Strength Control
Technical Diagnostics
Non-destructive Testing
of Oil and Gas Equipment

CONTENTS

INTRODUCTION. SCOPE AND APPLICATION OF TECHNICAL DIAGNOSTICS

REFERENCES

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2. **Основы технической диагностики нефтегазового оборудования: Учеб, пособие для вузов / Е.А. Богданов. — М.: Высш. шк., 2006. — 279 с.**
3. **Introduction to nondestructive testing: a training guide (Paul E. Mix)**
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MEANING AND IMPORTANCE OF TECHNICAL DIAGNOSTICS

Technical diagnostics is a field of knowledge covering the theory, methods and means of determining the technical condition of objects

διάγνωσις (GR) - recognition, definition (originally medical term)

Technical diagnostics is the examination of symptoms and syndromes to determine the nature of faults or failures of technical objects

- Fault: the condition of an item that occurs when one of its components or assemblies degrades or exhibits abnormal behavior.
- Failure: the termination of the ability of an item to perform a required function.
- Failure is an event as distinguished from fault, which is a state.

THE PURPOSE OF TECHNICAL DIAGNOSTICS

The purpose of technical diagnostics is to determine the possibility and conditions of further use of the diagnosed equipment and, as a result, to improve industrial and environmental safety.

The main problem of technical diagnostics is the recognition of the state of the technical system under conditions of limited information.

TASKS OF TECHNICAL DIAGNOSTICS

Tasks of technical diagnostics are:

- **Detection of defects and discrepancies, establishment of the reasons of their occurrence and on this basis determination of technical condition of the equipment;**
- **Forecasting of technical condition and residual resource (determination with the set probability of a time interval, during which the operational condition of the equipment will remain).**

OBJECTS OF TECHNICAL DIAGNOSTICS

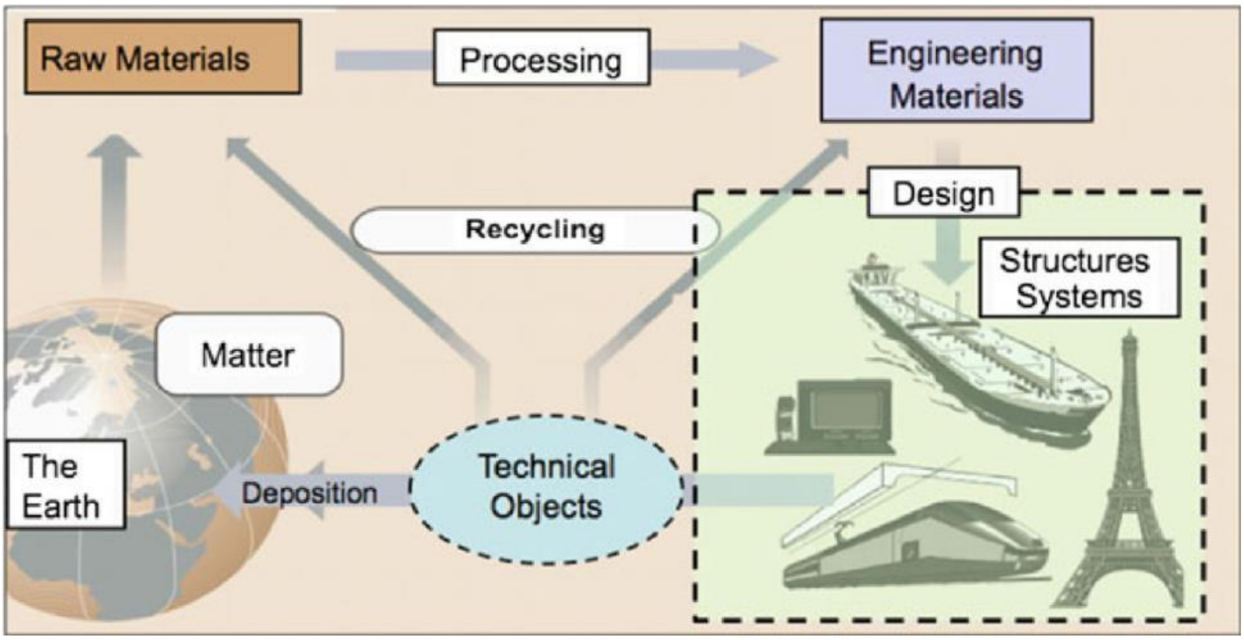
The main objects of technical diagnostics are:

- **engineering materials,**
- **engineering structures,**

- **engineering systems.**

Technical diagnostics can be applied in almost all areas of technology and industry in order to ensure product quality, economical and efficient processes and, most importantly, to assure safety and reliability.

The objects of technical diagnostics can be illustrated by the life cycle of all man-made technical items: from raw materials to engineering materials and via design and production to structures and systems, and finally, to deposition or recycling



TERM "FAILURE" IN VARIOUS TECHNOLOGY AREAS

So important task of technical diagnostics is the identification of faults and failures. Below you can see the examples of failure characteristics from various technology areas and industrial branches, defined in international standards (ISO).

- **Termination of the ability of a structure (a building or its parts) to perform its required (a specified) function. (Mechanical vibration and shock, ISO 16587; Buildings and constructed assets, ISO 15686)**
- **Premature malfunction or breakdown of a function or a component or the whole engine. (Internal combustion engines, ISO 2710).**

- **Sudden and unexpected ending of the ability of a component or equipment to fulfill its function. (Gas turbines, ISO 3977)**
- **Loss of structural integrity and/or transmission of fluid through the wall of a component or a joint. (Petroleum and natural gas industries, ISO 14692)**
- **Occurrence of bursting, leaking, weeping or pressure loss. (Plastics piping systems, ISO 7509).**
- **Any leakage or joint separation, unless otherwise determined to be due to a pipe or fitting defect. (Ships and marine technology, ISO 15837)**
- **Insufficient load-bearing capacity or inadequate serviceability of a structure or structural element. (Reliability for structures, ISO 2394)**

- System state which results in non-performance or impaired performance as a result of a hardware or software malfunction. (Road vehicles, ISO 17287).

ASPECTS OF DAMAGE IDENTIFICATION

The examples from the different technological areas and industrial sectors show that various faults and failures may detrimentally influence technical items. Damage identification by technical diagnostics has to consider generally four basic aspects:

- the existence of damage,
- damage location,
- damage type,
- damage severity.

RELIABILITY AND SAFETY

The probability that a technical item will perform its required functions without failure for a specified time period (lifetime) when used under specified conditions is called reliability.

Risk is the combination of the probability of an event and its consequence. ,

The term ‘‘risk’’ is generally used only when there is at least the possibility of negative consequences.

Safety is freedom from unacceptable risk.

TIME-SCALE OF THE OCCURRENCE OF FAULTS AND FAILURES

With regard to the time-scales of the occurrence of faults and failures in technical items, the following aspects are of general importance:

- The fault progression time indicating the change in severity of a fault over time
- The duration of a failure event, which may very short (e. g. brittle fracture) or may extend over a long period of time (e. g. loading time until fatigue failure occurs). A catastrophic failure is a sudden, unexpected failure of an item resulting in considerable damage to the item and/or associated components.
- The time-to-failure is the total time duration of operating time of an item from the instant it is first put in operation until failure, or from the instant of restoration until next failure.

THE CONDITION MONITORING

The detection and collection of information and data that indicate the state of an item is called condition monitoring.

The application of condition monitoring to technical structures and systems allows actions to be taken to avoid the consequences of failure, before the failure occurs.

Main phases of the process of condition monitoring:

- detection of problems, i.e. deviations from normal conditions,
- diagnosis of the faults and their causes,
- prognosis of future fault progression,
- recommendation of actions.

MAINTENANCE

Maintenance is the combination of all technical and administrative actions intended to retain an item in a state (or restore it to it), in which it can perform a required function.

