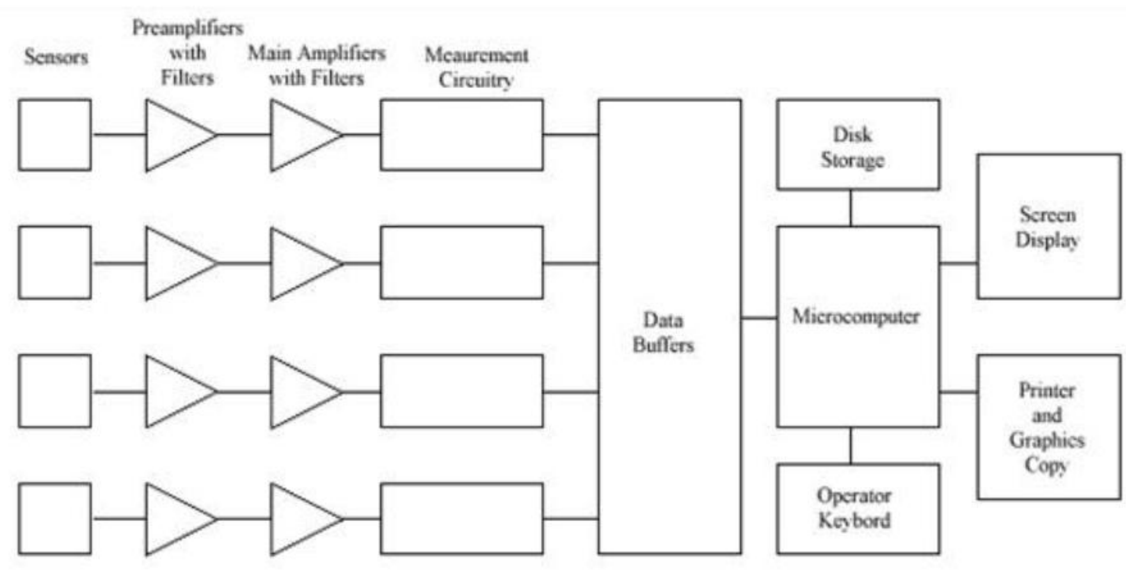
Wave Mode and Velocity

As mentioned earlier, using AE inspection in conjunction with other NDE techniques can be an effective method in gauging the location and nature of defects. Since source locations are determined by the time required for the wave to travel through the material to a sensor, it is important that the velocity of the propagating waves be accurately calculated. This is not an easy task since wave propagation depends on the material in question and the wave mode being detected. For many applications, Lamb waves are of primary concern because they are able to give the best indication of wave propagation from a source whose distance from the sensor is larger than the thickness of the material. For additional information on Lamb waves, see the wave mode page in the Ultrasonic Inspection section.

Equipment:



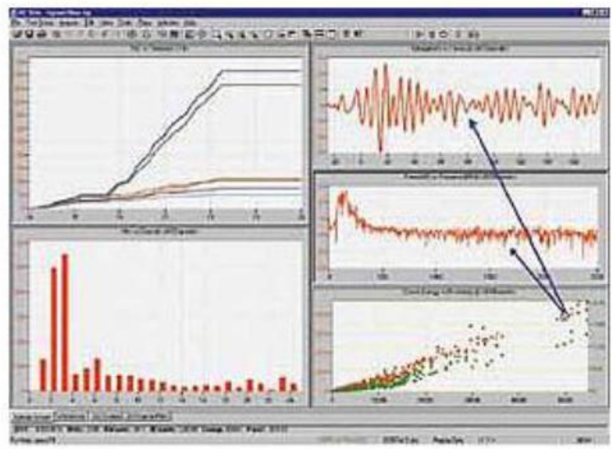
Acoustic emission testing can be performed in the field with portable instruments or in a stationary laboratory setting. Typically, systems contain a sensor, preamplifier, filter, and amplifier, along with measurement, display, and storage equipment (e.g. oscilloscopes, voltmeters, and personal computers). Acoustic emission sensors respond to dynamic motion that is caused by an AE event. This is achieved through transducers which convert mechanical movement into an electrical voltage signal. The transducer element in an AE sensor is almost always a piezoelectric crystal, which is commonly made from a ceramic such as lead zirconate titanate (PZT). Transducers are selected based on operating frequency, sensitivity and environmental characteristics, and are grouped into two classes: resonant and broadband. The majority of AE equipment is responsive to movement in its typical operating frequency range of 30 kHz to 1 MHz. For materials with high attenuation (e.g. plastic composites), lower frequencies may be used to better distinguish AE signals. The opposite holds true as well Ideally, the AE signal that reaches the mainframe will be free of background noise and electromagnetic interference. Unfortunately, this is not realistic. However, sensors and preamplifiers are designed to help eliminate unwanted signals. First, the preamplifier boosts the voltage to provide gain and cable drive capability. To minimize interference, a preamplifier is placed close to the transducer; in fact, many transducers today are equipped with integrated preamplifiers. Next, the signal is relayed to a bandpass filter for elimination of low frequencies (common to background noise) and high frequencies. Following completion of this process, the signal travels to the acoustic system mainframe and eventually to a computer or similar device for analysis and storage. Depending on noise conditions, further filtering or amplification at the mainframe may still be necessary.



