Programme-	**B. Tech**
Course -	**NON DESTRUCTIVE TESTING**
Course Code-	**BTOE-414 (2)**
Sem-	**7th**
Year-	**2020-21**
Unit-	**1**
Topic-	**Magnetic Particle Testing**
Sub-Topic-	**Magnetic Particle Testing, Magnets and magnetic materials, Magnetization and its methods, Magnetic fields, Detection media, Application of magnetic particles testing, Testing equipments machines and accessories, Inspection and interpretation, Application in industry. Liquid Penetrant Testing, Principle of liquid penetrant testing, Methods, Their advantages and disadvantages, Equipment used Penetrant materials, testing procedures, Inspection and interpretation, Applications in industry.**
Faculty-	**Vikas Kumar Tyagi**
E-mail-	**vikas.kumar.tyagi@monad.edu.in**

Overview of Non-destructive Testing (NDT):-

Non-destructive Testing (NDT) consists of a variety of non-invasive inspection techniques used to evaluate material properties, components, or entire process units. The techniques can also be utilized to detect, characterize, or measure the presence of **damage mechanisms** (e.g. corrosion or **cracks**). NDT is also commonly referred to as non-destructive examination (NDE), non-destructive evaluation (NDE), and non-destructive inspection (NDI). Many NDT techniques are capable of locating defects and determining the features of the defects such as size, shape, and orientation. The purpose of NDT is to inspect a component in a safe, reliable, and cost effective manner without causing damage to the equipment or shutting down plant operations. This is in contrast to destructive testing where the part being tested is damaged or destroyed during the inspection process.

NDT can be performed during or after manufacture, or even on equipment that is in service. In manufacturing, NDT inspections determine if parts are fit for a desired function. In other words, parts are inspected to ensure they will last a certain amount of time or cycles before failure. During operation, NDT inspections can be used to asses the current damage state of equipment, monitor damage mechanisms, and make informed decisions for remaining equipment life evaluations (e.g., **RBI**, **FFS**).

Overview of NDT Methods

NDT methods can generally be classified into two categories: conventional and advanced. Each method has its own characteristic advantages and limitations. More information on each test can be found in their respective Integripedia definitions.

Conventional NDT Techniques

Conventional methods are techniques that have matured over the course of decades and in this time, have become well-documented in codes, standards, and best practices. The setup and procedure of a conventional technique is typically simpler in comparison to advanced methods.

- **Acoustic Emission Testing** (AET)
- **Infrared Testing** (IR)
- Leak Testing (LT)
- **Liquid Penetrant Testing** (PT)
- Electromagnetic Testing (ET)
- **Magnetic Particle Testing** (MPT)
- **Radiographic Testing** (RT)
- Film Radiography (FR)
- **Ultrasonic Testing** (UT)
- Straight Beam
- **Vibration Analysis (VA)**
- **Visual Inspection** (VI)

Advanced NDT Techniques

Advanced methods tend to be less understood as they progress as emerging technologies, e.g. uncertain advantages or limitations, lack of technician qualification criteria, or little to no industry codification. Generally, the setup, procedure, and data interpretation of advanced methods is more complicated and can require specialized understanding and experience from a properly trained technician.

Furthermore, some methods can be further broken down into conventional and advanced techniques. Take two forms of ultrasonic testing for example, straight beam ultrasonic testing (UT) is a conventional technique used in simple applications whereas phased array ultrasonic testing (PAUT) is an advanced UT technique. As advanced techniques mature, new and more advanced versions of each emerge to start a new cycle of technical understanding and technician training.

- Electromagnetic Testing (ET)
    - Alternating Current Field Measurement
    - Eddy Current Testing (ECT)
    - **Magnetic Flux Leakage** (MFL)
- Laser Testing Methods (LM)
    - Holographic Testing
    - **Laser Profilometry**
    - Laser Shearography
- **Radiographic Testing** (RT)
    - Computed Radiography (CR)
    - Computed Tomography (CT)
    - Digital Radiography (DR)
- **Ultrasonic Testing** (UT)
    - Angle Beam
    - **Automated Ultrasonic Backscatter Technique (AUBT)**
    - **Electromagnetic Acoustic Transducer (EMAT)**
    - Immersion Testing
    - **Internal Rotary Inspection System (IRIS)**
    - **Long Range Ultrasonic Testing (LRUT)**
    - **Phased Array Ultrasonic Testing (PAUT)**
    - **Time-of-Flight-Diffraction (TOFD)**

Overall, NDT offers many advantages compared to destructive testing. The testing equipment is often portable and can be performed numerous times on a single component. The component itself can be thoroughly evaluated externally and internally for harmful flaws. The disadvantage is that the results are often qualitative and may be repeated and interpreted differently by various inspectors.

Industry Applications of NDT

NDT inspections are an integral part of the oil and gas and petrochemical industries, along with several other industries, including chemicals, aerospace, automotive, and defense. The overall goal of all these industries is to detect flaws in components to reduce failure and increase reliability.

In the petrochemical industry, NDT inspections are utilized throughout a facility's lifecycle. This cradle-to-grave approach is an important element of **asset integrity management**. Furthermore, NDT inspections provide historical data about the facility's process units and provide information on how often a component should be inspected, repaired, or replaced. Inspection intervals and tests may be changed depending on where the equipment is in its life-cycle (e.g. newly manufactured equipment vs. aging equipment). Performing multiple assessments throughout the equipment's life-cycle may seem expensive. However, inspections conducted at specific intervals may end up saving an organization millions of dollars if testing reveals threats and equipment is repaired before shutting down the facility or experiencing a catastrophic failure.

The most common pieces of equipment that undergo inspection in the petrochemical industry are storage tanks, heat exchangers, pressure vessels, and piping systems. When planning an NDT inspection, there are four considerations one should account for:

1. The type of damage mechanism to be inspected for
2. The minimum detectable flaw size, shape, and orientation of the defect
3. Where the defect is located (surface or internal)
4. The sensitivities and limitations of the NDT method

With the above factors considered, operators can optimize facility production and increase personnel and environmental safety.

Codes and Standards Bodies

NDT is often prescribed by **codes and standards** for the fabrication of components, safety critical parts, and in-service equipment. Therefore, it is critical for all refinery, chemical plant, gas plant, and pipeline owners to have thorough understanding and experience in the interdisciplinary field of NDT. In addition to the factors listed above (*Industry Application section*) personnel should continuously develop knowledge about evolving technology and performing up-to-date procedures.

Specific codes, standards, specifications, regulations, and recommended practices may depend on the country and industry performing NDT. The following is a list of organizations (standards bodies) that develop and publish industrial codes, standards, and recommended practices for NDT methods relating to the oil and gas and chemical processing industries:

- **The American Society for Non-destructive Testing** (ASNT)
- **ASTM International**
- **American Society of Mechanical Engineers** (ASME)
- **American Petroleum Institute** (API)
- **American Welding Society** (AWS)
- **National Board of Boiler and Pressure Vessel Inspectors** (NBBI)
- **International Organization for Standardization** (ISO)
- European Committee for Standardization (CEN)
- European Pressure Equipment Directive (PED)

A complete list of regulations created by the U.S. government may be found in the Code of Federal Regulations (CFR). Regulations critical to the petrochemical and chemical processing industries can be found under Title 10, Energy, and Title 49, Transportation.[1]

Training and Certification

Levels of Certification

Many NDT programs have three levels of qualification. A brief description of Level I, Level II, and Level III qualifications are outlined below and found in the ASNT Recommended Practice No. SNT-TC-1A document.[2]

Level I: At the end of a Level I certification program, individuals should be able to perform specific calibrations, specific NDT, and specific evaluations to determine if a component should be accepted or rejected for service.

Level II: Level II individuals should have the same abilities as Level I individuals and additionally, should be able to set-up, calibrate, perform, and evaluate NDT results with respect to applicable codes, standards, and specifications.

Level III: The highest qualified level of NDT personnel should have the same abilities as Level II individuals and additionally, be able to develop and qualify procedures, establish and approve techniques, interpret codes, standards, specifications and procedures, and assign particular NDT methods to use in specific applications.

Certification Requirements

Requirements are based on a combination of training, examination, and experience. Training is based on an accumulation of training course outlines from the NDT Body of Knowledge document. More detail on the ASNT NDT Body of Knowledge can be found in the ANSI/ASNT American National Standard CP-105. The purpose of the Body of Knowledge is to describe the knowledge and skills needed for different levels of certification. Several types of examinations are also necessary to meet minimum requirements and to recertify. Individuals may have to take a written exam, specific exam, or a practical exam depending on the certification desired. Experience in NDT or NDT-related fields as well as on-the-job training programs are also considered for certification.

Accredited Bodies for Training and Certification

American Petroleum Institute (API) — API offers numerous Individual Certification Programs (ICPs) specific to NDT personnel in the petroleum and petrochemical industries.

American Society for Non-destructive Testing (ASNT) — ASNT is a globally recognized organization that offers credentials for NDT personnel in a broad range of industries. Current certification programs include ASNT NDT Level II, ASNT NDT Level III, ASNT Central Certification Program (ACCP), and Industrial Radiography and Radiation Safety Personnel (IRRSP).

British Institute of Non-Destructive Testing (BINDT) — BINDT is an accredited certification body and offers a Personnel Certification in Non-Destructive Testing (PCN).

International Standards Organization (ISO) — ISO 9712 (Non-destructive testing -- Qualification and certification of NDT personnel) is a published standard that details the requirements for qualification and certification of personnel that perform NDT.

Natural Resources Canada (NRCan) — NRCan manages the Non-Destructive Testing Certification Body (NDTCB) which offers a Canadian General Standards Board (CGSB) certification.

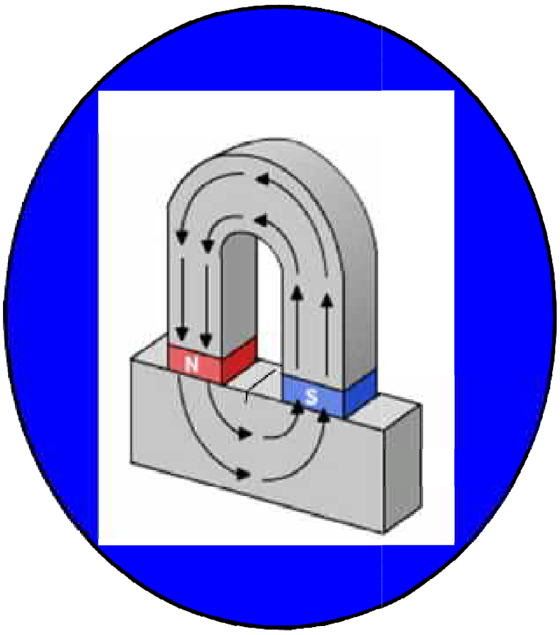
The Welding Institute (TWI) — TWI offers personnel credentials through their accredited CSWIP certification schemes.

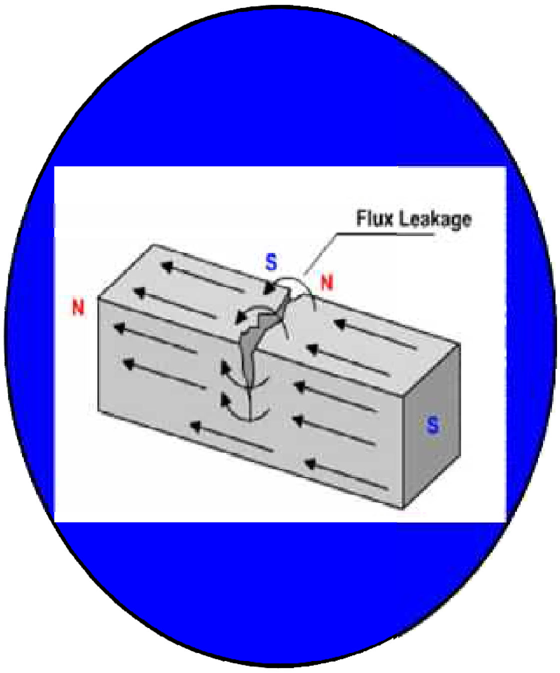
References:

1. 2016, "Codes and Standards Bodies Involved in NDT Industry," ASNT.
2. 2016, "Recommended Practice No. SNT-TC-1A: Personnel Qualification and Certification in Non-destructive Testing (2016)," ASNT.

Magnetic Particle Testing- is one of the most widely utilized NDT methods since it is fast and relatively easy to apply and part surface preparation is not as critical as it is for some other methods. This method uses magnetic fields and small magnetic particles (i.e. iron filings) to detect flaws in components. The only requirement from an inspect ability standpoint is that the component being inspected must be made of a ferromagnetic material (a materials that can be magnetized) such as iron, nickel, cobalt, or some of their alloys. The method is used to inspect a variety of product forms including castings, forgings, and weldament. Many different industries use magnetic particle inspection such as structural steel, automotive, petrochemical, power generation, and aerospace industries. Underwater inspection is another area where magnetic particle inspection may be used to test items such as offshore structures and underwater pipelines.

Basic Principles –





In theory, magnetic particle testing has a relatively simple concept. It can be considered as a combination of two non-destructive testing methods: magnetic flux leakage testing and visual testing. For the case of a bar magnet, the magnetic field is in and around the magnet. Any place that a magnetic line of force exits or enters the magnet is called a "pole" (magnetic lines of force exit the magnet from north pole and enter from the south pole).When a bar magnet is broken in the center of its length, two complete bar magnets with magnetic poles on each end of each piece will result. If the magnet is just cracked but not broken completely in two, a north and south pole will form at each edge of the crack. The magnetic field exits the North Pole and re-enters at the South Pole. The magnetic field spreads out when it encounters the small air gap created by the crack because the air cannot support as much magnetic field per unit volume as the magnet can. When the field spreads out, it appears to leak out of the material and, thus is called a flux leakage field.

Magnetic Particle Testing If iron particles are sprinkled on a cracked magnet, the particles will be attracted to and cluster not only at the pole sat the ends of the magnet, but also at the poles at the edges of the crack. This cluster of particles is much easier to see than the actual crack and this is the basis for magnetic particle inspection. The first step in a magnetic particle testing is to magnetize the component that is to be inspected. If any defects on or near the surface are present, the defects will create a leakage field. After the component has been magnetized, iron particles, either in a dry or wet suspended form, are applied to the surface of the magnetized part. The particles will be attracted and cluster at the flux leakage fields, thus forming a visible indication that the inspector can detect.

Advantages and Disadvantages:-The primary advantages and disadvantages when compared to other NDT methods are:

Advantages

•High sensitivity (small discontinuities can be detected).

•Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.

•Minimal surface preparation (no need for paint removal)

•Portable (small portable equipment & materials available in spray cans)

•Low cost (material sand associated equipment is relatively inexpensive)

Disadvantages –

Only surface and near surface defects can be detected.

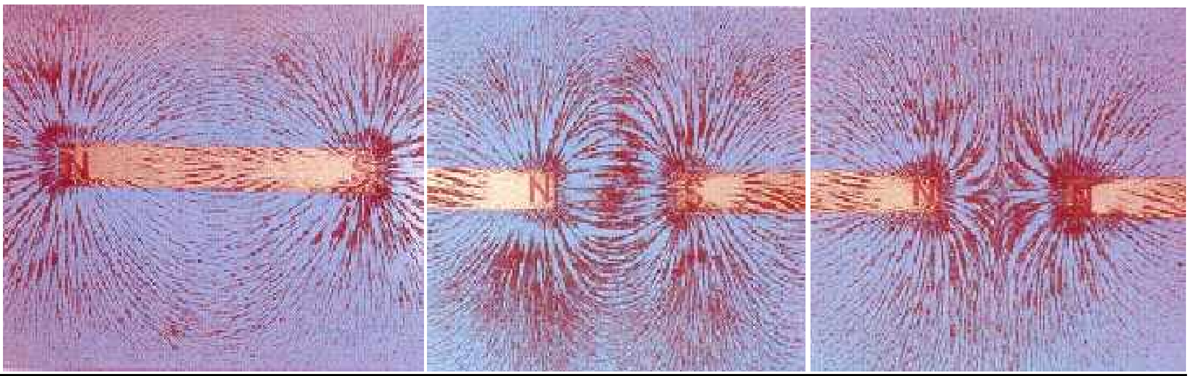
•Only applicable to ferromagnetic materials.

•Relatively small area can be inspected at a time.•

Only materials with a relatively nonporous surface can be inspected.

•The inspector must have direct access to the surface being inspected.

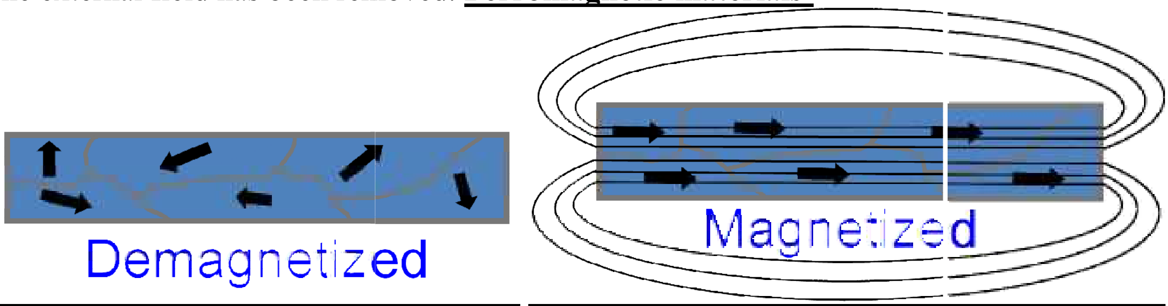
Magnetism:-



The concept of magnetism centers around the magnetic field and what is known as a dipole. The term "magnetic field" simply describes a volume of space where there is a change in energy within that volume. The location where a magnetic field exits or enters a material is called a magnetic pole. Magnetic poles have never been detected in isolation but always occur in pairs, hence the name dipole. Therefore, a dipole is an object that has a magnetic pole on one end and a second, equal but opposite, magnetic pole on the other. A bar magnet is a dipole with a north pole at one end and South Pole at the other. The source of magnetism lies in the basic building block of all matter, the atom. Atoms are composed of protons, neutrons and electrons. The protons and neutrons are located in the atom's nucleus and the electrons are in constant motion around the nucleus. Electrons carry a negative electrical charge and produce a magnetic field as they move through space. A magnetic field is produced whenever an electrical charge is in motion. The strength of this field is called the magnetic moment. When an electric current flows through a conductor, the movement of electrons through the conductor causes a magnetic field to form around the conductor. The magnetic field can be detected using a compass. Since all matter is comprised of atoms, all materials are affected in some way by a magnetic field; however, materials do not react the same way to the magnetic field.

