STELLA MARY'S COLLEGE OF ENGINEERING

(Accredited by NAAC, Approved by AICTE - New Delhi, Affiliated to Anna University Chennai)

Aruthenganvilai, Azhikal Post, Kanyalumari District, Tamilnadu - 629202.

ME8097 NON DESTRUCTIVE TESTING AND EVALUATION

(Anna University: R2017)

Prepared By

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DEPARTMENT OF MECHANICAL ENGINEERING

COURSE MATERIAL

REGULATION	**2017**
YEAR	**IV**
SEMESTER	**07**
COURSE NAME	**NON DESTRUCTIVE TESTING AND EVALUATION**
COURSE CODE	**ME8097**
NAME OF THE COURSE INSTRUCTOR	**Dr. J. JENIX RINO**

SYLLABUS:

UNIT I OVERVIEW OF NDT 7

NDT Versus Mechanical testing, Overview of the Non Destructive Testing Methods for the detection of manufacturing defects as well as material characterisation. Relative merits and limitations, various physical characteristics of materials and their applications in NDT, Visual inspection – Unaided and aided.

UNIT II SURFACE NDE METHODS 8

Liquid Penetrant Testing - Principles, types and properties of liquid penetrants, developers, advantages and limitations of various methods, Testing Procedure, Interpretation of results. Magnetic Particle Testing- Theory of magnetism, inspection materials Magnetisation methods, Interpretation and evaluation of test indications, Principles and methods of demagnetization, Residual magnetism.

UNIT III THERMOGRAPHY AND EDDY CURRENT TESTING (ET) 10

Thermography- Principles, Contact and non-contact inspection methods, Techniques for applying liquid crystals, Advantages and limitation - infrared radiation and infrared detectors, Instrumentations and methods, applications. Eddy Current Testing-Generation of eddy currents, Properties of eddy currents, Eddy current sensing elements, Probes, Instrumentation, Types of arrangement, Applications, advantages, Limitations, Interpretation/Evaluation.

UNIT IV ULTRASONIC TESTING (UT) AND ACOUSTIC EMISSION (AE) 10

Ultrasonic Testing-Principle, Transducers, transmission and pulse-echo method, straight beam and angle beam, instrumentation, data representation, A/Scan, B-scan, C-scan. Phased Array Ultrasound, Time of Flight Diffraction. Acoustic Emission Technique –Principle, AE parameters, Applications

UNIT V RADIOGRAPHY (RT) 10

Principle, interaction of X-Ray with matter, imaging, film and film less techniques, types and use of filters and screens, geometric factors, Inverse square, law, characteristics of films - graininess, density, speed, contrast, characteristic curves, Penetrameters, Exposure charts, Radiographic equivalence. Fluoroscopy- Xero-Radiography, Computed Radiography, Computed Tomography.

TEXT BOOKS:

1. Baldev Raj, T.Jayakumar, M.Thavasimuthu "Practical Non-Destructive Testing", Narosa Publishing House, 2014.

2. Ravi Prakash, "Non-Destructive Testing Techniques", 1st revised edition, New Age International Publishers, 2010

REFERENCES:

1. ASM Metals Handbook, "Non-Destructive Evaluation and Quality Control", American Society of Metals, Metals Park, Ohio, USA, 200, Volume-17.

2. ASNT, American Society for Non Destructive Testing, Columbus, Ohio, NDT Handbook,Vol. 1, Leak Testing, Vol. 2, Liquid Penetrant Testing, Vol. 3, Infrared and Thermal Testing Vol. 4, Radiographic Testing, Vol. 5, Electromagnetic Testing, Vol. 6, Acoustic Emission Testing, Vol. 7, Ultrasonic Testing

3. Charles, J. Hellier," Handbook of Nondestructive evaluation", McGraw Hill, New York 2001.

4. Paul E Mix, "Introduction to Non-destructive testing: a training guide", Wiley, 2nd Edition New Jersey, 2005

Course Outcome Articulation Matrix

	Program Outcome												*PSO*		
Course Code / CO No	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*1*	*2*	*3*
ME8097 / C426.1	3	2	0	3	0	0	0	0	2	3	0	3	3	3	0
ME8097 / C426.2	3	3	0	3	3	0	0	0	2	3	0	3	3	3	0
ME8097 / C426.3	3	3	0	3	3	0	0	0	2	3	0	3	3	3	0
ME8097 / C426.4	3	3	0	3	3	0	0	0	2	3	0	3	3	3	0
ME8097 / C426.5	3	3	0	3	3	0	0	0	2	3	0	3	3	3	0
Average	3	3	0	3	2	0	0	0	2	3	0	3	3	3	0

UNIT-I

OVERVIEW OF NDT

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:

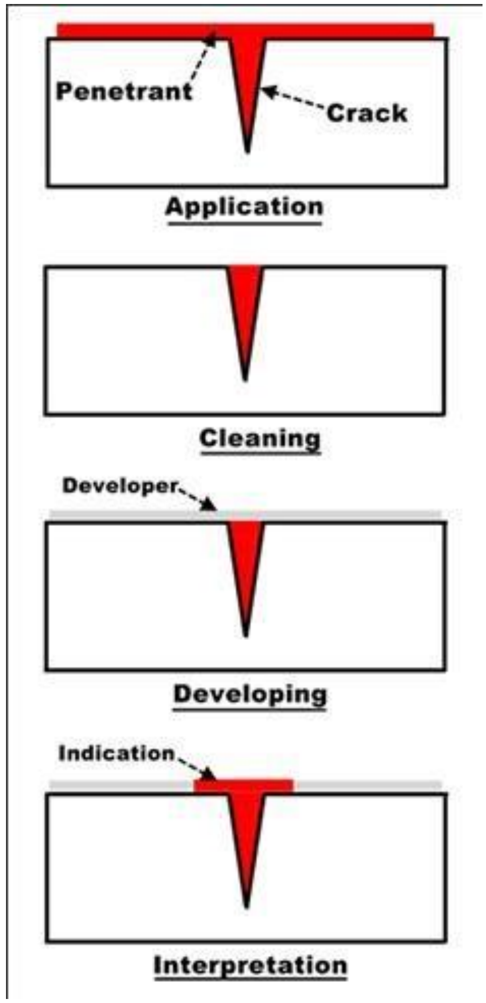
- Acoustic Emission Testing (AE),
- Electromagnetic Testing (ET),
- Guided Wave Testing (GW),
- Ground Penetrating Radar (GPR),
- Laser Testing Methods (LM),
- Leak Testing (LT),
- Magnetic Flux Leakage (MFL),
- Microwave Testing,
- Liquid Penetrant Testing (PT),
- Magnetic Particle Testing (MT),
- Neutron 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):

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 figure.

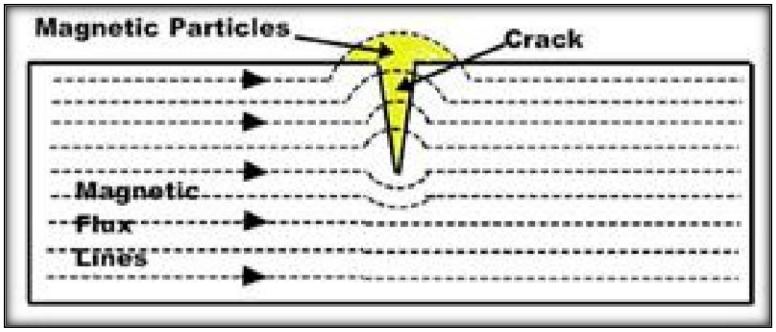
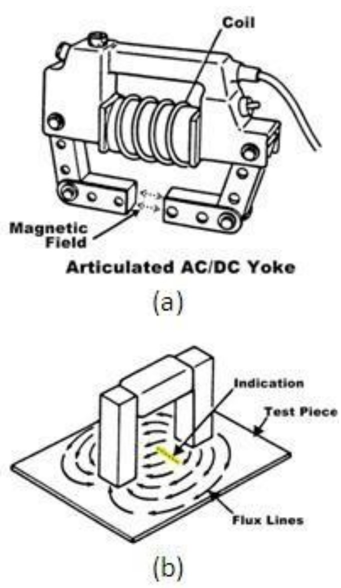


Fig : Magnetic particle testing

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:

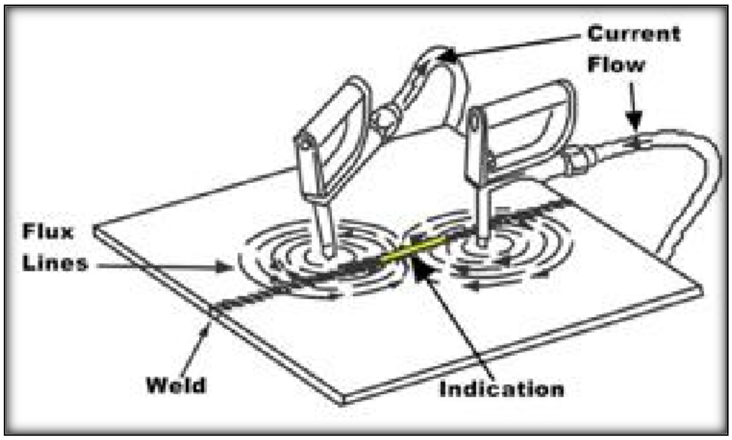
Most field inspections are performed using a Yoke, as shown at the right. As shown in Figure 2(a), an electric coil is wrapped around a central core, and when the current is applied, a magnetic field is generated that extends from the core down through the articulated legs into the part. This is known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



Yokes

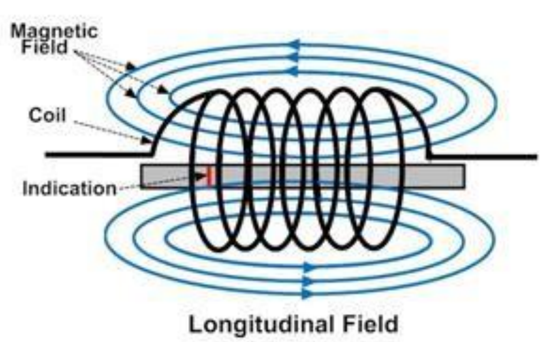
When the legs are placed on a ferromagnetic part and the yoke is energized, a magnetic field is introduced into the part as shown in (b). Because the flux lines do run from one leg to the other, discontinuities oriented perpendicular to a line drawn between the legs can be found. To ensure no indications are missed, the yoke is used once in the position shown then used again with the yoke turned 90º 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:



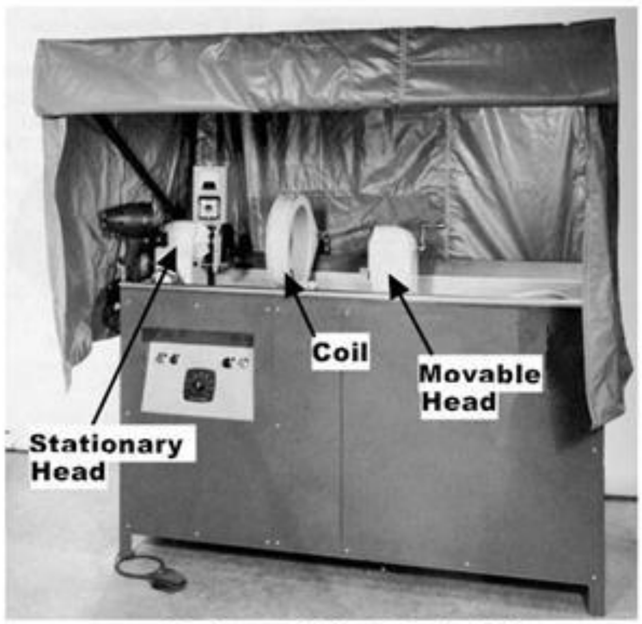
Prod units use *direct* induction, where the current runs through the part and a circular magnetic field is generated around the legs as shown in Figure 3. Because the magnetic field between the prods is travelling perpendicular to a line drawn between the prods, indications oriented parallel to a line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

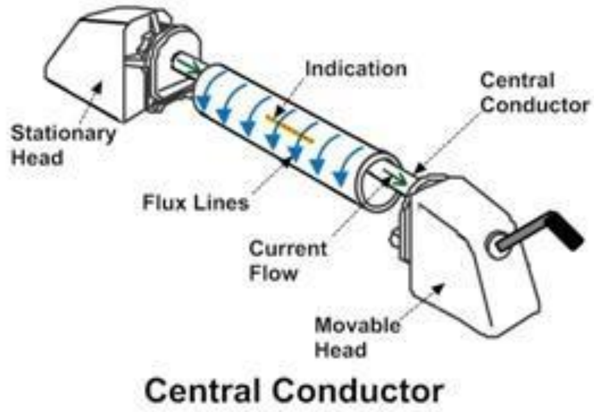
Heads:



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 90º 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."

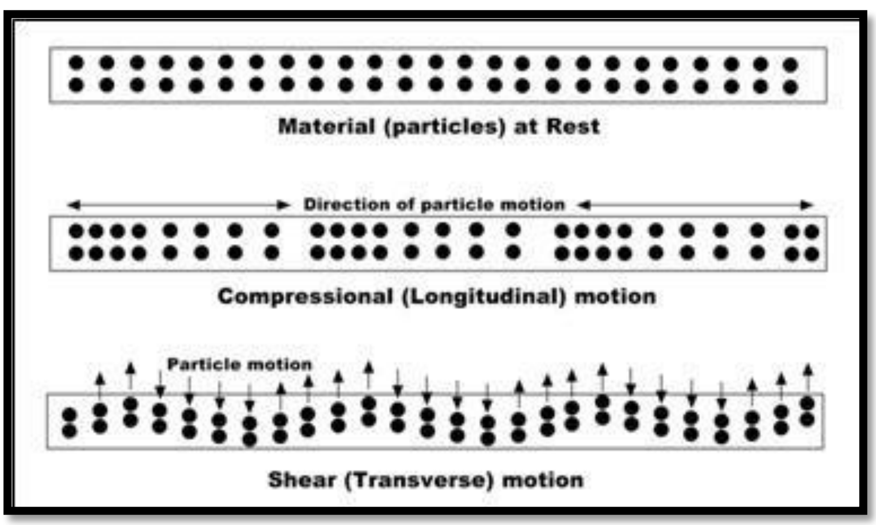
Central Conductor:



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:-

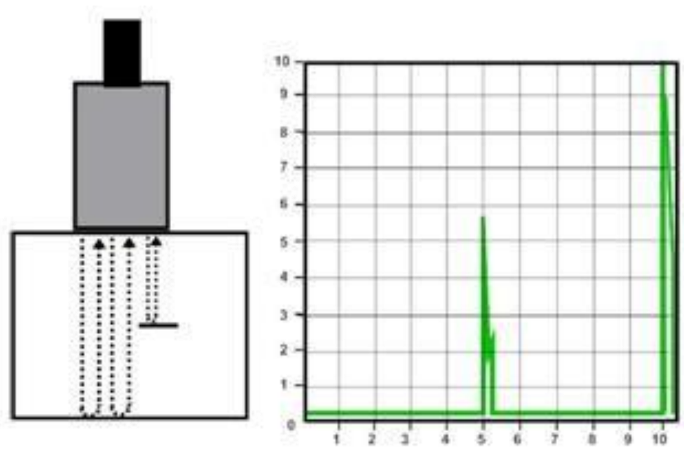
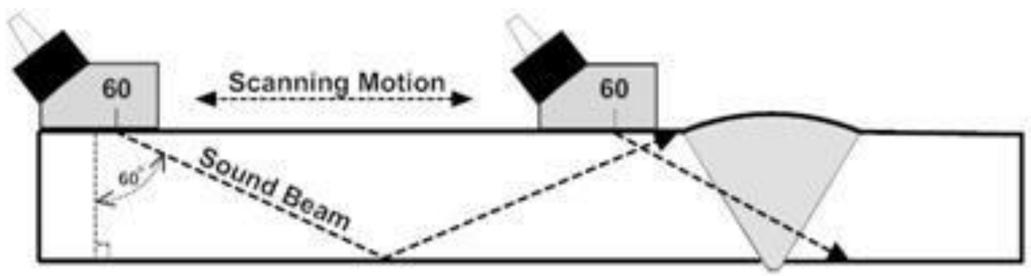


Fig: Straight Beam

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^o, 60^o and 70^o, with the angle being calculated up from a line drawn through the thickness of the part (not the part surface). A 60^o 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.