- **Predictive maintenance is emphasizing prediction of failure and taking action based on the condition of the equipment to prevent failure or degradation.**

- **Preventive maintenance is performed according to a fixed schedule, or according to a prescribed criterion that detects or prevents degradation of a functional structure, system or component, in order to sustain or extend its useful life.**

- **Corrective maintenance is carried out after fault recognition and intended to put an item into a state in which it can perform a required function.**

CONCEPTS, METHODS AND TECHNIQUES OF TECHNICAL DIAGNOSTICS

The basic methods of technical diagnostics are

- Structural Health Monitoring (SHM)

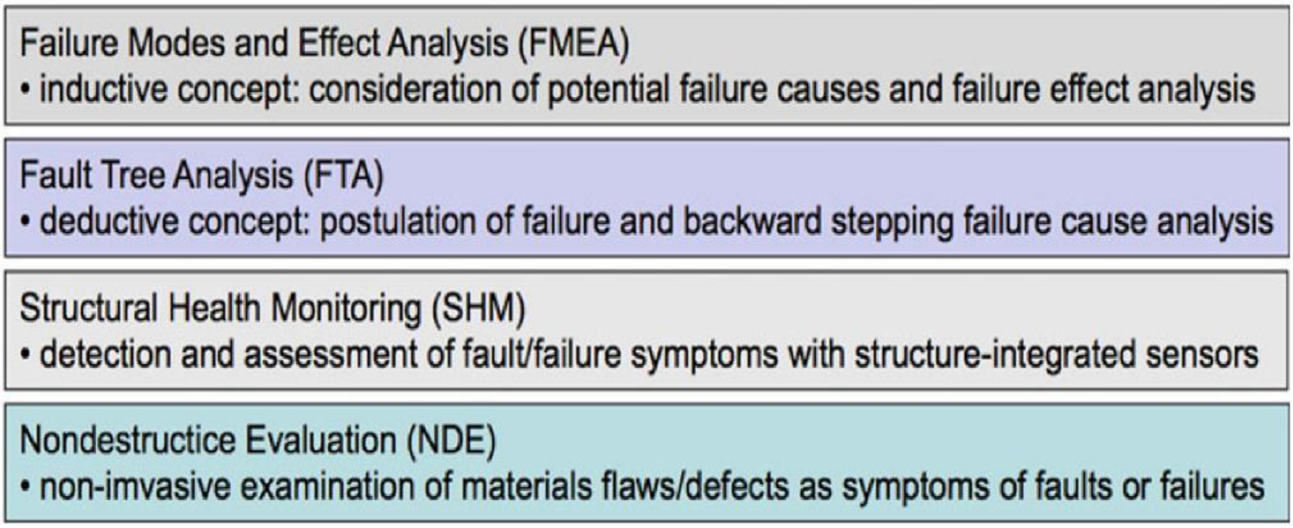
- Non-destructive Evaluation (NDE)

In combination with inductive and deductive concepts:

- The inductive conceptual approach consists of assuming particular failed states for components and then analyzing the effects on the system. So inductive approaches start at a possible basic cause and then analyze the resulting effects. A basic inductive method is the Failure Modes and Effects Analysis (FMEA).

- The deductive conceptual approach postulates that the system itself has failed in a certain way, and an attempt is made to find out what modes of system or subsystem (component) behavior contribute to this failure. A basic deductive method is the Fault Tree Analysis (FTA).

A summarizing overview of the concepts, methods and techniques of Technical Diagnostics is given below with key words of their definitions.



Failure Modes and Effect Analysis (FMEA)
- inductive concept: consideration of potential failure causes and failure effect analysis

Fault Tree Analysis (FTA)
- deductive concept: postulation of failure and backward stepping failure cause analysis

Structural Health Monitoring (SHM)
- detection and assessment of fault/failure symptoms with structure-integrated sensors

Nondestructice Evaluation (NDE)
- non-imvasive examination of materials flaws/defects as symptoms of faults or failures

FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

A failure modes and effects analysis (FMEA) is a structured procedure to determine equipment functions and functional failures. Each failure mode being assessed to the cause of the failure and the effects of the failure on the system. The FMEA method helps to identify potential failure modes based on past experience with similar products or processes.

A FMEA can identify, with reasonable certainty, those component failures having ‘‘non-critical’’ effects, but the number of possible component failure modes that can realistically be considered is limited. The objectives of the analysis are to identify single failure modes and to quantify these modes.

A FMEA table for a component of a system contains the following information:

- **Component designation**
- **Failure probability**
- **Component failure modes**
- **Percent of total failures attributable to each mode**
- **Effects on overall system, classified into various categories, e.g.**
  - critical
  - non-critical

Effects analysis refers to studying the consequences of those failures.

FAULT TREE ANALYSIS (FTA)

Fault tree analysis (FTA) attempts to model and analyze failure processes. As a deductive approach, FTA starts with an undesired event, such as failure of an engine, and then determines (deduces) its failure causes using a systematic, backward-stepping process.

• A Fault Tree (FT) is constructed as a logical illustration of the events and their relationships that are necessary and sufficient to result in the undesired event.

FTA is basically composed of logic diagrams that display the state of the system and is constructed using graphical design techniques. FTA usually involves events from hardware wear out, material failure or malfunctions or combinations of deterministic contributions to the event stemming from assigning a hardware/system failure rate to branches or cut sets. Typically failure rates are carefully derived from substantiated historical data such as mean time between failure of the components, unit, subsystem or function.

• Success Tree (ST) is the logical complement into which a FT can be transformed.

A ST shows the specific ways the undesired event can be prevented from occurring. The ST provides conditions that, if assured, guarantee that the undesired event will not occur.

STRUCTURAL HEALTH MONITORING (SHM)

Structural health monitoring (SHM) is the process of implementing a damage detection and characterization strategy for engineering structures.

The objective of SHM is to monitor the in situ behavior of a structure accurately and efficiently, to assess its performance under various service loads, to detect damage or deterioration, and to determine the health or condition of the structure. The SHM process involves the observation of a system over time using an array of sensors, and the statistical analysis of these measurements to determine the current state of system health. The SHM system should be able to provide, on demand, reliable information pertaining to the safety and integrity of a structure.

The physical diagnostic tool of SHM is the comprehensive integration of various sensing devices and auxiliary systems, including a sensor system, a data acquisition system, a data processing system, a communication system, a damage-detection and modelling system.

SHM has several fundamental axioms, or general principles:

1. All materials have inherent flaws or defects or - deviations of an ideal crystal structure:

- Point defects or missing atoms: vacancies, interstitial or substituted atoms
- Line defects or rows of missing atoms: dislocations
- Area defects: grain boundaries, phase boundaries, twins
- Volume defects: cavities, precipitates.

2. The assessment of damage requires a comparison between two system states;

3. Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage present and the damage severity can generally only be done in a supervised learning mode;

4a. Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information;

4b. Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions;

5. The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system;

6. There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability;

7. The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments.

NON-DESTRUCTIVE EVALUATION (NDE)

Nondestructive Evaluation (NDE) is the umbrella term for non-invasive methods of testing, evaluation and characterization based on physical principles of sensing and assessment.

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NDE is an important method for performance control and condition monitoring. In engineering systems, flaws and especially cracks in the materials of structural systems' components can be crucially detrimental.

For this reason the detection of defects and cause analysis are essential parts of quality control of engineering structures and systems and their safe successful use.

Established NDE methods for technical diagnostics include:

- **radiography,**
- **ultrasound,**
- **eddy current,**
- **magnetic particle,**
- **liquid penetration,**
- **thermography,**
- **visual inspection techniques**

NDE has been developing intensively over the last decades, which has led to a wide variety of methods and techniques that are very fruitfully used for technical diagnostics in factories and structures. The reason for this is the rapid progress in the development of new sensors, instrumentation and robotics combined with the development of new materials.

Industrial application of the NDE methods is also widespread and includes engineering, aerospace, civil engineering, petroleum, electric power, etc.

The use of NDE methods in several industries is standard practice, for example, to support the monitoring of the state of vessels or pressure pipes, where the correct operation of components under constant pressure conditions plays an important role for safety and reliability.

Nondestructive testing (NDT) is any of a wide group of analysis techniques used in science and technology industry to evaluate the properties of a material, component or system without causing damage.