Schematic Diagram of a Basic Four-channel Acoustic Emission Testing System

After passing the AE system mainframe, the signal comes to a detection/measurement circuit as shown in the figure directly above. Note that multiple-measurement circuits can be used in multiple sensor/channel systems for source location purposes (to be described later). At the measurement circuitry, the shape of the conditioned signal is compared with a threshold voltage value that has been programmed by the operator. Signals are either continuous (analogous to Gaussian, random noise with amplitudes varying according to the magnitude of the AE events) or burst-type. Each time the threshold voltage is exceeded, the measurement circuit releases a digital pulse. The first pulse is used to signify the beginning of a hit. (A hit is used to describe the AE event that is detected by a particular sensor. One AE event can cause a system with numerous channels to record multiple hits.) Pulses will continue to be generated while the signal exceeds the threshold voltage. Once this process has stopped for a predetermined amount of time, the hit is finished (as far as the circuitry is concerned). The data from the hit is then read into a microcomputer and the measurement circuit is reset.

Hit Driven AE Systems and Measurement of Signal Features:



Although several AE system designs are available (combining various options, sensitivity, and cost), most AE systems use a hit-driven architecture. The hit-driven design is able to efficiently measure all detected signals and record digital descriptions for each individual feature (detailed later in this section). During periods of inactivity, the system lies dormant. Once a new signal is detected, the system records the hit or hits, and the data is logged for present and/or future display.

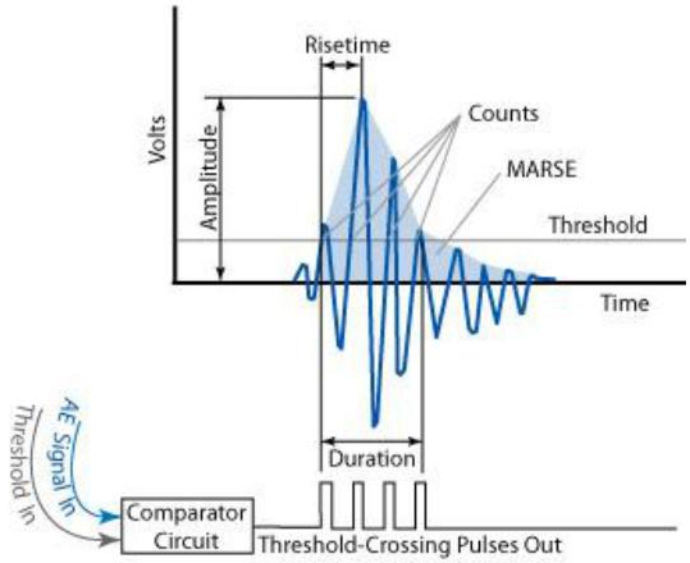
Also common to most AE systems is the ability to perform routine tasks that are valuable for AE inspection. These tasks include quantitative signal measurements with corresponding time and/or load readings, discrimination between real and false signals (noise), and the collection of statistical information about the parameters of each signal.

AE Signal Features

With the equipment configured and setup complete, AE testing may begin. The sensor is coupled to the test surface and held in place with tape or adhesive. An operator then monitors the signals which are excited by the induced stresses in the object. When a useful transient, or burst signal is correctly obtained, parameters like amplitude, counts, measured area under the rectified signal envelope (MARSE), duration, and rise time can be gathered. Each of the AE signal feature shown in the image is described below.

Amplitude, A, is the greatest measured voltage in a waveform and is measured in decibels (dB). This is an important parameter in acoustic emission inspection because it determines the detectability of the signal. Signals with amplitudes below the operator-defined, minimum threshold will not be recorded.

Rise time, R, is the time interval between the first threshold crossing and the signal peak. This parameter is related to the propagation of the wave between the source of the acoustic emission event and the sensor. Therefore, rise time is used for qualification of signals and as a criterion for noise filter.