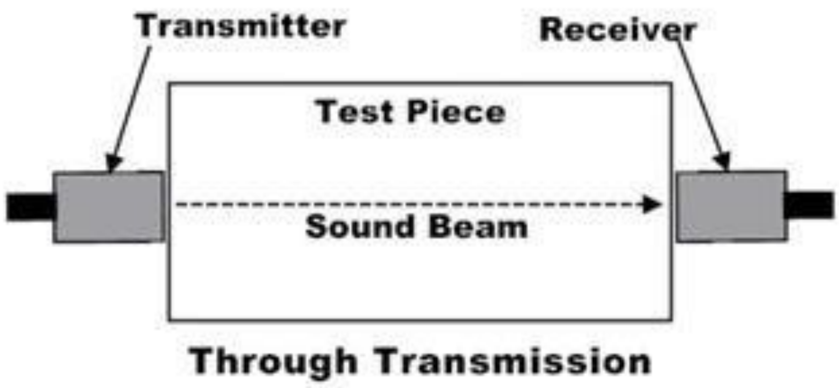
In angle beam inspections, the transducer and wedge combination (also referred to as a "probe") is moved back and forth towards the weld so that the sound beam passes through the full volume of the weld. As with straight beam inspections, reflectors aligned more or less perpendicular to the sound beam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

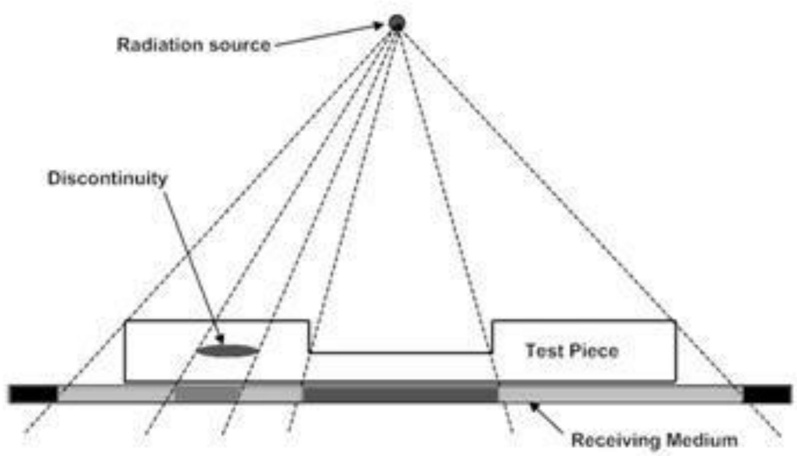
Phased Array:

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 light 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.

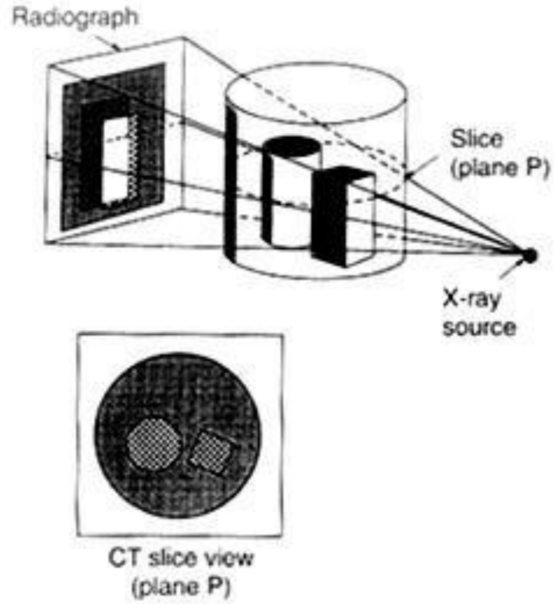
To be a usable film, the area of interest (weld area, etc.) on the film must be within a certain density (darkness) range and must show enough contrast and sensitivity so that discontinuities of interest can be seen. These items are a function of the strength of the radiation, the distance of the source 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.

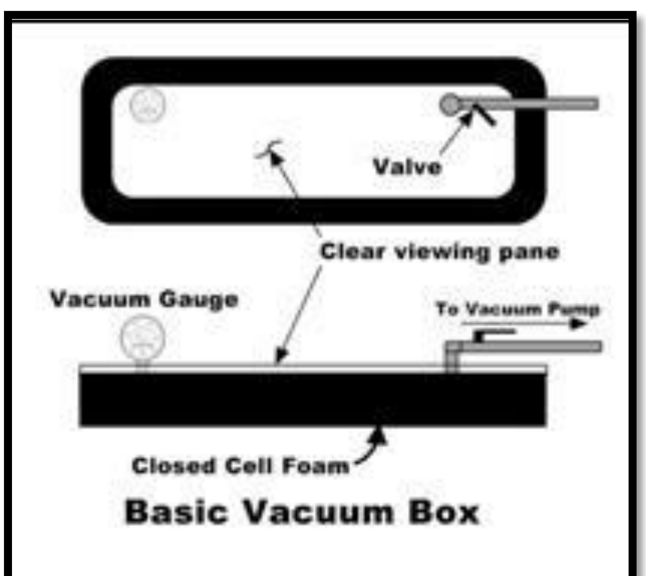
Laser Shearography:

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:

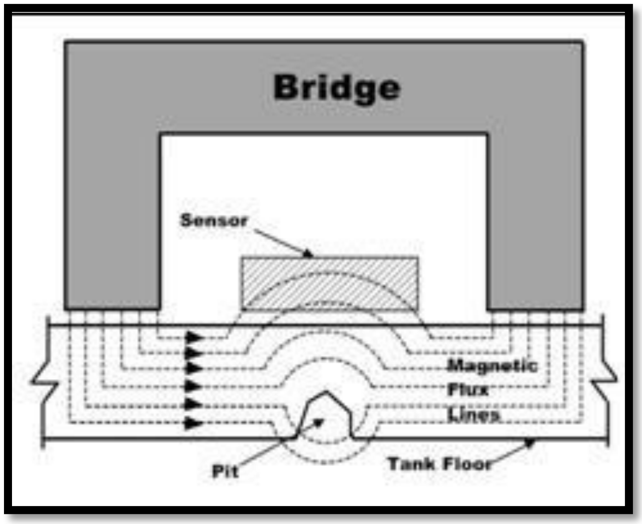
Halogen Diode Testing is done by pressurizing a system with a mixture of air and a halogen-based tracer gas. After a set period of time, a halogen diode detection unit, or "sniffer", is used to locate leaks.

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 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.



Magnetic flux Leakage

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.

UNIT-II

SURFACE NDE METHOD

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.

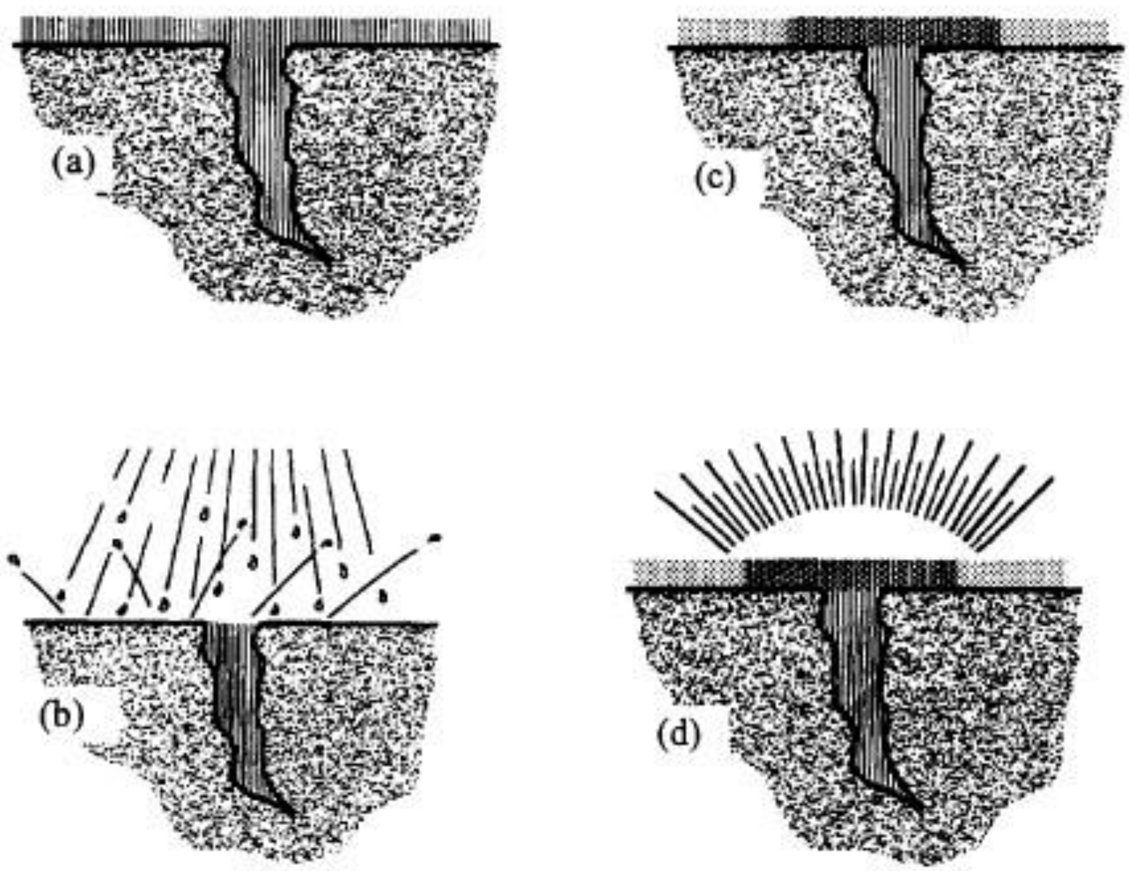


Figure: Four stages of liquid penetrant process.

(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.

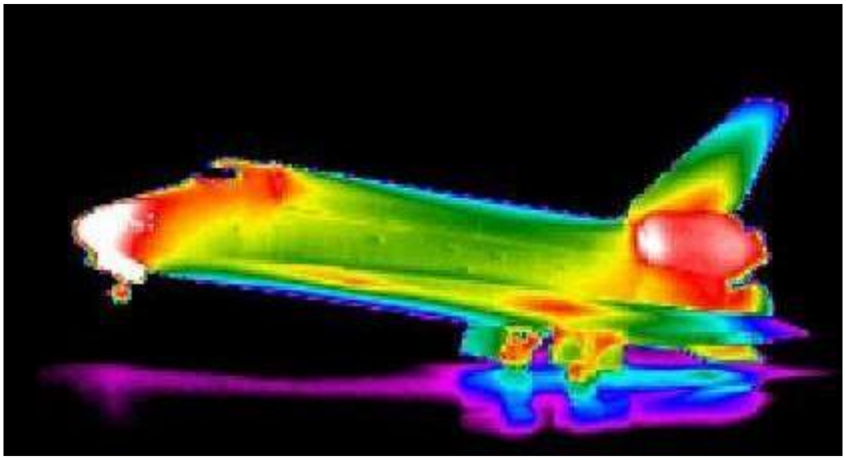
UNIT-III

THERMOGRAPHY AND EDDY CURRENT TESTING

Thermography- Principles, Contact and non-contact inspection methods, Techniques for applying liquid crystals, Advantages and limitation - infrared radiation and infrared detectors, Instrumentations and methods, applications. Eddy Current Testing-Generation of eddy currents, Properties of eddy currents, Eddy current sensing elements, Probes, Instrumentation, Types of arrangement, Applications, advantages, Limitations, Interpretation/Evaluation.

Thermography Testing

Introduction to Thermal Testing



NASA/JPL-Caltech/IPAC

Thermal NDT methods involve the measurement or mapping of surface temperatures as heat flows to, from and/or through an object. The simplest thermal measurements involve making point measurements with a thermocouple. This type of measurement might be useful in locating hot spots, such as a bearing that is wearing out and starting to heat up due to an increase in friction.

In its more advanced form, the use of thermal imaging systems allows thermal information to be very rapidly collected over a wide area and in a non-contact mode. Thermal imaging systems are instruments that create pictures of heat flow rather than of light.

Thermal imaging is a fast, cost effective way to perform detailed thermal analysis. The image above is a heat map of the space shuttle as it lands.

Thermal measurement methods have a wide range of uses. They are used by the police and military for night vision, surveillance, and navigation aid; by firemen and emergency rescue personnel for fire assessment, and for search and rescue; by the medical profession as a diagnostic tool; and by industry for energy audits, preventative maintenance, processes control and nondestructive testing. The basic premise of thermographic NDT is that the flow of heat from the surface of a solid is affected by internal flaws such as disbands, voids or inclusions. The use of thermal imaging systems for industrial NDT applications will be the focus of this material.

Thermography Testing

Introduction

Thermography testing is a nondestructive testing (NDT) imaging technique that allows the visualization of heat patterns of an object.

It is also called as thermal imaging, infrared thermography **IR** or simply thermography.

Principle

This testing method based on the fact that most components in a system show an increase in temperature when malfunctioning or due to variation in temperature differences at the sub surface defects. This temperature differences observed on the investigated surface during inspection will be monitored by an infrared camera.

Measurement of Temperature using Infrared Methods

When using a Thermal Imager, it is helpful to have a basic knowledge of infrared theory.

Basics Physics

An object when heated radiates electromagnetic energy. The amount of energy is related to the object's temperature. The Thermal Imager can determine the temperature of the object without physical contact by measuring the emitted energy.

Electromagnetic Spectrum

The energy from a heated object is radiated at different levels across the electromagnetic spectrum. In most industrial applications it is the energy radiated at infrared wavelengths which is used to determine the object's temperature. Figure 3.1 shows various forms of radiated energy in the electromagnetic spectrum including X-rays, Ultra Violet, Infrared and Radio. They are all emitted in the form of a wave and travel at the speed of light. The only difference between them is their wavelength which is related to frequency

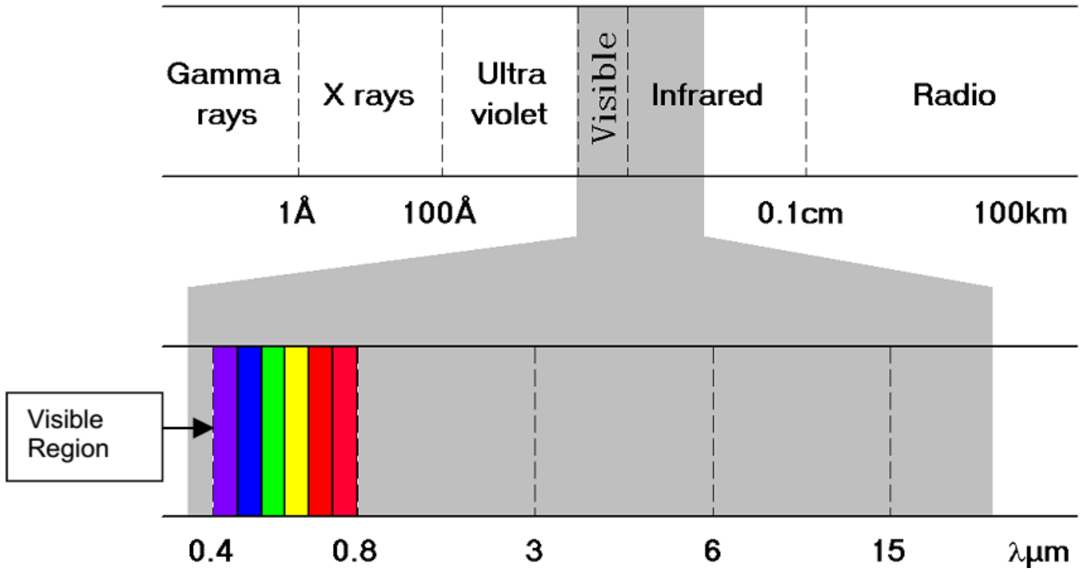


Fig.3.1 The Infrared region of the Electromagnetic spectrum

The human eye responds to visible light in the range 0.4 to 0.75 microns.