The terms

- **nondestructive examination (NDE),**
- **nondestructive inspection (NDI),**
- **and nondestructive evaluation (NDE)**

are also commonly used to describe this technology.

NOTABLE EVENTS IN ACADEMIC AND INDUSTRIAL NDT

1854 Hartford, Connecticut – A boiler at the Fales and Gray Car works explodes, killing 21 people and seriously injuring 50. Within a decade, the State of Connecticut passes a law requiring annual inspection (in this case visual) of boilers.

1880–1920 – The "Oil and Whiting" method of crack detection is used in the railroad industry to find cracks in heavy steel parts. (A part is soaked in thinned oil, then painted with a white coating that dries to a powder. Oil seeping out from cracks turns the white powder brown, allowing the cracks to be detected.) This was the precursor to modern liquid penetrant tests.

1895 – Wilhelm Conrad Röntgen discovers what are now known as X-rays. In his first paper he discusses the possibility of flaw detection.

1920 – Dr. H. H. Lester begins development of industrial radiography for metals.

1924 – Lester uses radiography to examine castings to be installed in a Boston Edison Company steam pressure power plant.

1926 – The first electromagnetic eddy current instrument is available to measure material thicknesses.

1927-1928 – Magnetic induction system to detect flaws in railroad track developed by Dr. Elmer Sperry and H.C. Drake.

1929 – Magnetic particle methods and equipment pioneered (A.V. DeForest and F.B. Doane.)

1930s – Robert F. Mehl demonstrates radiographic imaging using gamma radiation from Radium, which can examine thicker components than the low-energy X-ray machines available at the time.

1935–1940 – Liquid penetrant tests developed (Betz, Doane, and DeForest)

1935–1940s – Eddy current instruments developed (H.C. Knerr, C. Farrow, Theo Zuschlag, and Fr. F. Foerster).

1940–1944 – **Ultrasonic test** method developed in USA by Dr. Floyd Firestone, who applies for a U.S. invention patent for same on May 27, 1940 and is issued the U.S. patent as grant no. 2,280,226 on April 21, 1942. Extracts from the first two paragraphs of this seminal patent for a nondestructive testing method succinctly describe the basics of ultrasonic testing. "My invention pertains to a device for detecting the presence of inhomogeneities of density or elasticity in materials. For instance if a casting has a hole or a crack within it, my device allows the presence of the flaw to be detected and its position located, even though the flaw lies entirely within the casting and no portion of it extends out to the surface." Additionally, "The general principle of my device consists of sending high frequency vibrations into the part to be inspected, and the determination of the time intervals of arrival of the direct and reflected vibrations at one or more stations on the surface of the part." Medical **echocardiography** is an offshoot of this technology.

1946 – First neutron radiographs produced by Peters.

1950 – The Schmidt Hammer (also known as "Swiss Hammer") is invented. The instrument uses the world's first patented non-destructive testing method for concrete.

1950 – J. Kaiser introduces acoustic emission as an NDT method.

1955 – ICNDT founded. World organizing body for Nondestructive Testing.

1955 – First NDT World Conference takes place in Brussels, organized by ICNDT. NDT World Conference takes place every four years.

1963 – Frederick G. Weighart's and James F. McNulty (U.S. radio engineer)'s co-invention of **Digital radiography** is an offshoot of the pairs development of nondestructive test equipment at Automation Industries, Inc., then, in El Segundo, California. See James F. McNulty also at article Ultrasonic testing.

1996 – Rolf Diederichs founded the first Open Access NDT Journal in the Internet. Today the Open Access NDT Database NDT.net

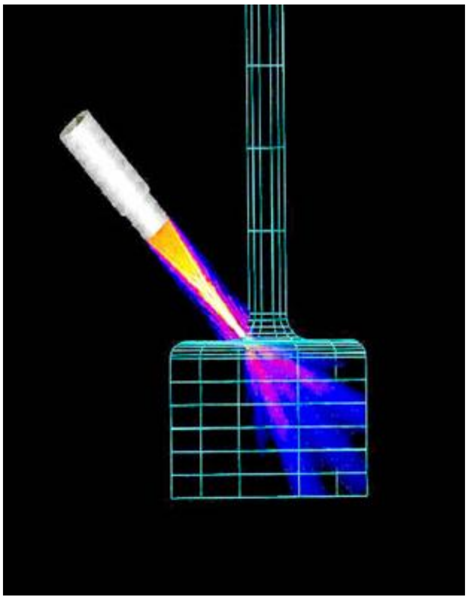
1998 – The European Federation for Non-Destructive Testing (EFNDT) was founded in May 1998 in Copenhagen at the 7th European Conference for Non-Destructive Testing (ECNDT). 27 national European NDT societies joined the powerful organization.

2008 – NDT in Aerospace Conference was established DGZfP and Fraunhofer IIS hosted the first international congress in Bavaria, Germany.

2008 – Academia NDT International has been officially founded and has its base office in Brescia (Italy) www.academia-ndt.org

2012 – ISO 9712:2012 ISO Qualification and Certification of NDT Personnel

2020 – Indian Society for Non-destructive Testing (ISNT) Accreditation Certification from NABCB for Qualification and Certification of NDT Personnel as per ISO 9712:2012



DEFINITION OF NDT (NDE)

NDT is the use of noninvasive techniques to determine the integrity of a material, component or structure or quantitatively measure some characteristic of an object, i.e. inspect or measure without doing harm.

WHAT ARE SOME USES OF NDE METHODS?

- Flaw Detection and Evaluation
- Leak Detection
- Location Determination
- Dimensional Measurements
- Structure and Microstructure Characterization
- Estimation of Mechanical and Physical Properties
- Stress (Strain) and Dynamic Response Measurements
- Material Sorting and Chemical Composition Determination

DISCONTINUITIES— ORIGINS AND CLASSIFICATION

Structural materials are composed of atoms and molecules that ideally have material continuity extending down into the microscopic scale. However, absolute homogeneity and continuity never exist in any engineering component.

Engineering materials always possess some discontinuities, although they may be very small and they may or may not be acceptable. Examples of these discontinuities include

- voids,
- inclusions,
- laps,
- folds,
- cracks,
- chemical segregation, and
- local changes in microstructure.

Geometric surface discontinuities include

- sharp angles,
- notches,
- gouges,
- scratches,
- galling,
- fretting,
- pitting, and
- welding undercut.

Discontinuities are evaluated completely by

- location,
- number,
- shape,
- size,
- orientation,
- type.

The origin and types of discontinuities depend primarily on the manufacturing processes and the service histories of engineering components. In some cases, the operational environment may induce the growth and development of preexisting discontinuities. Discontinuities in structures may originate at any manufacturing step and may be introduced during the component use, maintenance, and repair.

Challenges to engineering-material integrity largely involve the discontinuities in components. Disruptions in continuity may be either internal or on the surface. Discontinuities may be macroscopic or microscopic and they may limit the strength, ductility, toughness, and endurance of a component. A primary responsibility of the examiner is to detect and characterize discontinuities in a component. The location and type of discontinuity is dependent on the fabrication and operation history of a component. An examiner is given an advantage when he or she understands the relationship of product form and history to the consequent discontinuities in a component.

Understanding the origin of discontinuities in engineering components should result in efficiencies in nondestructive examinations and enhancements in quality of examination results.

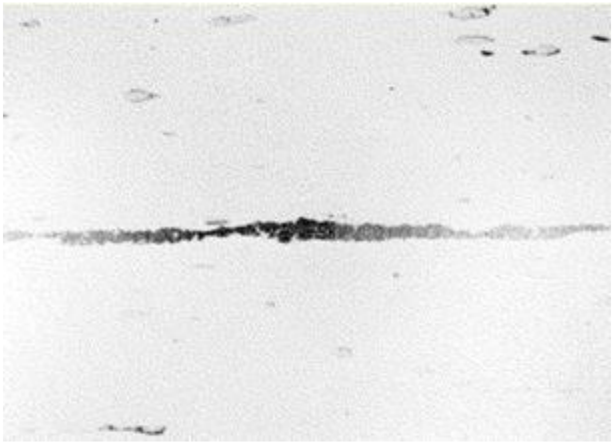
Contents:

I. PRIMARY PRODUCTION OF METALS

The extraction of metals from ores requires processes that often carry over some of the mineral impurities from the rocks and the chemical additions used in the refinement process. These impurities exist in large part as low-density **nonmetallic slags**. Slag inclusions within a structure are discontinuities, usually called **nonmetallic inclusions**.