Duration, D, is the time difference between the first and last threshold crossings. Duration can be used to identify different types of sources and to filter out noise. Like counts (N), this parameter relies upon the magnitude of the signal and the acoustics of the material.

MARSE, E, sometimes referred to as energy counts, is the measure of the area under the envelope of the rectified linear voltage time signal from the transducer. This can be thought of as the relative signal amplitude and is useful because the energy of the emission can be determined. MARSE is also sensitive to the duration and amplitude of the signal, but does not use counts or user defined thresholds and operating frequencies. MARSE is regularly used in the measurements of acoustic emissions.

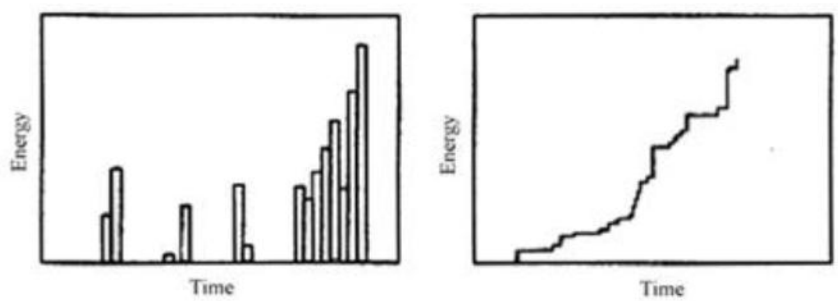
Counts, N, refers to the number of pulses emitted by the measurement circuitry if the signal amplitude is greater than the threshold. Depending on the magnitude of the AE event and the characteristics of the material, one hit may produce one or many counts. While this is a relatively simple parameter to collect, it usually needs to be combined with amplitude and/or duration measurements to provide quality information about the shape of a signal.

Data Display

Software-based AE systems are able to generate graphical displays for analysis of the signals recorded during AE inspection. These displays provide valuable information about the detected events and can be classified into four categories: location, activity, intensity, and data quality (crossplots).

Location displays identify the origin of the detected AE events. These can be graphed by X coordinates, X-Y coordinates, or by channel for linear computed-source location, planar computed-source location, and zone location techniques. Examples of each graph are shown to the right.

Activity displays show AE activity as a function of time on an X-Y plot (figure below left). Each bar on the graphs represents a specified amount of time. For example, a one-hour test could be divided into 100 time increments. All activity measured within a given 36 second interval would be displayed in a given histogram bar. Either axis may be displayed logarithmically in the event of high AE activity or long testing periods. In addition to showing measured activity over a single time period, cumulative activity displays (figure below right) can be created to show the total amount of activity detected during a test. This display is valuable for measuring the total emission quantity and the average rate of emission.) can be created to show the total amount of activity detected during a test. This display is valuable for measuring the total emission quantity and the average rate of emission.



Intensity displays are used to give statistical information concerning the magnitude of the detected signals. As can be seen in the amplitude distribution graph to the near right, the number of hits is plotted at each amplitude increment (expressed in dB's) beyond the user-defined threshold. These graphs can be used to determine whether a few large signals or many small ones created the detected AE signal energy. In addition, if the Y-axis is plotted logarithmically, the shape of the amplitude distribution can be interpreted to determine the activity of a crack (e.g. a linear distribution indicates growth).

The fourth category of AE displays, crossplots, is used for evaluating the quality of the data collected. Counts versus amplitude, duration versus amplitude, and counts versus duration are frequently used crossplots. As shown in the final figure, each hit is marked as a single point, indicating the correlation between the two signal features. The recognized signals from AE events typically form a diagonal band since larger signals usually generate higher counts. Because noise signals caused by electromagnetic interference do not have as many threshold-crossing pulses as typical AE source events, the hits are located below the main band. Conversely, signals caused by friction or leaks have more threshold-crossing pulses than typical AE source events and are subsequently located above the main band. In the case of ambiguous data, expertise is necessary in separating desirable and unwanted hits.