The vast majority of infrared temperature measurement is made in the range 0.2 to 20 microns. Although emissions are mostly unable to be detected by a standard camera the Thermal Imager can focus this energy via an optical system on to a detector in a similar way to visible light. The detector converts infrared energy into an electrical voltage which after amplification and complex signal processing is used to build the thermal picture in the operator's viewfinder on board the Thermal Imager.

Energy Distribution

Figure 3.2 shows the energy emitted by a target at different temperatures. As can be seen the higher the target temperature the higher the peak energy level. The wavelength at which peak energy occurs becomes progressively shorter as temperature increases. At low temperatures the bulk of the energy is at long wavelengths.

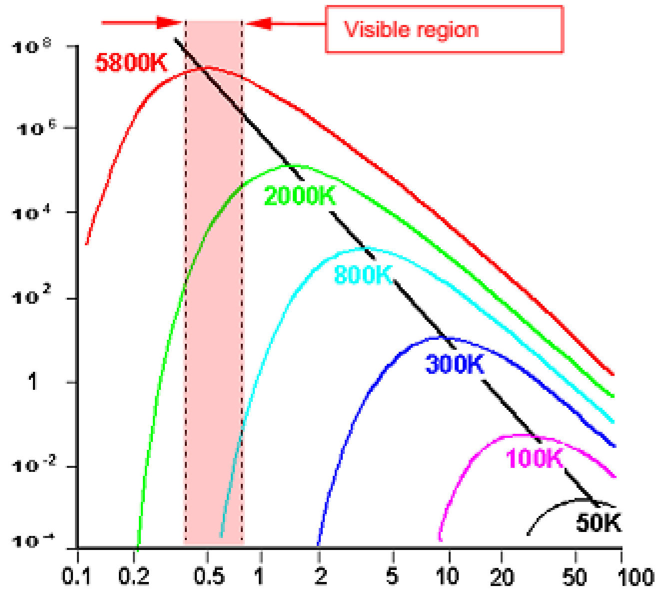


Fig.3.2 Infrared energy and distribution across the Electromagnetic spectrum

Emissivity

The amount of energy radiated from an object is dependent on its temperature and its emissivity. An object which has the ability to radiate the maximum possible energy for its temperature is known as a Black Body. In practice there are no perfect emitters and surfaces tend to radiate somewhat less energy than a Black Body.

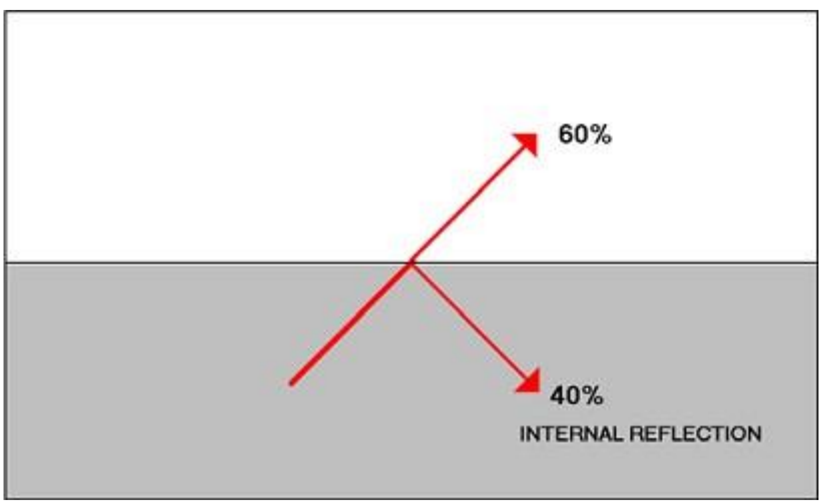


Fig 3.3 The Infrared energy reflected at a body surface

Figure 3.3 shows why objects are not perfect emitters of infrared energy. As energy moves towards the surface a certain amount is reflected back inside and never escapes by radiative means. From this example it can be seen that only 60% of the available energy is actually emitted. The emissivity of an object is the ratio of the energy radiated to that which the object would emit if it were a Black Body.

Hence emissivity is expressed as:-

$$\textbf{Emissivity} = \frac{\textbf{Radiation emitted by an object at temperature T}}{\textbf{\textit{Radiation emitted by a Black Body at temperature T}}}$$

Emissivity is therefore an expression of an object’s ability to radiate Infrared energy.

Emissivity values

The value of emissivity tends to vary from one material to another. With metals a rough or oxidized surface usually has a higher emissivity than a polished surface.

Here are some examples:

Material	Emissivity
Steel polished	**0.18**
Steel oxidised	**0.85**
Brass polished	**0.10**
Brass oxidised	**0.61**
Aluminium polished	**0.05**
Aluminium oxidised	**0.30**
Cement and Concrete	**0.90**
Asphalt	**0.90**
Red Brick 0.93	**0.93**
Graphite 0.85	**0.85**
Cloth 0.85	**0.85**

It can be shown that there is a relationship between emissivity and reflectivity. For an opaque object this is **Emissivity + Reflectivity = 1.0**

Hence a highly reflective material is a poor emitter of infrared energy and will therefore have a low emissivity value.

Effects of Emissivity

If a material of high emissivity and one of low emissivity were placed side by side inside a furnace and heated to exactly the same temperature, the material with low emissivity would appear to the eye much duller. This is due to the different emissivity’s of the materials causing them to radiate at different levels, making the low emissivity material appear cooler than the high emissivity material, even though they are at exactly the same temperature. The Thermal Imager would see this in the same way as the eye and produce an error in making the temperature measurement. The temperature of an object cannot be determined by simply measuring its emitted infrared energy, a knowledge of the object’s emissivity must also be known.

The emissivity of an object can be determined as follows:

1) Consult manufacturers literature (always ensure these have been evaluated at the operating wavelength of your Thermal Imager as emissivity can vary with wavelength).

2) Have the object's emissivity evaluated by a laboratory method.

There are two main ways to overcome the problem of emissivity.

a) Mathematically correct the temperature measurement value. This is usually carried out within the signal processor of the Thermal Imager. Most modern Thermal Imagers have a compensation setting which can quickly and easily be set by the operator.

b) It may be possible to paint the surface of a low emissivity target with a high and constant emissivity coating. This tends to elevate the target to a much higher emissivity level, but this may not be possible on all process plants. When carrying out Thermographic inspections, faults are often identified by comparing heat patterns in similar components operating under similar loads. This is an alternative to very precisely predicting the emissivity of each individual component and obtaining absolute temperature values.

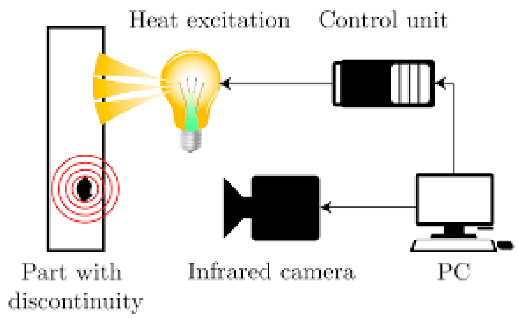
Characteristics of Infrared

- It is not visible as its wave length is larger than the visible light.
- It is radiated naturally from all objects having the temperature of absolute 0^0 K or higher, hence it is applicable to all kinds of field.
- It has characteristics of heating an object, hence it is sometimes called as "heat ray".
- It is a kind of electromagnetic wave and it can travel through vacuum.
- Infrared energy and temperature of an object are co related, therefore temperature distribution can be observed.

Basic Principle of Thermography Testing.

The principle of infrared thermography is based on the physical phenomenon that any body of a temperature above absolute zero (-273.15 °C) emits electromagnetic radiation. There is clear correlation between the surface of a body and the intensity and spectral composition of its emitted radiation. By determining its radiation intensity, the temperature of an object can thereby be determined in a non-contact way.

Thermography testing uses an infrared cameras containing large number of infrared sensors which can be detect and measure small temperature differences. The image showing the temperature differences can be processed and displayed as a color or grey scale map.



Advantages:

i. fast inspection rate;

ii. contactless, no coupling needed as in the case of conventional ultrasounds. It should be noted, however, that UT requires a coupling media between the transducer and the specimen and that induction thermography coils have to be relatively close to the inspected surface;

iii. security of personnel, there is no harmful radiation involved as in the case of x-ray radiography. However, high power external stimulation (such as powerful flashes) requires eye protection and heat-induced ultrasound requires protective ear plugs;

iv. imaging capabilities, results are relatively easy to interpret, since they are (often) obtained in image or video formats;

v. applications are varied and numerous;

vi. unique inspection tool for some inspection applications as in the case of open microcracks in thermally sprayed coatings difficult to inspect with other NDT approaches; and

vii. the number of training hours required for level I certification is half the requirement for other NDT techniques such as ultrasounds and x-rays.

Limitations:

• non-uniform heating, difficulty of obtaining a fast, uniform and highly energetic thermal stimulation over a large surface (particularly for the optical pulsed scenario).

For this reason, several processing techniques have been proposed as discussed below;

• thermal losses by convection and heat radiation that might induce spurious contrasts affecting the reliability of the interpretation;

• cost of the equipment, IR camera and thermal stimulation units for active thermography, although this is relative, active thermography is more expensive than some NDT techniques (visual inspection, some ultrasound devices, etc), however, it has very competitive costs when compared to more sophisticated equipment such as phase array (ultrasound or eddy currents) and x-rays systems;

• capability to detect only defects resulting in a measurable change of the thermal properties from the inspected surface;

• ability to inspect a limited thickness of material under the surface, although detection of defect several centimeters under the surface is sometimes possible, notably by LT using very low modulation frequencies; and

• emissivity variations, low emissivity materials strongly reflect thermal radiations from the environment, surface painting can be employed to increase and equalize emissions when possible.

Classification of Thermography Testing

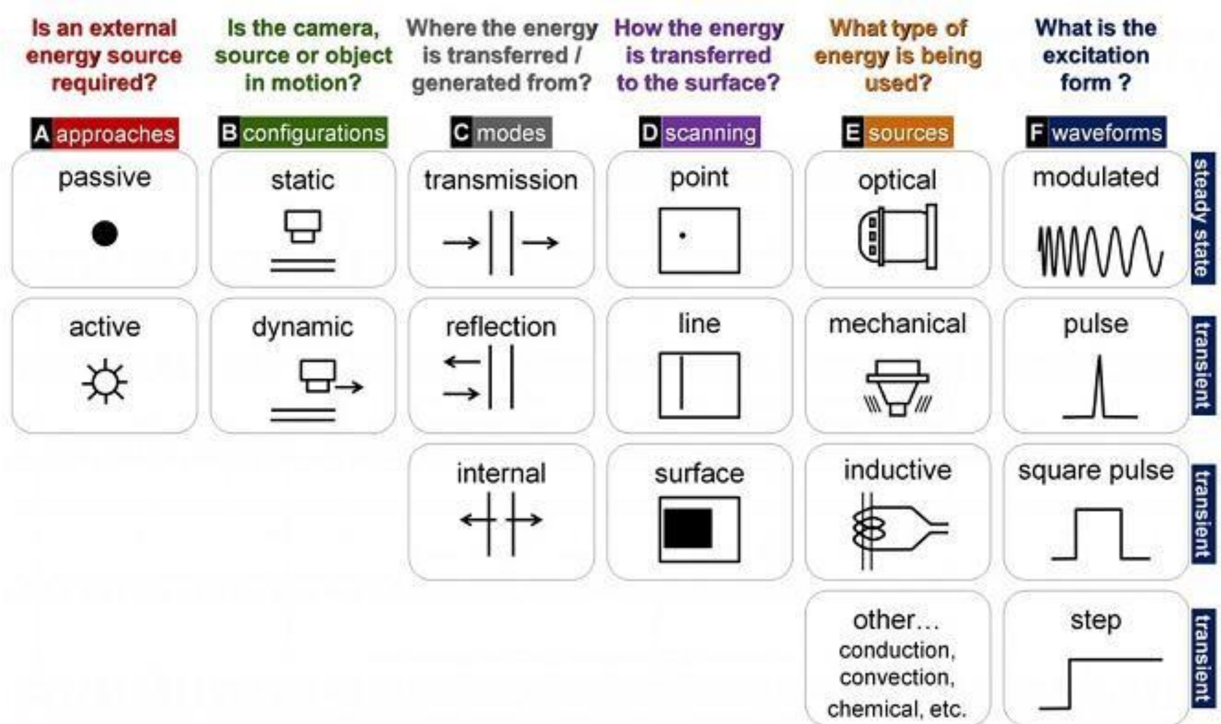
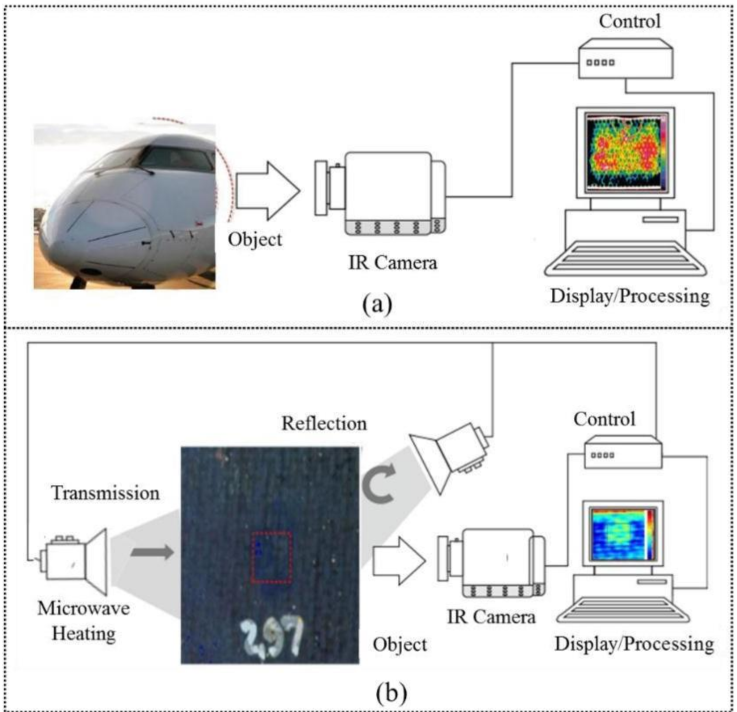


Fig 3.4 Classification of Thermography Testing

Thermography Testing – Passive approach

Passive, in which materials and structures are naturally at different (higher or lower) temperature than the background, e.g. the human body is normally at a temperature higher than the ambient, hence it is easily detected by an IR camera without any additional stimulation

Fig. 3.5 Configuration of Passive approach



For the passive approach (figure 3.4, top), an object or a system, a human hand in this case, having a distinctive thermal contrast with respect to the environment can be monitored using an IR camera without any additional energy input. A computer system is used to display and process images. The setup is very similar for active IR thermography (figure 3.4, bottom) with the difference that an energy source is required to generate a thermal contrast between the feature of interest and its surroundings, two internal foreign material inserts on a tile specimen in the case. The passive approach is often qualitative, such as the diagnosis of the presence of a given abnormality or *hot/cold spots* with respect to the immediate surroundings. Typical applications are the monitoring of electrical and electronic components or the detection of humidity or insulation problems in buildings. Quantitative analysis is also possible such as in the inspection of civil engineering and cultural heritage structures using solar loading cycles and water ingress characterization in aircraft structures upon landing among others.