Small amounts of the slags are often retained within the metals during primary production and become incorporated in alloys. Slags may be carried over into secondary forming operations to generate stringers and laminations. Inclusions in steel often are composed of the silicates and sulfides that come from the iron ore.

Many of the nonmetallic inclusions are plastic at high temperatures and capable of being deformed during hot working of steels. When steel is shaped by being deformed at relatively high temperatures, these included particles will elongate in the direction of flow of the steel. Elongated inclusions in a steel structure are called stringers.



Silicate stringer in cold drawn bar of steel (235X)

Stringers in adequately high number will result in directionality, a property called “geometric anisotropy,” in the steel. Such steel will have a fibrous structure like wood and will be stronger along the elongated fibrous structure and weaker across the elongated structure. Rupture and cracking along the weak planes of this structure during subsequent forming or use generates a discontinuity called “lamellar tearing.”

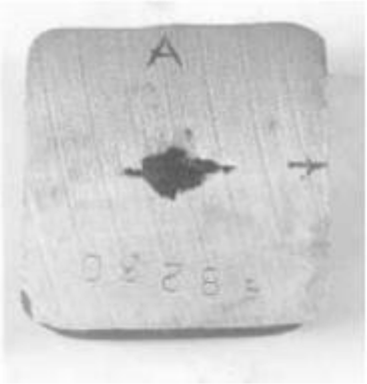
The inhomogeneities of inclusions common in steels and in other alloys are generally acceptable if the size and total inclusion content is relatively small and the distribution is adequately random.

II. CASTING

A metal or an alloy is transformed from a liquid to a crystalline solid by the extraction of thermal energy from the melt during casting in a mold.

Casting of alloys entails the change of a metallic liquid solution into a crystalline solid alloy. The crystallization of a solid begins at small and discrete locations called nucleating sites, and alloy crystals grow from these sites into the alloy melt.

Casting volume is less than the melt volume after the liquid changes to a crystalline solid. This phenomenon is called **solidification shrinkage**. Unfilled spaces in the cast solid are created by the shrinkage of the included melt. These voids are called **shrinkage voids** or **shrinkage porosity**.

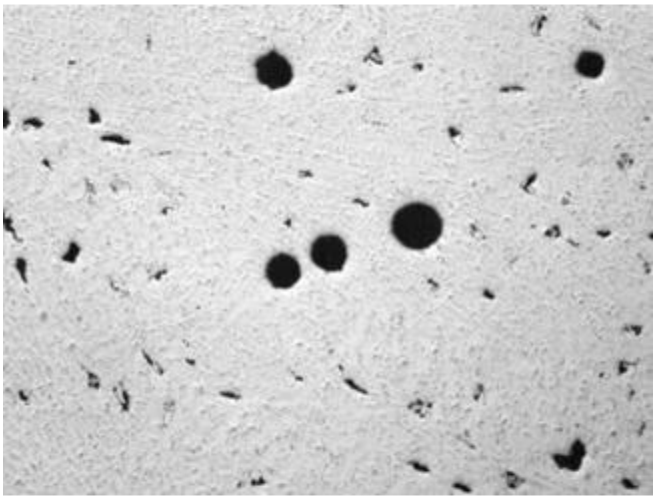


A cross section through a billet showing void from solidification shrinkage

Gas evolution from melts may also cause porosity in cast structures.

Unlike shrinkage porosity, gas develops in the solidifying melt with pressure. The gases will try to move within the melt to lower-pressure regions. This occasionally leads to elongated void structures called **wormholes**. These elongated pores form as the gas tries to move away from the solid interfaces in the casting.

Gas porosity, like shrinkage porosity, will decrease the load bearing capacity of a component.

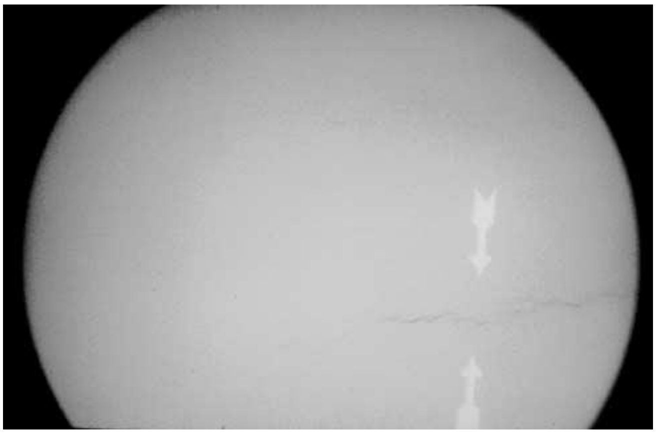

Gas porosity in aluminium alloy die casting

Dissolved gas emanating near the surface of a component may cause splitting and deforming of material near the surface. The appearance and name of this form of surface and near-surface discontinuity is “**blistering**.”

There are occasions when a casting mold may contain regions that are not completely filled. These discontinuities in structure are called **casting cavities**.

Shrinkage and the stresses arising from shrinkage after casting may be adequate to rupture a casting. This is called **solidification shrinkage cracking**.

Shrinkage cracks may later propagate in an alloy and cause failure during subsequent heating and mechanically forming. This damage is a form of hot cracking and hot tearing


Radiograph of hot tear in a casting

These solidification and hot cracking discontinuities are deleterious to service and are unacceptable.

Inclusions of foreign objects in casting typically occur when pieces of refractory are broken off into the melt. The refractory may come from the primary production process or from refractories used in casting molds and pouring crucibles.

There is another form of discontinuity characteristic of casting called a cold shut. This is a discontinuity on the surface of a casting caused by a stream of liquid metal solidifying on and not fusing with a previously solidified part of the component.

A cold shut may also refer separately to a plugging of a channel in a mold by early solidification, which then prevents the entire mold cavity from filling, resulting in **casting cavities**.

A **scab** is a surface discontinuity that has a rough and porous texture, usually with a cavity underneath caused by refractory inclusion near the surface. Scabs are more commonly found in thin sections of castings.

A mold parting line may give rise to a geometric discontinuity on the casting called a **casting seam**. A mold parting line seam is one indication of a casting process. Parting lines may also be dressed out of a component after casting.

Macroscopic chemical segregation is a condition that often occurs in very large alloy castings, such as ingots. The segregated glassy material formed during casting is called **slag**. Relatively large local aggregates of slag challenge the mechanical strength of an alloy.

III. CRACKS

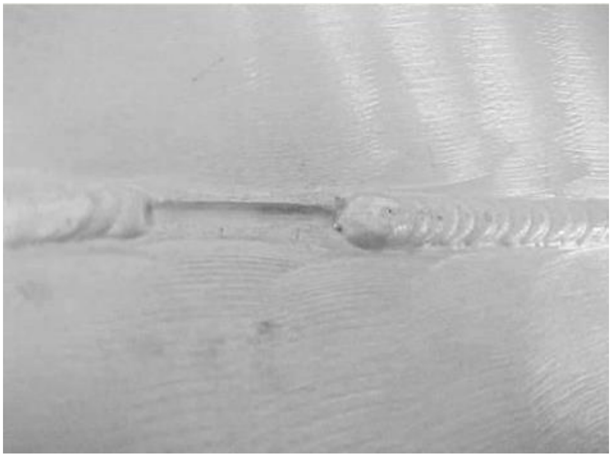
Crack is a planar physical breach in continuity in a material that had previously been continuous.

Forces from forming operations or usage of components are generally the cause of cracks.

Cracking may occur during casting operations. Metallic materials are weaker at high temperatures and the forces from differential contraction may be enough to cause cracking. Evolution of gas in the interior of a casting at high temperatures may cause pressure that is adequate to crack the interior of the casting.