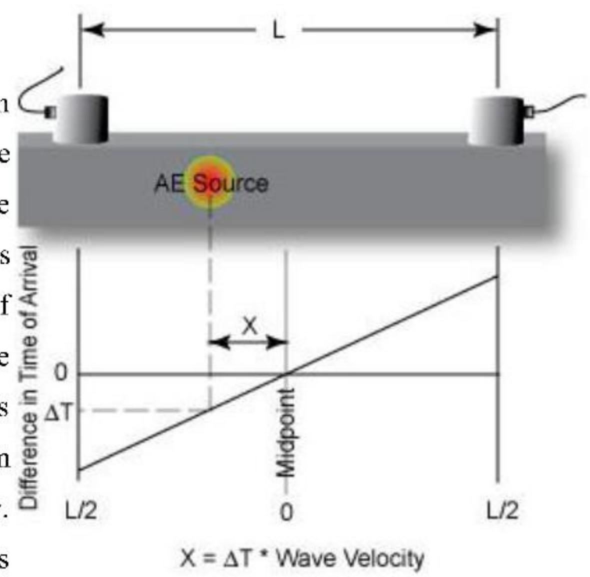
AE Source Location Techniques:

Multi-Channel Source Location Techniques:

Locating the source of significant acoustic emissions is often the main goal of an inspection. Although the magnitude of the damage may be unknown after AE analysis, follow up testing at source locations can provide these answers. As previously mentioned, many AE systems are capable of using multiple sensors/channels during testing, allowing them to record a hit from a single AE event. These AE systems can be used to determine the location of an event source. As hits are recorded by each sensor/channel, the source can be located by knowing the velocity of the wave in the material and the difference in hit arrival times among the sensors, as measured by hardware circuitry or computer software. By properly spacing the sensors in this manner, it is possible to inspect an entire structure with relatively few sensors.

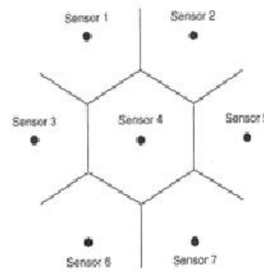
Source location techniques assume that AE waves travel at a constant velocity in a material. However, various effects may alter the expected velocity of the AE waves (e.g. reflections and multiple wave modes) and can affect the accuracy of this technique. Therefore, the geometric effects of the structure being tested and the operating frequency of the AE system must be considered when determining whether a particular source location technique is feasible for a given test structure.

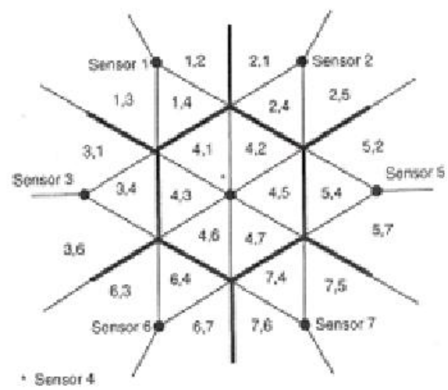
Linear Location Technique`



Several source location techniques have been developed based on this method. One of the commonly used computed-source location techniques is the linear location principle shown to the right. Linear location is often used to evaluate struts on truss bridges. When the source is located at the midpoint, the time of arrival difference for the wave at the two sensors is zero. If the source is closer to one of the sensors, a difference in arrival times is measured. To calculate the distance of the source location from the midpoint, the arrival time is multiplied by the wave velocity. Whether the location lies to the right or left of the midpoint is determined by which sensor first records the hit. This is a linear relationship and applies to any event sources between the sensors.

Because the above scenario implicitly assumes that the source is on a line passing through the two sensors, it is only valid for a linear problem. When using AE to identify a source location in a planar material, three or more sensors are used, and the optimal position of the source is between the sensors. Two categories of source location analysis are used for this situation: zonal location and point location.