Reaction of Materials to Magnetic Field: - When a material is placed within a magnetic field, the magnetic forces of the material's electrons will be affected. This effect is known as Faraday's Law of Magnetic Induction. However, materials can react quite differently to the presence of an external magnetic field. The magnetic moments associated with atoms have three origins: the

electron motion, the change in motion caused by an external magnetic field, and the spin of the electrons .In most atoms, electrons occur in pairs where these pairs spin in opposite directions. The opposite spin directions of electron pairs cause their magnetic fields to cancel each other. Therefore, no net magnetic field exists. Alternately, materials with some unpaired
Electrons will have a net magnetic field and will react more to an external field. According to their interaction with a magnetic field, materials can be classified as:
Diamagnetic materials- which have a weak, negative susceptibility to magnetic fields. Diamagnetic materials are slightly repelled by a magnetic field and the material does not retain the magnetic properties when the external field is removed. In diamagnetic materials all the electrons are paired so there is no permanent net magnetic moment per atom. Most elements in the periodic table, including copper, silver, and gold, are diamagnetic.
Paramagnetic materials: - which have a small, positive susceptibility to magnetic fields. These materials are slightly attracted by a magnetic field and the material does not retain the magnetic properties when the external field is removed. Paramagnetic materials have some unpaired electrons. Examples of paramagnetic materials include magnesium, molybdenum, and lithium. Ferromagnetic materials have a large, positive susceptibility to an external magnetic field. They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties after the external field has been removed. **Ferromagnetic materials-**



Ferromagnetic materials have some unpaired electrons so their atoms have a net magnetic moment. They get their strong magnetic properties due to the presence of magnetic domains. In these domains, large numbers of atom's moments are aligned parallel so that the magnetic force within the domain is strong (this happens during the solidification of the material where the atom moments are aligned with in each crystal" i.e., grain" causing a strong magnetic force in one direction).When a ferromagnetic material is in the unmagnetized state, the domains are nearly randomly organized(since the crystals are in arbitrary directions) and the net magnetic field for the part as a whole is zero. When a magnetizing force is applied, the domains become aligned to produce a strong magnetic field within the part. Iron, nickel, and cobalt are examples of ferromagnetic materials. Components made of these materials are commonly inspected using the magnetic particle method.
Magnetic Field Characteristics: Magnetic Field In and Around a Bar Magnet The magnetic field surrounding a bar magnet. A magnetograph can be created by placing a piece of paper over a magnet and sprinkling the paper with iron filings. The particles align themselves with the lines of magnetic force produced by the magnet. It can be seen in the magnetograph that there are poles all along the length of the magnet but that the poles are concentrated at the ends of the magnet (the north and south poles).
Magnetic Fields in and around Horseshoe and Ring:- Magnets come in a variety of shapes and one of the more common is the horseshoe (U) magnet. The horseshoe magnet has north and south poles just like a bar magnet but the magnet is curved so the poles lie in the same plane. The magnetic lines of force flow from pole to pole just like in the bar magnet. However, since the poles are located closer together and a more direct path exists for the lines of flux to travel between the poles, the magnetic field is concentrated between the poles. **General Properties of**

Magnetic Lines of Force:- Magnetic lines of force have a number of important properties, which include:

•They seek the path of least resistance between opposite magnetic poles (in a single bar magnet shown, they attempt to form closed loops from pole to pole). •They never cross one another.

•They all have the same strength.

•Their density decreases with increasing distance from the poles.

•Their density decreases (they spread out) when they move from an area of higher permeability to an area of lower permeability.

•They are considered to have direction as if flowing, though no actual movement occurs.

•They flow from the South Pole to the North Pole within a material and North Pole to South Pole in air.

Electromagnetic Fields:-Magnets are not the only source of magnetic fields. The flow of electric current through a conductor generates a magnetic field. When electric current flows in a long straight wire, a circular magnetic field is generated around the wire and the intensity of this magnetic field is directly proportional to the amount of current carried by the wire. The strength of the field is strongest next to the wire and diminishes with distance .In most conductors; the magnetic field exists only as long as the current is flowing. However, in ferromagnetic materials the electric current will cause some or all of the magnetic domains to align and a residual magnetic field will remain. Also, the direction of the magnetic field is dependent on the direction of the electrical current in the wire. The direction of the magnetic field around a conductor can be determined using a simple rule called the “right-hand clasp rule”. If a person grasps a conductor in one's right hand with the thumb pointing in the direction of the current, the fingers will circle the conductor in the direction of the magnetic field. Note: remember that current flows from the positive terminal to the negative terminal (electrons flow in the opposite direction).

Magnetic Field Produced by a Coil :When a current carrying wires formed into several loops to form a coil, the magnetic field circling each loop combines with the fields from the other loops to produce a concentrated field through the center of the coil (the field flows along the longitudinal axis and circles back around the outside of the coil).

When the coil loops are tightly wound, a uniform magnetic field is developed throughout the length of the coil. The strength of the magnetic field increases not only with increasing current but also with each loop that is added to the coil. A long, straight coil of wire is called a solenoid and it can be used to generate a nearly uniform magnetic field similar to that of a bar magnet. The concentrated magnetic field inside a coil is very useful in magnetizing ferromagnetic materials for inspection using the magnetic particle testing method.

Quantifying Magnetic Properties:- The various characteristics of magnetism can be measured and expressed quantitatively. Different systems of units can be used for quantifying magnetic properties. SI units will be used in this material. The advantage of using SI units is that they are traceable back to an agreed set of four base units; meter, kilogram, second, and Ampere.

•The unit for magnetic field strength His ampere/meter (A/m). A magnetic field strength of 1 A/mis produced at the center of a single circular conductor with a 1meterdiameter carrying a steady current of 1 ampere

.•The number of magnetic lines of force cutting through a plane of a given area at a right angle is known as the magnetic flux density, B. The flux density or magnetic induction has the Tesla as its unit. One Tesla is equal to 1 Newton/(A/m). From these units, it can be seen that the flux density is a measure of the force applied to a particle by the magnetic field.

•The total number of lines of magnetic force in a material is called magnetic flux, ϕ. The strength of the flux is determined by the number of magnetic domains that are aligned within a material. The total flux is simply the flux density applied over an area. Flux carries the unit of a weber, which is simply a Tesla-meter2.

•The magnetization M is a measure of the extent to which an object is magnetized. It is a measure of the magnetic dipole moment per unit volume of the object. Magnetization carries the same units as a magnetic field A/m.

The Hysteresis Loop and Magnetic Properties- A great deal of information can be learned about the magnetic properties of a material by studying its hysteresis loop. A hysteresis loop shows the relationship between the induced magnetic flux density (B) and the magnetizing force (H). It is often referred to as the B-H loop. An example hysteresis loop is shown below. The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line as His increased. As the line demonstrates, the greater the amount of current applied (H+), the stronger the magnetic field in the component (B+). At point "a"
all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in magnetic flux. The material has reached the point of magnetic saturation. When His reduced to zero, the curve will move from point "a" to point "b". At this point, it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph and indicates the level of residual magnetism in the material (Some of the magnetic domains remain aligned but some have lost their alignment).As the magnetizing force is reversed, the curve moves to point "c", where the flux has been reduced to zero. This is called the point of coercively on the curve (the reversed magnetizing force has flipped enough of the domains so that the net flux within the material is zero).The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material. As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction, point "d". Reducing H to zero brings the curve to point "e". It will have a level of residual magnetism equal to that achieved in the other direction. Increasing H back in the positive direction will return B to zero. Notice that the curve did not return to the origin of the graph because some force is required to remove the residual magnetism. The curve will take a different path from point "f" back to the saturation point where it with complete the loop. From the hysteresis loop, a number of primary magnetic properties of a material can be determined:

1. **Retentivity**-A measure of the residual flux density corresponding to the saturation induction of a magnetic material. In other words, it is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation (The value of Bat point bon the hysteresis curve).

2**. Residual Magnetism or Residual Flux**-The magnetic flux density that remains in a material when the magnetizing force is zero. Note that residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.

3.**Coercive Force**-The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero(The value of Hat point con the hysteresis curve).4.Permeability, μ-A property of a material that describes the ease with which a magnetic flux is established in the material.

References:

1. Betz, C. E. (1985), Principles of Magnetic Particle Testing (PDF), American Society for Non-destructive Testing, p. 234, ISBN 978-0-318-21485-6, archived from the original (PDF) on 2011-07-14, retrieved 2010-03-02.

2. https://www.trinityndt.com/services_mt.php

3. https://inspectioneering.com/tag/magnetic+particle+inspection

Liquid penetrant testing (PT):-

This is a method which can be employed for the detection of open-to-surface discontinuities in any industrial product which is made from a non-porous material. This method is widely used for testing of non-magnetic materials. In this method a liquid penetrant is applied to the surface of the product for a certain predetermined time, after which the excess penetrant is removed from the surface. The surface is then dried and a developer is applied to it. The penetrant which remains in the discontinuity is absorbed by the developer to indicate the presence as well as the location, size and nature of the discontinuity. The process is illustrated in Figure 1

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

(1) Post emulsifiable fluorescent dye penetrant.

(2) Solvent removable fluorescent dye penetrant.

(3) Water washable fluorescent dye penetrant.

(4) Post emulsifiable visible dye penetrant.

(5) Solvent removable visible dye penetrant.

(6) Water washable visible dye penetrant.

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

(1) Relatively low cost.

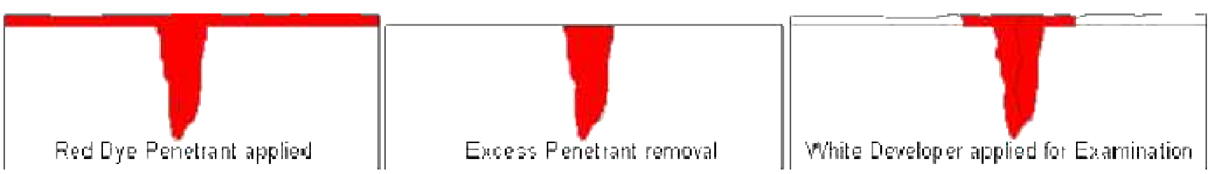
(2) Highly portable NDT method.

(3) Highly sensitive to fine, tight discontinuities.

(4) Fairly simple method.

(5) Can be used on a variety of materials.

(6) All surface discontinuities are detected in one operation, regardless of orientation.



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

(1) Test surface must be free of all contaminants (dirt, oil, grease, paint, rust, etc.).

(2) Detects surface discontinuities only.

(3) Cannot be used on porous specimens and is difficult to use on very rough surfaces.

(4) Removal of all penetrant materials, following the test, is often required.

(5) There is no easy method to produce permanent record

Inspection steps

1. Pre-cleaning:
   The test surface is cleaned to remove any dirt, paint, oil, grease or any loose scale that could either keep penetrant out of a defect, or cause irrelevant or false indications. Cleaning methods may include solvents, alkaline cleaning steps, vapor °reasing, or media blasting. The end goal of this step is a clean surface where any defects present are open to the surface, dry, and free of contamination. Note that if media blasting is used, it may "work over" small discontinuities in the part, and an etching bath is recommended as a post-blasting treatment.
2. Application of Penetrant:
   The penetrant is then applied to the surface of the item being tested. The penetrant is allowed "dwell time" to soak into any flaws (generally 5 to 30 minutes). The dwell time mainly depends upon the penetrant being used, material being tested and the size of flaws sought. As expected, smaller flaws require a longer penetration time. Due to their incompatible nature one must be careful not to apply solvent-based penetrant to a surface which is to be inspected with a water-washable penetrant.
3. Excess Penetrant Removal:
   The excess penetrant is then removed from the surface. The removal method is controlled by the type of penetrant used. Water-washable, solvent-removable, lipophilic post-emulsifiable, or hydrophilic post-emulsifiable are the common choices. Emulsifiers represent the highest sensitivity level, and chemically interact with the oily penetrant to make it removable with a water spray. When using solvent remover and lint-free cloth it is important to not spray the solvent on the test surface directly, because this can remove the penetrant from the flaws. If excess penetrant is not properly removed, once the developer is applied, it may leave a background in the developed area that can mask indications or defects. In addition, this may also produce false indications severely hindering your ability to do a proper inspection.
4. Application of Developer:
   After excess penetrant has been removed a white developer is applied to the sample. Several developer types are available, including: non-aqueous wet developer, dry powder, water suspendable, and water soluble. Choice of developer is governed by penetrant compatibility (one can't use water-soluble or suspendable developer with water-washable penetrant), and by inspection conditions. When using non-aqueous wet developer (NAWD) or dry powder, the sample must be dried prior to application, while soluble and

suspendable developers are applied with the part still wet from the previous step. NAWD is commercially available in aerosol spray cans, and may employ acetone, isopropyl alcohol, or a propellant that is a combination of the two. Developer should form a semi-transparent, even coating on the surface.
The developer draws penetrant from defects out onto the surface to form a visible indication, commonly known as bleed-out. Any areas that bleed-out can indicate the location, orientation and possible types of defects on the surface. Interpreting the results and characterizing defects from the indications found may require some training and/or experience.

5. Inspection:
The inspector will use visible light with adequate intensity (100 foot-candles or 1100 lux is typical) for visible dye penetrant. Ultraviolet (UV-A) radiation of adequate intensity (1,000 micro-watts per centimeter squared is common), along with low ambient light levels (less than 2 foot-candles) for fluorescent penetrant examinations. Inspection of the test surface should take place after 10 to 30 minute development time, depends of product kind. This time delay allows the blotting action to occur. The inspector may observe the sample for indication formation when using visible dye. It is also good practice to observe indications as they form because the characteristics of the bleed out are a significant part of interpretation characterization of flaws.
6. Post Cleaning:
The test surface is often cleaned after inspection and recording of defects, especially if post-inspection coating processes are scheduled.

Advantages and Disadvantages

The primary advantages and Disadvantages when compared to other NDT methods are:

Advantages

- High sensitivity (small discontinuities can be detected).
- Few material limitations (metallic and non-metallic, magnetic and nonmagnetic, and conductive and nonconductive materials may be inspected).
- Rapid inspection of large areas and volumes.
- Suitable for parts with complex shapes.
- Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.
- Portable (materials are available in aerosol spray cans)
- Low cost (materials and associated equipment are relatively inexpensive)

Disadvantages

- Only surface breaking defects can be detected.

- Only materials with a relatively nonporous surface can be inspected.
- Pre-cleaning is critical since contaminants can mask defects.
- Metal smearing from machining, grinding, and grit or vapor blasting must be removed.
- The inspector must have direct access to the surface being inspected.
- Surface finish and roughness can affect inspection sensitivity.
- Multiple process operations must be performed and controlled.
- Post cleaning of acceptable parts or materials is required.
- Chemical handling and proper disposal is required.

Liquid Penetrant Testing Application

i. Liquid Penetrant Testing Application on Welding

This test is used to detect the hot crack which can happen during solidification process of deposited weld metal, and it might happen in weld metal or in weld heat affected zone. The surface lack of fusion also can be identified by this test.

The surface porosity is a common surface defect that can be found visually and more accurately by dye penetration test. The acceptance criteria for the liquid penetrant test for welding have been addressed on the ASME Code Section VIII Div 1 Mandatory appendix 8.

This part covers the criteria for both pressure vessels and rotating equipment such as pumps and compressors. Please note the API codes such as API 610 and API 617 do not address the acceptance criteria for Penetrant test directly and normally is referred to ASME.

ii. Liquid Penetrant Test Application on Casting

The casting surface porosity, surface shrinkage, hot tear and cold shut can be detected by liquid penetrant inspection. The acceptance criteria have been addressed in ASME Section

This acceptance criteria covers both fixed equipment, e.g., pressure vessels, heat exchangers, and rotating equipment, e.g., pumps, compressors, etc. The ASME Section VIII is pressure vessel code, but API codes such as API 610 (for Pumps) or API 617 (for the compressor) refer the users to the ASME code for acceptance criteria.

iii. Liquid Penetrant Testing Application on Forging

The forging surface detects are Laps and Bursts which both can easily be identified by performing a liquid penetrant test.

iv. Liquid Penetrant Testing on Plate

This test is used to detect lamination. This is a common defect that happens in plate material. This can be detected if the lamination is open to the surface.

References:

1.https://www.ndeed.org/EducationResources/CommunityCollege/PenetrantTest/PTMaterials/surfaceenergy.htm.

2. Kohan, Anthony Lawrence (1997), Boiler operator's guide (4th ed.), McGraw-Hill Professional, p. 240, ISBN 978-0-07-036574-2.

3. http://www.nde-ed.org/EducationResources/CommunityCollege/PenetrantTest/MethodsTech/materialsmear.htm

Unit-	**II**
Topic-	**Electromagnetic Methods**
Sub-Topic-	**Electromagnetic Methods, Eddy current theory, Magnetic flux leakage theory, Eddy current sensing probes, Flux leakage sensing probes, Principle of electromagnetic testing, Mathematical analysis, Flaw detection in conductors, Various types of eddy current techniques used and advantages of various electromagnetic methods for crack detection etc.**

Electromagnetic Testing:- **Electromagnetic testing** (**ET**), as a form of non-destructive testing, is the process of inducing electric currents or magnetic fields or both inside a test object and observing the electromagnetic response. If the test is set up properly, a defect inside the test object creates a measurable response.

The term "electromagnetic testing" is often intended to mean simply eddy-current testing (ECT). However, with an expanding number of electromagnetic and magnetic test methods, "electromagnetic testing" is more often used to mean the whole class of electromagnetic test methods, of which eddy-current testing is just one. Also useful for the testing of drill pipes.

Common methods:

- Eddy-current testing (ECT) is used to detect near-surface cracks and corrosion in metallic objects such as tubes and aircraft fuselage and structures. ECT is more commonly applied to non ferromagnetic materials, since in ferromagnetic materials the depth of penetration is relatively small.
- Remote field testing (RFT) is used for non-destructive testing (NDT) of steel tubes and pipes.
- Magnetic flux leakage testing (MFL) is also used for non-destructive testing (NDT) of steel tubes and pipes. At present RFT is more commonly used in small diameter tubes and MFL in larger diameter pipes over long travel distances.
- Wire rope testing is MFL applied to steel cables, to detect broken strands of wire.
- Magnetic particle inspection (MT or MPI) is a form of MFL where small magnetic particles in the form of a powder or liquid are sprayed on the magnetized steel test object and gather at surface-breaking cracks.
- Alternating current field measurement (ACFM) is similar to eddy current applied to steel. Its most common application is to detect and size cracks in weld from the company that developed it.
- Pulsed eddy current enables the detection of large-volume metal loss in steel objects from a considerable stand-off, allowing steel pipes to be tested without removing insulation.

References:

1. Description". *Archived from* the original *on 2006-05-28*. Retrieved 2006-08-06.

2. Hugo L. Libby, Introduction to Electromagnetic Nondestructive Test Methods, New York : Wiley-Interscience, 1971.

3. The American Society for Nondestructive Testing, NDT Handbook, 3rd ed., Vol. 5, Electromagnetic Testing

4. William Lord, "Electromagnetic NDT Techniques — A 40 Year Retrospective or Retirement for Cause in Materials Evaluation, June 2006, p. 547 to 550.

Electromagnetic Testing:

Eddy-current testing (also commonly seen as Eddy Current Testing and ECT) is one of many electromagnetic testing methods used in non-destructive testing (NDT) making use of electromagnetic induction to detect and characterize surface and sub-surface flaws in conductive materials.

ECT Principle

In its most basic form, the single element ECT probe, a coil of conductive wire is excited with an alternating electrical current. This wire coil produces an alternating magnetic field around itself in the direction ascertained by the right-hand rule. The magnetic field oscillates at the same frequency as the current running through the coil. When the coil approaches a conductive material, currents opposed to the ones in the coil are induced in the material, which follow circular paths. These circular currents are called eddy currents.

Variations in the electrical conductivity and magnetic permeability of the test object, and the presence of defects causes a change in the flow pattern, intensity and phase of eddy currents. In turn a corresponding change in phase and amplitude of the coupled magnetic field that can be detected by measuring the impedance changes in the coil. This is a telltale sign of the presence of defects and the basis of standard ECT (using pancake coil).

Applications:

The two major applications of eddy current testing maybe broadly classified as surface inspection and tubing inspections.