There are **also crack-like discontinuities** that are not formed by forces. These are disruptions in continuity of a component that are caused by the overlaying of two surfaces that are not joined, except along a boundary. An example of a crack-like discontinuity would be lack of fusion in a welding operation. The surface of the weldment is not fused to the base material substrate, and this discontinuity is geometrically similar to a crack. Lack of fusion, like a crack, can initiate fatigue cracking during component use.

Lack of penetration in a welding operation, generally at the root of a weld, may also provide a discontinuity in a structure that has crack-like geometry. For instance, incomplete penetration in an autogenous weld used to join pipe will yield two mating base material surfaces that are a crack-like discontinuity in the joint.



Lack of penetration in weld

IV. WELDING DISCONTINUITIES

There are many welding processes, and each may give rise to discontinuities. Some of them are common to casting and some are occasionally unique to the welding process.

Welding over slag covered surfaces may trap slag inside the weldment. Inclusion of nonmetallic material is common to welding processes. Slag inclusions in welding have the same effect as the **slag inclusions** in cast components. Slag weakens a structure by limiting its load-bearing capability.

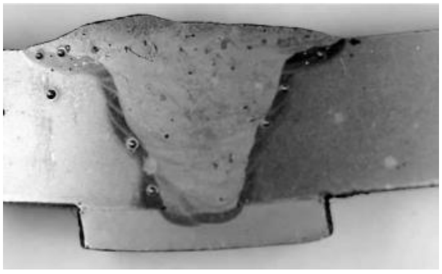
Welding discontinuities include **solidification cracks** that are caused by the casting operation. There is a stress condition that arises in welding operations due to the differential expansion and contraction of the base material.

The differential expansion and subsequent restraint on cooling may give rise to forces that exceed the ultimate strength of either the base material, weldment, or heat-affected zone. This may cause deformation, cracking, fracture, and at the least, residual stresses. Postweld heat treatment (PWHT) is sometimes additionally required to relieve the residual stresses in a weld and to make beneficial changes in microstructure.

Cracking that is created in the base material adjacent to the fusion zone of a weld is called **underbead cracking**. Cracking occurring in the process of postweld heat treatment is called **reheat cracking**.

Discontinuities called **lack of fusion** are found in local unfused regions between beads in a weld or between the base material and the weld. Incomplete melting of a substrate in a welding process causes lack of fusion. These discontinuities are potential initiation sites for fatigue cracks.

A microstructural change that occurs in welding is called the heat-affected zone (HAZ). The HAZ is the unmelted region of base material adjacent to the weldment that has a microstructure that is altered by the high temperature of the welding operation.


Cross section of a weld showing heat affected zone as a dark band adjacent to the weld.

Other microscopic and material property changes may occur in the HAZ of different alloys. For instance, an alloy that is strengthened by work hardening will soften in the HAZ from a weld.

Heat affected zone properties may result in some damage mechanisms being available. For instance, the HAZ of some stainless steels has a microstructure that may be susceptible to stress corrosion cracking.

Similar to casting operations, welding may introduce gas into the molten weldment that subsequently is released, resulting in gas **wormholes** and **porosity**.

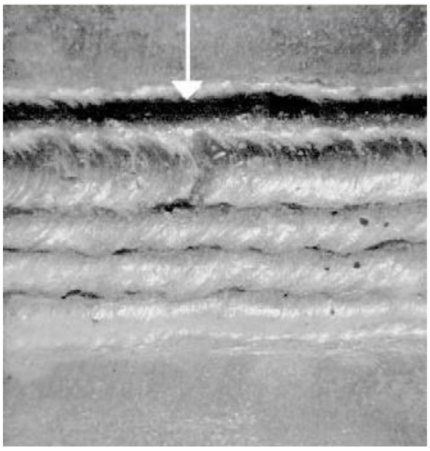
There is also the possibility of damage due to incorporation of hydrogen atoms into a steel weldment. This typically occurs when water and organic molecules are split apart and disassociated in the high-energy welding process.

If the alloy is relatively low strength and ductile, the material around the gas bubbles will plastically deform to accommodate the damage.

If the alloy is very strong, it will resist the formation of the bubbles and the first accommodation to stress may be cleavage and fracture of the crystalline structure. This damage is called **hydrogen cracking** or **delayed cracking**.

Because of the sensitivity of hydrogen damage in high-strength steels, sources of hydrogen must be controlled. Requirements are found for dryness and cleanliness of the base material and for use of low-hydrogen consumables for the filler materials and fluxes.

There are **geometric discontinuities** associated with welding. One of these is the formation of a ditching at the weld toe. The weld toe is the edge of the fusion zone on the surface of a base material. This discontinuity is called undercut and it has the effect of creating a “notch” effect on the surface.



Undercut at the edges of weld beads in a multiple pass weld.

Excessive crown reinforcement of a weldment usually results in a discontinuous geometric transition with the base material. The geometric discontinuity at the toe of the weld in this case will be a region of stress concentration. When this condition exceeds a design criterion it is called **excessive convexity**. The same type condition may occur when the weld crown is concave. The concave discontinuity is called "**excess concavity**" when it exceeds a design or code criterion.

A joint that is incompletely filled represents a geometric departure from design. This condition is called **lack of penetration**.

V. DISCONTINUITIES RESULTING FROM PLASTIC DEFORMATION

Forging is a process that forms an alloy by shaping it in a die under compressive loading. The flow of the metal is responsive to distributed loads and the ability of the metal to flow is dependent on its temperature. The higher the temperature, the easier the flow and the greater the ductility.

It is possible that the stress resulting from a forming operation may exceed the strength of the material, causing the material to break apart. In a forging operation, this load-induced cracking is called a burst. A burst may be entirely internal or the cracking may extend to the surface of the component.

Multiple forging bursts in a steel blank

The volume of a body is approximately constant when a component is mechanically formed. During the flowing of the alloy, material occasionally will lap over itself due to surface flow instability. The folded material will not fuse if the temperature is low and if the surface is contaminated with dirt. This type of discontinuity is called a fold or a lap. A long straight lap may be called a **seam**. Laps and folds have crack-like characteristics and they are considered to be rejectable discontinuities.

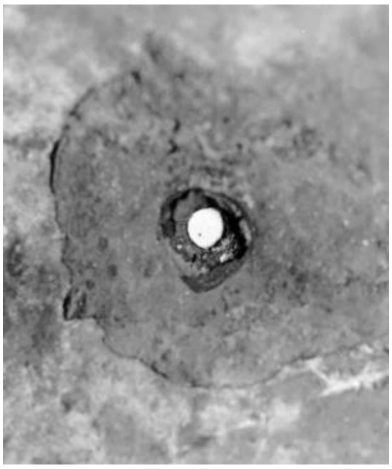
There are geometric discontinuities caused by pressing scale and debris left in forging dies into the surface of a component. These indentations are called **scale pits**.

A crack that transects a section is called a **split**. Splits may occur in forging and in other forming techniques. Rolling, swaging, spin forming, and extrusion may give rise to cracks, laps, burst, splits, scale pits, etc.

VI. CORROSION-INDUCED DISCONTINUITIES

Electrochemical corrosion requires an anode, a cathode, an electrolyte, and an electrical connection between the cathode and anode. The degradation generally occurs on the anode of the cathode–anode couple. Many operational environments provide the opportunity for electrochemical corrosion and resulting discontinuities.

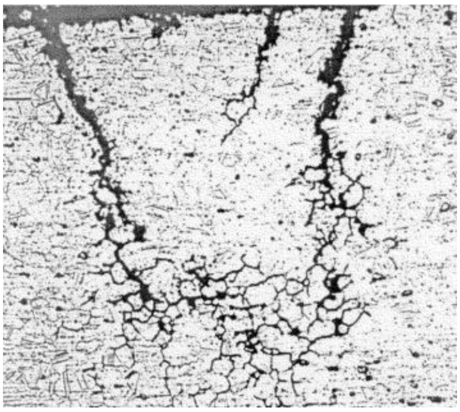
A common surface discontinuity caused by corrosion is pitting. It is a localized attack on a surface on which specific regions are anodic to the remaining surface. The pitting usually has associated debris of corrosion products that provides an environment that assists in the continued local attack. Pitting behavior is a product of the alloy and the chemistry of the electrolyte. There are many combinations of alloy and electrolyte that will not result in pitting.