Advantages

i. Passive thermography provides unique opportunities to quickly test large areas of a structure without taking the equipment out of service.

ii. It is most effective when looking for strong thermal indications that have persistence, such as water or other fluid ingress.

iii. Passive thermography does not always require expensive thermal imaging equipment.

iv. There are many affordable, handheld systems available today that are capable of resolving strong, persistent thermal signatures.

Limitations

i. Effective result in passive thermography testing depends on temperature difference or thermal contrast exists between the feature of interest

ii. An experienced thermographer is needed to interrupt thermos graphic results

iii. Raw thermal data is qualitative one and relying on the training and expertise of the thermographer

Applications

1 Monitoring electrical and electronics components

2 Detection of insulation problems in building

3 Water entry in aircraft structures upon landing

Thermography Testing Active Approach

Active, in which an external stimulus is needed in order to produce a thermal contrast in the object surface, e.g. an object containing internal defects (such as voids, delaminations, foreign material inclusions, etc) will require submission to a thermal disequilibrium in order to produce distinctive surface thermal patterns between the defects and the sound material that can be detected with an IR camera.

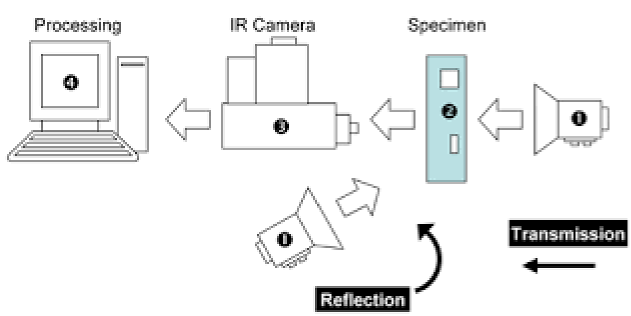
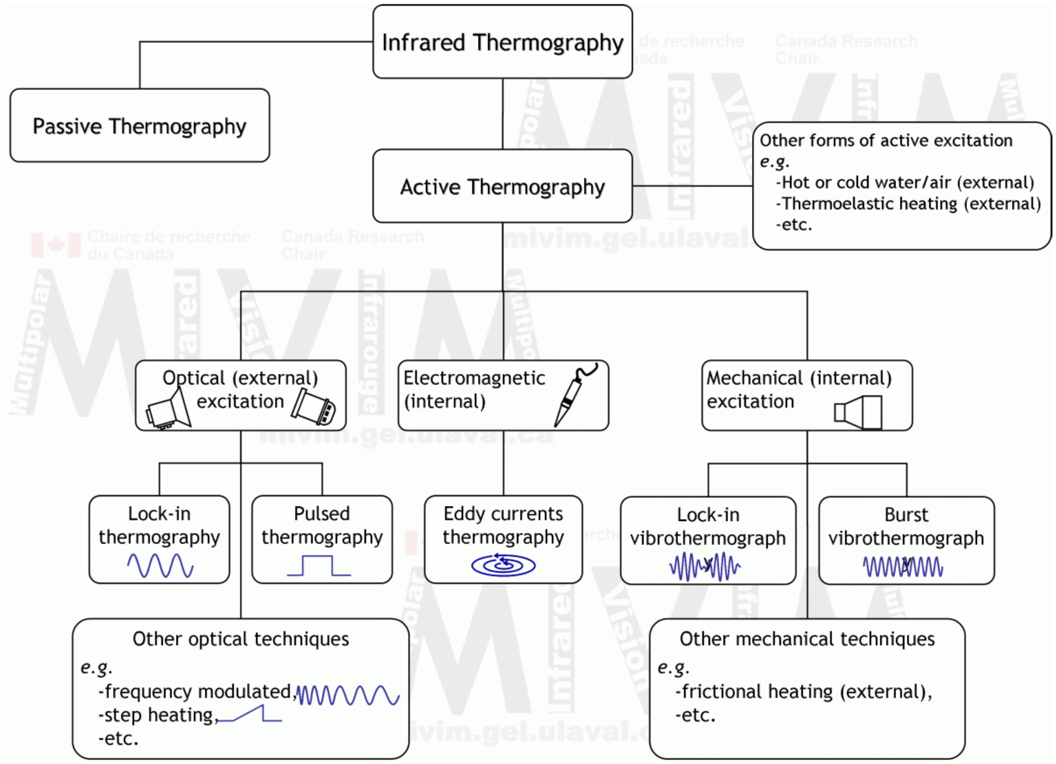


Fig.3.6 Active approach of thermography testing

Active thermography finds a large number of applications in NDT since practically *any* form of energy can be used to stimulate the inspected object, provided that the thermo- physical properties of the eventual defects are different enough to the non-defective areas in order to produce a measurable thermal contrast. Besides, the time of application of the external stimulus can be synchronized with the acquisition, providing the possibility of developing quantitative data analysis, e.g. the time of appearance of a subsurface defect is proportional to its depth.

Advantages



i. Possibility to perform one sided inspection
ii. Real time data acquisition is possible
iii. Appropriate on most multi-layer structure and porous material used in industries
iv. Inspection of large surface is possible
v. Relatively unaffected by the object's geometry

Limitations

i. Sensible to duration of heating sources
ii. Expensive
iii. Surface condition and thickness of the object has influence on the data output

Applications

i. Structural evaluation of glass reinforced polymer(GRP) pipes
ii. Assessment of damage on carbon Fiber Reinforced Plastic panels
iii. Checking sand witched panels of aircrafts
iv. Identification of subsurface defects like racks, blowholes, porosity and inclusions in metals

Active Thermography Techniques

Pulsed Thermography

Pulse thermography (PT) is one of the most popular thermal stimulation methods. The reason for the popularity is the speed of the inspection relying on a thermal stimulation pulse, which is usually a flash, with a duration ranging from a few milliseconds for high thermal conductivity material inspection such as metals to a few seconds for low thermal conductivity specimens such as plastics.

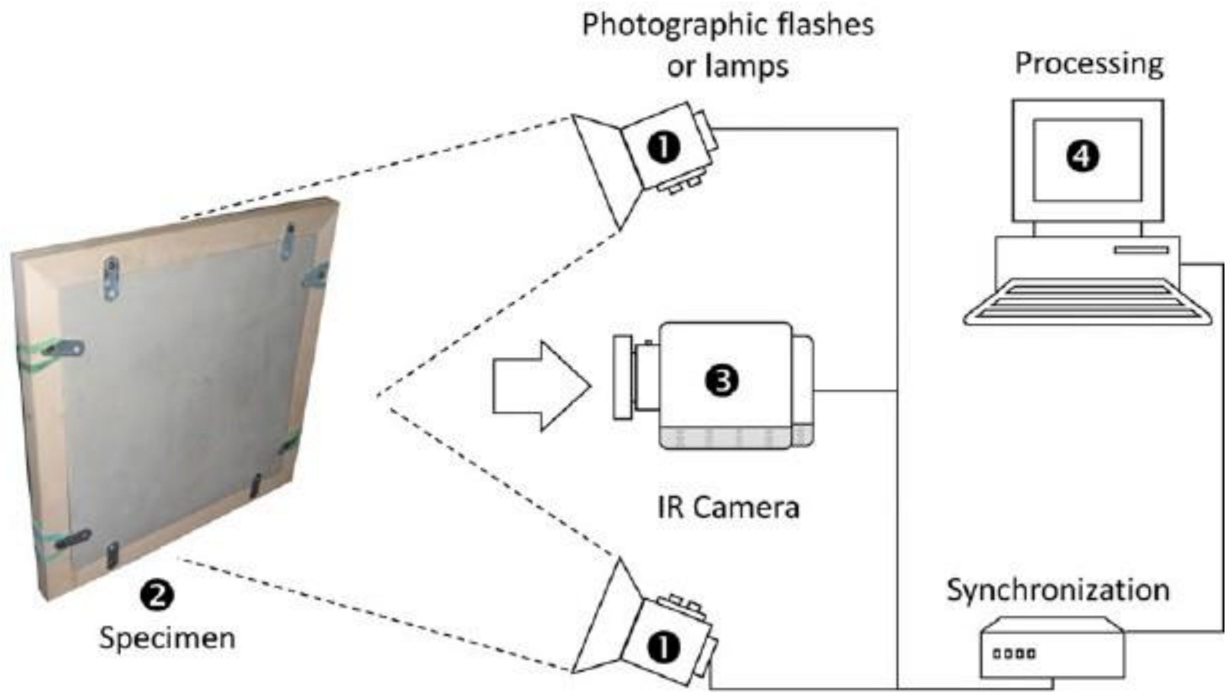


Fig 3.7 Pulsed Thermography

The heating pulse which is prominent only for a short period of time prevents damage to the component and the heating is generally limited to a few degrees above the component's initial temperature. The temperature of the material rises during the pulse and after the pulse; it decays because the thermal energy propagates by diffusion under the surface. Later, the presence of a subsurface defect like a disbond reduces the diffusion rate. Therefore, when observing the surface temperature, such a subsurface defect appears as an area of different temperature with respect to the surrounding sound area. The reduced diffusion rate caused by the subsurface defect presence translates into heat accumulation and hence, the higher surface temperature just over the defect. The phenomenon occurs in time so that deeper defects are observed later and with a reduced thermal contrast. The relationship between the observation time t and the subsurface defect depth z is given as:

$$t = \frac{z^2}{\alpha}$$

Where α is the thermal diffusivity of the material and is given by the equation:

$$\alpha = \frac{K}{pc}$$

Where K is the thermal conductivity, ρ is the density and C is the specific heat capacity of the material. Various configurations for pulse thermography are:

(a) **Point inspection**: A laser or a focused light beam is used for heating.

(b) **Line inspection**: Line lamps, heated wire, scanning laser and air jets are used.

(c) **Surface inspection**: Lamps, flash lamps and scanning laser are used.

If the temperature of the sample being inspected is already higher than the ambient temperature, it can be of interest to make use of a cold thermal source such as a line of air jets or water jets; sudden contact with ice, snow, etc. A thermal front propagates the same way whether being hot or cold, therefore what is important is the temperature differential between the thermal source and the specimen. An advantage of a cold thermal source is that it does not induce thermal reflections into the IR camera as a hot thermal source does. The main limitations of cold stimulation sources are related to practical considerations like for instance it is generally easier and more efficient, to heat rather than to cool a sample. There are two types of observation methods. Reflection, in which the thermal source and detector are located on the same side of the inspected component. And transmission, in which the thermal source and the detector are located on either side of the inspected component.

The reflection approach is generally used for the detection of defects located close to the surface being heated, while the transmission approach is used for the detection of defects close to the rear surface. Fully integrated systems combining acquisition head and heating unit are commercially available.

Advantages

i. Pulsed thermography is a faster technique and easy to deploy
ii. Numerous processing techniques are available
iii. Highly suitable to detect voids and inclusions
iv. Quantitative assessment of detect is possible

Limitations

i. Affected by non-uniform heating, emissivity variations, environmental reflections and surface geometry

ii. Surface preparation is required for low emissivity materials

iii. Thermal losses by convection and radiation may affect the interpretation of result/output

Applications

i. Locating anchoring points beneath the outer skin of aircraft to facilitate drilling and fixing

ii. Defect detection under multiply composite

iii. Determination of impact damages on CRPF panels

iv. Measurement of drilling induced defects on laminates

v. Identification of the cracks in turbine components

vi. Detection of water accumulation, corrosion in aircraft passes.

Lock-In Thermography (LT)

Lock-in thermography (LT) also known as modulated thermography is a technique derived from photo thermal radiometry, in which, a small surface spot is periodically illuminated by an intensity modulated laser beam to inject thermal waves into the specimen. The thermal response is recorded at the same time using an infrared detector and decomposed by a lock-in amplifier to extract the amplitude and phase of the modulation. Photo thermal radiometry was a raster point-by point technique that required long acquisition times (especially in the case of deep defects involving very low modulation frequencies, see below). Furthermore, extra hardware, i.e. lock-in amplifier, is needed in order to retrieve the amplitude and phase of the response. Fortunately, it is possible to dramatically simplify and speed up the acquisition process for NDT applications by replacing:

(1) the laser beams with one or several modulated heating sources, e.g. halogen lamps, that cover the entire specimen surface instead of only a point;

(2) the infrared detector with an infrared camera capable of monitoring the whole (or a large part of the) surface (typically in a 320x256 or 640x512 pixel matrix configuration); and

(3) the lock-in hardware with a software capable of recovering mathematically the amplitude and phase of the response. This is what is called lock-in thermography.

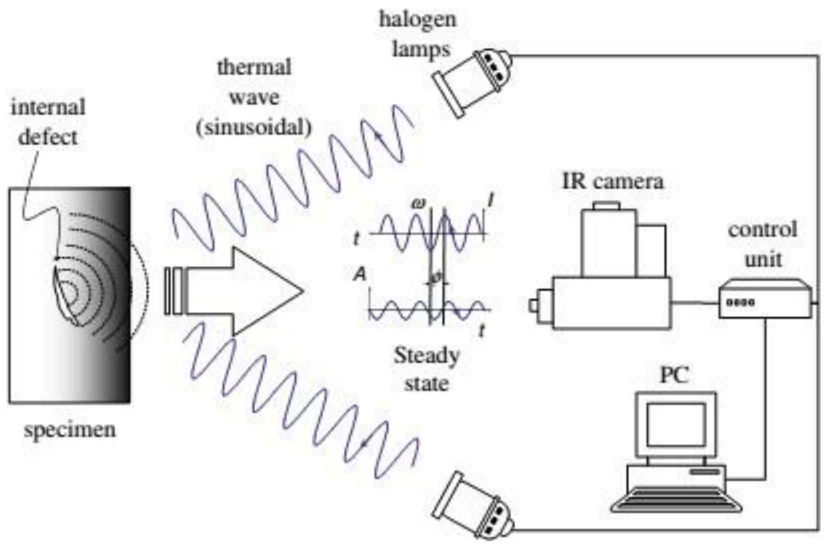


Fig. 3.8 Lock in Thermography technique

Sinusoidal waves are typically used in LT, although other periodic waveforms are possible. Using sinusoids as input has the advantage that the frequency and shape of the response are preserved; only the amplitude and phase delay of the wave may change (i.e. sinusoidal fidelity). The periodic wave propagates by radiation through the air until it touches the specimen surface where heat is produced and propagates through the material. Internal defects act as barrier for heat propagation, which produces changes in amplitude and phase of the response signal at the surface.

Experimental setup and data acquisition for lock-in experiments

Two lamps are shown although it is possible to use several lamps mounted on a frame to reduce the non-uniform heating and/or to increase the amount of energy delivered to the surface. The lamps send periodic waves (*e.g.* sinusoids) at a given modulation frequency ω, for at least one cycle, ideally until a steady state is achieved, which depends on the specimen's thermal properties and the defect depth, see Eq.

$$\mu \equiv \sqrt{\frac{2 \cdot \alpha}{\omega}} = \sqrt{\frac{\alpha}{\pi \cdot f}}$$

In practice however, only a few cycles are needed to adequately retrieve phase and amplitude data, much before attaining steady state conditions.

Figure 5 shows an example of the raw output signal for a sinusoidal input at two different points. As can be seen, noise is omnipresent and processing is required not only to extract the amplitude and/or phase information but also to de- noise the signal.