Tubing inspection is generally limited to non-ferromagnetic tubing and is known as conventional eddy current testing. Conventional ECT is used for inspecting steam generator tubes in nuclear plants and heat exchanger tubes in power and petrochemical industries. The technique is very sensitive to detect and size pits. Wall loss or corrosion can be detected but sizing is not accurate.

Advantages:

- Sensitivity to surface defects
- Can detect through several layers
- Can detect through surface coatings
- Accurate conductivity measurements
- Can be automated
- Little pre-cleaning required
- Portability

Disadvantages:

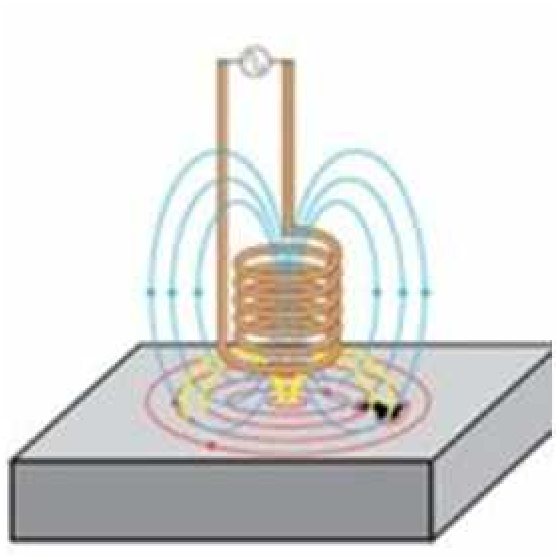
- Very susceptible to magnetic permeability changes
- Only effective on conductive materials
- Will not detect defects parallel to surface
- Not suitable for large areas and/or complex geometries
- Signal interpretation required
- No permanent record (unless automated)

Techniques of Electromagnetic Testing

Tube inspection can be performed by techniques which employ electromagnetic phenomena (as in Eddy Current Testing) as detailed below:

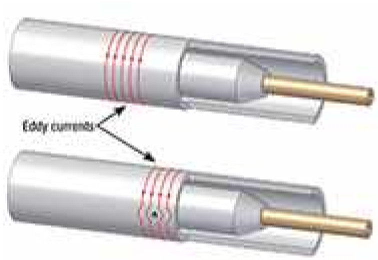
Conventional Eddy Current Testing (ECT)

Surface Testing



Surface inspection is used extensively in the aerospace industry wherein very sensitive ECT techniques are implemented to detect tight cracks. Surface inspection can be performed both on ferromagnetic and non-ferromagnetic materials.

Tube Testing

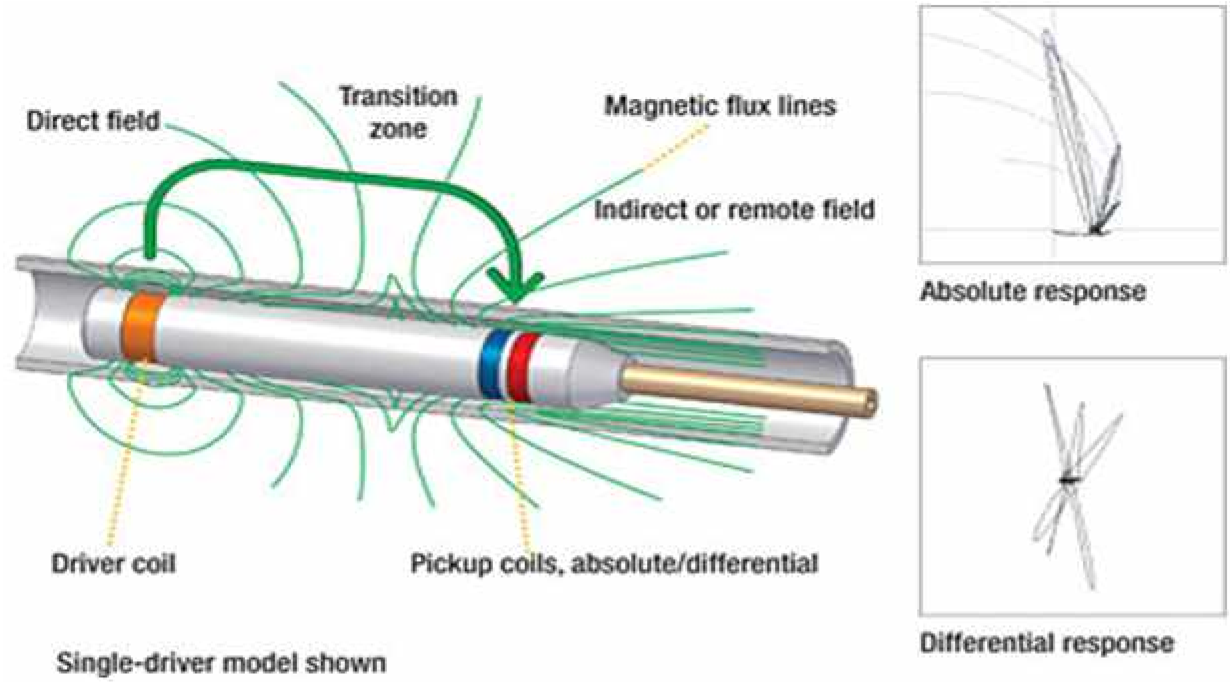


Eddy current testing is a noncontact method used to inspect non-ferromagnetic tubing. This technique is suitable for detecting and sizing metal discontinuities such as corrosion, erosion, wear, pitting, baffle cuts, wall loss, and cracks in nonferrous materials.

- Two coils are excited with an electrical current, producing a magnetic field around them. The magnetic fields penetrate the tube material and generate opposing alternating currents in the material. These currents are called eddy currents

- Any defects that change the eddy current flow also change the impedance of the coils in the probe
- These changes in the impedance of the coils are measured and used to detect defects in the tube

Tube Inspection with Remote Field Testing (RFT)



Remote field testing (RFT) is being used to successfully inspect ferromagnetic tubing such as carbon steel or ferritic stainless steel. This technology offers good sensitivity when detecting and measuring volumetric defects resulting from erosion, corrosion, wear, and baffle cuts. Remote field probes are used all around the world to successfully inspect heat exchangers, feed-water heaters, and boiler tubes.

- RFT with up to four different frequencies and real-time mixes

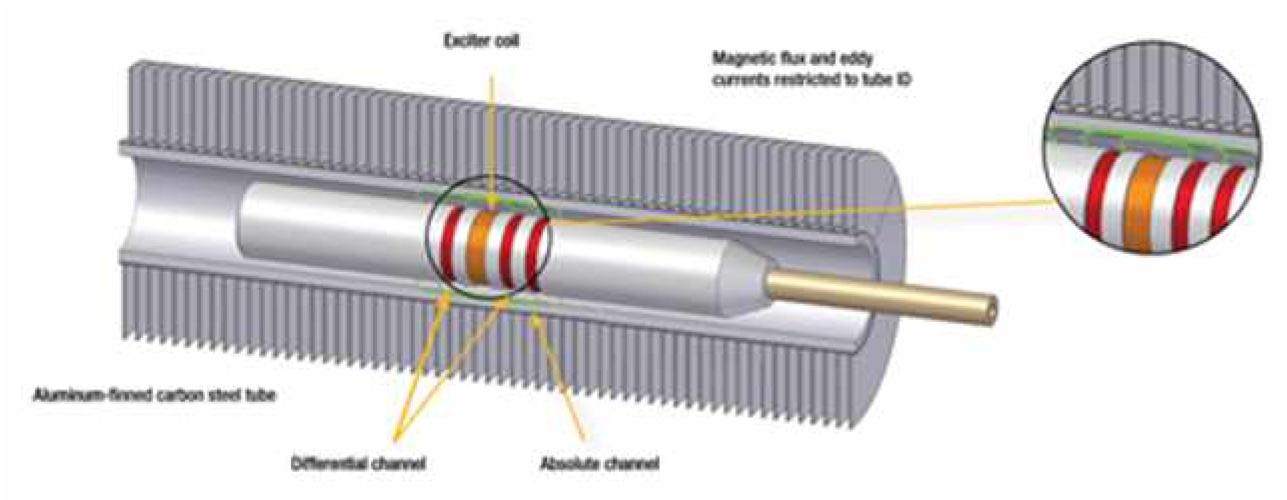
This feature provides more flexibility for mixing and defect validation. The detection and sizing of flaws at the support plate is made easier with multi frequency inspections and dual-driver operations.

- RFT with frequencies ranging from 20 Hz to 250 kHz

The high frequency available in the market extends RFT inspection to thin materials with low permeability, such as 400-series stainless steel, and other ferromagnetic alloys.

Tube Inspection With Near Field Testing (NFT)

- Air coolers
- Carbon steel heat exchangers

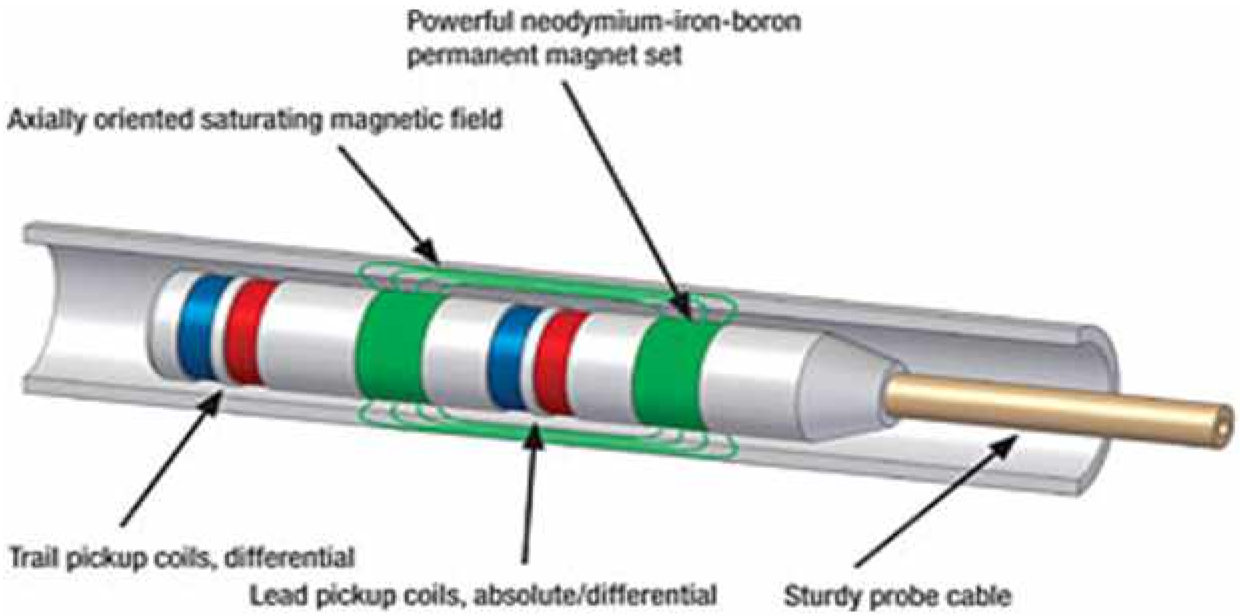


Near field testing (NFT) technology is a rapid and inexpensive solution intended specifically for fin-fan carbon-steel tubing inspection. This new technology relies on a simple driver-pickup eddy current probe design providing very simple signal analysis.

NFT probes can be successfully used to inspect carbon steel heat exchangers, and air cooler tubes.

NFT is specifically suited to the detection of internal corrosion, erosion, or pitting on the inside of carbon steel tubing. The NFT probes measure lift-off or "fill factor," and convert it to amplitude-based signals (no phase analysis). Because the eddy current penetration is limited to the inner surface of the tube, NFT probes are not affected by the fin geometry on the outside of the tubes.

Tube Inspection With Near Field Testing (NFT)



Magnetic flux leakage (MFL) is a fast inspection technique, suitable for measuring wall loss and detecting sharp defects such as pitting, grooving, and circumferential cracks. MFL is effective for aluminium-finned carbon steel tubes, because the magnetic field is almost completely unaffected by the presence of such fins.

NFT probes can be successfully used to inspect feed water heater tubes, air cooler tubes and carbon steel heat exchanger tubes.

References:

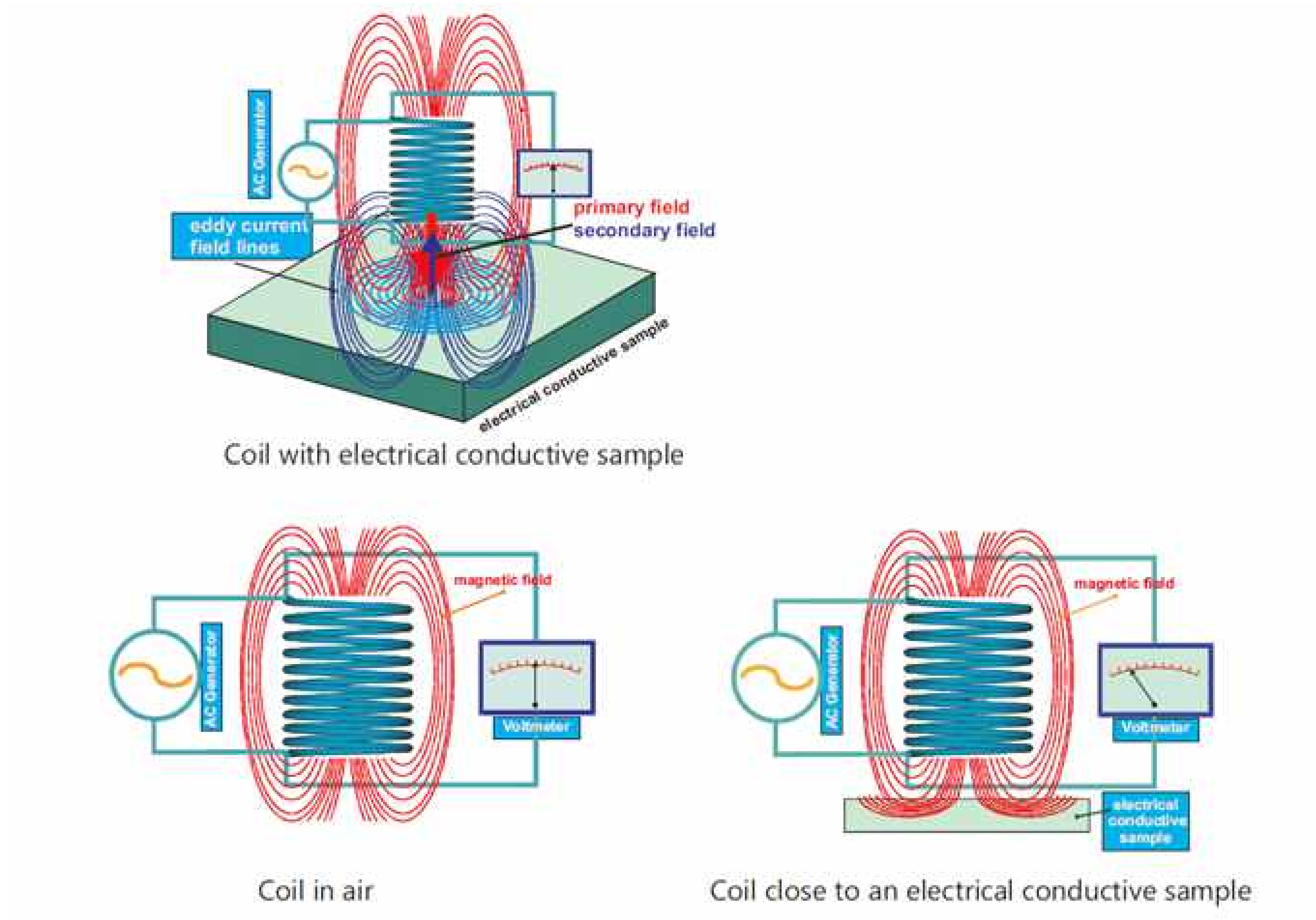
1. "Description". Archived from the original on 2006-05-28. Retrieved 2006-08-06.

2. Hugo L. Libby, Introduction to Electromagnetic Non-destructive Test Methods, New York : Wiley-Interscience, 1971.

3. The American Society for Non-destructive Testing, NDT Handbook, 3rd ed., Vol. 5, Electromagnetic Testing.

Eddy Current Principle:

The eddy current method is based on the principle of generating circular electrical currents (eddy currents) in a conductive material. This is achieved by the use of a coil connected to an alternating current generator driving an alternating magnetic field (primary field). The current flow induced by this primary field within the conductive material will itself produce a magnetic field (secondary field) in opposition to the primary field according to Lenz's law. This reaction can be measured as a change of the impedance of the coil/sample arrangement (change in amplitude and phase of the voltage related to the generator current driving the coil). A coil in air is not influenced by eddy currents, but moving the coil towards an electrical conductive sample results in a signal, which can be used for distance measurement, e.g. measurement of non-conductive coating thickness on electrical conductive material.

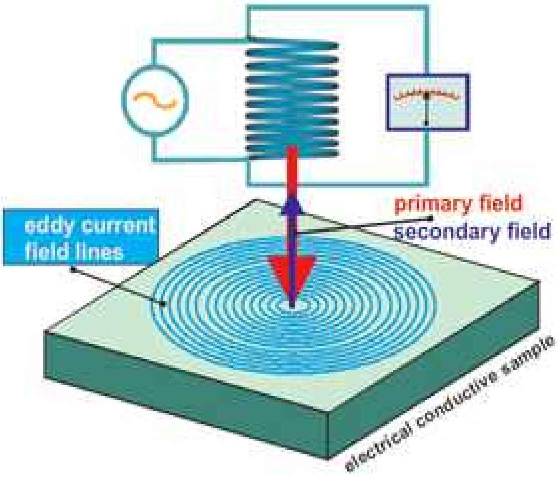


Coil with electrical conductive sample

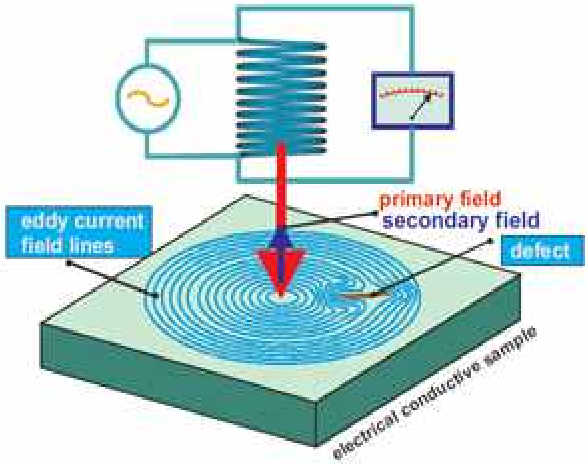
Coil in air

Coil close to an electrical conductive sample

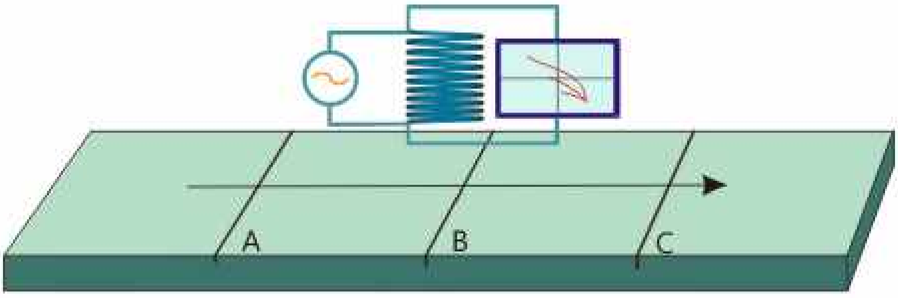
The eddy currents will always go the easiest way, and if cracks exist in the material, the current will go around the crack. This change of eddy current flow also can be detected by monitoring the impedance of the coil and is mainly used for detection of cracks.