Corrosion pit that penetrated a pipe wall (5×). The forms of pits are variable and range over a wide spectrum of geometry. Pits may be conical in form; they may mushroom beneath the surface or take tortuous paths (a form called wormhole corrosion).

Pitting damage is potentially deleterious. In addition to loss and penetration of the material, the rough surface of the pitting is a ready initiation site for fatigue cracking in components that are subjected to cyclic tensile loads. Additionally, the fatigue resistance of an alloy may be lowered in the electrolyte. Any alloy or metal may be susceptible to stress corrosion cracking under certain conditions.

There are situations where corrosive attack will cause strips of material to disengage from a component surface. Elongation and segregation of the alloy microstructure cause the selective subsurface attack. This discontinuity is called **delamination**.



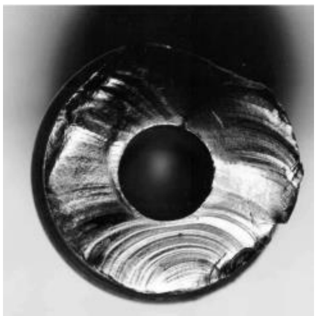
Stress corrosion cracking in nickel alloy (200×)

VII. OPERATIONALLY INDUCED DISCONTINUITIES— FATIGUE CRACKING

Alloys that are subjected to cyclic tensile loading may exhibit **surface cracks after a critical number of load cycles**. This damage may occur even though the component has maximum tensile stress far below the yield stress for the material.

Cracking will often initiate at a discontinuity in the form of a discontinuous geometric change or inhomogeneity in the alloy. Once begun, **a fatigue crack** usually will propagate irreversibly, a small amount with each cycle of tensile load. Eventually, the fatigue crack will grow large enough to cause a catastrophic failure of the component.

A fatigue crack will propagate on the plane(s) of maximum tensile stress. Often, the distributed tensile load is perpendicular to the planar surface of the material. In these situations, the fatigue cracking will be relatively flat. The consequence of this is a sequence of concentric ridges that are called beach marks. The beach marks radiate from the initiation site of the cracking and extend to the point where the crack runs catastrophically due to ductile failure or brittle failure.



Beach marks in a drill rod fractured by fatigue

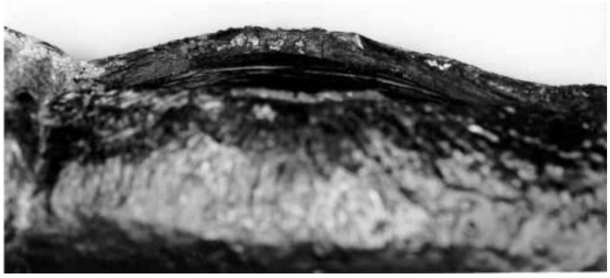
Another characteristic of fatigue is **macroscopic plastic deformation with no change of shape** associated with the crack propagation. Fatigue cracking preserves the shape of the component and fatigue cracks are often hard to see, requiring augmented inspection techniques for detection.

Conditions of thermal cycling may cause possibility of the creation of **thermally induced fatigue cracking**. These cracks usually occur over an ? a and they are often in a checkerboard pattern. Thermal cracks are initiators of crack propagation due to other operational stresses.

In grinding operations on steels it is possible to raise the temperature of a surface layer high enough to cause the thermal stresses what can give rise to a cracking pattern that is called crazing. Craze cracks are also initiation sites for fatigue.

VIII. OPERATIONALLY INDUCED DISCONTINUITIES—CREEP

High-temperature operation of alloys for long periods of time may give rise to an operationally induced cracking called creep cracking. This condition may occur even if the stresses are relatively low. The cracks are usually preceded by discontinuities in the form of creep voids, which are small and distributed. The creep voids grow and then cracking links these voids. The catastrophic failure due to high-temperature creep is usually a relatively low ductility failure characterized by thick lip rupture/

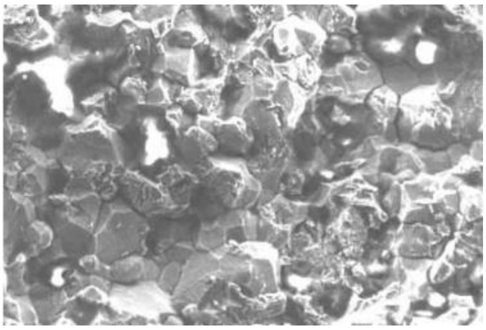


Thick lip fracture from creep in a power plant superheated tube

IX. OPERATIONALLY INDUCED DISCONTINUITIES—BRITTLE FRACTURE

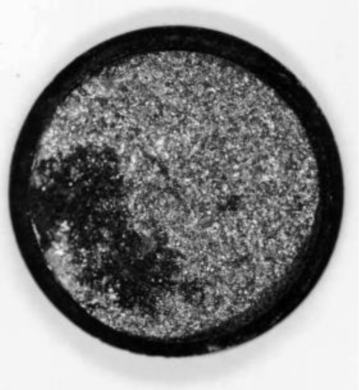
Brittle fracture is usually catastrophic in nature and nearly always emanates from a discontinuity. Some materials such as glasses are inherently brittle and some alloys may be made brittle due to their process history and environment.

There are conditions of precipitation of phases at grain boundaries of alloys that cause the grain boundaries to be brittle, and brittle fracture in those cases will tend to be confined to the envelope of the grains. Fracture about the grain boundaries has a characteristic appearance called a “rock-candy” fracture surface.



“Rock candy” fracture surface of a grade 8 bolt cracked by hydrogen embrittlement

In other cases, the brittle cracking occurs through the grains on crystallographic planes of weakness. This gives a specular, faceted appearance to the brittle cracked surface



Brittle fracture surface of fastener. Bright flecks are planar cleavage facets of ferrite in the steel

Ferritic steels will change toughness and ductility as a function of temperature, becoming “glass-like” below a critical transition temperature. The critical temperature is a function of steel alloy chemistry and microstructure and it ranges from far below the freezing point of water to hundreds of degrees centigrade.

In all cases, brittle fracture will begin at a discontinuity in a structure. For a given discontinuity in a material there is a given static stress that must be exceeded before a crack may propagate. This is the basis for categorizing crack-like discontinuities as critical in size.

X. GEOMETRIC DISCONTINUITIES

Geometric discontinuities are often involved as sites of cracking and failure. These discontinuities may be created by deficiencies in the design, manufacture, operation, and repair of a component. Sharp transitions in surface slope will be locations of stress concentration, and under cyclic loading conditions these locations will be the first to crack due to fatigue.

An open and sharp relief in the surface of a component is called a notch. The dimensions and the slope transition of the sides of the notch are critical characteristics of the extent of stress concentration that will exist under operational loads.

Gouges are usually considered to be relatively shallow grooves or cuts on a surface. Gouges may be caused by plastic deformation or by cutting action. A cut in a surface is a discontinuity similar to a gouge, except that it is usually caused by the removal of material from the surface by interaction with other components, similar to machining. Water and high-velocity gas flow (erosion), abrasive particle wear, mechanical wear, local plastic deformation, and local chemical action may cause gouges.

Galling is a surface condition caused by the metallurgical bonding of surfaces under pressure and the local tearing out of surface material during motion between the surfaces.

There are other machining-related discontinuities that have specific and unique characteristics. These include excessive undercut, sharp radius, scoring, scratching, and burring.

Fretting is a wear condition that occurs during operations when two surfaces repeatedly rub in a reciprocating motion. The debris from the surface interactions and oxidation products are included between the surfaces and act as a grinding medium. The result of this motion is a roughened surface that invariably will have reduced fatigue resistance.