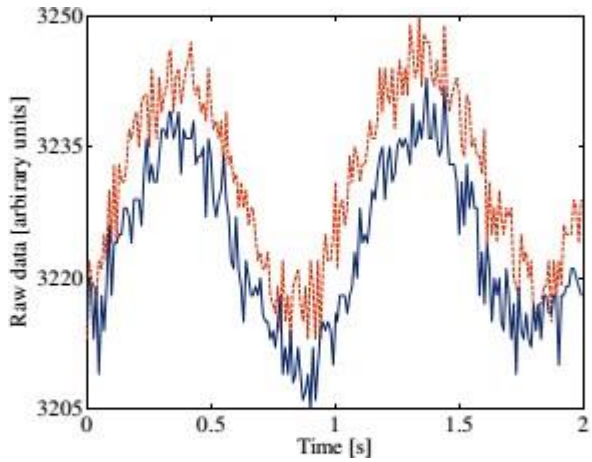


Fig 3.9 Raw Output Data

Advantages

i. A complete LT experiment is carried out by inspecting the specimen at several frequencies, covering a wide range from low to high frequencies, and then a fitting function can be used to complete the amplitude or phase profiles for each point (*i.e.* each pixel).

ii. Direct relationship between depth and the inspection frequency that allows depth estimations to be performed from amplitude or phase data without further processing.

iii. The energy required to perform an LT experiment is generally less than in other active techniques, which might be interesting if a low power source is to be used or if special care has to be given to the inspected part, *e.g.* cultural heritage pieces, works of art, frescoes, etc.

Disadvantages

i. Inspection by lock-in thermography is in general slower than other approaches such as pulsed thermography

Applications

i. Coatings thickness,

ii. Detection of delaminations,

iii. Determination of local fiber orientation,

Vibro Thermography Testing

Vibrothermography (VT), also known as *ultrasound thermography* or *thermosonics*, utilizes mechanical waves to directly stimulate internal defects and without heating the surface as in optical methods (*e.g* LT and PT). If we though of optical lock-in thermography to be the successor of photothermal radiometry as mentioned before, vibrothermography can be seen as the successor of *optoacoustics* or *photoacoustics* in which microphones or piezoceramics in contact with the specimen and a lock-in amplifier were used to detect the thermal wave signature from a defect. This was performed in a point-by-point manner and lack of practical interest at the time. The theory behind however, was the base for the later development of VT.

In the classical ultrasound C-scan NDT inspection, a transducer is placed in contact with the sample with the help of a coupling media. The ultrasonic waves travel through the specimen and are transmitted back to the surface where the transducer pick-up the reflected signal (pulsed-echo technique), or they are collected on the opposite side (transmission). In any case, the principle of defect detection is based on the differences in specific acoustic impedances (Z) between materials. In VT, ultrasonic waves will travel freely through a homogeneous material, whereas an internal defect will produce a complex combination of absorption, scattering, beam spreading and dispersion of the waves, whose principal manifestation will be in the form of heat. Heat then will travel by conduction in all directions, an IR camera can be directed to one of the surfaces of the specimen to capture the defect signature. Ultrasonic waves are ideal for NDT since they are not audible to humans (although some low frequencies harmonics are present), defect detection is independent from of its orientation inside the specimen, and both internal and open surface defects can be detected. Hence, VT is very useful for the detection of cracks and delaminations. Sonic waves, audible for humans, vibrate between 20 Hz and 20 kHz. The range for ultrasonic waves, no audible to humans, is between 20 kHz and 1 MHz, although most transducers operate between 15 and 50 kHz. Unlike electromagnetic waves, mechanical elastic waves such as sonic and ultrasonic waves do not propagate in a vacuum; on the contrary, they require a medium to travel. They travel faster in solids and liquids than through the air. This brings about an important aspect of VT: although contactless (through air) ultrasonics is currently under intense investigation in many areas, the common approach in VT is to use a coupling media such as a piece of fabric water-based gels or aluminum, between the transducer and the specimen to reduce losses. The next paragraph describes the experimental setup for a VT experiment.

Experimental setup and data acquisition for vibrothermography

There are basically two configurations for VT that can be sought as analog to optical methods described above. The first one is lock-in vibrothermography (or amplitude modulated VT), analog to the LT approach; and the second technique is burst vibrothermography, which is analog to PT. These two approaches are illustrated in Figure 3.10 and Figure 3.11.

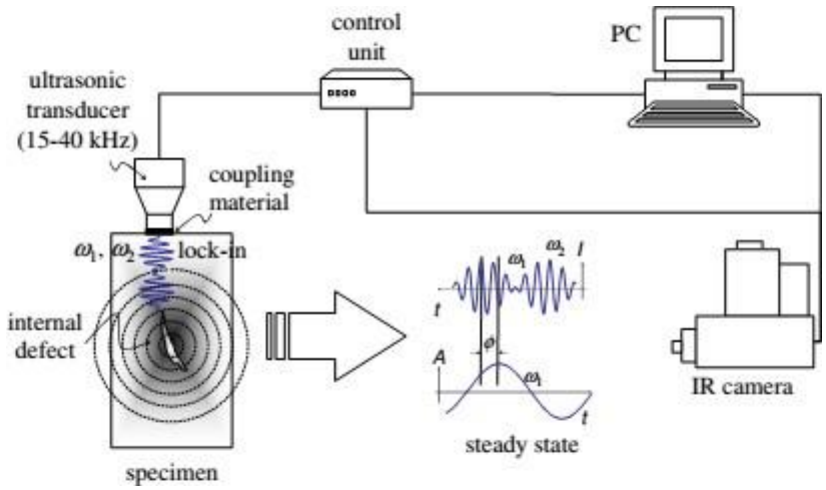


Fig. 3.10 Configuration of lock in vibrothermography

It should be mentioned that is also possible to modulate the frequency either in lock-in or burst VT [40]. This approach is sometimes called *wobbulation*. The idea is to cover a range of ultrasonic frequencies, instead of only one, since it is not always possible to predict the right frequency for a particular application. Ultrasonic wobbulation can be compared to a heat pulse, which is composed of thermal waves at many frequencies. Wobbulation is useful as well to prevent the appearance of *standing waves*, which are produced when working at the natural harmonics resonance frequency of the material. In practice however, it is sometimes preferable to repeat the acquisition at a different frequency since the commercial transducers commonly used are not suitable for frequency modulations.

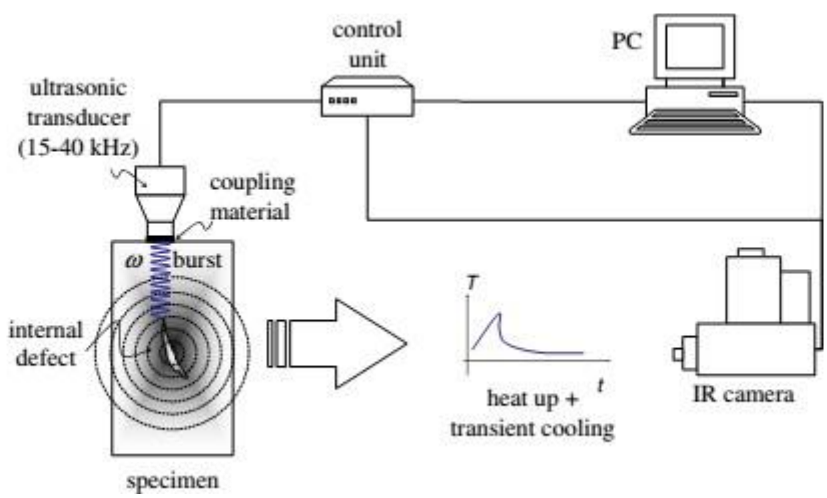


Fig. 3.11 configuration for Burst vibrothermography

The ultrasound wave is produced by a transducer made of a stack of piezo elements and concentrated in a titanium horn that acts like a hammer. Hence, the part being inspected should be firmly immobilized (but without damaging) to avoid cantilever effects, clapping and sliding of the transducer. The transducer horn should be pressed against the sample as well to improve the coupling transmission of the ultrasound into the specimen. Insertion of a material between the transducer and the sample is strongly recommended not only as a coupling medium, but also to avoid damage of the sample and correct misalignment. A bad coupling implies a poor ultrasound transmission but more seriously it creates unwanted heat in the vicinity of the ultrasound injection point.

After the elastic waves are injected to the specimen, they travel through the material and dissipate their energy mostly at the defects so heat is locally released. The thermal waves then travel by conduction to the surface, where they can be detected with an IR camera.

When compared to optical/external techniques, the thermal wave travels half the distance in a VT experiment since heat propagation is performed from the defect to the surface, whereas for optical techniques heat travels from the surface to the defects and back to the surface. Hence, VT is very fast, even faster than PT. A typical experiment last from a fraction of a second to several seconds. In addition, the longer the transducer operates at the surface; the most heat is released at the contact surface, increasing the probability of damaging the area. Furthermore, the pressure applied between the horn and the specimen has a great impact on the thermal response.

Laws of Thermal Imaging in Thermography Testing

Stefan's law of radiation

We know from our daily experience that all hot bodies radiate heat. This was quantified and explained by an Austrian physicist, Joseph Stefan (1853-93) who proposed a law, known as Stefan's law of radiation, which states A body radiates heat per unit area per unit time proportional to the fourth power of its absolute temperature.

$$H = \sigma T^4$$

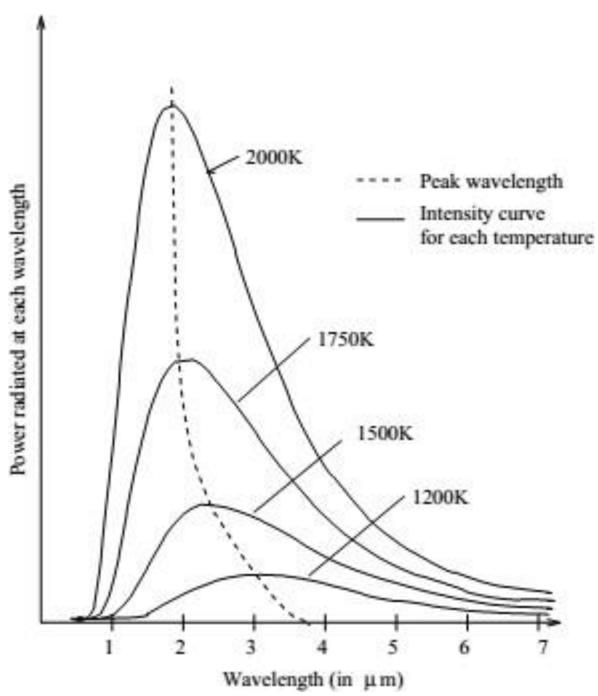
Where H: Heat radiated per unit area per unit time, σ: proportionality constant, known as Stefan's constant = $5.67 \times 10^{-8}\ Wm^{-2}\ K^{-4}$ and T: absolute temperature of the body. The body which follows the aforesaid law is termed as Black body. But, for any real object the law never holds true. So, another parameter was introduced to quantitatively specify the resemblance of an object to a black body. This parameter is known as emissivity (ϙ). Emissivity is defined as the ratio of heat radiated by a real object (H_{object}) at a given temperature to the heat that would have been radiated by an ideal black body ($H_{black-body}$) at the same temperature.

$$€=\frac{H_{object}}{H_{black-body}}$$

Thus, € = 1 signifies that the body is a perfect black body. Materials like lamp black, are having € ≈ 0.95 and are considered to be a black body for all practical purposes. One common way of converting a non-blackbody to a blackbody is to apply a thin layer of black paint on it. The thin paint layer, being in contact with the body, will have the same temperature as that of the body. So overall the object will act like a blackbody.

Wien's displacement law

So far, the radiated energy was referred to as heat. But strictly speaking the energy is released in the form of electro-magnetic wave. Light is an electro-magnetic wave that our eyes respond to. The typical wavelength of visible light varies from 4000˚A to 8000˚A (1˚A = 10^{-10} m). The red light is having the longest wavelength and is least energetic while the violet is having the shortest wavelength and is most energetic. But there is a whole lot of electro- magnetic wave lying beyond the range of visible light. They cannot be seen with the naked eye. Waves having wavelength longer than that of the red are known infra-red (IR) and are primarily emitted by hot bodies. The intensity vs. wavelength plot for a hot body is shown in figure. The figure shows that the intensity of the emitted radiation peaks at some specific wavelength which is the characteristic of temperature. The peak shifts toward the shorter wavelength side with the increase in temperature. This is known as Wien's displacement law. Additionally, the total amount of radiated energy, which is a function of the area under the curve, also increases with temperature as suggested by Stefan's law.

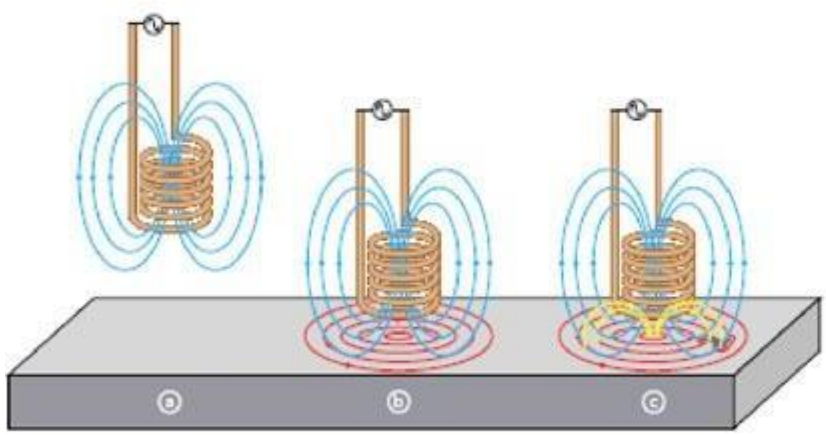


EDDY CURRENT TESTING

INTRODUCTION

Magnetism, the underlying principle behind electric motors and generators, relays and stereo speakers, is also the force that enables an important category of NDT tools called eddy current instruments. Eddy current testing is widely used in the aerospace industry and in other manufacturing and service environments that require inspection of thin metal for potential safety-related or quality-related problems. In addition to crack detection in metal sheets and tubing, eddy current can be used for certain metal thickness measurements such as identifying corrosion under aircraft skin, to measure conductivity and monitor the effects of heat treatment, and to determine the thickness of nonconductive coatings over conductive substrates. Both field portable and fixed system instruments are available to meet a wide variety of test needs.

Eddy current NDT can examine large areas very quickly, and it does not require use of coupling liquids. In addition to finding cracks, eddy current can also be used to check metal hardness and conductivity in applications where those properties are of interest, and to measure thin layers of nonconductive coatings like paint on metal parts. At the same time, eddy current testing is limited to materials that conduct electricity and thus cannot be used on plastics. In some cases, eddy current and ultrasonic testing are used together as complementary techniques, with eddy current having an advantage for quick surface testing and ultrasonics having better depth penetration.



a—The alternating current flowing through the coil at a chosen frequency generates a magnetic field around the coil.

b—When the coil is placed close to an electrically conductive material, eddy current is induced in the material.

c—If a flaw in the conductive material disturbs the eddy current circulation, the magnetic coupling with the probe is changed and a defect signal can be read by measuring the coil impedance variation.

Eddy current testing is based on the physics phenomenon of electromagnetic induction. In an eddy current probe, an alternating current flows through a wire coil and generates an oscillating magnetic field. If the probe and its magnetic field are brought close to a conductive material like a metal test piece, a circular flow of electrons known as an eddy current will begin to move through the metal like swirling water in a stream.

That eddy current flowing through the metal will in turn generate its own magnetic field, which will interact with the coil and its field through mutual inductance. Changes in metal thickness or defects like near- surface cracking will interrupt or alter the amplitude and pattern of the eddy current and the resulting magnetic field. This in turn affects the movement of electrons in the coil by varying the electrical impedance of the coil. The eddy current instrument plots changes in the impedance amplitude and phase angle, which can be used by a trained operator to identify changes in the test piece.