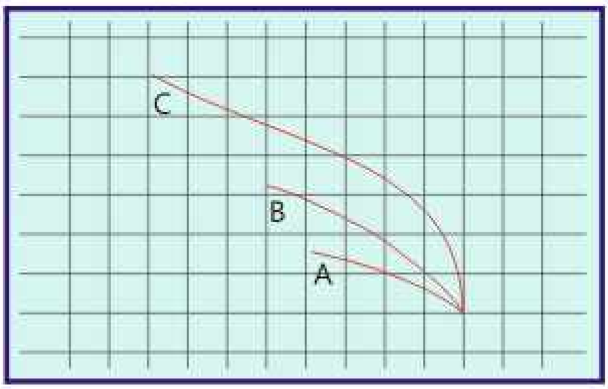
Coil on a defect-free sample



Coil on a sample with a defect



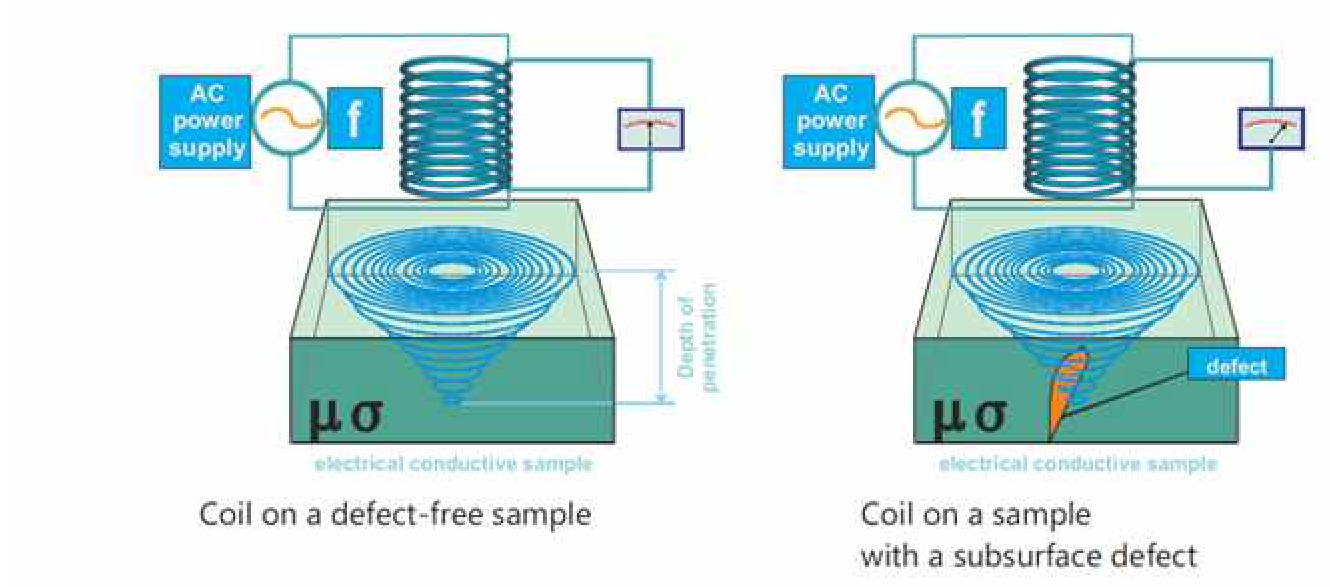
Moving the coil over the surface



Signals from cracks in the impedance plane view

The eddy currents are flowing beneath the surface of the material with the highest density close to the surface. The depth of penetration of the eddy currents depends on the conductivity and permeability of the material and the frequency of the alternating field. At high frequencies the eddy currents concentrate at the surface, while with lower frequencies deeper regions within the material are penetrated.
By utilizing this on e.g. a sheet of aluminium, both, cracks on top of the sheet and on the other side can be detected. It is also applicable to detect subsurface corrosion and to determine the thickness of conductive sheets.
This effect is used mainly for non-ferromagnetic material. Due to the high permeability of ferromagnetic material the standard eddy current method here is limited to the region close to the

surface. There exist extended methods to inspect e.g. the subsurface of thick-walled ferromagnetic pipes or plates.



References:

1. Israel D. Vagner; B.I. Lembrikov; Peter Rudolf Wyder (17 November 2003). Electrodynamics of Magnetoactive Media. Springer Science & Business Media. pp. 73–. ISBN 978-3-540-43694-2.

2. Walt Boyes (25 November 2009). Instrumentation Reference Book. Butterworth-Heinemann. pp. 570–. ISBN 978-0-08-094188-2.

3. Howard Johnson; Howard W. Johnson; Martin Graham (2003). High-speed Signal Propagation: Advanced Black Magic. Prentice Hall Professional. pp. 80–. ISBN 978-0-13-084408-8.

4. Wangsness, Roald. Electromagnetic Fields (2nd ed.). pp. 387–8.

Eddy Current Sensing Probes- Eddy current sensors are primarily used for displacement and position measurement of electrically conductive targets. They are generally used for measuring ferromagnetic and non-ferromagnetic materials. They are suitable for applications in harsh industrial environments due to their superior tolerance for oil, dirt, dust, moisture and magnetic interference fields. Available in miniature and sub-miniature models, they can also be used for measurement in a space where area is restricted. How does eddy current sensor works?

Eddy current sensor operating principle:

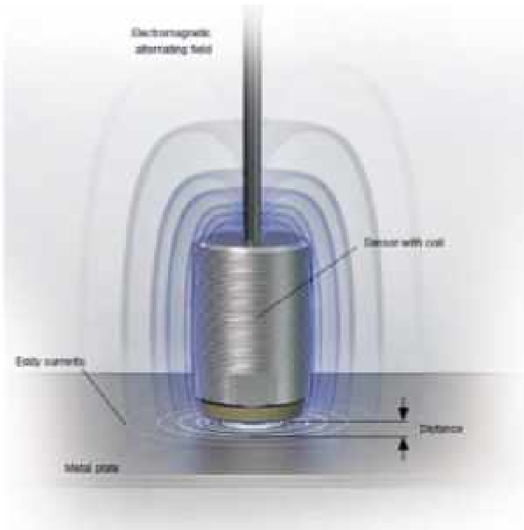


Fig.1 Schematic of eddy current operating principle

Eddy current sensor operates based on the inductive eddy-current principle. It measures the distance based on the extraction of energy from an oscillating circuit, which is required to generate eddy current in an electrically-conductive materials.

When the sensing coil is supplied with an alternating current, it causes a magnetic field to form around the coil. If an electrically conducting material is placed in this field, eddy current field is induced according to the Faraday's induction law. When the object moves, it causes the change in the impedance of the coil, which is proportional to the change in the distance between the sensor and the target

Advantages of eddy current sensor

Eddy current sensors have superior temperature stability and resistance towards pressure, temperature, dirt and oil. Capable of operating at pressure up to 4000 bar, they are one of the best wear-free, non-contact sensors for measuring displacement and position in harsh industrial environment.

The sensors are also capable of measuring at high speed up to 100 kilo Samples per second. The sensor head can also be customized based on specific customer requests to fit in different applications. The sensors are generally miniature in size and therefore, are suitable for measuring in an area where access is restricted. These sensors are also low-cost and can be used in high-volume OEM applications.

Potential applications for eddy current sensor

Due to its resistance and stability to measure under extreme environment, eddy current sensors are used in a wide range of industrial applications. Some examples include:

- Measure vibrations of actuators in steel galvanising plants
- Cylinder movements in an internal combustion engine
- Measure thickness of sheet metals in roller gap
- Measure movement of hydraulic cylinders
- Used in airplanes to measure movement of door lock switches and landing gear flaps

References:

1. O. Postolache, I. M. Dias Pereira, H. G. Ramos and A. L. Ribeiro, "NDT on Aluminum Aircraft Plates based on Eddy Current Sensing and Image Processing", *Proc IEEE I2MTC Conf*, vol. I, pp. 1803-1808, May, 2008.

2. P. Ripka, M. Vopálenský, A. Platil, M. Döscher, K. Lenssen and H. Hauser, "AMR magnetometer", *Journal of Magnetism and Magnetic Materials*, vol. 254-255, pp. 639-641, January 2003.

<u>Magnetic Flux Leakage</u> :(**TFI** or Transverse Field Inspection technology) is a magnetic method of non-destructive testing that is used to detect corrosion and pitting in steel structures, most commonly pipelines and storage tanks. The basic principle is that a powerful magnet is used to magnetize the steel. At areas where there is corrosion or missing metal, the magnetic field "leaks" from the steel. In an MFL (or Magnetic Flux Leakage) tool, a magnetic detector is placed between the poles of the magnet to detect the leakage field. Analysts interpret the chart recording of the leakage field to identify damaged areas and to estimate the depth of metal loss.

Introduction to pipeline examination

There are many methods of assessing the integrity of a pipeline. In-line-Inspection (ILI) tools are built to travel inside a pipeline and collect data as they go. The type of ILI we are interested in here, and the one that has been in use the longest for pipeline inspection, is the magnetic flux leakage inline inspection tool (MFL-ILI). MFL-ILIs detect and assess areas where the pipe wall may be damaged by corrosion. The more advanced versions are referred to as "high-resolution" because they have a large number of sensors. The high-resolution MFL-ILIs allow more reliable and accurate identification of anomalies in a pipeline, thus, minimizing the need for expensive verification excavations (i.e. digging up the pipe to verify what the problem is). Accurate assessment of pipeline anomalies can improve the decision making process within an Integrity Management Program and excavation programs can then focus on required repairs instead of calibration or exploratory digs. Utilizing the information from an MFL ILI inspection is not only cost effective but, as well, can also prove to be an extremely valuable building block of a Pipeline Integrity Management Program.

The reliable supply and transportation of product in a safe and cost-effective manner is a primary goal of most pipeline operating companies and managing the integrity of the pipeline is paramount in maintaining this objective. In-line-inspection programs are one of the most effective means of obtaining data that can be used as a fundamental base for an Integrity Management Program. There are many types of ILI tools that detect various pipeline defects, but high-resolution MFL tools are becoming more prevalent as its applications are surpassing those to which it was originally designed. Originally designed for detecting areas of metal loss, the modern High Resolution MFL tool is proving to be able to accurately assess the severity of corrosion features, define dents, wrinkles, buckles, and, in some cases, cracks. Having a device that can perform simultaneous tasks reliably is more efficient and ultimately provides cost saving benefits.

<u>References:</u>

1. DUMALSKI, Scott, FENYVESI, Louis – Determining Corrosion Growth Accurately and Reliably.

2. MORRISON, Tom, MANGAT, Naurang, DESJARDINS, Guy, BHATIA, Arti – Validation of an In-Line Inspection Metal Loss Tool, presented at International Pipeline Conference, Calgary, Alberta, Canada, 2000.

3. NESTLEROTH, J.B, BUBENIK, T.A, - Magnetic Flux Leakage (MFL) Technology – for The Gas Research Institute – United States National Technical Information Center 1999.

4. REMPEL, Raymond - Anomaly detection using Magnetic Flux Leakage (MFL) Technology - Presented at the Rio Pipeline Conference and Exposition, Rio de Janeiro, Brasil 2005.

Magnetic Flux Leakage (MFL) Probes: - Magnetic flux leakage (MFL) is an electromagnetic non-destructive testing technique used to detect corrosion and pitting.

MFL uses a powerful magnet to magnetize the conductive material under test (usually steel). Where there are defects — corrosion or material loss — the magnetic field "leaks" from the steel.

MFL probes incorporate a magnetic detector placed between the poles of the magnet where it can detect the leakage field. During inspection, a magnetic circuit of sorts forms between the part and the probe. The magnetic field induced in the part saturates it until it can no longer hold any more flux. The flux overflows and leaks out of the pipe wall and strategically placed sensors can accurately measure the three-dimensional vector of the leakage field.

Because magnetic flux leakage is a vector and that a sensor can only measure one direction, any given probe must have three sensors to accurately measure the axial, radial, and circumferential components of an MFL signal.

As a MFL tool navigates the pipeline a magnetic circuit is created between the pipe wall and the tool. Brushes typically act as a transmitter of magnetic flux from the tool into the pipe wall, and as the magnets are oriented in opposing directions, a flow of flux is created in an elliptical pattern. High Field MFL tools saturate the pipe wall with magnetic flux until the pipe wall can no longer hold any more flux. The remaining flux leaks out of the pipe wall and strategically placed tri-axial Hall effect sensor heads can accurately measure the three-dimensional vector of the leakage field.

Given the fact that magnetic flux leakage is a vector quantity and that a hall sensor can only measure in one direction, three sensors must be oriented within a sensor head to accurately measure the axial, radial and circumferential components of an MFL signal. The axial component of the vector signal is measured by a sensor mounted orthogonal to the axis of the pipe, and the radial sensor is mounted to measure the strength of the flux that leaks out of the pipe. The circumferential component of the vector signal can be measured by mounting a sensor perpendicular to this field. Earlier MFL tools recorded only the axial component but high-resolution tools typically measure all three components. To determine if metal loss is occurring on the internal or external surface of a pipe, a separate eddy current sensor is utilized to indicate wall surface location of the anomaly. The unit of measure when sensing an MFL signal is the gauss or the tesla and generally speaking, the larger the change in the detected magnetic field, the larger the anomaly.

Benefits:

- Using MFL can yield the following benefits:
- One of the few methods used to inspect finned tubes (is also an alternative)
- Can be used on all ferromagnetic materials
- Good sensitivity to pitting

- High-speed inspection

References:

1. NVE Magnetic Sensor Catalogue, [online] Available: www.nve.com/sensorcatalog.php.

2. WESTWOOD, Stephen, CHOLOWSKY, Sharon. - Tri-Axial Sensors and 3-Dimensional Magnetic Modelling of Combine to Improve Defect Sizing From Magnetic Flux Leakage Signals. presented at NACE International, Northern Area Western Conference, Victoria, British Columbia, Canada 2004.

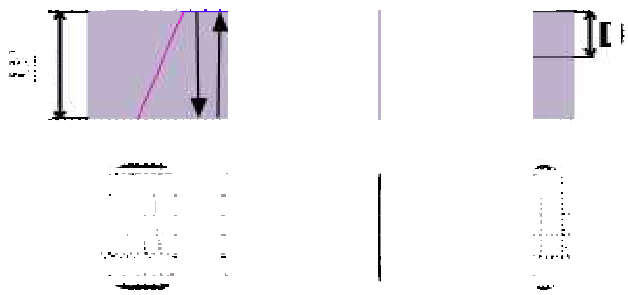
3. AMOS, D. M. - "Magnetic flux leakage as applied to aboveground storage tank flat bottom tank floor inspection", Materials Evaluation, 54(1996), p. 26.

Unit-	**III**
Topic-	**Ultrasonic Methods**
Sub-Topic-	**Ultrasonic Methods, Physical principle of sound, Ultrasonic waves propagation and their characteristics, Generation of ultrasonic waves, Ultrasonic transducers, Ultrasonic testing equipment, Ultrasonic flaw detector, Fundamental of ultrasonic testing, Contract and immersion testing, Merits and demerits, Defect location in angle beam testing, Immersion testing techniques, Ultrasonic signal display, Detection of defects and their characterization, DGS methods, Time of flight diffraction method (TOFD).**

<u>Ultrasonic Testing (UT):</u> is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in the object or material tested. In most common UT applications, very short ultrasonic pulse-waves with center frequencies ranging from 0.1-15 MHz, and occasionally up to 50 MHz, are transmitted into materials to detect internal flaws or to characterize materials. A common example is ultrasonic thickness measurement, which tests the thickness of the test object, for example, to monitor pipe work corrosion.

Ultrasonic testing is often performed on steel and other metals and alloys, though it can also be used on concrete, wood and composites, albeit with less resolution. It is used in many industries including steel and aluminium construction, metallurgy, manufacturing, aerospace, automotive and other transportation sectors.

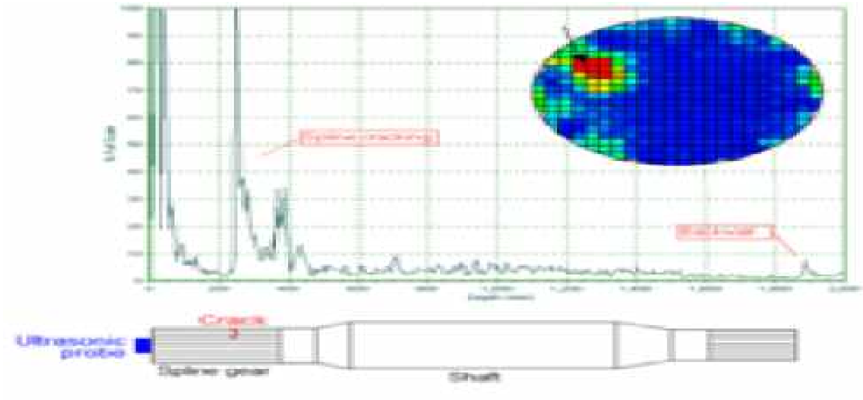
How it works:



Principle of ultrasonic testing. LEFT: A probe sends a sound wave into a test material. There are two indications, one from the initial pulse of the probe, and the second due to the back wall echo. RIGHT: A defect creates the third indication and simultaneously reduces the amplitude of the back wall indication. The depth of the defect is determined by the ratio D/E_p.

In ultrasonic testing, an ultrasound transducer connected to a diagnostic machine is passed over the object being inspected. The transducer is typically separated from the test object by a couplant (such as oil) or by water, as in immersion testing. However, when ultrasonic testing is conducted with an Electromagnetic Acoustic Transducer (EMAT) the use of couplant is not required.

There are two methods of receiving the ultrasound waveform: reflection and attenuation. In reflection (or pulse-echo) mode, the transducer performs both the sending and the receiving of the pulsed waves as the "sound" is reflected back to the device. Reflected ultrasound comes from an interface, such as the back wall of the object or from an imperfection within the object. The diagnostic machine displays these results in the form of a signal with an amplitude representing the intensity of the reflection and the distance, representing the arrival time of the reflection. In attenuation (or through-transmission) mode, a transmitter sends ultrasound through one surface, and a separate receiver detects the amount that has reached it on another surface after travelling through the medium. Imperfections or other conditions in the space between the transmitter and receiver reduce the amount of sound transmitted, thus revealing their presence. Using the couplant increases the efficiency of the process by reducing the losses in the ultrasonic wave energy due to separation between the surfaces.



Non-destructive testing of a swing shaft showing spline cracking

Advantages

1. High penetrating power, which allows the detection of flaws deep in the part.
2. High sensitivity, permitting the detection of extremely small flaws.
3. In many cases only one surface needs to be accessible.
4. Greater accuracy than other non-destructive methods in determining the depth of internal flaws and the thickness of parts with parallel surfaces.
5. Some capability of estimating the size, orientation, shape and nature of defects.
6. Some capability of estimating the structure of alloys of components with different acoustic properties.
7. Non-hazardous to operations or to nearby personnel and has no effect on equipment and materials in the vicinity.
8. Capable of portable or highly automated operation.
9. Results are immediate. Hence on the spot decisions can be made.