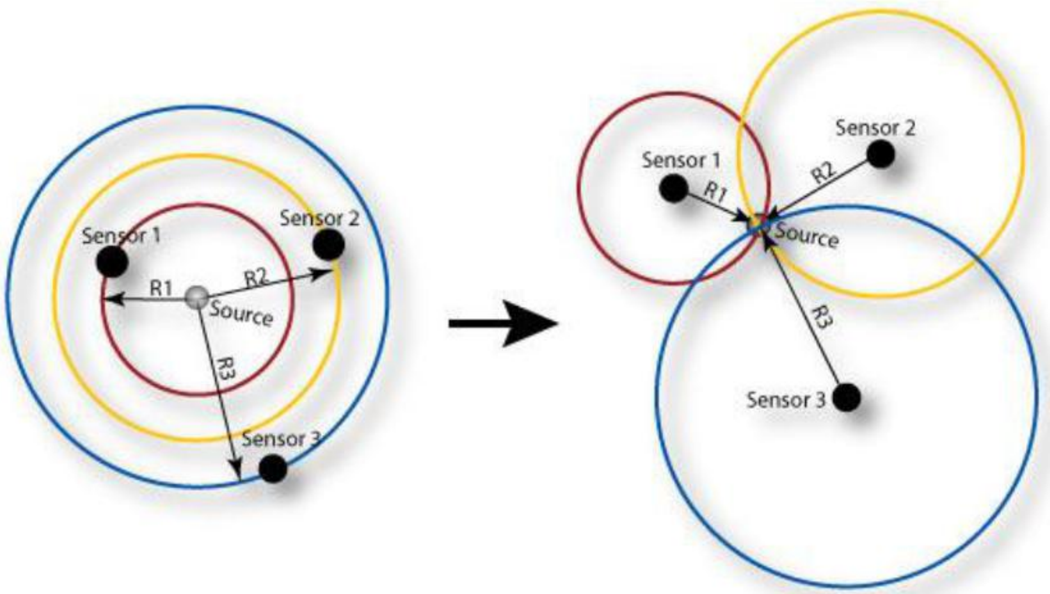
Zonal Location Technique

As the name implies, zonal location aims to trace the waves to a specific zone or region around a sensor. This method is used in anisotropic materials or in other structures where sensors are spaced relatively far apart or when high material attenuation affects the quality of signals at multiple sensors. Zones can be lengths, areas or volumes depending on the dimensions of the array. A planar sensor array with detection by one sensor is shown in the upper right figure. The source can be assumed to be within the region and less than halfway between sensors.

When additional sensors are applied, arrival times and amplitudes help pinpoint the source zone. The ordered pair in lower right figure represents the two sensors detecting the signal in the zone and the order of signal arrival at each sensor. When relating signal strength to peak amplitude, the largest peak amplitude is assumed to come from the nearest sensor, second largest from the next closest sensor and so forth.

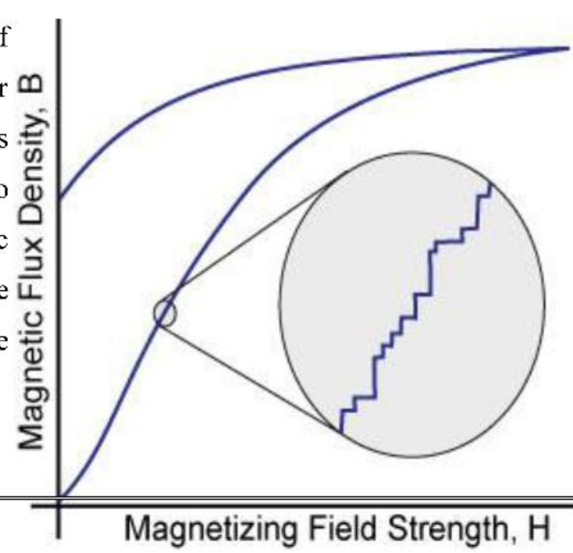
Point Location

In order for point location to be justified, signals must be detected in a minimum number of sensors: two for linear, three for planar, four for volumetric. Accurate arrival times must also be available. Arrival times are often found by using peak amplitude or the first threshold crossing. The velocity of wave propagation and exact position of the sensors are necessary criteria as well. Equations can then be derived using sensor array geometry or more complex algebra to locate more specific points of interest.



AE Barkhausen Techniques:

Barkhausen Effect



The Barkhausen effect refers to the sudden change in size of ferromagnetic domains that occur during magnetization or demagnetization. During magnetization, favorably oriented domains develop at the cost of less favorably oriented domains. These two factors result in minute jumps of magnetization when a ferromagnetic sample (e.g. iron) is exposed to an increasing magnetic field (see figure). Domain wall motion itself is determined by many factors like microstructure, grain boundaries, inclusions, and stress and strain. By the same token, the Barkhausen effect is too a function of stress and strain.

Barkhausen Noise

Barkhausen noise can be heard if a coil of wire is wrapped around the sample undergoing magnetization. Abrupt movements in the magnetic field produce spiking current pulses in the coil. When amplified, the clicks can be compared to Rice Krispies or the crumbling a candy wrapper. The amount of Barkhausen noise is influenced by material imperfections and dislocations and is likewise dependent on the mechanical properties of a material. Currently, materials exposed to high energy particles (nuclear reactors) or cyclic mechanical stresses (pipelines) are available for nondestructive evaluation using Barkhausen noise, one of the many branches of AE testing.

Applications

Acoustic emission is a very versatile, non-invasive way to gather information about a material or structure. Acoustic Emission testing (AET) is be applied to inspect and monitor pipelines, pressure vessels, storage tanks, bridges, aircraft, and bucket trucks, and a variety of composite and ceramic components. It is also used in process control applications such as monitoring welding processes. A few examples of AET applications follow.