Eddy current density is highest near the surface of the part, so that is the region of highest test resolution. The standard depth of penetration is defined as the depth at which the eddy current density is 37% of its surface value, which in turn can be calculated from the test frequency and the magnetic permeability and conductivity of the test material. Thus, variations in the conductivity of the test material, its magnetic permeability, the frequency of the AC pulses driving the coil, and coil geometry will all have an effect on test sensitivity, resolution, and penetration.

There are many factors that will affect the capabilities of an eddy current inspection. Eddy currents traveling in materials with higher conductivity values will be more sensitive to surface defects but will have less penetration into the material, with penetration also being dependent on test frequency. Higher test frequencies increase near surface resolution but limit the depth of penetration, while lower test frequencies increase penetration. Larger coils inspect a greater volume of material from any given position, since the magnetic field flows deeper into the test piece, while smaller coils are more sensitive to small defects. Variations in permeability of a material generate noise that can limit flaw resolution because of greater background variations.

While conductivity and permeability are properties of the test material that are outside of the operator's control, the test frequency, coil type, and coil size can be chosen based on test requirements. In a given test, resolution will be determined by the probe type while detection capability will be controlled by material and equipment characteristics. Some inspections involve sweeping through multiple frequencies to optimize results, or inspection with multiple probes to obtain the best resolution and penetration required to detect all possible flaws. It is always important to select the right probe for each application in order to optimize test performance.

Advantages

i. Sensitive to small cracks and other defects
ii. Detects surface and near surface defects
iii. Inspection gives immediate results
iv. Equipment is very portable
v. Method can be used for much more than flaw detection
vi. Minimum part preparation is required

vii. Test probe does not need to contact the part

viii. Inspects complex shapes and sizes of conductive material

Limitations

i. Only conductive materials can be inspected

ii. Surface must be accessible to the probe

iii. Skill and training required is more extensive than other techniques

iv. Surface finish and and roughness may interfere

v. Reference standards needed for setup

vi. Depth of penetration is limited

vii. Flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable

Applications

i. Material sorting – mix up of various grade of materials either chemically different or variation in mechanical properties or metallurgically difference in structures can sorted using Eddy current testing equipments.

ii. Surface and subsurface flaw detection in conducting materials. Flaws could be cracks, laminations, and other discontinuities that can be detrimental to the product performance.

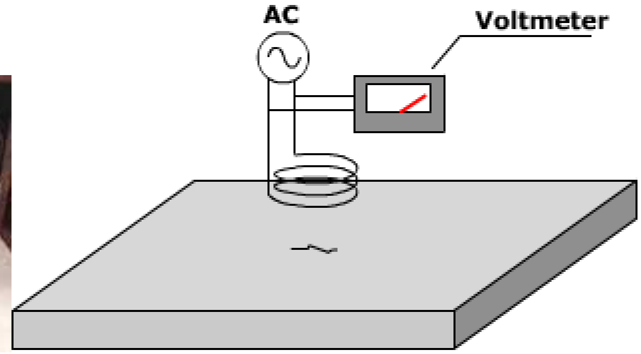
iii. Conductivity testing for metals.

iv. Accurate measurement of Coating thickness with Eddy current testing. The coating can be conductive or non-conductive with few limitations on the accuracy of the measurements.

v. This NDT inspection method can also be used for thickness testing and measurement of especially low thicknesses of conductive materials where there is a restriction on using Ultrasonic thickness gauging due to component configuration or the quantum of inspection. Eddy current inspections can be either contact or non-contact type tests.

vi. Eddy current testing is an effective means of verification of integrity of structures and estimation of corrosion damages for heat exchanger tubes. Routine in-service maintenance inspections using Eddy current techniques yield reliable data for analysis and condition monitoring of plants and structures.

Eddy Current Instruments



Eddy current instruments can be purchased in a large variety of configurations. Both analog and digital instruments are available. Instruments are commonly classified by the type of display used to present the data. The common display types are analog meter, digital readout, impedance plane and time versus signal amplitude. Some instruments are capable of presenting data in several display formats.

The most basic eddy current testing instrument consists of an alternating current source, a coil of wire connected to this source, and a voltmeter to measure the voltage change across the coil. An ammeter could also be used to measure the current change in the circuit instead of using the voltmeter.

Factors that affect Eddy Current Inspection

A number of factors, apart from flaws, will affect the eddy current response from a probe. In order to successfully assess flaws or any of the below factors, we must be able to minimize the effect of other factors on the results. The main factors are:

Material conductivity

The conductivity of a material has a very direct effect on the eddy current field. Conductivity is often measured by an eddy current technique and using eddy currents can help establish the different factors affecting conductivity, such as material composition, heat treatment, work hardening, etc.

Permeability

This may be described as the ease with which a material can be magnetized. For non- ferrous metals (copper, brass, aluminum, etc.), and for austenitic stainless steels the permeability is the same as that of 'free space,' i.e. the relative permeability (μr) is one.

For ferrous metals however the value of μr may be several hundred, and this has a very significant influence on the eddy current response, in addition it is not uncommon for the permeability to vary greatly within a metal part due to localized stresses, heating effects, etc.

For ferrous material the eddy current flow is concentrated extremely close to the surface, making sub-surface defects difficult to detect unlike non-ferrous material unless you strongly magnetize the material or use special remote field probes.

Frequency

Eddy current response is greatly affected by the test frequency chosen. Fortunately this is one property we can control. Higher frequencies reduce the depth of penetration and increase the phase difference between near and far defects making it easier to detect and differentiate smaller defects; lower frequencies increase the depth of signal penetration, enabling deeper testing to be carried out but at the cost of reduced defect sensitivity.

Geometry

In a real part there will be geometrical features such as curvature, edges and grooves and will affect the eddy current response. Test techniques must recognize this in order to maintain consistent inspection results. For example in testing an edge for cracks the probe must be scanned parallel to the edge so that small changes may be easily seen.

Proximity/Lift-Off

Moving a probe coil relative to the surface of the material has two main effects: There will
be a ‘lift-off” signal as the probe is moved.
A reduction in sensitivity as the coil to surface spacing increases.

Depth of Penetration

Eddy current inspection gives stronger signals from a flaw when that flaw is closer to the surface of the material. This signal declines with a greater depth of penetration. Higher conductivity and permeability levels in a material lead to less penetration. However, using a lower frequency can compensate for this.

Eddy Current Testing Probes

Eddy current probes are available in a large variety of shapes and sizes. In fact, one of the major advantages of eddy current inspection is that probes can be custom designed for a wide variety of applications. Eddy current probes are classified by the configuration and mode of operation of the test coils. The configuration of the probe generally refers to the way the coil or coils are packaged to best "couple" to the test area of interest. An example of different configurations of probes would be bobbin probes, which are inserted into a piece of pipe to inspect from the inside out, versus encircling probes, in which the coil or coils encircle the pipe to inspect from the outside in. The mode of operation refers to the way the coil or coils are wired and interface with the test equipment. The mode of operation of a probe generally falls into one of four categories:

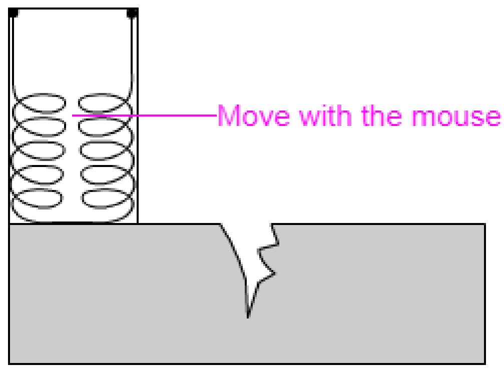
- absolute,
- differential,
- reflection and
- hybrid.

Absolute Probes

Absolute probes generally have a single test coil that is used to generate the eddy currents and sense changes in the eddy current field. As discussed in the physics section, AC is passed through the coil and this sets up an expanding and collapsing magnetic field in and around the coil. When the probe is positioned next to a conductive material, the changing magnetic field generates eddy currents within the material. The generation of the eddy currents take energy from the coil and this appears as an increase in the electrical resistance of the coil. The eddy currents generate their own magnetic field that opposes the magnetic field of the coil and this changes the inductive reactance of the coil. By measuring the absolute change in impedance of the test coil, much information can be gained about the test material.

Absolute coils can be used for flaw detection, conductivity measurements, liftoff measurements and thickness measurements. They are widely used due to their versatility. Since absolute probes are sensitive to things such as conductivity, permeability liftoff and temperature, steps must be taken to minimize these variables when they are not important to the inspection being performed. It is very common for commercially available absolute probes to have a fixed "air loaded" reference coil that compensates for ambient temperature variations.

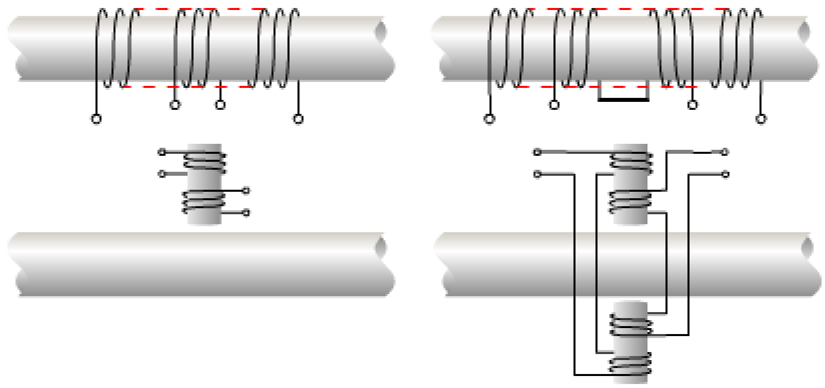
Differential Probes



Differential probes have two active coils usually wound in opposition, although they could be wound in addition with similar results. When the two coils are over a flaw-free area of test sample, there is no differential signal developed between the coils since they are both inspecting identical material. However, when one coil is over a defect and the other is over good material, a differential signal is produced. They have the advantage of being very sensitive to defects yet relatively insensitive to slowly varying properties such as gradual dimensional or temperature variations. Probe wobble signals are also reduced with this probe type. There are also disadvantages to using differential probes. Most notably, the signals may be difficult to interpret. For example, if a flaw is longer than the spacing between the two coils, only the leading and trailing edges will be detected due to signal cancellation when both coils sense the flaw equally.

Reflection Probes

Reflection probes have two coils similar to a differential probe, but one coil is used to excite the eddy currents and the other is used to sense changes in the test material. Probes of this arrangement are often referred to as driver/pickup probes. The advantage of reflection probes is that the driver and pickup coils can be separately optimized for their intended purpose. The driver coil can be made so as to produce a strong and uniform flux field in the vicinity of the pickup coil, while the pickup coil can be made very small so that it will be sensitive to very small defects.



Some absolute and differential "transformer" type eddy current probes

The through-transmission method is sometimes used when complete penetration of plates and tube walls is required.

Hybrid Probes

An example of a hybrid probe is the split D, differential probe shown to the right. This probe has a driver coil that surrounds two D shaped sensing coils. It operates in the reflection mode but additionally, its sensing coils operate in the differential mode. This type of probe is very sensitive to surface cracks. Another example of a hybrid probe is one that uses a conventional coil to generate eddy currents in the material but then uses a different type of sensor to detect changes on the surface and within the test material. An example of a hybrid probe is one that uses a Hall effect sensor to detect changes in the magnetic flux leaking from the test surface. Hybrid probes are usually specially designed for a specific inspection application

Eddy Current Testing Probes on the Basis of Applications

Eddy current probes are classified by the configuration and mode of operation of the test coils. The configuration of the probe generally refers to the way the coil or coils are packaged to best "couple" to the test area of interest. Some of the common classifications of probes based on their configuration include surface probes, bolt hole probes, inside diameter (ID) probes, and outside diameter (OD) probes.

Surface Probes

Surface probes are usually designed to be handheld and are intended to be used in contact with the test surface. Surface probes generally consist of a coil of very fine wire encased in a protective housing. The size of the coil and shape of the housing are determined by the intended use of the probe. Most of the coils are wound so that the axis of the coil is perpendicular to the test surface. This coil configuration is sometimes referred to as a pancake coil and is good for detecting surface discontinuities that are oriented perpendicular to the test surface. Discontinuities, such as delaminations, that are in a parallel plane to the test surface will likely go undetected with this coil configuration.

Wide surface coils are used when scanning large areas for relatively large defects. They sample a relatively large area and allow for deeper penetration. Since they do sample a large area, they are often used for conductivity tests to get more of a bulk material measurement. However, their large sampling area limits their ability to detect small discontinuities.

Pencil probes have a small surface coil that is encased in a long slender housing to permit inspection in restricted spaces. They are available with a straight shaft or with a bent shaft, which facilitates easier handling and use in applications such as the inspection of small diameter bores. Pencil probes are prone to wobble due to their small base and sleeves are sometimes used to provide a wider base

Bolt Hole Probes

Bolt hole probes are a special type of surface probe that is designed to be used with a bolt hole scanner. They have a surface coil that is mounted inside a housing that matches the diameter of the hole being inspected. The probe is inserted in the hole and the scanner rotates the probe within the hole.

ID or Bobbin Probes

ID probes, which are also referred to as Bobbin probes or feed-through probes, are inserted into hollow products, such as pipes, to inspect from the inside out. The ID probes have a housing that keep the probe centered in the product and the coil(s) orientation somewhat constant relative to the test surface. The coils are most commonly wound around the circumference of the probe so that the probe inspects an area around the entire circumference of the test object at one time.

OD or Encircling Coils

OD probes are often called encircling coils. They are similar to ID probes except that the coil(s) encircle the material to inspect from the outside in. OD probes are commonly used to inspect solid products, such as bars.

Magnetic sensors in Eddy Current Testing

There are several magnetic sensors capable of determining values of magnetic flux density. Some of the most mentioned in the literature of non-destructive testing are SQUIDS, fluxgates, Hall probes, magnetoresistive sensors and sensing coils. Sensing coils are used to access the electromotive force (e.m.f.) due to time varying magnetic fields and the other magnetic field sensors measure the magnetic flux density directly.

SQUID

The most sensitive low field sensor is the superconductivity quantum interference device (SQUID). Developed about 1962, its operation is based on two effects: the Josephson junction and the flux quantization. SQUIDs give a measure of the magnetic flux across the pick-up coil section or can have a more complex configuration with two pick-up coils wound in opposite direction, functioning as a magnetic gradiometer. Advantages of SQUID systems for NDE include high sensitivity (≈10-100 fT Hz^{-12}), wide bandwidth (from DC to 10 kHz) and broad dynamic range (>80 dB). Although the extensive research done in the past two decades in the context of NDE in areas like flaw characterization, analysis of the magnetic properties of materials and corrosion, cooling is still a barrier to the acceptance of the method. The development of high temperature superconductivity (HTS) materials in SQUIDs will certainly increase the number of applications but due to their unavoidable higher cost and handling convenience, SQUIDs will always be used only when other NDE sensors fail to ensure the required performance.

Fluxgate

Another magnetic sensor that can provide field sensitivities in the range of a few tens of nano Tesla is fluxgate. Fluxgate sensors measure the absolute strength of a surrounding magnetic field. In the most common type, the measuring principle is based on the "second harmonic principle". The sensor incorporates two coils, a primary and a secondary, wrapped around a common high-permeability ferromagnetic core. A current in the primary coil produces a field which periodically saturates (in both directions) the probe coil. If an external magnetic field is applied to the sensor, the symmetry of the cycling saturation is disturbed and a second harmonic amplitude of the reference signal corresponding to the external field strength appears. Fluxgate sensors have a field sensitivity up to 10 pT/√Hz in the range [10^{-10} ; 10^{-3}] T, a frequency bandwidth from DC to 1 kHz and a dynamic range of more than 140 dB. As depicted in Table 1 fluxgate sensors present some advantages for nondestructive testing when compared with other magnetic sensors, however these devices tend to be bulky and not so rugged as smaller more integrated sensor technologies.