Disadvantages

1. Manual operation requires careful attention by experienced technicians. The transducers alert to both normal structure of some materials, tolerable anomalies of other specimens (both termed "noise") and to faults therein severe enough to compromise specimen integrity. These signals must be distinguished by a skilled technician, possibly requiring follow up with other non-destructive testing methods.
2. Extensive technical knowledge is required for the development of inspection procedures.
3. Parts those are rough, irregular in shape, very small or thin or not homogeneous are difficult to inspect.
4. Surface must be prepared by cleaning and removing loose scale, paint, etc., although paint that is properly bonded to a surface need not be removed.
5. Couplants are needed to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected unless a non-contact technique is used. Non-contact techniques include Laser and Electro Magnetic Acoustic Transducers (EMAT).

References:

1. Matlack, K. H.; Kim, J.-Y.; Jacobs, L. J.; Qu, J. (2015-03-01). "Review of Second Harmonic Generation Measurement Techniques for Material State Determination in Metals". Journal of Nondestructive Evaluation. 34 (1): 273. doi:10.1007/s10921-014-0273-5. ISSN 0195-9298.

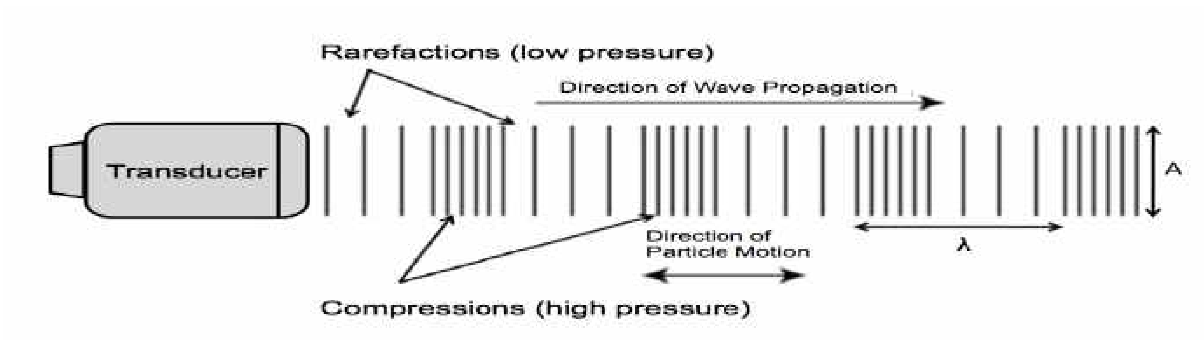
2. Mostavi, Amir; Kamali, Negar; Tehrani, Niloofar; Chi, Sheng-Wei; Ozevin, Didem; Indacochea, J. Ernesto (2017). "Wavelet Based Harmonics Decomposition of Ultrasonic Signal in Assessment of Plastic Strain in Aluminum". Measurement. 106: 66–78. doi:10.1016/j.measurement.2017.04.013.

3. U.S. Patent 3,260,105 for Ultrasonic Testing Apparatus and Method to James F. McNulty at lines 37-48 and 60-72 of Column 1 and lines 1-4 of Column 2.

Physical principle of sound: - sound is a form of mechanical energy that travels in a longitudinal wave in a series of compressions (high pressure) and rarefactions (low pressure). The transmission of sound requires a medium such as air, liquid, or tissue. Because all mediums have some elastic properties, energy and momentum are transported by means of disturbance from one point to another, without the transport of matter.

Wavelength and frequency are terms often used to describe the relationship between the compressions and rarefactions. The area that includes one complete compression and rarefaction is called a cycle. Wavelength (λ) is the distance over which the acoustic disturbance repeats itself at any instant of time during the cycle. It is summarized by the equation $\lambda = c/f$, where f is the frequency and c is the speed of sound. The period of a wave is the time it takes for one cycle to occur. Frequency is the number of cycles that occur per second, and is measured in Hertz (Hz).

Human hearing has a limited range of 20 Hz to 20 kilohertz (kHz). Ultrasound is considered those frequencies greater than 20 kHz, while diagnostic ultrasound utilizes frequencies greater than 1 megahertz (MHz). Amplitude (A) is the maximum increase (or decrease) in pressure due to the presence sound. It is often described as the "height" of the wave, and has no relationship to the wavelength or frequency.



Frequency is important factor in ultrasound imaging. High frequency transducers (> 7MHz) have better resolution at shallow depths, but have limited imaging capability the deeper the wave penetrates the tissue. Lower frequencies allow for better imaging of deeper structures, but with poorer image resolution. Both images below are of the left neck. The image on the left was generated by a 9 MHz transducer creating a shallow (approximately 3cm in depth), but high resolution image of the internal jugular vein (IJV), common carotid artery (CCA) and thyroid gland. The image on the right shows the same structures imaged with a lower frequency (4MHz) transducer. Although the image depth has increased to 6cm, the resolution is greatly diminished.

Sound travels at different speeds through different medium. This is known as propagation velocity. In diagnostic ultrasound, human tissue is the medium in which sound travels. The standardized propagation velocity of sound through tissue is approximately 1,540 m/s,which is derived by averaging the different velocities of soft tissues in the body. By comparison, the propagation velocity of air is quite slow at 331 m/s and in bone it can be as fast as 5000 m/s.

References:

1.Aldrich J E. Basic physics of ultrasound imaging. *Crit Care Med*. 2007;35(5 Suppl):S131-S137.

2.Zagzebski JA. Physics and instrumentation in Doppler and B-mode ultrasonography. In: Zweibel WJ. *Introduction to Vascular Ultrasonography*. 4th ed. Philadelphia, PA: W.B. Saunders Company; 2000:17-43.

3.Marhofer P, Frickey N. Ultrasonographic guidance in pediatric regional anesthesia part 1: Theoretical background. *Paed Anaesth*. 2006;16(10):1008-1018.

4.Sites B D, Brull R, Chan V W, et al. Artifacts and pitfall errors associated with ultrasound-guided regional anesthesia. part I: understanding the basic principles of ultrasound physics and machine operations. *Reg Anesth Pain Med* 2007;32(5):412-418.

5.Falyar CR. Ultrasound in anesthesia: applying scientific principles to clinical practice. *AANA J*. 2010 Aug; 78(4):332-40.

Ultrasonic Transducers: Frequency is defined as the number of signals or waves that can be appeared in a fixed time. Units for the frequency are Hertz (Hz). These frequencies are divided into several ranges depending upon the frequency values. They are Very Low Frequencies (VLF), Low Frequencies (LF), Medium Frequencies (MF), High Frequencies (HF), Very High Frequencies (VHF), Ultra-High Frequencies (UHF), Super High Frequencies (SHF), and Extremely High Frequencies (EHF). The frequency range may be varies based on the type of frequencies. The frequency range of VLF ranges from 3 to 30 kHz. The frequency range of LF ranges from 30 kHz to 300 kHz. The frequency range of MF ranges from 300 to 3000 kHz. The frequency range of HF ranges from 3 MHz to 30 MHz. The frequency range of UHF ranges from 300 MHz to 3000 MHz. The frequency range of SHF ranges from 3 GHz to 30 GHz. The frequency range of EHF ranges from 30 GHz to 300 GHz. This article discusses an overview of the ultrasonic transducer and its working.

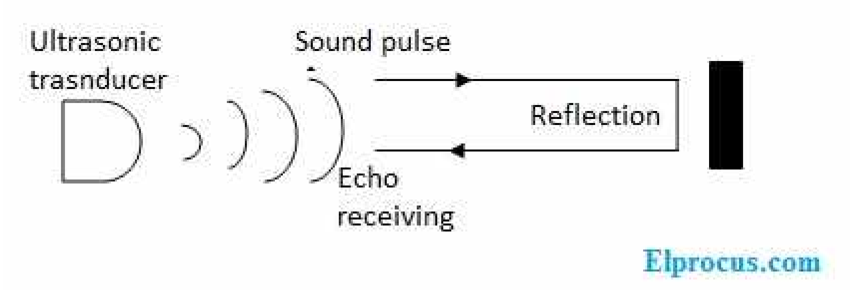
The ultrasonic transducer is one type of sound-related sensor. These transducers send the electrical signals to the object and once the signal strikes the object then it reverts to the transducer. In this process, this transducer measures the distance of the object not by the intensity of the sound. These transducers use ultrasonic waves for the measurement of a few parameters. It has a wide range of applications in various fields. The frequency range of ultrasonic waves is above 20 kHz. These are mainly used in measuring distance applications. The following image indicates the ultrasonic transducer.

Ultrasonic-transducer

These transducers can be defined as a transducer which is used to convert one type of energy to ultrasonic vibration. By these ultrasonic vibrations, this transducer measures the distance of the object. These are available in two types like active and passive

Ultrasonic Transducer Working Principle:

When an electrical signal is applied to this transducer, it vibrates around the specific frequency range and generates a sound wave. These sound waves travel and whenever any obstacle comes, these sound waves will reflect the transducer inform of echo. And at the end of the transducer, this echo converts into an electrical signal. Here, the transducer calculates the time interval between the sending of the sound wave to the receiving the echo signal. The ultrasonic sensor sends the ultrasonic pulse at 40 kHz which travels through the air. These transducers are better than the infrared sensors because these ultrasonic transducer/sensors are not affected by the smoke, black materials, etc. Ultrasonic sensors exhibit excellence in suppressing background interference.



Ultrasonic-transducer

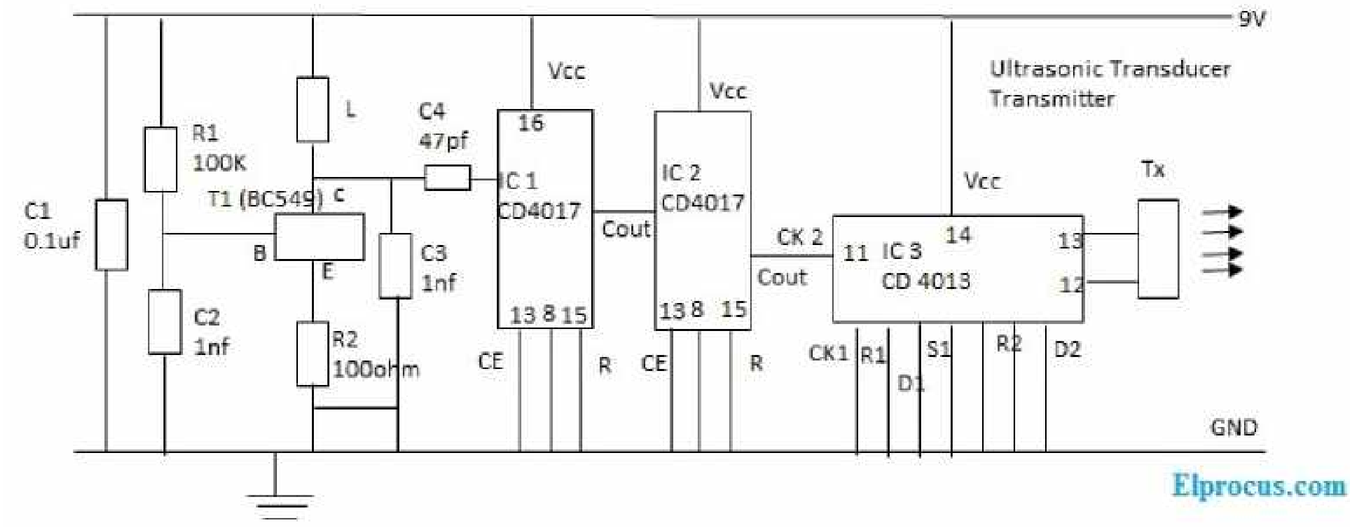
Ultrasonic transducers are mainly used for finding the distance by using ultrasonic waves. The distance can be measured by the following formula.

D = ½ * T * C

Circuit Diagram

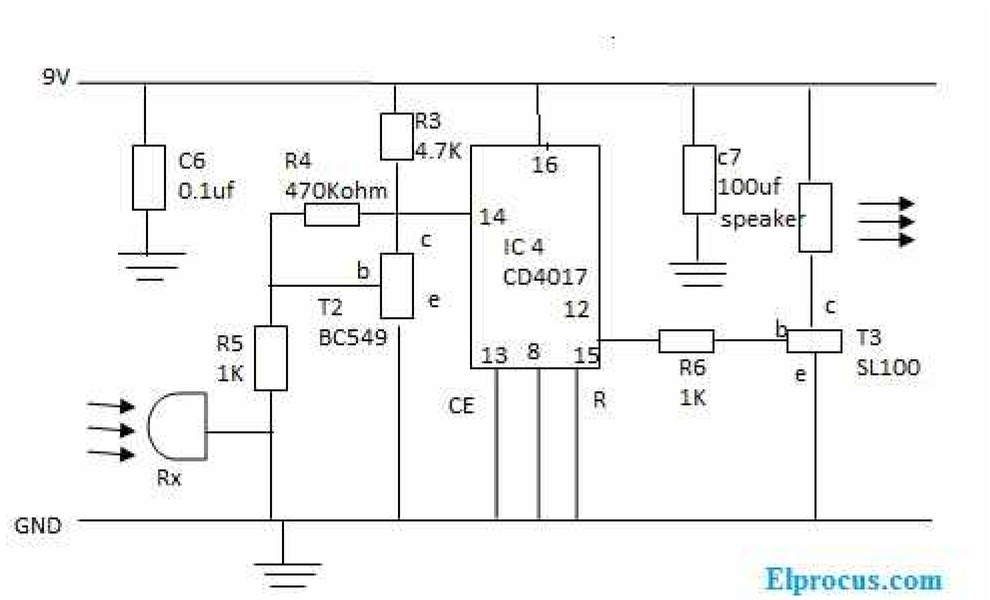
The ultrasonic transducer has a transmitter and receiver circuit, they built with 555 timers or CMOS technology. The transmitter and receiver of this transducer are works on the same frequency.

The transmitter of this transducer transmits the ultrasonic waves towards the object and when the sound waves strike the object then the sound signals are converted to ultrasonic and electrical signals. The following diagram indicates the transmitter circuit diagram of the ultrasonic transducer.



Ultrasonic-transducer-transmitter

The receiver circuit receives the signals after the striking of ultrasonic waves to the object and then convert them to electrical form. The following diagram indicates the receiver circuit diagram of the ultrasonic transducer.



Ultrasonic-transducer-receiver

Ultrasonic Transducer Types

There are various types of ultrasonic transducers available based on factors like piezoelectric crystal arrangement, footprint, and frequency. They are

Linear Ultrasonic Transducers – In this type of transducers, piezoelectric crystal arrangement is linear.

Standard Ultrasonic Transducers – This type is also called as convex transducers. In this type, the piezoelectric crystal is in a curvy form. For in-depth examinations these are preferable.

Phased Array Ultrasonic Transducers – Phased array transducers have a small footprint and low frequency. (its center frequency is 2 MHz – 7 MHz)

For non-destructive testing, the ultrasonic transducers are again having different types. They contact transducers, angle beam transducers, Delay line transducers, immersion transducers, and dual element transducers.

Applications

The applications of Ultrasonic Transducers are

These transducers have many applications in different fields like industrial, medical, etc. These are having more applications because of ultrasonic waves. This helps finds the targets, measure the distance of the objects to the target, to find the position of the object, to calculate the level also the ultrasonic transducers are helpful.

In the medical field, the ultrasonic transducer is having the applications in diagnostic testing, surgical devices while treating cancer, internal organ testing, heart checkups, eyes and uterus checkups ultrasonic transducers are useful.

In the industrial field, ultrasonic transducers have few important applications. By these transducers, they can measure the distance of certain objects to avoid a collision, in production line management, liquid level control, wire break detection, people detection for counting, vehicle detection and many more.

Advantages and Disadvantages

Any system has advantages and a few disadvantages. Here will discuss the **advantages of the ultrasonic transducer.**

- These ultrasonic transducers can able to measure in any type of material. They can sense all types of materials.
- The ultrasonic transducers are not affected by temperature, water, dust or any.
- In any type of environment, the ultrasonic transducers will work in a good manner.
- It can measure in high sensing distances also.

The **disadvantages of these transducers** include the following.

- Ultrasonic transducers are sensitive to temperature variation. This temperature variation may change the ultrasonic reaction.
- It will face problems while reading the reflections from small objects, thin and soft objects.

Thus, this is all about an overview of an ultrasonic transducer. From the above information, finally, we can conclude that this device is used to measure the distance to an object by using sound waves. It measures distance by sending out a sound wave at a specific frequency and listening for that sound wave to bounce back.

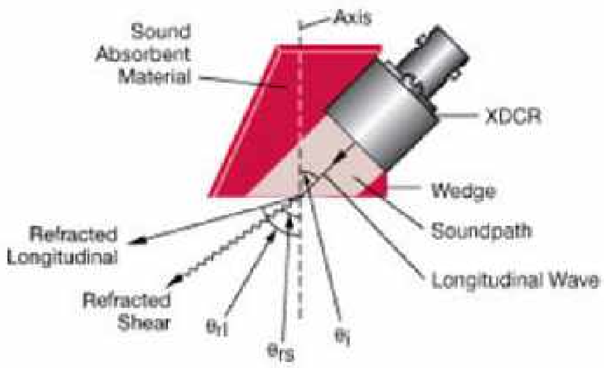
Reference:

1. www.elprocus.com.

Defect location in angle beam testing:

While straight beam techniques can be highly effective at finding laminar flaws, they are not effective when testing many common welds, where discontinuities are typically not oriented parallel to the surface of the part. The combination of weld geometry, the orientation of flaws, and the presence of the weld crown or bead require inspection from the side of the weld using a beam generated at an angle. Angle beam testing is by far the most commonly used technique in ultrasonic flaw detection.

Angle beam probes consist of a transducer and a wedge, which may be separate parts or built into a single housing. They use the principle of refraction and mode conversion at a boundary to produce refracted shear or longitudinal waves in a test piece as shown below.

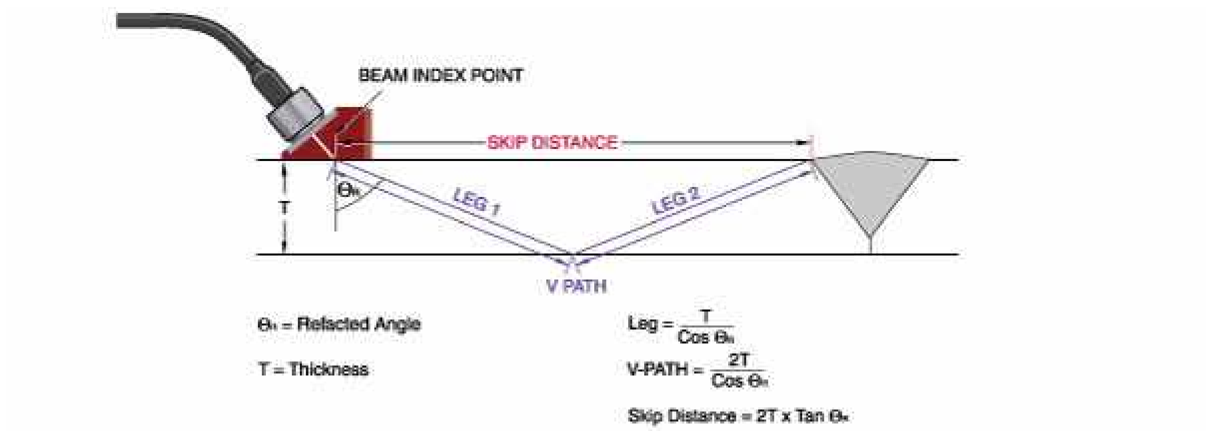


Most commonly used angle beam probes generate a refracted shear wave at standardized angles of 45, 60, or 70 degrees in the test material. The incident angle necessary to produce a desired refracted angle is based on material sound velocities and is calculated from Snell's Law through the equation below.