Weld Monitoring

During the welding process, temperature changes induce stresses between the weld and the base metal. These stresses are often relieved by heat treating the weld. However, in some cases tempering the weld is not possible and minor cracking occurs. Amazingly, cracking can continue for up to 10 days after the weld has been completed. Using stainless steel welds with known inclusions and accelerometers for detection purposes and background noise monitoring, it was found by W. D. Jolly (1969) that low level signals and more sizeable bursts were related to the growth of microfissures and larger cracks respectively. ASTM E 749-96 is a standard practice of AE monitoring of continuous welding.

Bucket Truck (Cherry Pickers) Integrity Evaluation

Accidents, overloads and fatigue can all occur when operating bucket trucks or other aerial equipment. If a mechanical or structural defect is ignored, serious injury or fatality can result. In 1976, the Georgia Power Company pioneered the aerial manlift device inspection. Testing by independent labs and electrical utilities followed. Although originally intended to examine only the boom sections, the method is now used for inspecting the pedestal, pins, and various other components. Normally, the AE tests are second in a chain of inspections which start with visual checks. If necessary, follow-up tests take the form of magnetic particle, dye penetrant, or ultrasonic inspections. Experienced personnel can perform five to ten tests per day, saving valuable time and money along the way. ASTM F914 governs the procedures for examining insulated aerial personnel devices.

Gas Trailer Tubes

Acoustic emission testing on pressurized jumbo tube trailers was authorized by the Department of Transportation in 1983. Instead of using hydrostatic retesting, where tubes must be removed from service and disassembled, AET allows for in situ testing. A 10% over-pressurization is performed at a normal filling station with AE sensors attached to the tubes at each end. A multichannel acoustic system is used to detection and mapped source locations. Suspect locations are further evaluated using ultrasonic inspection, and when defects are confirmed the tube is removed from use. AET can detect subcritical flaws whereas hydrostatic testing cannot detect cracks until they cause rupture of the tube. Because of the high stresses in the circumferential direction of the tubes, tests are geared toward finding longitudinal fatigue cracks.

Bridges

Bridges contain many welds, joints and connections, and a combination of load and environmental factors heavily influence damage mechanisms such as fatigue cracking and metal thinning due to corrosion. Bridges receive a visual inspection about every two years and when damage is detected, the bridge is either shut down, its weight capacity is lowered, or it is singled out for more frequent monitoring. Acoustic Emission is increasingly being used for bridge monitoring applications because it can continuously gather data and detect changes that may be due to damage without requiring lane closures or bridge shutdown. In fact, traffic flow is commonly used to load or stress the bridge for the AE testing.

Aerospace Structures

Most aerospace structures consist of complex assemblies of components that have been design to carry significant loads while being as light as possible. This combination of requirements leads to many parts that can tolerate only a minor amount of damage before failing. This fact makes detection of damage extremely important but components are often packed tightly together making access for inspections difficult. AET has found applications in monitoring the health of aerospace structures because sensors can be attached in easily accessed areas that are remotely located from damage prone sites. AET has been used in laboratory structural tests, as well as in flight test applications. NASA's Wing Leading Edge Impact Detection System is partially based on AE technology. The image to the right shows a technician applying AE transducers on the inside of the Space Shuttle Discovery wing structure. The impact detection system was developed to alert NASA officials to events such as the sprayed-on-foam insulation impact that damaged the Space Shuttle Columbia's wing leading edge during launch and lead to its breakup on reentry to the Earth's atmosphere.

Others

- Fiber-reinforced polymer-matrix composites, in particular glass-fiber reinforced parts or structures (e.g. fan blades)
- Material research (e.g. investigation of material properties, breakdown mechanisms, and damage behavior)
- Inspection and quality assurance, (e.g. wood drying processes, scratch tests)
- Real-time leakage test and location within various components (small valves, steam lines, tank bottoms)
- Detection and location of high-voltage partial discharges in transformers
- Railroad tank car and rocket motor testing

There are a number of standards and guidelines that describe AE testing and application procedures as supplied by the American Society for Testing and Materials (ASTM). Examples are ASTM E 1932 for the AE examination of small parts and ASTM E1419-00 for the method of examining seamless, gas-filled, pressure vessels.