Surface finish is not usually considered to be a discontinuity. However, surface finish strongly influences the fatigue resistance of a material, and for given environmental conditions, smoother surfaces provide a greater resistance to fatigue cracking.

XI. SUMMARY

Challenges to engineering-material integrity largely involve the discontinuities in components. Disruptions in continuity may be either internal or on the surface. Discontinuities may be macroscopic or microscopic and they may limit the strength, ductility, toughness, and endurance of a component.

A primary responsibility of the examiner is to detect and characterize discontinuities in a component. The location and type of discontinuity is dependent on the fabrication and operation history of a component. An examiner is given an advantage when he or she understands the relationship of product form and history to the consequent discontinuities in a component.

Understanding the origin of discontinuities in engineering components should result in efficiencies in nondestructive examinations and enhancements in quality of examination results.

XII. GLOSSARY OF METALLURGY AND DISCONTINUITY TERMS

Anisotropy The material condition in which material vector properties change with direction.

Annealing Any treatment of metals and alloys at relatively elevated temperatures for the purpose of altering the properties of the material. The types of changes include softening, reducing residual stress, and recrystallizing.

Artifact An indication originating from a source other than a discontinuity that resembles an indication from a discontinuity.

Billet A solid, semifinished, round or square product that has been formed by hot working (e.g., forging, rolling, and extrusion).

Blister A surface or near-surface discontinuity in metal and cast alloy components caused by gas evolution during casting. Small blisters are called “pinheads” or “pepper blisters.”

Blowhole A discontinuity in the form of a hole in a casting or a weld that is caused by gas entrapment during solidification.

Brazing Joining of metals and alloys by bonding; the alloys have liquidus temperatures above 800° F (below the liquidus temperatures of the materials being joined).

Brittle Cracking The propagation of a crack that requires relatively little energy and results in little or no plastic deformation.

Brittleness The material quality that leads to fracture after little or no plastic deformation.

Burr Ragged edge on a part usually caused by a machining or grinding process.

Burst Fissure or rupture caused by improper rolling or forging.

Capillary Action The movement of liquid within narrow spaces that is caused by surface tension between the liquid and the substrates. The mechanism that is used to fill or penetrate a joint in soldering and brazing.

Cast Structure The microscopic and macroscopic distribution of grains and chemistry that is characteristic of a casting.

Casting Shrinkage The reduction in component volume during casting. The reductions are caused by 1) liquid shrinkage, which is the reduction of volume of the liquid as it cools to the liquidus temperature; 2) solidification shrinkage, which is the total reduction of volume of the alloy through solidification; 3) the shrinkage of the casting as it cools to room temperature.

Casting Discontinuties Discontinuities that are generated in casting operations.

Charpy Test An impact fracture test that characterizes the energy required to break a standard specimen. The test machine is a pendulum hammer.

Chatter The vibration of a tool in a grinding or cutting operation. Also, the wavy surface on a machined component caused by chattering of the working tool.

Checks Multiple small cracks on the surface of components caused during manufacturing.

Cleavage The splitting of a crystal on a crystallographic plane of relatively high density.

Constituent A characteristic geometric arrangement of microscopic phases.

Cold Shut A discontinuity on the surface of a casting caused by the impingement of melt (without fusion) within a part of a casting.

Cold Working Plastically deforming a material at relatively low temperatures, resulting in creation of dislocation defects in the crystal structure.

Columnar Crystal Structure Elongated grains that are perpendicular to a casting surface.

Corrosion The electrochemical degradation of metallic materials.

Corrosion Fatigue An acceleration of fatigue damage caused by a corrosive environment.

Crack A breach in material continuity in the form of a narrow planar separation.

Crater A local depression in the surface of a component caused by excessive chip contact in machining or arc disturbance of a weldment.

Creep Cracks Cracking that is caused by linking of creep voids at the end of tertiary creep.

Creep Voids Small voids that form in the third stage of creep.

Crevice Corrosion The loss of surface material in a crevice subjected to an electrolyte.

Decarburization The loss of carbon from the surface of a ferrous alloy because of high temperature oxidation of carbon.

Defect A component discontinuity that has shape, size, orientation, or location such that it is detrimental to the useful service of the part.

Dendrite A tree-like crystal structure that forms in some casting and vapor deposition crystallization.

Ductility The ability of a material to deform plastically without fracturing.

Exfoliation A corrosion degradation mode that causes layers parallel to the surface of an alloy to be separated and elevated due to the formation of corrosion product.

Fatigue Progressive cracking leading to fracture that is caused by cyclic tensile loading in the range of elastic stress, eventually initiating small cracks that sequentially and irreversibly enlarge under the action of fluctuating stress.

Flakes Short internal fissures in ferrous materials caused by stresses produced by evolution of hydrogen after hot working. Fractured surfaces containing flakes with bright and shiny surfaces.

Folds Discontinuities composed of overlapping surface material.

Forging Discontinuties Discontinuities that are created in forging operations.

Fracture A break, rupture, or crack large enough to cause a full or partial separation of a component.

Fretting Low-amplitude reciprocal motion between two component surfaces under pressure causing surface roughness.

Gas Holes Holes created by gas escaping from molten metal during solidificaton.

Gas Porosity Minute voids distributed in a casting that are caused by the release of gas during the solidification process.

Geometric Discontinuity A sharp change in surface configuration that may be specified or an unplanned consequence of manufacture.

Gouge A groove cut in a surface caused by mechanical, thermal, or other energy sources.

Grain An individual crystal in a polycrystalline material.

Grain Boundary The narrow zone of material between crystals of differing orientation.

Grinding Cracks Shallow cracks formed in a surface of relatively hard materials because of excessive grinding heat.

Gross Porosity Pores, gas holes, or globular voids in weldments or castings that are larger and in greater number than is acceptable in good practice.

Heat-Affected Zone The portion of base material that was not melted during brazing, cutting, or welding whose microstructure and physical properties have been altered by the heat of the joining operation.

Hot Cracks Cracks that are caused by differential contraction between a casting and its mold. These may be branched and scattered through the interior and on the surface of the casting.

Hot Tear A relatively large fracture formed in the interior or on the surface of a cast component due to restricted contraction.

Hydrogen Embrittlement Low ductility caused by cracking of the interior of a component due to the evolution and precipitation of hydrogen gas.

Inclusion Usually a solid foreign material that is encapsulated in an alloy. Inclusions comprised of compounds such as oxides, sulphides, or silicates are referred to as nonmetallic inclusions.

Incomplete Fusion Failure of weldment to fuse with the base material or the underlying or adjacent weld bead in a weld.

Incomplete Penetration Fusion into a joint that is not as full as dictated by design.

Inherent Discontinuity A discontinuity that is generated in the primary production of a material.

Lack of Fusion Failure of a weldment to fuse with the base material in a weld.

Lamination Separation or structural weakness, usually in plate that is aligned parallel to the surface of a component. This may be caused by the elongation during plastic

forming of segregates that are the result of pipe, blisters, seams, and inclusions.

Lamellar tearing The typical rupture of a material that is weakened by elongated slag inclusion. The crack surfaces have the appearance of wood fracture.

Lap A surface discontinuity appearing as a seam caused by the folding over of hot alloy fins, ears, or corners during forging, rolling, or other plastic forming without fusing the folds to the underlying material.

Macroshrinkage Casting discontinuity that is detectable at magnifications less than ten times and that is the result of voids caused by solidification shrinkage of contained material.

Metallurgical Notch A material discontinuity, usually involving hardness, that has the geometric characteristics of a crack.

Microfissure A microscopic crack.

Microsegregates Segregates that are microscopic in size.

Microshrinkage Cracking Microscopic cracks that are caused by solidification shrinkage.

Microshrinkage Porosity Microscopic pores that are caused by solidification shrinkage.

Nonmetallic Inclusion A slag or glass-like inclusion in an alloy.

Notch A sharp reentrant on a surface of a component that causes a local concentration of stress.

Phase Diagram A descriptive map that shows the existance of equilibrium phases, usually as a function of alloy composition and temperature.

Phase Diagram—Binary A phase diagram between two components.