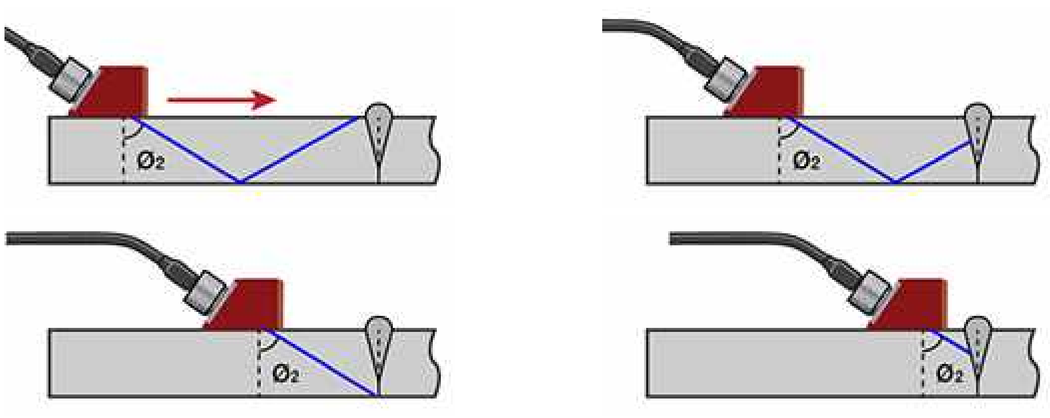
$$\sin\theta_i / c_i = \sin\theta_{rl} / c_{rl} = \sin\theta_{rs} / c_{rs}$$

θ_i = Incident Angle of the Wedge
θ_{rl} = Angle of the Refracted Longitudinal Wave
θ_{rs} = Angle of the Refracted Shear Wave
c_i = Velocity of the Incident Material (Longitudinal)
c_{rl} = Material Sound Velocity (Longitudinal)
c_{rs} = Velocity of the Test Material (Shear)

In the typical case of a plastic or epoxy wedge coupled to steel, low incident angles will generate both longitudinal and shear wave beam components, and specialized longitudinal wave angle beam wedges do exist. However at commonly used inspection angles only a primary shear wave will be generated, since the L-wave solution to the equation would exceed 90 degrees, which is not possible.

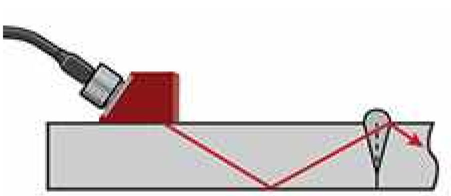


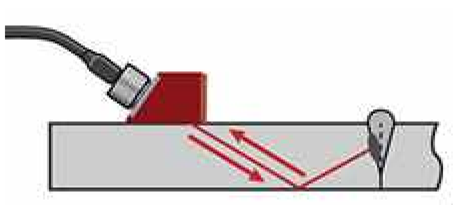
In typical inspections the sound beam will travel at the generated angle down to the bottom of the test piece and then reflect upward at the same angle. Moving the probe back and forth causes the sound beam to sweep across the full height of a weld. This scanning motion enables inspection of the entire weld volume and detection of discontinuities both at the fusion lines and within the weld body.

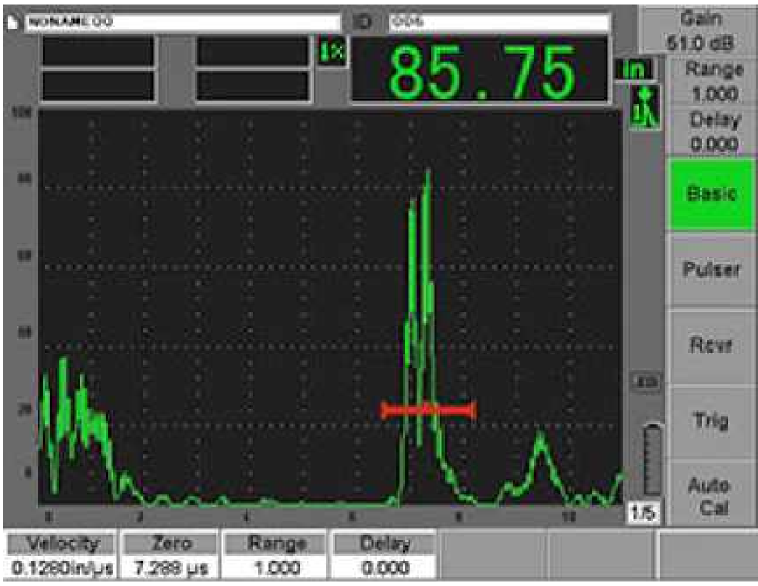


As in the case of straight beam testing, in angle beam testing the operator looks for reflections corresponding to discontinuities. During initial setup the operator must note any echoes that originate from weld bead or other geometric structures. Additional echoes appearing within the zone representing the weld would correspond to a lack of fusion, cracking, porosity, or other discontinuities whose type, depth, and size can be determined through further analysis.

In the example below, the sound beam passes through a good weld without reflecting back, and no significant indications are seen on the screen. A discontinuity within the weld zone, however, causes a strong reflection with the zone of interest marked by the red gate.







Reference:

1. https://www.olympus-ims.com/en/ndt-tutorials/flaw-detection/weld-inspection/

Immersion Ultrasonic Testing :

Another way to couple the sound from transducer to a test object is coupling the sound with water. This can be done with squirters where the sound travels through a jet of water or by immersing the transducer and test object in a tank of water. Both techniques are called immersion testing. In **immersion testing**, the transducer is placed in the water, above the test object, and a beam of sound is projected.

The graph of peaks using the immersion method is slightly different. Between the initial pulse and the back wall peaks there will be an additional peak caused by the sound wave going from the water to the test material. This additional peak is called the front wall peak. The ultrasonic tester can be adjusted to ignore the initial pulse peak, so the first peak it will show is the front wall peak. Some energy is lost when the waves hit the test material, so the front wall peak is slightly lower than the peak of the initial pulse.

Ultrasonic testing is an NDT test technique that interrogates components and structures to detect internal and surface breaking defects, and measures wall thickness on hard (typically metallic or ceramic) components and structures.

How does ultrasonic testing work?

Ultrasonic operates on the principle of injecting a very short pulse of ultrasound (typically between 0.1 MHz and 100 Mhz) into a component or structure, and then receiving and analyzing any reflected sound pulses.

Conventionally, an operator scans a transducer over the surface of the component in such a way that he inspects all the area that is required to be tested by means of a scanning motion. The inspection relies on the training and integrity of the operator to ensure that he has inspected all that is necessary.

Sound pulses reflected from features within the component or structures are conventionally displayed on a screen. The operator also has to interpret these signals and report if the component or structure is defective or acceptable according to the test specification that he is given.

Typical detection limits for fine grained steel structures or components (hand scanning) are single millimeter sized defects. Smaller defects can be detected by immersion testing and a programmed scan pattern with higher frequency ultrasound (slower testing). Detection limits are in the order of 0.1 to 0.2 mm, although smaller defects (typically 0.04mm diameter) can be detected under laboratory conditions.

<u>Reference:</u>

1. https://www.nde-ed.org/EducationResources/HighSchool/Sound/immersion.htm.

Sizing Technique: Technique which enables an estimate of the size of a discontinuity to be made from its ultrasonic indications. Flaw sizing is critical to engineering evaluations to assess wear limits, crack growth rates and fitness of purpose criteria. Accuracy required is not always possible and each technique has its advantages and disadvantages. Some techniques are DGS (AVG), Amplitude, Transit Time, TOFD, Satellite Pulse (diffraction), Multimodal Transducer Techniques, Zonal Method using focused Probes. The principal techniques are carried out by the probe movement and evaluation of the amplitude or time of flight. Small flaws may be sized by either method. If flaws extend beyond the confines of the beam in any direction, then a probe movement method will be required.

A further aspect of flaw characterization is flaw sizing. This is critical to engineering evaluations to assess wear limits, crack growth rates and fitness for purpose criteria. Accuracy required by the engineer is not always possible to achieve by the ultrasonic technician and each sizing technique has its advantages and disadvantages. Various options available to the operator have been discussed in several locations throughout this text. These are summarized with a brief description of some of their pros and cons in the following table.

Sizing Method	**Advantages**	**Disadvantages**
AVG (DGS)	simple go/no-go system can be applied to different shapes	requires special curves no indication of vertical extent
Amplitude	simple to use on smooth easy to adapt to plane mechanized systems	correction for beam size reflectors unreliable in vertical
Transmit time	simple to plot sound path with respect to probe position on part reasonable accurate	requires access from several sides not all new surfaces will provide good reflection
TOFD	single pass operation very accurate not amplitude dependent	requires B-scan presentation and access to both sides of defect from one surface
Satellite Pulse	uses standard equipment not amplitude dependent	not effective at all angles signals are usually weak
Multimodal Transducer	quick and accurate not amplitude based	probes are expensive Techniques Limited characterization possible
Zonal Method Using Focused	simple to incorporate into reduced geometry signals	probes expensive Probes mechanized systems sizing limited to assigned zone amplitude based

The sizing methods listed above have been described elsewhere with the exception of the satellite pulse and zonal methods.

The satellite pulse technique was a fore runner to the multimodal transducer sizing methods. **Figures 1 and 2** illustrate the principles involved in the satellite pulse technique. Both voids and linear defects can be sized quickly and relatively accurately using standard UT equipment.

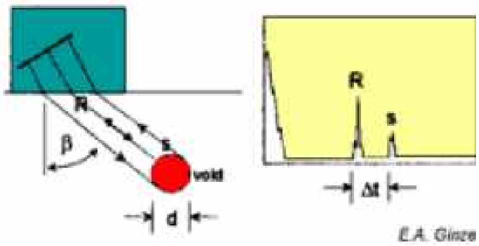


Figure 1

�= refracted angle
R = main reflected pulse
s = surface wave signal (lagging satellite)
delta t = time between R & S

To estimate the void diameter the shear wave velocity and Rayleigh wave velocities are used to derive an equation.

Where c = shear wave velocity
delta t = time difference measured on the CRT (A-scan display)

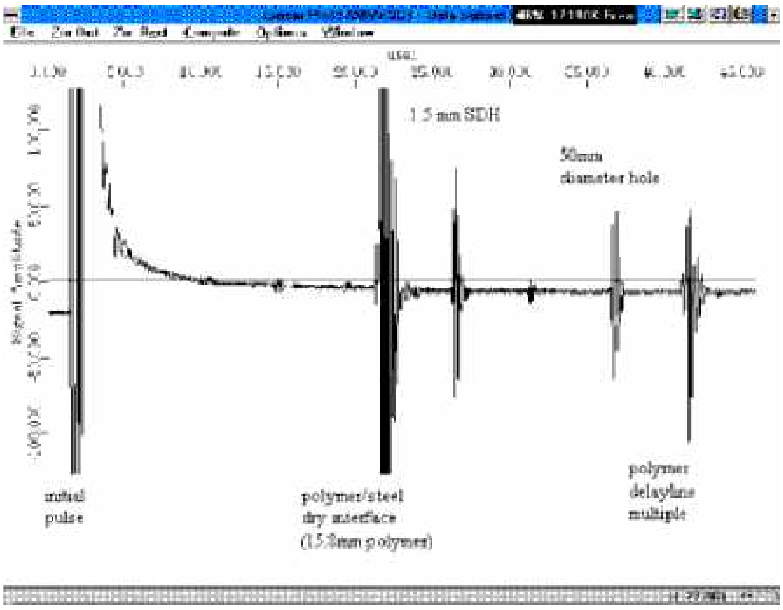


Figure 2

� = refracted angle
R = main reflected pulse
s = tip diffracted satellite pulse
delta t = time between R & s

Similar to the calculations for a void an equation can be derived for the depth of a surface breaking linear flaw.

$$h = \frac{(c)\Delta t}{2\cos\beta}$$

The technique, when used for linear flaws, works better for smaller refracted angles (40� to 50�) as the difference in time from tip to tip is decreased as the angle of incidence approaches the horizontal.

The zonal method of sizing using focused probes is a convenient way to automate a weld inspection. Vertical extent of a flaw is the most important detail to an engineer. It effectively indicates remaining wall thickness. If probes can be arranged to investigate small increments of the wall, arranging several probes in an array will allow the operator to quickly establish how many zones a defect occurs in. **Figure 3** shows a 10mm thick weld with 5 zones. Six probes are positioned to investigate probable areas of defects. If the beam is focused its overlap with adjacent zones in small (less than 6-l0dB) and a signal can be assigned a maximum vertical extent of 2mm for each probe it is detected by. Two probes are used in the root area to accommodate geometry changes. Where a defect has sufficient vertical extent to be seen by more than one probe its vertical extent is reasonably estimated within about 10% of the wall thickness. For example, if a flaw is seen to occur in two adjacent zones it can be assigned a maximum vertical extent of 4mm.

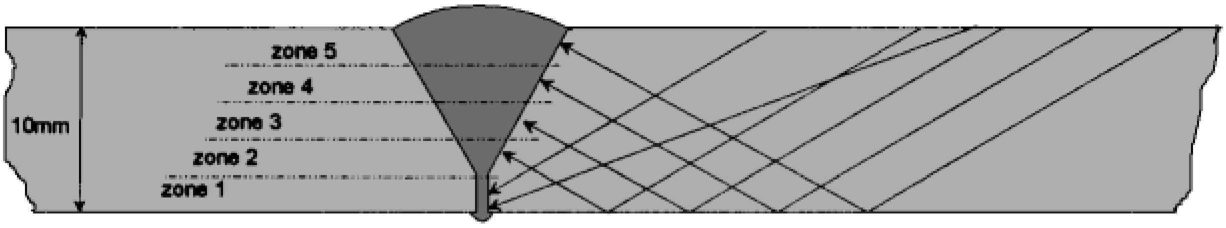


Figure 3:
Six intemally focueed probes with 2 mm diameter spot sizes centred on 5 zones each 2 mm high (eymmetric each side)

The variety of sizing techniques is relatively large and not all options are noted in codes and specifications. This means the operator may be burdened with using methods they know are not adequate for the needs of the project. Conversely, the code requirements for sizing may be unreasonable to use with the equipment available or the degree of accuracy is not possible or not reasonable considering the end use. To avoid such predicaments a knowledgeable technician should provide input in development of rejection criteria. Also, sizing methods required in codes, standards and procedures should be reviewed with regard to any advances made in the industry to ensure the best options (i.e. those most appropriate not necessarily the most accurate) can be used when necessary.

Reference:

1. https://www.ndt.net/ndtaz/content.php?id=311

Unit-	**IV**
Topic-	**Principle of Radiography**
Sub-Topic-	**Principle of radiography, Types of radiography, Equipments for neutron radiography, X-ray radiography, Equipments for X-ray radiography, Advantages and applications of fluoroscopy and photo fluoroscopy. Hardness Testing, Brinell hardness testing, Rockwell hardness tests, Micro hardness testing, Vickers hardness testing, Theory behind hardness testing methods.**

The principles of radiography in Non-Destructive Examination:

X-rays and gamma radiation have wavelengths shorter than 100 nanometres (nm). Energy, at these wavelengths, will penetrate solid material. The shorter the wavelength, the greater the penetration. Like visible light, X-rays and Gamma radiation also have a photochemical effect on silver halide and can therefore produce an image on film. Thus, by passing penetrating radiation through an object, and recording the emerging radiation on a film, a two dimensional picture of the differences in thickness or density of the object can be obtained. Hence, flaws in the object can be detected.

This process was discovered by William Roentgen in 1895 and was soon applied to medicine and then to industrial components. It is based on the principle that radiation is absorbed and scattered as it passes through an object. If there are variations in thickness or density (e.g. due to defects) in an object, more or less radiation passes through and affects the film exposure. Flaws show up on the film, usually as dark areas.

With training, an inspector can tell, from the shape of the dark areas on the film, what and where the flaws are. If the flaw in the object makes little difference to the through thickness of the object, it is unlikely to show on the radiograph. A lamination can, therefore, be difficult to detect by radiography. Cracks parallel to the beam, porosity, slag inclusions and root defects show very well.

The biggest disadvantage is that short wavelength radiations are ionising. This means they can cause chemical changes in the human body. No ionising radiation is safe, as small amounts can cause genetic damage and increase the likelihood of cancers. Stringent safety precautions are needed when using radiography and this makes it rather time consuming, disruptive and expensive.

Industrial radiography uses two sources of penetrating radiation:

- X-ray sets, of varying power, that run from an electric mains or on-site generators
- Radioactive isotopes, carried in shielding containers, which do not need a supply of electricity

Types of radiography:

1. Projection radiography

2. Computed tomography

3. Dual energy X-ray absorptiometry

4. Fluoroscopy

5. Angiography

6. Contrast radiography

7. X-rays

8. Gamma rays

References:

1. R Hamshaw, Introduction to the Non-Destructive Testing of Welded Joints, 2nd edition, Abington Publishing, Cambridge, UK, 1996 (ISBN 1 85573 314 5).

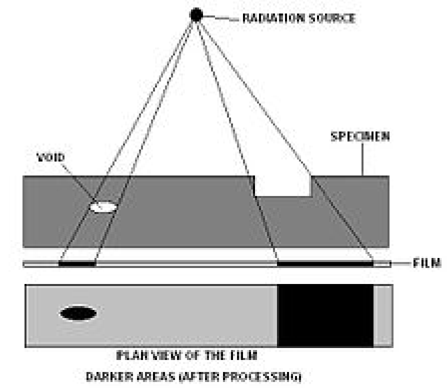
2. Radiography in Modern Industry, 4th Edition, published by Kodak Ltd, Rochester, New York, USA, 1980.

3. Alan Martin and Samuel A Harbison, An Introduction to Radiation Protection, published by Chapman and Hall, 1986, 3rd edition, 1986 (ISBN 0-412-27810-3).

X-Ray Radiography: **Industrial radiography** is a modality of non-destructive testing that uses ionizing radiation to inspect materials and components with the objective of locating and quantifying defects and degradation in material properties that would lead to the failure of engineering structures. It plays an important role in the science and technology needed to ensure product quality and reliability.

Industrial Radiography uses either X-rays, produced with X-ray generators, or gamma rays generated by the natural radioactivity of sealed radionuclide sources. After crossing the specimen, photons are captured by a detector, such as a silver halide film, a phosphor plate or flat panel detector. The examination can be performed in static 2D (named radiography), in real time 2D, (fluoroscopy) or in 3D after image reconstruction (computed tomography or CT). It is also possible to perform tomography nearly in real time (4-dimensionnal computed tomography or 4DCT). CdTe detectors can also be used to analyse the X-ray spectrum. Particular techniques such as X-ray fluorescence (XRF), X-ray diffractometry (XRD), and several other ones complete the range of tools that can be used in industrial radiography.