Leak testing:

It is conventional to use the term "leak" to refer to an actual discontinuity or passage through which a fluid flows or permeates. "Leakage" refers to the fluid that has flown through a leak. "Leak rate" refers to the rate of fluid per unit of time under a given set of conditions, and is properly expressed in units of mass per unit time. Modern leak testing is thus based on the notion that all containment systems leak, the only rational requirement that can be imposed is that such systems leak at a rate no greater than some finite maximum allowable rate, however small that may be as long as it is within the range of sensitivity of a measuring system.

There are two basic types of leaks : one is an essentially localized i.e., a discrete passage through which fluid may flow (crudely, a hole). Such a leak may take the from of a tube, crack, orifice, or the like. A system may also leak through permeation of a somewhat extended barrier; such a leak is called a distributed leak. Gases may flow through solids having no holes large enough to permit more than a small fraction of the gas to flow through any one hole. This process involves diffusion through the solid and may involve various surface phenomena such as absorption, dissociation, migration, and desorption of gas molecules.

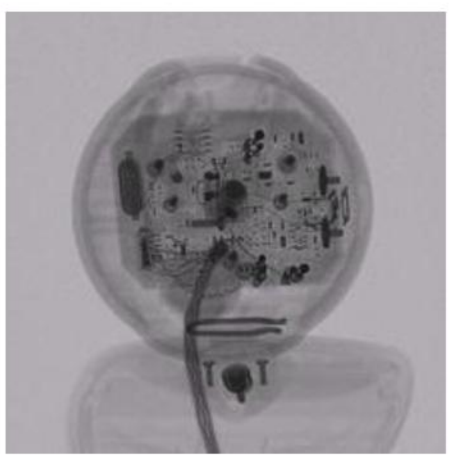
A distinction may be drawn between "real" and "virtual" leaks. Real leaks are the type described above, "virtual leak" refers to gradual desorption of gases from surfaces or components within a vacuum system. It is not uncommon for a vacuum system to have real and virtual leaks simultaneously.

It is convenient to categorize leak-testing methods according to whether the method is primarily applicable to the testing of internally pressurized systems or to vacuum systems. There are two basic ways to detect leaks in internally pressurized gas systems: (1) any reduction in the total quantity of gas contained within the system may be detected and (2) the escaping gas may itself be detected. For small leaks in pressurized gas systems, some method of directly sensing the escaping gas is usually necessary, especially when it is essential to locate the leak. Some of the methods used for this purpose are described here. The sound produced by the escaping gas may be listened to. The pressurized test system may be submerged in a liquid bath and visually observed. A soap solution may be applied on the outer surface of a pressurized system and bubbles formed due to escaping gas be observed. Detectors which are sensitive to specific gases may be used such as mass spectrometers as helium leak detectors and the radiation detectors for detection of leaking radioactive krypton-85 gas. The leak testing of vacuum systems also makes use of several specially adopted versions of specific gas detectors.

Typical applications of leak testing include testing of metals and non-porous materials, enclosures and seals, vacuum leak test of experimental and operating equipment, testing of welds, testing of brazing and adhesive bonds, testing of vacuum chambers and metal gasket seals, reactor fuel element inspection and testing of liquid-metal containers and components.

The application of leak testing techniques is, however, limited because direct access is required to at least one side of the test system and special type of sniffer or probe is required. Smeared metal or containments may plug the leak passage. Radiation and other residual gas hazards are possible.

Computed Tomography:



Industrial computed tomography (CT) scanning is any computer-aided tomographic process; usually X-ray computed tomography, that uses irradiation to produce three-dimensional internal and external representations of a scanned object. Industrial CT scanning has been used in many areas of industry for internal inspection of components. Some of the key uses for industrial CT scanning have been flaw detection, failure analysis, metrology, assembly analysis and reverse engineering applications.[1][2] Just as in medical imaging, industrial imaging includes both nontomographic radiography (industrial radiography) and computed tomographic radiography (computed tomography).

Types of scanners:

Line beam scanning is the traditional process of industrial CT scanning. X-rays are produced and the beam is collimated to create a line. The X-ray line beam is then translated across the part and data is collected by the detector. The data is then reconstructed to create a 3-D volume rendering of the part.

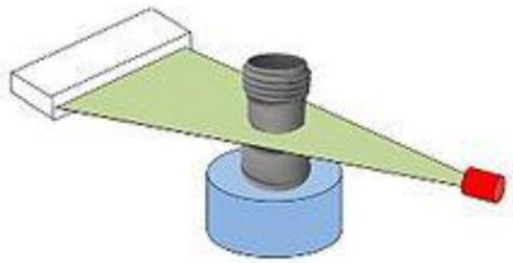


Fig: Line beam scanning

In *cone beam scanning*, the part to be scanned is placed on a rotary table. As the part rotates, the cone of X-rays produce a large number of 2D images that are collected by the detector. The 2D images are then processed to create a 3D volume rendering of the external and internal geometries of the part.