Hall Sensor

Hall sensor is a slab of a semiconductor material and its operation is based on Hall effect. When a current is applied from one end of the slab material to the other charge carriers begin to flow. If at the same time an external magnetic field, B, is applied to the slab, the current carriers are deflected by Lorentz force and give rise to an output voltage proportional to B. The effect occurs either with direct or alternating fields and the voltage across the two parallel faces varies at the same frequency as B, provided the current is DC. Flux density can be measure from 100 nT with a resolution better that 1 nT. The active areas are as small as $(0.1\times0.025).10^{-3}$ m. The sensitive layer of the device lays parallel to the surface of the testing sample and measures the magnetic field in a direction perpendicular to the surface.

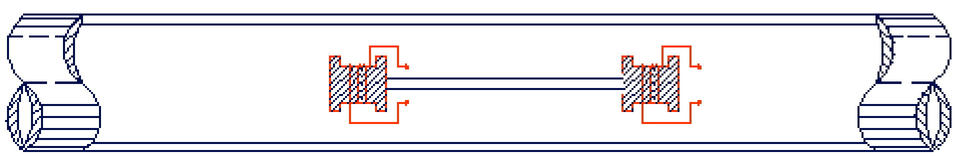
Anisotropic Magnetoresistance

The dependence of the change of electrical resistance of a material on the angle between the direction of electric current and direction of magnetization, known as anisotropic magnetoresistance (AMR), was first observed by William Thomson (Lord Kelvin) in 1851. It was only 100 years later that thin films technology made possible the manufacture of practical sensors exhibiting a sufficiently large magnetoresistive effect to be used in measurements. AMR have a sensitivity 1 mG to 6 G, a frequency bandwidth from DC to 5 MHz and a dynamic range of 120 dB. They have a limited magnetic field range meaning that their saturation field is quite low. These solid state magnetic sensors can be one, two and three-axis.

Giant Magnetoresistance

Giant magnetoresistors (GMR) are devices based on the giant magnetoresistivity phenomenon reported for the first time in 1988. The best use of GMR for magnetic field sensors is with a Wheatstone bridge configuration.

Remote Field Sensing



Eddy current testing for external defects in tubes where external access is not possible (e.g. buried pipelines), is conducted using internal probes. When testing thick-walled ferromagnetic metal pipes with conventional internal probes, very low frequencies (e.g. 30 Hz for a steel pipe 10 mm thick) are necessary to achieve the through-penetration of the eddy currents. This situation produces a very low sensitivity of flaw detection. The degree of penetration can, in principle, be increased by the application of a saturation magnetic field. However, because of the large volume of metal present, a large saturation unit carrying a heavy direct current may be required to produce an adequate saturating field.

The difficulties encountered in the internal testing of ferromagnetic tubes can be greatly alleviated with the use of the remote field eddy current method. This method provides measurable through penetration of the walls at three times the maximum frequency possible with the conventional direct field method. This technique was introduced by Schmidt in 1958.

Although it has been used by the petroleum industry for detecting corrosion in their installations since the early 1960s, it has only recently evoked general interest. This interest is largely because the method is highly sensitive to variations in wall thickness, but relatively insensitive to fill-factor changes. The method has the added advantage of allowing equal sensitivities of detection at both the inner and outer surfaces of a ferromagnetic tube. It cannot, however, differentiate between signals from these respective surfaces.

Practical application of Eddy current testing Detection of

Surface Breaking Cracks

Eddy current equipment can be used for a variety of applications such as the detection of cracks (discontinuities), measurement of metal thickness, detection of metal thinning due to corrosion and erosion, determination of coating thickness, and the measurement of electrical conductivity and magnetic permeability. Eddy current inspection is an excellent method for detecting surface and near surface defects when the probable defect location and orientation is well known.

Defects such as cracks are detected when they disrupt the path of eddy currents and weaken their strength. The images to the right show an eddy current surface probe on the surface of a conductive component. The strength of the eddy currents under the coil of the probe ins indicated by color. In the lower image, there is a flaw under the right side of the coil and it can be see that the eddy currents are weaker in this area.

Of course, factors such as the type of material, surface finish and condition of the material, the design of the probe, and many other factors can affect the sensitivity of the inspection. Successful detection of surface breaking and near surface cracks requires:

1. A knowledge of probable defect type, position, and orientation.
2. Selection of the proper probe. The probe should fit the geometry of the part and the coil must produce eddy currents that will be disrupted by the flaw.
3. Selection of a reasonable probe drive frequency. For surface flaws, the frequency should be as high as possible for maximum resolution and high sensitivity. For subsurface flaws, lower frequencies are necessary to get the required depth of penetration and this results in less sensitivity. Ferromagnetic or highly conductive materials require the use of an even lower frequency to arrive at some level of penetration.
4. Setup or reference specimens of similar material to the component being inspected and with features that are representative of the defect or condition being inspected for.

The basic steps in performing an inspection with a surface probe are the following:

1. Select and setup the instrument and probe.

2. Select a frequency to produce the desired depth of penetration.
3. Adjust the instrument to obtain an easily recognizable defect response using a calibration standard or setup specimen.
4. Place the inspection probe (coil) on the component surface and null the instrument.
5. Scan the probe over part of the surface in a pattern that will provide complete coverage of the area being inspected. Care must be taken to maintain the same probe- to-surface orientation as probe wobble can affect interpretation of the signal. In some cases, fixtures to help maintain orientation or automated scanners may be required.
6. Monitor the signal for a local change in impedance that will occur as the probe moves over a discontinuity.

UNIT- IV

ULTRASONIC TESTING AND ACOUSTIC EMISSION TESTING

Fundamental principles:

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.

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

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 $Z\backslash$ 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.

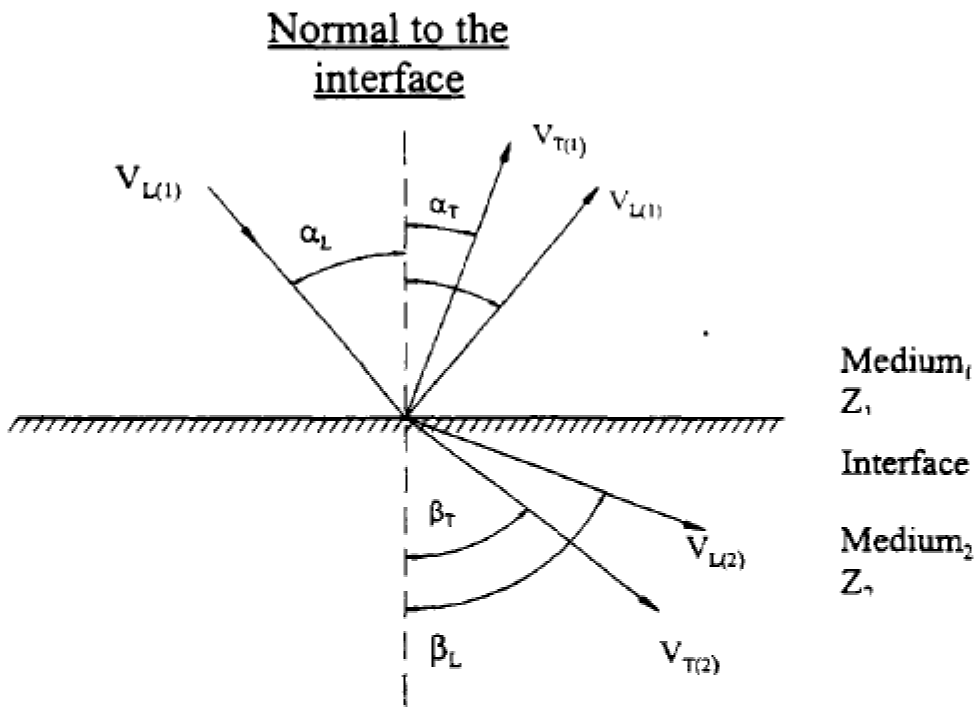


Figure: Phenomena of reflection, refraction and mode conversion for an incident wave.

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.

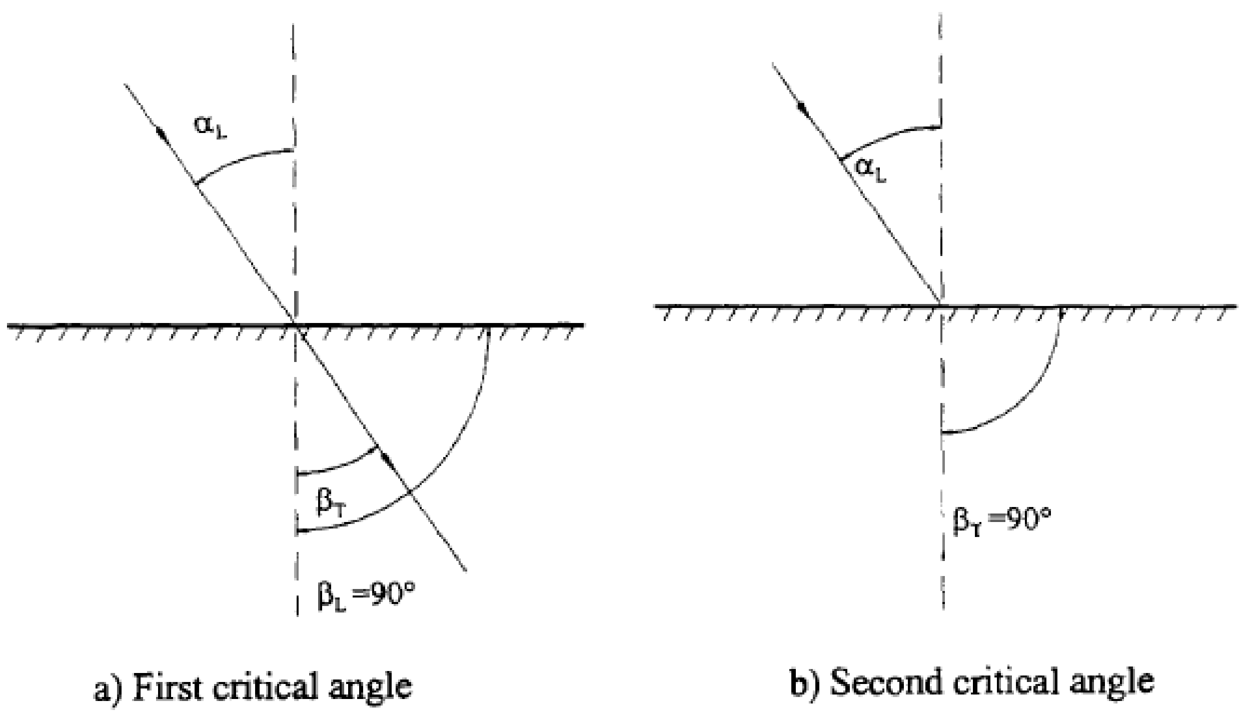


Figure : First and second critical angles.

2.1 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.

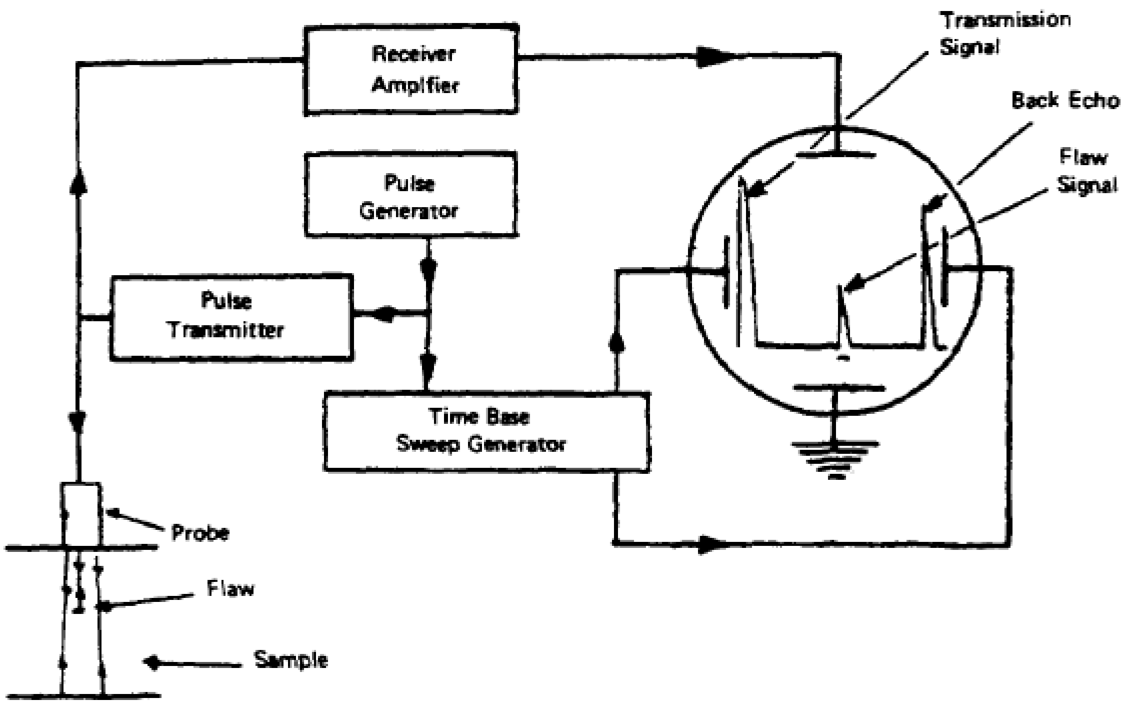


Figure: A typical ultrasonic test unit.

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.

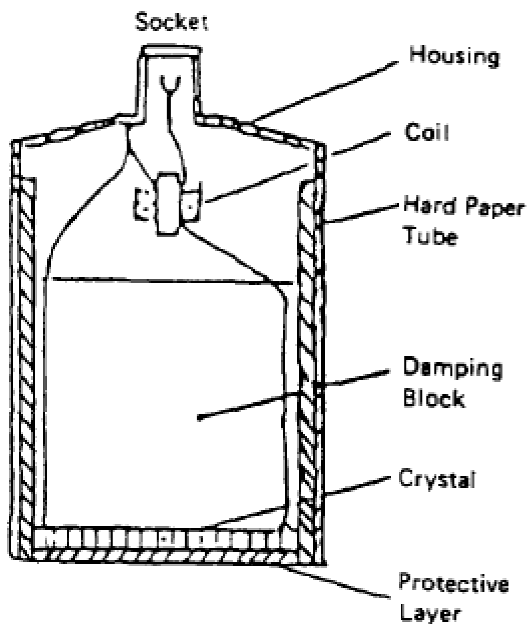


Figure: A typical normal beam single crystal ultrasonic probe.