Inspection techniques can be portable or stationary. Industrial radiography is used in welding, casting parts or composite pieces inspection, in food inspection and luggage control, in sorting and recycling, in EOD and IED analysis, aircraft maintenance, ballistics, turbine inspection, in surface characterisation, coating thickness measurement, in counterfeit drug control



Benefits

- Can inspect assembled components
- Minimum surface preparation required
- Detects both surface and subsurface defects
- Provides a permanent record of the inspection
- Verify internal flaws on complex structures
- Isolate and inspect internal components
- Automatically detect and measure internal flaws
- Measure dimensions and angles within the sample without sectioning
- Sensitive to changes in thickness, corrosion, flaws and material density changes

Applications

Radiographic Testing is widely used in the;

- Aerospace industries
- Military defence
- Offshore industries
- Marine industries
- Power-gen industries
- Petrochem industries
- Waste Management
- Automotive industries
- Manufacturing industries
- Transport industries

References:

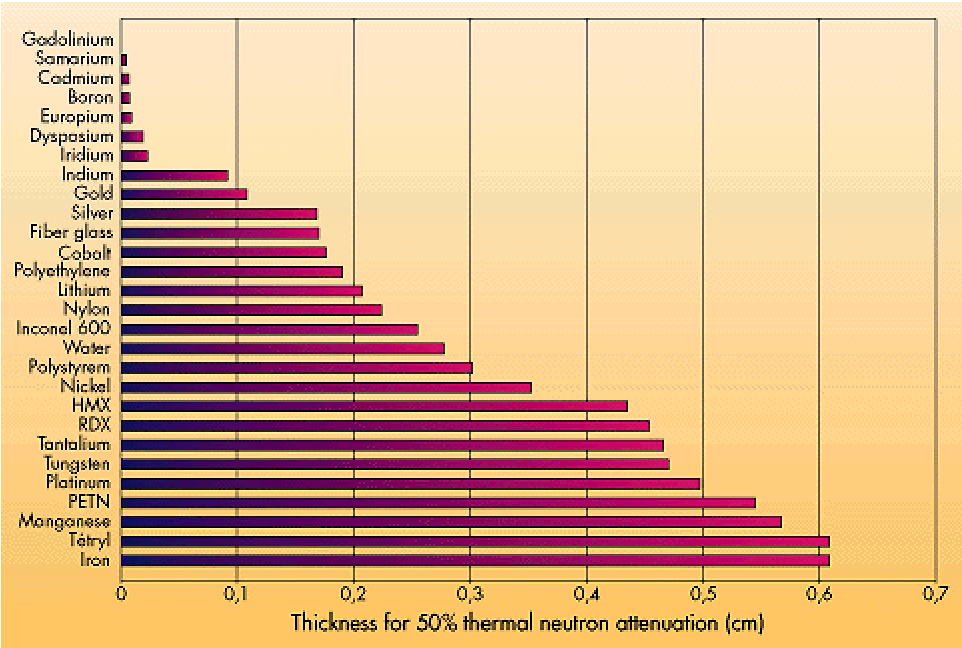
1. Loughborough University Library – Spotlight Archive Archived 2008-12-07 at the Wayback Machine. Lboro.ac.uk (2010-10-13). Retrieved on 2011-12-29.

2. Woodford, Colin; Ashby, Paul. "Non-Destructive Testing and Radiation in Industry" (PDF). IAEA International Nuclear Information System. Retrieved 31 May 2020.

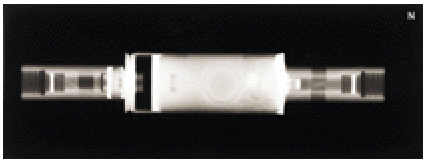
3. Radio Isotope (Gamma) Sources". NDT Resource Center. Retrieved 31 May 2020.

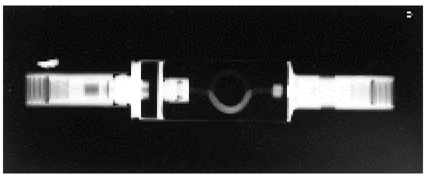
4. International Atomic Energy Agency (1999). Safety Reports Series #13 : Radiation protection and safety in industrial radiography (PDF). ISBN 9201003994.

Neutron radiography: Neutron Radiography is an imaging technique which provides images similar to X-ray radiography. The difference between neutron and X-ray interaction mechanisms produce significantly different and often complementary information. While X-ray attenuation is directly dependent on atomic number, neutrons are efficiently attenuated by only a few specific elements. For example, organic materials or water are clearly visible in neutron radiographs because of their high hydrogen content, while many structural materials such as aluminium or steel are nearly transparent. The next table shows how most materials behave when placed in the path of a neutron beam.



Industrial applications

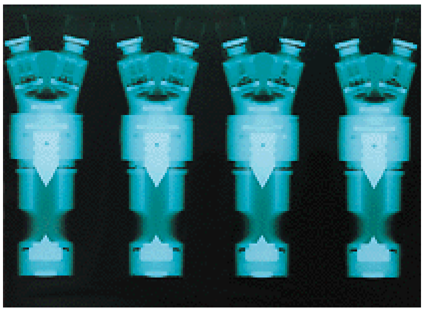




Comparison of neutron radiography and X-ray radiography of an ARIANE cartridge fuse (DASSAULT-AVIATION)

At the present time, Neutron Radiography is one of the main NDT techniques able to satisfy the quality-control requirements of explosive devices used in space programmes. Most of the detonating devices of the Ariane space programme have been systematically submitted to NR examination at the CEA facilities for more than 20 years. The detection of cracks of 0.1 mm thickness in the explosive charge is common and the efficiency of the technique enables easily distinguishes differences in the compression of the explosive even through different metallic containers such as lead, aluminium or steel. The ability to detect compounds containing hydrogen atoms is also used to inspect oil levels and insulating organic materials. Neutron radiography also facilitates the checking of adhesive layers in composite materials, surface layers (polymers, varnishes etc). All types of O-rings and joints containing hydrogen can be observed even through a few centimetres thickness of steel.

Facilities



Two nuclear research reactors in Saclay carry out industrial NR inspections. The main facility is located at the neutron guide end of the ORPHEE reactor. This reactor is currently in operation 250 days a year. The beam quality has a very high intensity free from parasitic gamma rays. The beam has cold neutron components which produce high contrast radiographs. The second facility is installed at the ISIS reactor, it is used when the ORPHEE reactor is shut down.

Reference:

1. http://www-llb.cea.fr/neutrono/nr1.html

Fluoroscopy: - **Fluoroscopy** is an imaging technique that uses X-rays to obtain real-time moving images of the interior of an object. In its primary application of medical imaging, a **fluoroscope** allows a physician to see the internal structure and function of a patient, so that the pumping action of the heart or the motion of swallowing, for example, can be watched. This is useful for both diagnosis and therapy and occurs in general radiology, interventional radiology, and image-guided surgery. In its simplest form, a fluoroscope consists of an X-ray source and a fluorescent screen, between which a patient is placed. However, since the 1950s most fluoroscopes have included X-ray image intensifiers and cameras as well, to improve the image's visibility and make it available on a remote display screen. For many decades fluoroscopy tended to produce live pictures that were not recorded, but since the 1960s, as technology improved, recording and playback became the norm.

Fluoroscopy is similar to radiography and X-ray computed tomography (X-ray CT) in that it generates images using X-rays. The original difference was that radiography fixed still images on film whereas fluoroscopy provided live moving pictures that were not stored. However, today radiography, CT, and fluoroscopy are all digital imaging modes with image analysis software and data storage and retrieval.

The use of X-rays, a form of ionizing radiation, requires the potential risks from a procedure to be carefully balanced with the benefits of the procedure to the patient. Because the patient must be exposed to a continuous source of X-rays instead of a momentary pulse, a fluoroscopy procedure generally subjects a patient to a higher absorbed dose of radiation than an ordinary (still) radiograph. Only important applications such as health care, bodily safety, food safety, non-destructive testing, and scientific research meet the risk-benefit threshold for use. In the first half of the 20th century, shoe-fitting fluoroscopes were used in shoe stores, but their use was discontinued because it is no longer considered acceptable to use radiation exposure, however small the dose, for nonessential purposes. Much research has been directed toward reducing radiation exposure, and recent advances in fluoroscopy technology such as digital image processing and flat panel detectors, have resulted in much lower radiation doses than former procedures.

Fluoroscopy is also used in airport security scanners to check for hidden weapons or bombs. These machines use lower doses of radiation than medical fluoroscopy. The reason for higher doses in medical applications is that they are more demanding about tissue contrast, and for the same reason they sometimes require contrast media.

Mechanism of action: Visible light can be seen by the naked eye (and thus forms images that people can look at), but it does not penetrate most objects (only translucent ones). In contrast, X-rays can penetrate a wider variety of objects (such as the human body), but they are invisible to the naked eye. To take advantage of the penetration for image-forming purposes, one must somehow convert the X-rays' intensity variations (which correspond to material contrast and thus image contrast) into a form that is visible. Classic film-based radiography achieves this by the variable chemical changes that the X-rays induce in the film, and classic fluoroscopy achieves it by fluorescence, in which certain materials convert X-ray energy (or other parts of the spectrum) into visible light. This use of fluorescent materials to make a viewing scope is how fluoroscopy got its name.

As the X-rays pass through the patient, they are attenuated by varying amounts as they pass through or reflect off the different tissues of the body, casting an X-ray shadow of the radiopaque tissues (such as bone tissue) on the fluorescent screen. Images on the screen are produced as the unattenuated or mildly attenuated X-rays from radiolucent tissues interact with atoms in the screen through the photoelectric effect, giving their energy to the electrons. While much of the energy given to the electrons is dissipated as heat, a fraction of it is given off as visible light.

Early radiologists would adapt their eyes to view the dim fluoroscopic images by sitting in darkened rooms, or by wearing red adaptation goggles. After the development of X-ray image intensifiers, the images were bright enough to see without goggles under normal ambient light.

Nowadays, in all forms of digital X-ray imaging (radiography, fluoroscopy, and CT) the conversion of X-ray energy into visible light can be achieved by the same types of electronic sensors, such as flat panel detectors, which convert the X-ray energy into electrical signals, small bursts of current that convey information that a computer can analyze, store, and output as images. As fluorescence is a special case of luminescence, digital X-ray imaging is conceptually similar to digital gamma ray imaging (scintigraphy, SPECT, and PET) in that in both of these imaging mode families, the information conveyed by the variable attenuation of invisible electromagnetic radiation as it passes through tissues with various radiodensities is converted by an electronic sensor into an electric signal that is processed by a computer and made output as a visible-light image.

Common procedures using fluoroscopy

- investigations of the gastrointestinal tract, including barium enemas, defecating proctograms, barium meals and barium swallows, and enteroclysis.
- Liver biopsy is performed under fluoroscopic guidance at many centers.
- Orthopaedic surgery to guide fracture reduction and the placement of metalwork.
- Podiatric Surgery to guide fracture reduction and in use in certain procedures that have extensive hardware.
- Angiography of the leg, heart and cerebral vessels.
- Placement of a PICC (peripherally inserted central catheter)
- Placement of a weighted feeding tube (e.g. Dobhoff) into the duodenum after previous attempts without fluoroscopy have failed.
- Urological surgery – particularly in retrograde pyelography.
- Cardiology for diagnostic angiography, percutaneous coronary interventions, (pacemakers, implantable cardioverter defibrillators and cardiac resynchronization devices)
- Discography, an invasive diagnostic procedure for evaluation for intervertebral disc pathology.
- Lumbar puncture, the fluroscopy helps to guide where the needles of the spinal tap can go. Fluoroscopy may reduce the number of attempts required for a successful lumbar puncture.

Another common procedure is the **modified barium swallow study** during which barium-impregnated liquids and solids are ingested by the patient. A radiologist records and, with a speech pathologist, interprets the resulting images to diagnose oral and pharyngeal swallowing dysfunction. Modified barium swallow studies are also used in studying normal swallow function.

References:

1. Fluoroscopy". Merriam-Webster Dictionary.

2. "X-ray shoe fitting, London (1921)". Democrat and Chronicle. 1921-07-03. p. 2. Retrieved 2017-11-05.

3. "X-ray shoe fitting with foot-o-scope (1922)". The Scranton Republican. 1922-09-27. p. 9. Retrieved 2017-11-05.

4. "Pennsylvania halts x-ray shoe fitting (1957)". The Eugene Guard. 1957. p. 10. Retrieved 2017-11-05.

Hardness Testing: Hardness is a characteristic of a material, not a fundamental physical property. It is defined as the resistance to indentation, and it is determined by measuring the permanent depth of the indentation.

More simply put, when using a fixed force (load) and a given indenter, the smaller the indentation, the harder the material. Indentation hardness value is obtained by measuring the depth or the area of the indentation using one of over 12 different test methods.

Hardness testing is used for two general characterizations

1.Material Characteristics
• Test to check material
• Test harden ability
• Test to confirm process
• Can be used to predict Tensile strength

2. Functionality
• Test to confirm ability to function as designed.
• Wear Resistance
• Toughness
• Resistance to impact

Hardness Testing Considerations
The following sample characteristics should be consider prior to selecting the hardness testing method to use:

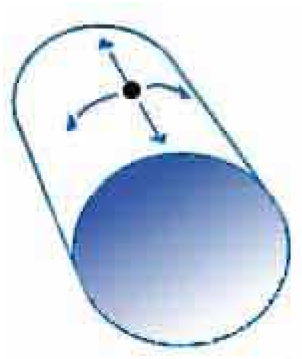
• Material
• Sample Size
• Thickness
• Scale
• Shape of sample, round, cylindrical, flat, irregular
• Gage R & R

Material
The type of material and expected hardness will determine test method. Materials such as hardened bearing steels have small grain size and can be measured using the Rockwell scale due to the use of diamond indenters and high PSI loading. Materials such as cast irons and powder metals will need a much larger indenter such as used with Brinell scales. Very small parts or small sections may need to be measured on a micro hardness tester using the Vickers or Knoop Scale.

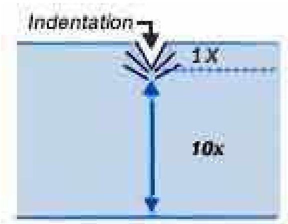
When selecting a hardness scale, a general guide is to select the scale that specifies the largest load and the largest indenter possible without exceeding defined operation conditions and accounting for conditions that may influence the test result.

Sample Size
The smaller the part, the lighter the load required to produce the required indentation. On small parts, it is particularly important to be sure to meet minimum thickness requirements and properly space indentations away from inside and outside edges. Larger parts need to be fixture properly to

ensure secure placement during the test process without the chance for movement or slippage. Parts that either overhang the anvil or are not easily supported on the anvil should be clamped into place or properly supported.



Cylindrical Samples
A correction to a test result is needed when testing on cylinder shapes with small diameters due to a difference between axial and radial material flow. Roundness correction factors are added to your testing result based on the diameter of convex cylinder surfaces. Additionally, it is important to maintain a minimum spacing equal to 2~1/2 times the indentation's diameter from an edge or another indentation.



Sample Thickness
Your sample should have a minimal thickness that is at least 10x (ten times) the indentation depth that is expected to be attained. There are minimum, allowable thickness recommendations for regular and superficial Rockwell methods

Scales
Sometimes it is necessary to test in one scale and report in another scale. Conversions have been established that have some validity, but it is important to note that unless an actual correlation has been completed by testing in different scales, established conversions may or may not provide reliable information. Refer to ASTM scale conversion charts for non-austenitic metals in the high hardness range and low hardness range. Also refer to ASTM standard E140 for more scale conversion information.

Gage R&R
Gage Repeatability and Reproducibility Studies were developed to calculate the ability of operators and their instruments to test accordingly within the tolerances of a given test piece. In hardness testing, there are inherent variables that preclude using standard Gage R&R procedures and formulas with actual test pieces. Material variation and the inability to retest the same area on

depth measuring testers are two significant factors that affect GR&R results. In order to minimize these effects, it is best to do the study on highly consistent test blocks in order to minimize these built-in variations.

Reference:

1. https://www.hardnesstesters.com/test-types/hardness-testing-basics.

Brinell Hardness Testing:

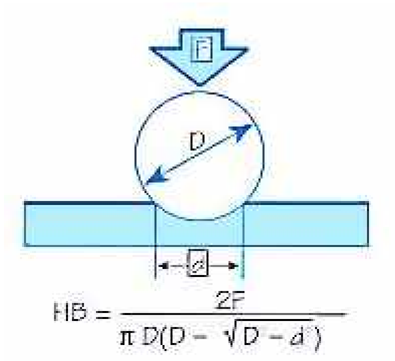
Hardness is a characteristic of a material, not a fundamental physical property. It is defined as the resistance to indentation, and it is determined by measuring the permanent depth of the indentation.

More simply put, when using a fixed force (load) and a given indenter, the smaller the indentation, the harder the material. Indentation hardness value is obtained by measuring the depth or the area of the indentation using one of over 12 different test methods.

The **Brinell hardness test method** as used to determine Brinell hardness is defined in ASTM E10. Most commonly it is used to test materials that have a structure that is too coarse or that have a surface that is too rough to be tested using another test method, e.g., castings and forgings. Brinell testing often use a very high test load (3000 kgf) and a 10mm diameter indenter so that the resulting indentation averages out most surface and sub-surface inconsistencies.

The Brinell method applies a predetermined test load (F) to a carbide ball of fixed diameter (D) which is held for a predetermined time period and then removed. The resulting impression is measured with a specially designed Brinell microscope or optical system across at least two diameters – usually at right angles to each other and these results are averaged (d). Although the calculation below can be used to generate the Brinell number, most often a chart is then used to convert the averaged diameter measurement to a Brinell hardness number.

Common test forces range from 500kgf often used for non-ferrous materials to 3000kgf usually used for steels and cast iron. There are other Brinell scales with load as low as 1kgf and 1mm diameter indenters but these are infrequently used.



Test Method Illustration

D = Ball diameter
d = impression diameter
F = load
HB = Brinell result

typically the greatest source of error in Brinell testing is the measurement of the indentation. Due to disparities in operators making the measurements, the results will vary even under perfect conditions. Less than perfect conditions can cause the variation to increase greatly. Frequently the test surface is prepared with a grinder to remove surface conditions.

The jagged edge makes interpretation of the indentation difficult. Furthermore, when operators know the specifications limits for rejects, they may often be influenced to see the measurements in a way that increases the percentage of “good” tests and less re-testing.

Two types of technological remedies for countering Brinell measurement error problems have been developed over the years. Automatic optical Brinell scopes, such as the B.O.S.S. system, use computers and image analysis to read the indentations in a consistent manner. This standardization helps eliminate operator subjectivity so operators are less-prone to automatically view in-tolerance results when the sample’s result may be out-of-tolerance.

Brinell units, which measure according to ASTM E103, measure the samples using Brinell hardness parameters together with a Rockwell hardness method. This method provides the most repeatable results (and greater speed) since the vagaries of optical interpretations are removed through the use of an automatic mechanical depth measurement.

Using this method, however, results may not be strictly consistent with Brinell results due to the different test methods – an offset to the results may be required for some materials. It is easy to establish the correct values in those cases where this may be a problem.

Reference:

1. https://www.hardnesstesters.com/test-types/brinell-hardness-testing.

Rockwell Hardness Test:

The **Rockwell hardness test method**, as defined in ASTM E-18, is the most commonly used hardness test method. You should obtain a copy of this standard, read and understand the standard completely before attempting a Rockwell test.