Fig: Cone beam scanner

Analysis and inspection techniques:

Various inspection uses and techniques include part-to-CAD comparisons, part-to-part comparisons, assembly and defect analysis, void analysis, wall thickness analysis, and generation of CAD data. The CAD data can be used for reverse engineering, geometric dimensioning and tolerance analysis, and production part approval

Assembly:

One of the most recognized forms of analysis using CT is for assembly, or visual analysis. CT scanning provides views inside components in their functioning position, without disassembly. Some software programs for industrial CT scanning allow for measurements to be taken from the CT dataset volume rendering. These measurements are useful for determining the clearances between assembled parts or the dimension of an individual feature.

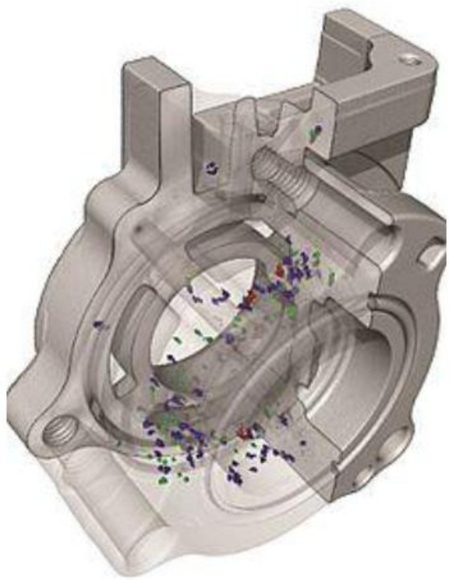


Fig: An industrial computed tomography (CT) scan conducted on an aluminum casting to identify internal failures such as voids. All color coordinated particles within casting are voids/porosity/air pockets, which can additionally be measured and are color coordinated according to size.

Void, crack and defect detection:

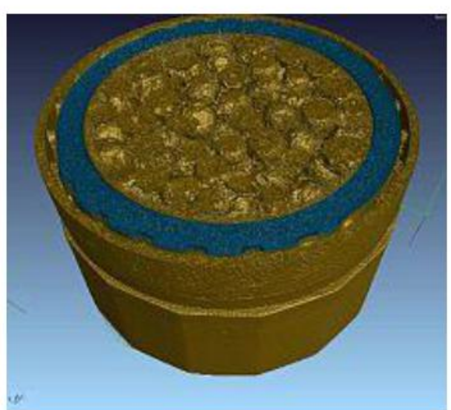


Fig: Flight through a 3D reconstruction of a disposable pepper grinder. Glass in blue.

Traditionally, determining defects, voids and cracks within an object would require destructive testing. CT scanning

can detect internal features and flaws displaying this information in 3D without destroying the part. Industrial CT scanning (3D X-ray) is used to detect flaws inside a part such as porosity,[7] an inclusion, or a crack.
Metal casting and moulded plastic components are typically prone to porosity because of cooling processes, transitions between thick and thin walls, and material properties. Void analysis can be used to locate, measure, and analyze voids inside plastic or metal components.

Geometric dimensioning and tolerancing analysis:

Traditionally, without destructive testing, full metrology has only been performed on the exterior dimensions of components, such as with a coordinate-measuring machine (CMM) or with a vision system to map exterior surfaces. Internal inspection methods would require using a 2D X-ray of the component or the use of destructive testing. Industrial CT scanning allows for full non-destructive metrology. With unlimited geometrical complexity, 3D printing allows for complex internal features to be created with no impact on cost, such features are not accessible using traditional CMM. The first 3D printed artefact that is optimised for characterisation of form using computed tomography CT

Image-based finite element methods

Image-based finite element method converts the 3D image data from X-ray computed tomography directly into meshes for finite element analysis. Benefits of this method include modelling complex geometries (e.g. composite materials) or accurately modelling "as manufactured" components at the micro-scale.

Aapplications of Computed Tomography (CT):

The number of industrial applications of Computed Tomography (CT) is large and rapidly increasing. After a brief market overview, the paper gives a survey of state of the art and upcoming CT technologies, covering types of CT systems, scanning capabilities, and technological advances. The paper contains a survey of application examples from the manufacturing industry as well as from other industries, e.g., electrical and electronic devices, inhomogeneous materials, and from the food industry. Challenges as well as major national and international coordinated activities in the field of industrial CT are also presented.