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

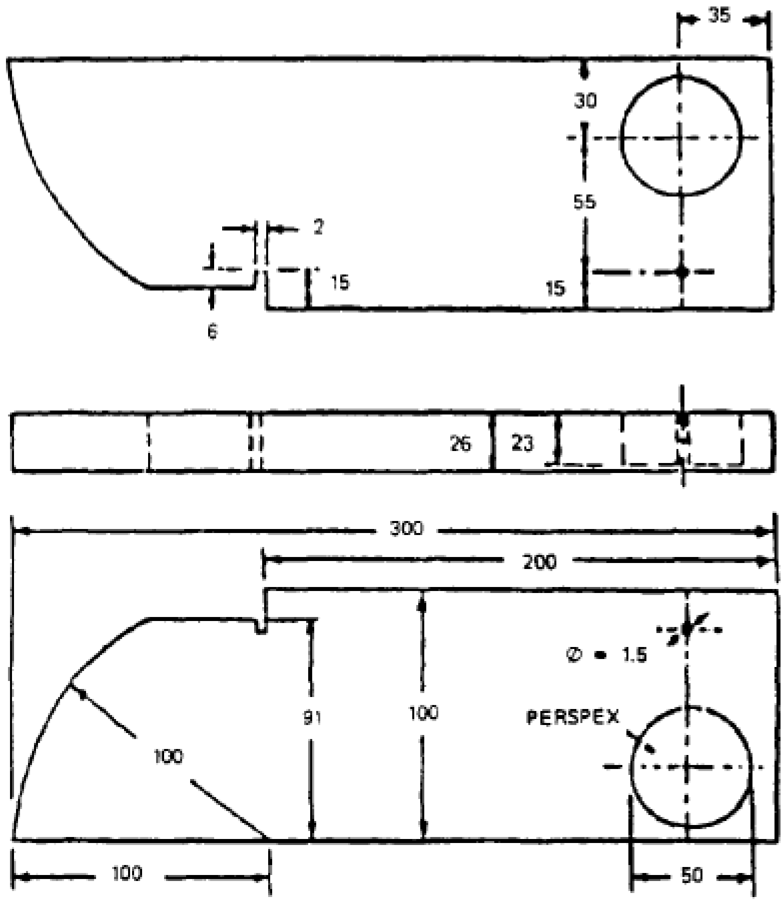


Figure : I.I.W test block.

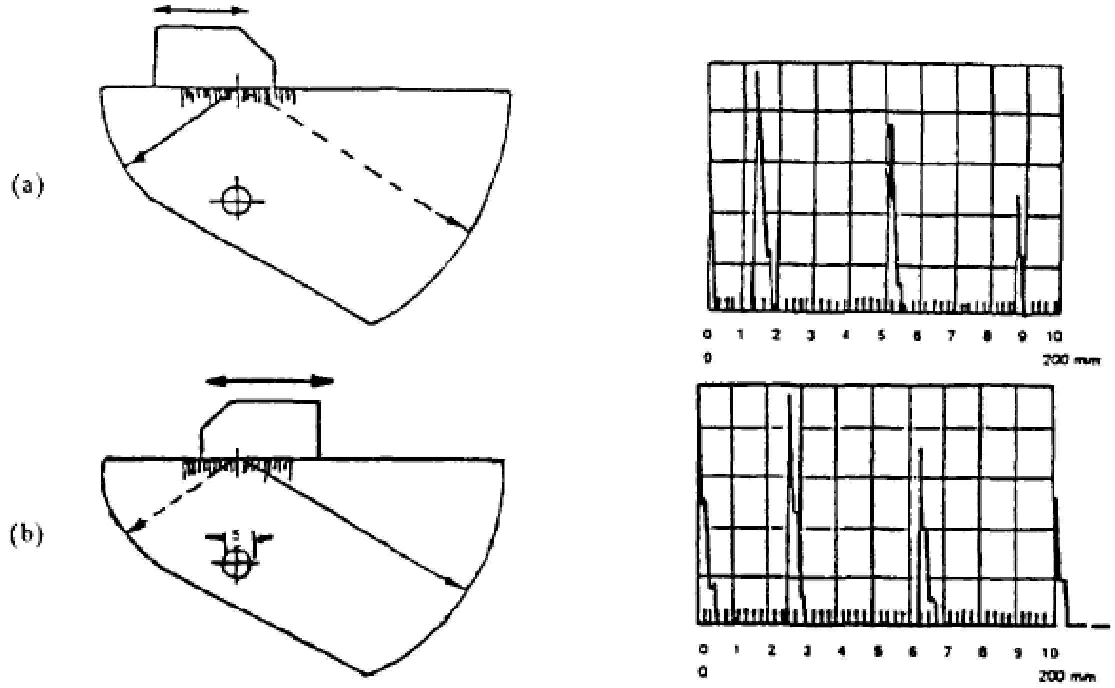


Figure : V2 test block (a) with the probe index at the zero point and directed to the 25 mm radius, (b) with the probe index at the zero point and directed to the 50 mm radius.

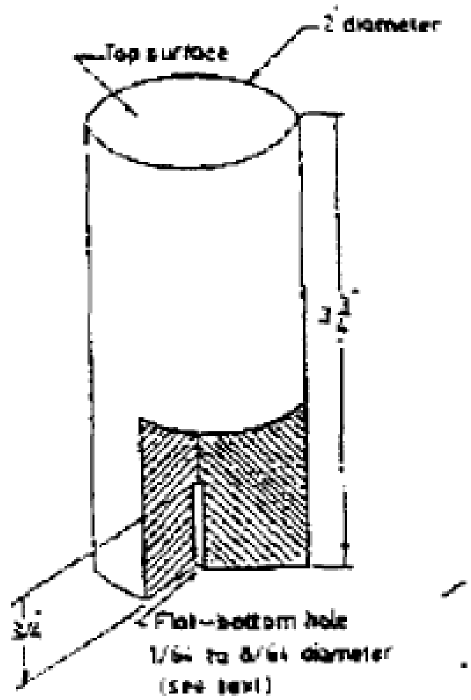


Figure : Flat bottom hole type test block.

2.2 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.

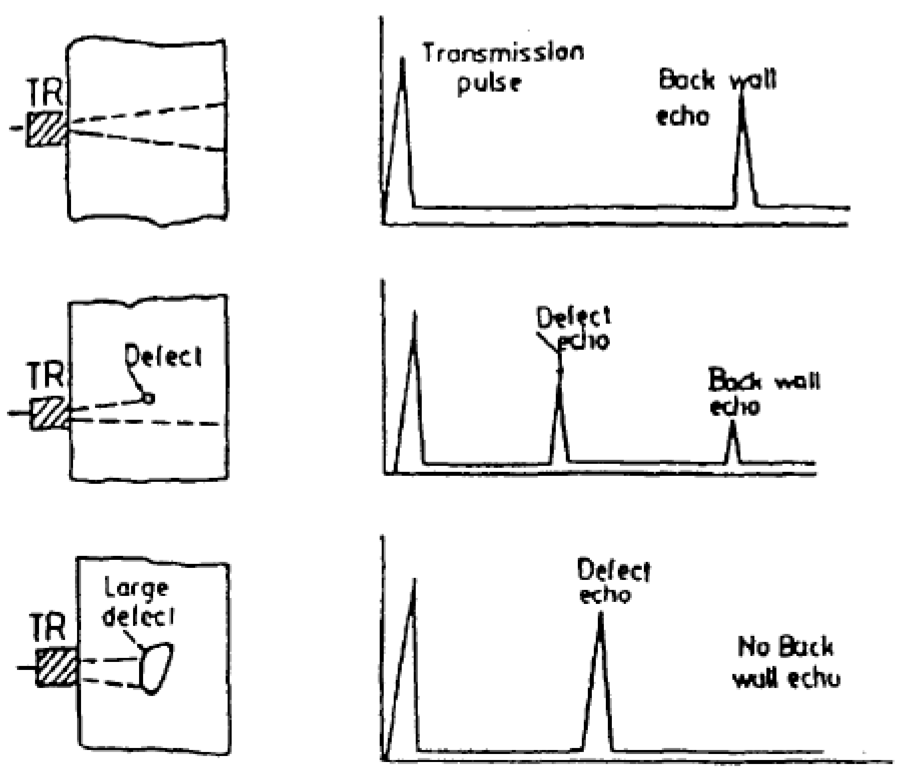


Figure: Principle of pulse echo method of ultrasonic testing (a) defect free specimen (b) specimen with small defect (c) specimen with large defect.

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.

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.

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.

Disadvantages

1. Manual operation requires careful attention by experienced technicians.
2. Extensive technical knowledge is required for the development of inspection procedures.
3. Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.
4. Discontinuities that are present in a shallow layer immediately beneath the surface may not be detectable.
5. Couplants are needed to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected.
6. Reference standards are needed, both for calibrating the equipment and for characterizing flaws.

UNIT- V

RADIOGRAPHY

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.

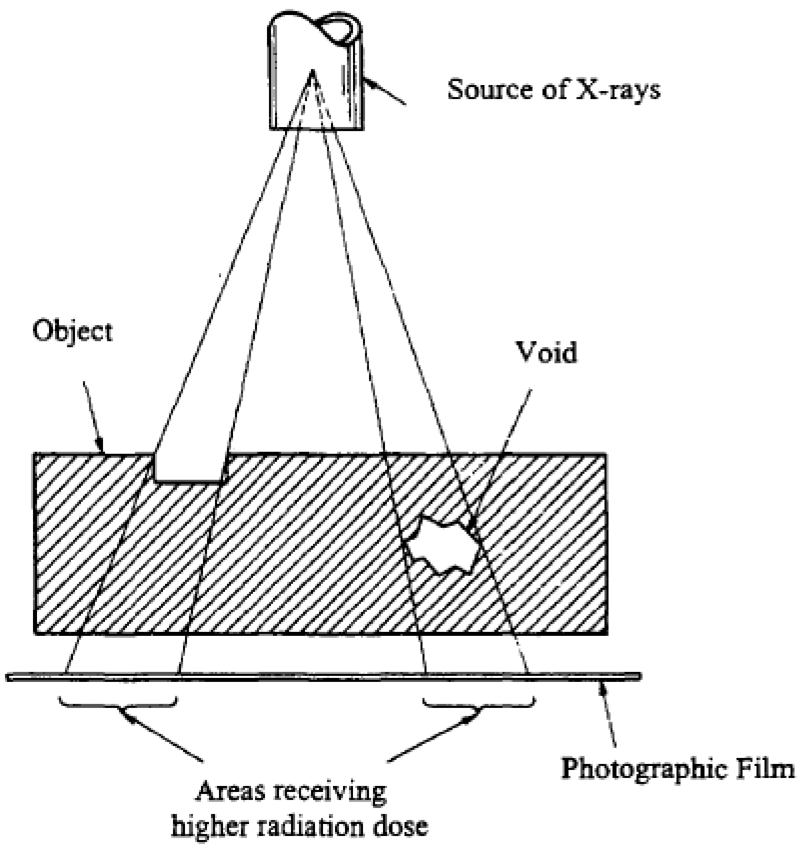


Figure : Arrangement of source, specimen and film in a typical radiographic set up

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 1= the intensity of X-rays transmitted through a thickness x of material having attenuation coefficient u .

(x) They affect photographic emulsions.

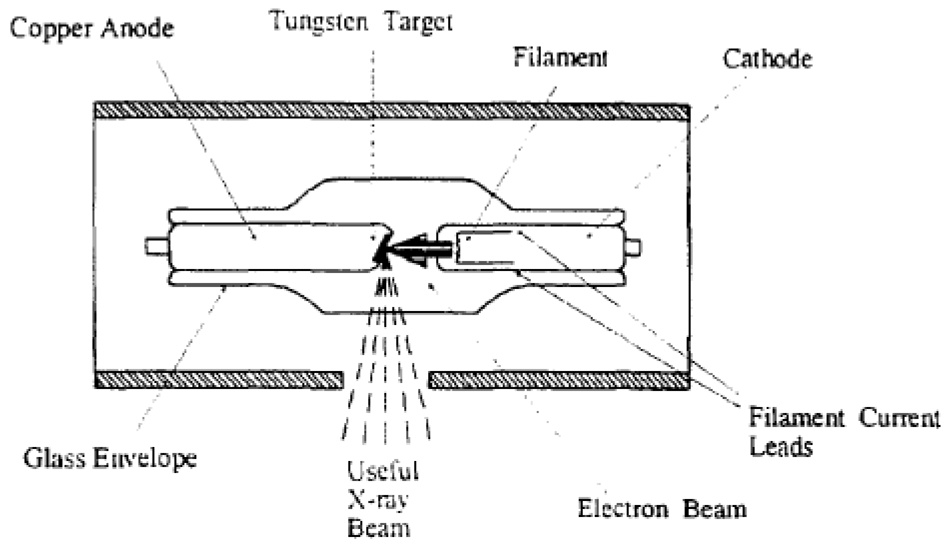
(xi) While passing through a material they are either absorbed or scattered.

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.



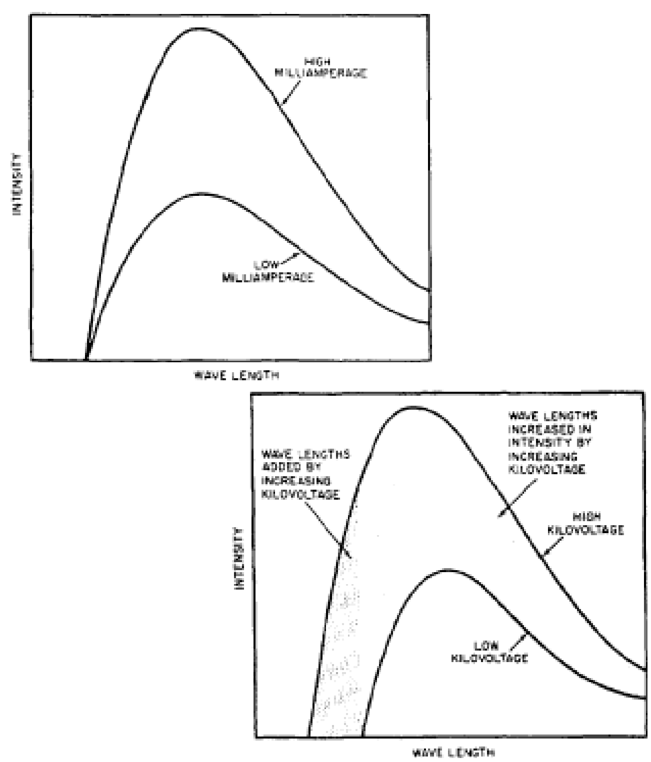


Figure : Effect of tube current (mA) and voltage (kV) on the intensity of X rays.

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.

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.

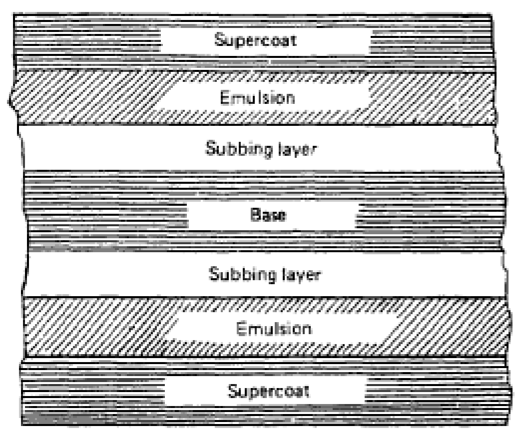


Figure : Construction of radiographic films

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.

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:

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.

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.

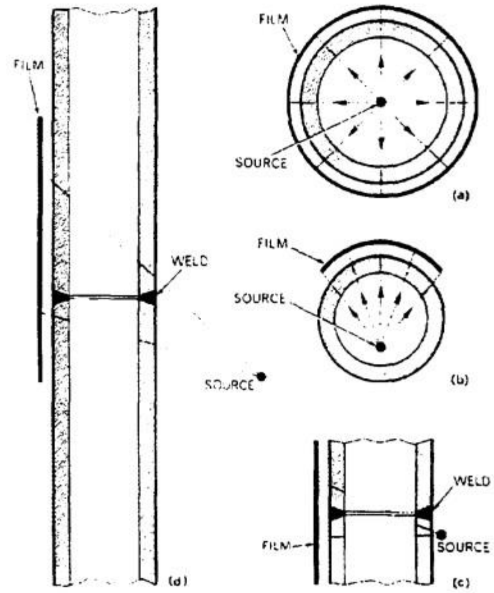


Figure 3.15: Various techniques for weld inspection.

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.