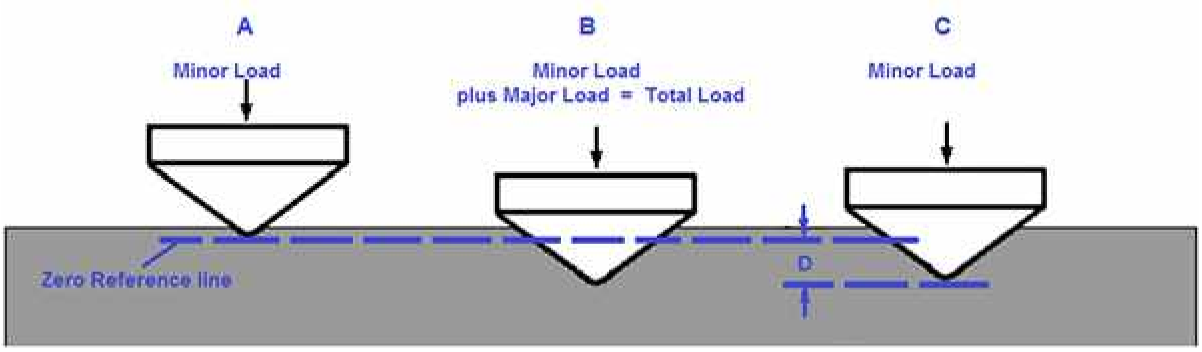
The Rockwell test is generally easier to perform, and more accurate than other types of hardness testing methods. The Rockwell test method is used on all metals, except in condition where the test metal structure or surface conditions would introduce too much variations; where the indentations would be too large for the application; or where the sample size or sample shape prohibits its use.

The Rockwell method measures the permanent depth of indentation produced by a force/load on an indenter. First, a preliminary test force (commonly referred to as preload or minor load) is applied to a sample using a diamond or ball indenter. This preload breaks through the surface to reduce the effects of surface finish. After holding the preliminary test force for a specified dwell time, the baseline depth of indentation is measured.

After the preload, an additional load, call the major load, is added to reach the total required test load. This force is held for a predetermined amount of time (dwell time) to allow for elastic recovery. This major load is then released, returning to the preliminary load. After holding the preliminary test force for a specified dwell time, the final depth of indentation is measured. The Rockwell hardness value is derived from the difference in the baseline and final depth measurements. This distance is converted to a hardness number. The preliminary test force is removed and the indenter is removed from the test specimen.

Preliminary test loads (preloads) range from 3 kgf (used in the "Superficial" Rockwell scale) to 10 kgf (used in the "Regular" Rockwell scale). Total test forces range from 15kgf to 150 kgf (superficial and regular) to 500 to 3000 kgf (macro hardness).

Test Method Illustration
A = Depth reached by indenter after application of preload (minor load)
B = Position of indenter during Total load, Minor plus Major loads
C = Final position reached by indenter after elastic recovery of sample material
D = Distance measurement taken representing difference between preload and major load position. This distance is used to calculate the Rockwell Hardness Number.



A variety of indenters may be used: conical diamond with a round tip for harder metals to ball indenters' ranges with a diameter ranging from 1/16" to ½" for softer materials.

When selecting a Rockwell scale, a general guide is to select the scale that specifies the largest load and the largest indenter possible without exceeding defined operation conditions and accounting for conditions that may influence the test result. These conditions include test specimens that are below the minimum thickness for the depth of indentation; a test impression that falls too close to the edge of the specimen or another impression; or testing on cylindrical specimens.

Additionally, the test axis should be within 2-degress of perpendicular to ensure precise loading; there should be no deflection of the test sample or tester during the loading application from conditions such as dirt under the test specimen or on the elevating screw. It is important to keep the surface finish clean and decarburization from heat treatment should be removed.

Sheet metal can be too thin and too soft for testing on a particular Rockwell scale without exceeding minimum thickness requirements and potentially indenting the test anvil. In this case a diamond anvil can be used to provide a consistent influence of the result.

Another special case in testing cold rolled sheet metal is that work hardening can create a gradient of hardness through the sample so any test is measuring the average of the hardness over the depth of indentation effect. In this case any Rockwell test result is going to be subject to doubt, there is often a history of testing using a particular scale on a particular material that operators are used to and able to functionally interpret.

Reference:

1. https://www.hardnesstesters.com/test-types/rockwell-hardness-testing.

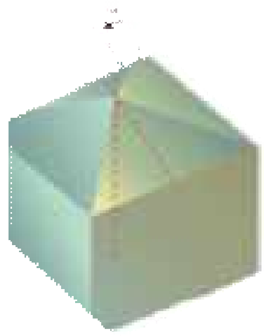
Micro hardness Testing: Hardness test methods use an indenter probe that is displaced into a surface under a specific load. The indentation typically has a defined dwell time. In traditional mechanical testing, the size or depth of indentation is measured to determine hardness. Hardness testing is divided into two ranges: macro hardness and micro hardness. Macro hardness covers testing with an applied load over 1 kg or about 10 Newton (N). Micro hardness testing, with applied loads under 10 N, is typically used for smaller samples, thin specimens, plated surfaces or thin films. The two most common micro hardness techniques are Vickers and Knoop hardness tests.

For more accurate and reproducible results, micro hardness testing needs to account for effects of sample size, preparation and, environment. Samples must fit in the sample stage and be perpendicular to the indenter tip. An extremely rough surface may reduce the accuracy of indentation data; a proven method for polishing samples is recommended. The micro hardness tester needs to be isolated from vibrations. For samples with multiple phases or variation in grain sizes, statistical data is required.

Traditional micro hardness test methods optically analyze the indented impression, convoluting data with operator bias. Unlike Vickers or Knoop hardness test methods, instrumented indentation uses a three-sided pyramidal (Berkovich) indenter. This shape allows the tip to be theoretically designed to an atomic point. Using a high load nanoindenter for micro hardness testing with forces ranging up to 1 Newton (N), instrumented indentation with an array of indents using dynamic measurements yields unparalleled accurate and reliable micro hardness data with no operator bias.

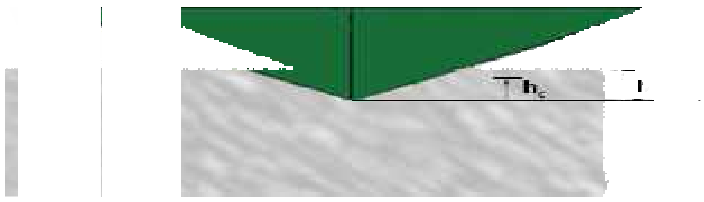
Vickers Hardness

The Vickers hardness test uses a Vickers indenter (below) pressed into a surface to a specified force. The force is usually held for 10 seconds. After the indentation is finished, the resulting indent is analyzed optically to measure the lengths of the diagonals to determine the size of the impression.



Schematic of a Vickers indentation probe.

There is a degree of operator bias in this method, especially in the lower range of the applied load. According to ASTM E384-11, indentation diagonals should be greater than 17 microns in length. For coated samples, this test is not valid for coating thicknesses under 60 microns.

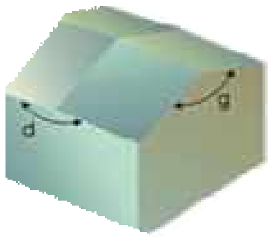


Vickers indentation schematic.

For many types of samples, the contact depth (h_c) is not identical to the displacement depth (h) due to surrounding material getting elastically deflected during the indentation, as shown schematically (left). In addition to the above-mentioned sample and environmental considerations, this effect also affects accuracy and precision for micro hardness data.

Knoop Hardness

The Knoop hardness test is also a micro hardness technique that is similar to the Vickers hardness test method. A Knoop indenter is used to press into a surface to measure hardness. The Knoop indenter, however, is shaped differently than a Vickers indenter for micro hardness or a Berkovich indenter used in nanoindentation. The shape for the Knoop indenter is more elongated or rectangular. The Knoop hardness test method is usually done with lighter loads for micro hardness testing and careful sample preparation is required. Knoop hardness testing is applied to samples needing indentations close together or on the edge of a sample, both benefitting from the different probe shape.



Schematic of a Knoop indentation probe.

A designated load is applied for a specified dwell time. In contrast to the Vickers hardness method, the Knoop test method uses only the long axis. The resulting indentation measurements are then converted to a Knoop hardness number using a chart. For the Knoop indenter probe shown here, angles are d=172.50° and g=130.00°.

Due to the limitations with a lower applied load range, validity issues for thin films, and an increase in nanotechnology resulting in smaller dimensions, micro and nanoindentation methods have been developed.

Reference:

1. https://www.hardnesstesters.com/test-types/rockwell-hardness-testing.

Vickers Hardness Testing: The Vickers hardness test method, also referred to as a micro hardness test method, is mostly used for small parts, thin sections, or case depth work.

The Vickers method is based on an optical measurement system. The Micro hardness test procedure, ASTM E-384, specifies a range of light loads using a diamond indenter to make an indentation which is measured and converted to a hardness value. It is very useful for testing on a wide type of materials, but test samples must be highly polished to enable measuring the size of the impressions. A square base pyramid shaped diamond is used for testing in the Vickers scale. Typically loads are very light, ranging from 10gm to 1kgf, although "Macro" Vickers loads can range up to 30 kg or more.

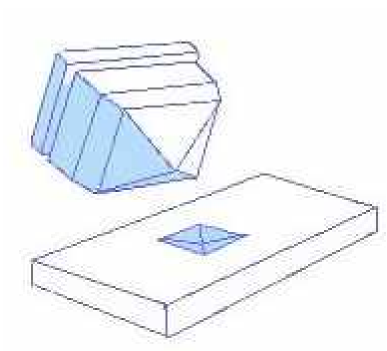
The Micro hardness methods are used to test on metals, ceramics, and composites - almost any type of material.

Since the test indentation is very small in a Vickers test, it is useful for a variety of applications: testing very thin materials like foils or measuring the surface of a part, small parts or small areas, measuring individual microstructures, or measuring the depth of case hardening by sectioning a part and making a series of indentations to describe a profile of the change in hardness.

Sectioning is usually necessary with a micro hardness test in order to provide a small enough specimen that can fit into the tester. Additionally, the sample preparation will need to make the specimen's surface smooth to permit a regular indentation shape and good measurement, and to ensure the sample can be held perpendicular to the indenter.

Often the prepared samples are mounted in a plastic medium to facilitate the preparation and testing. The indentations should be as large as possible to maximize the measurement resolution. (Error is magnified as indentation sizes decrease) The test procedure is subject to problems of operator influence on the test results.

.



Opposing indenter faces are set at a 136 degree angle from one another.

Reference:-

1. https://www.hardnesstesters.com/test-types/vickers-hardness-testing.

Theory behind hardness testing methods: Hardness testing is an essential tool for distinguishing between materials and for the analysis, development and improvement of materials and technologies in the context of basic research (materials science, materials engineering, and materials diagnostics).

It involves the determination of characteristic values (hardness values) that are of crucial importance for assessing the use of materials in industry (suitability of a material for a technically relevant part), their acceptance during inspections as part of quality assurance (incoming goods and outgoing goods inspections), for distinguishing between materials (e.g. in the case of material confusion) and for clarification of cases of damage (damage analysis).

Hardness testing is today one of the most frequently employed methods for mechanical material testing, in particular for metals.

On the one hand, this test method allows qualitative relationships to other material properties (e.g. strength, rigidity, density) or to the behaviour of the materials under certain loads (e.g. wear resistance) to be established.

On the other hand, the hardness test is comparatively quick and simple to perform and causes relatively little damage to the specimen, i.e. only very minor marks are left on the specimen surface.

It also provides a simple method for quality control (incoming goods and outgoing goods inspection). The hardness test method also allows a wide variety of geometries to be tested.

Hardness is a measure of how mechanically resistant a material (test work piece) is to the mechanical penetration of another, harder body (indenter).

The hardest natural material is diamond. Diamond is therefore used as an indenter (industrial diamond).

The definition of hardness differs from that of strength, which describes the resistance of a material to deformation and separation.

Hardness is not a fundamental property of a material. There are hardness ranges, however, within which certain materials lie. Hardness can be changed by heat, i.e. a work piece takes on a different (higher) hardness value after heat treatment.

There are no set defined values for hardness. The hardness value determined during a hardness test can depend on:

- the choice of test method
- the test force applied to the indenter
- the length of time that the indenter remains in the material
- the indenter geometry
- the work piece geometry

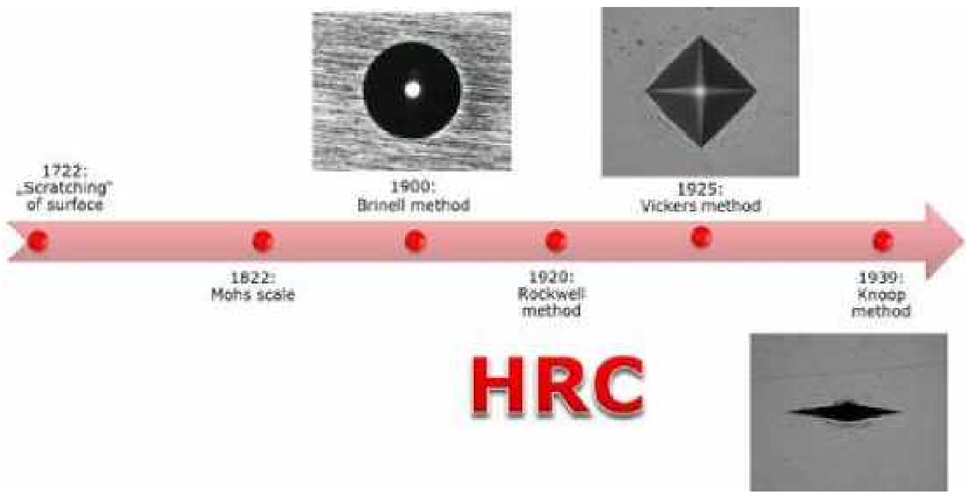
A principle distinction between the hardness testing methods generally used in technical testing is made between methods with static force application and those with dynamic force application.

Methods with static application of the test force are predominantly used for testing the hardness of metals, whereby either the penetration depth or the size of the indentation caused by an indenter is measured. A distinction is made with the static hardness testing methods between depth measurement methods and optical measurement methods.

Depth measurement methods measure the residual depth of indentation left by the indenter. The Rockwell method is the only standardised depth measurement method (see ISO 6508, ASTM E18). There are also other, non-standardised depth measurement methods: Brinell and Vickers in the depth (HBT, HVT).

Optical measurement methods measure the residual size of indentation left by the indenter. Standardised optical hardness testing methods are Brinell (ISO 6506, ASTM E10), Knoop (ISO 4545, ASTM E92, ASTM E384) and Vickers (ISO 6507, ASTM E92, ASTM E384).

Alternatively, methods involving dynamic force application, such as the Leeb rebound method, in which the height of a ball rebound is measured, can also be used for hardness testing.



The most important dates in the history of hardness testing are as follows:

- **1722**: R. A. Reaumur develops a "scratching" of the surface of minerals using steel.
- **1822**: The Mohs scale for mineral testing is invented. This is a ten-point scratch hardness scale in which each material can be scratched using the next harder material. The Mohs hardness values are still used today in mineralogy, but are not suitable for determining the hardness of technical materials (metals). The individual hardness steps are relatively large and have different intervals.

Mohs hardness	**Type of mineral**	**Vickers hardness (HV)**
1	Talcum	2HV
2	Gypsum	35HV
3	Calcite	100HV
4	Fluorspar	200HV
5	Apatite	540HV
6	Orthoclase	800HV
7	Quartz	1.100HV
8	Topaz	1.400HV
9	Corundum	2.000HV
10	Diamond	10.000HV

- **1900**: J. A. Brinell develops a ball indentation test that later becomes known as the Brinell method.
- **1920**: S. R. Rockwell develops the pre-load method named after him for testing his ships.
- **1925**: The Vickers method was invented by R. Smith and G. Sandland in England. It allows micro hardness tests to be carried out.
- **1939**: F. Knoop, C. G. Peters and W. B. E. Emerson develop the Knoop method at the National Bureau of Standards (USA).

Hardness testing of metals is performed in accordance with the following common static methods that are defined in the standards listed below (ISO vs. ASTM).

Test methods	**ISO**	**ASTM**
Brinell	ISO 6506	ASTM E10
Vickers	ISO 6507	ASTM E92, ASTM E384
Rockwell	ISO 6508 DIN 50103	ASTM E18
Knoop	ISO 4545	ASTM E92, ASTM E384

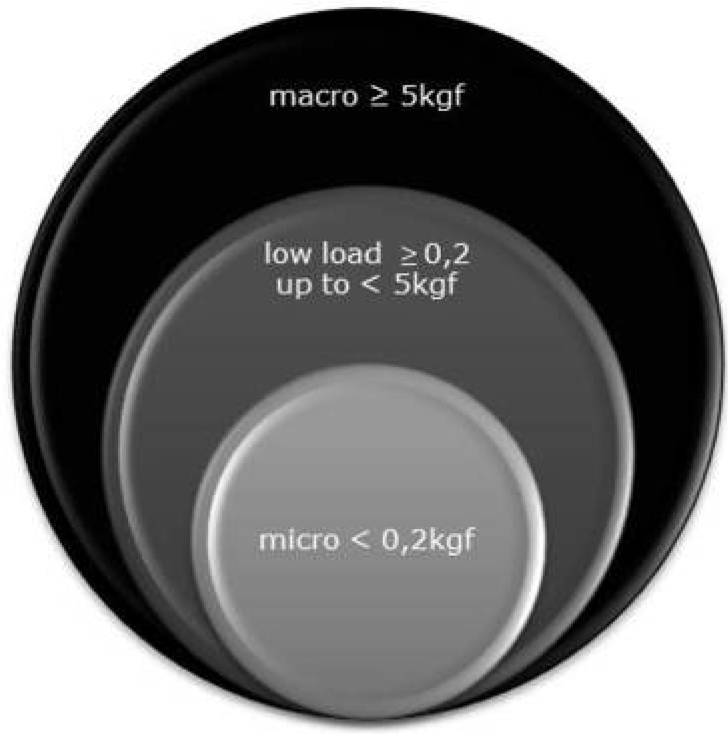
Depending on the field of application, different main loads (test loads) are used during hardness testing. Depending on the level of the main load applied to a test work piece during the hardness test, a distinction is made between micro, small load and macro hardness testing in the ISO standard.

In the **macro range** (conventional hardness range), large test loads ≥ 5 kgf are used which result in correspondingly large hardness impressions in the test work pieces. The macro hardness testing methods include Brinell, Vickers and Rockwell.

A hardness test in the **low-load range** is one in which the test load lies between 0.2 kgf and 5 kgf (test load ≥ 0.2 kgf and < 5 kgf). The most common low-load testing method is Vickers. Low-load hardness testing is used predominantly for testing small parts, thick coatings and materials with a low hardness. < 5 kgf).

During **micro hardness testing**, low test loads < 0.2 kgf are used, which only leave very small indents in the test pieces (most common method: Vickers). Micro hardness testing can therefore be used to test the hardness of thin layers or, e.g., the hardness of individual crystallites or inclusions.

Categorisation of hardness testing by load range



.

Methods with static force application are predominantly used for the hardness testing of metals that can be distinguished according to the following criteria:

- form of the indenter (ball, pyramid or cone)
- indenter material (hardened steel, carbide metal or diamond)
- size of the test force applied to a test specimen
- method of evaluation: measurement of the penetration depth (depth measurement method) or size of the indentation (optical measuring method) caused by the indenter.

Reference:

1. https://www.emcotest.com/en/the-world-of-hardness-testing/hardness-know-how/theory-of-hardness-testing/.