Phase Diagram—Ternary A phase diagram between three components; the representation uses a three dimensional representation of data. The interior of an equilateral triangle base providing unique location representing all the compositions possible between the three components.

Pitting Forming of small cavities in a surface by corrosion, arcing, wear, or other mechanical means.

Primary Processing Discontinuities Discontinuities that are generated in the first forming steps of an alloy.

Scratches Small grooves in a surface created by the cutting or deformation from a particle or foreign proturberance moving on that surface.

Secondary Processing Discontinuities Discontinuities that are generated in the secondary and finishing forming steps.

Segregation Nonuniform distribution of alloying elements, impurities, or phases in alloys.

Service Discontinuities Discontinuities that are generated by service conditions.

Slag An aggragate of nonmetallic glasses that is found in primary metals production

and in welding processes. Slag may be used as a covering to protect the underlying alloy from oxidation.

Split A rupture in a component, usually open to the surface.

Stringers Nonmetallic inclusions that are elongated by a hot forming process.

Scale Pits Surface discontinutities in the form of local indentations caused by the capture and rolling of scale into the surface of an alloy.

Voids A cavity inside a casting or weldment that is usually caused by solidification shrinkage.

Welding Discontinuities Any breaches in material continuity that are generated in welding processes.

Weld Undercut A groove at the toe or root of a weld caused by melting of the base material.

XIII. DISCONTINUITY GUIDE

The following table provides examples of discontinuities. These examples are designed as a reference and to provide the reader with a representation as to how some of the conditions described herein and in other chapters can appear. All discontinuities are different.

When there is doubt regarding the classification and type of discontinuities, this guide may help. Following the table is a collection of figures that illustrate some of the discontinuities (Fig. below).

Discontinuity Guide

Nondestructive Test Methods	Visual	Fluorescent Penetrant	Visble Penetrant	Wet D. C. Magnetic Particle	Dry D. C. Magnetic Particle	Dry A. C. Magnetic Particle	Eddy Current	Thermal Infrared	Radiography	Straight Beam Ultrasonics	Angle Beam Ultrasonics
Types of Discontinuities	Surface and Near Surface Methods								Subsurface		
Process Category											
Inherent											
Laminations	P	U	U	U	U	U	U	U	U	A(1)[c]	U
Pipe[d]	U	U	U	U	U	U	U	U	A(2)	A(1)	A(3)
Seams	P	A(4)	A(5)	A(1)	A(2)	A(3)	P	P	U	U	P[b]
Stringers	U	U	U	A(1)	A(2)	A(3)	P	U	P	P	P[a]
Mechanical Forming Processes											
Flare or Split	U	U	U	U	U	U	U	U	U	A(1)	A(2)
Forging Bursts	P	A(2)	A(3)	A(1)	A(4)	A(5)	P	P	P	P	P
Forging Laps	P	A(2)	A(3)	A(1)	P	P	P	U	U	P	P
Rolling Lap (Seam)	P	A(2)	A(3)	A(1)	P	P	P	U	U	P	P
Casting Process											
Casting Cold Shuts	P	P	P	P	P	P	P	U	A(1)	P	P
Casting Shrinkage Cracks	U	U	U	P	P	U	U	U	A(1)	A(2)	P
Gas Porosity	U	U	U	U	P	U	U	U	A(1)	A(2)	P
Hot Tears	U	U	U	P	P	U	U	U	A(1)	A(2)	P
Scabs	P	A(3)	A(4)	A(1)	A(2)	A(5)	P	P	U	U	P
Shrinkage Porosity	P[e]	P[e]	P[e]	U	U	U	U	U	A(1)	A(2)	P
Inclusions	U	P[e]	P[e]	P[e]	P[e]	P[e]	U	U	A(1)	A(2)	P
Secondary Process											
Grinding Checks	P	A(2)	A(3)	A(1)	P	P	P	U	U	U	P
Machining Tears	P	A(2)	A(3)	A(1)	U	U	U	U	U	U	U
Plating Cracks	P	A(2)[e]	A(3)[e]	A(1)	P	P[e]	P	U	U	U	U
Quench and Heat Cracks	P	A(2)	A(3)	A(1)	A(4)	A(5)	P	P	P	U	P
Welding/Joining											
Crater Cracks	P	A(2)	A(3)	A(1)	P	P	P	U	U	P	P
Dense Inclusion	U	U	U	U	P	U	U	U	A(1)	P	U
Excessive Concavity	A(1)	U	U	U	U	U	U	U	U	U	U
Excessive Convexity	A(1)	U	U	U	U	U	U	U	U	U	U
Incomplete Penetration	P	U	U	U	U	U	U	U	A(1)	U	A(2)
Lack of Fusion	U	U	U	P	P	U	U	U	A(2)	P	A(1)
Porosity	P	P	P	P	U	U	U	U	A(1)	P	U
Slag Inclusion	U	U	U	P	A(2)	U	U	U	A(1)	P	P
Subsurface Cracks	U	U	U	U	U	U	P	U	A(1)	A(1)	A(1)
Surface Cracks	P[e]	P[e]	P[e]	U	P	P	P	U	A(2)	U	A(1)
Underbead Cracks	U	U	U	U	U	U	P	U	A(1)	A(1)	A(1)
Undercut	A(1)	U	U	U	U	U	U	U	U	U	P
Brazing											
Lack of Fill	U	U	U	U	U	U	U	U	U	A(1)	U
Unbond[f]	U	U	U	U	U	U	U	U	U	A(1)	U
Service											
Brittle Overload Crack	P	A(5)	A(4)	A(2)	A(1)	A(3)	P	U	P	P	P
Corrosion Pitting	P	A(1)	A(2)	U	U	U	P	U	P	P	U
Fatigue Cracking	P	A(5)	A(4)	A(2)	A(1)	A(3)	P	P	P	P	P
Fretting	A(1)	U	U	U	U	U	U	U	U	U	U
Graphitization	U	U	U	U	U	U	P	U	U	U	A(1)
Metallurgical Notch	U	U	U	U	U	U	P	U	P	U	P
Overload Cracking	P	A(5)	A(4)	A(2)	A(1)	A(3)	P	U	P	P	P
Segregation	U	U	U	U	U	U	P	U	A(1)	A(2)	A(3)
Stress Corrosion Cracking	P	A(1)	A(2)	P	U	U	A(3)	U	P	U	P
Wear	A(1)	U	U	U	U	U	U	U	U	U	U

Key:

U = Unsatisfactory; P = Possible; A(1) = First order of preference; A(2) = second order of preference; A(3) = third order of preference; A(4) = fourth order of preference

[a] Inspection of billet possible.

[b] Possible using surface waves.

[c] Assuming it is completely internal.

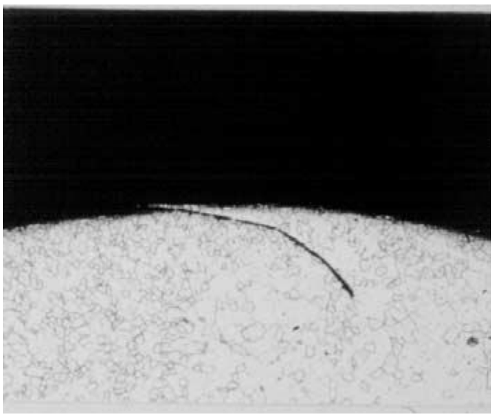
[d] May be seen on ends by penetrant or magnetic particle.

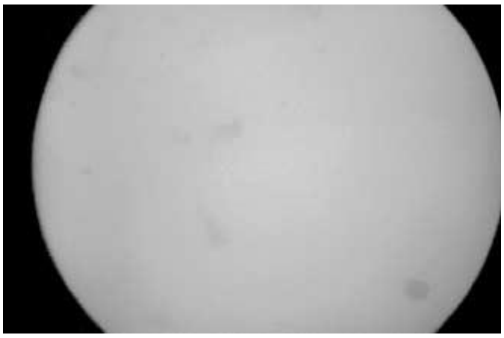
[e] If open to surface.

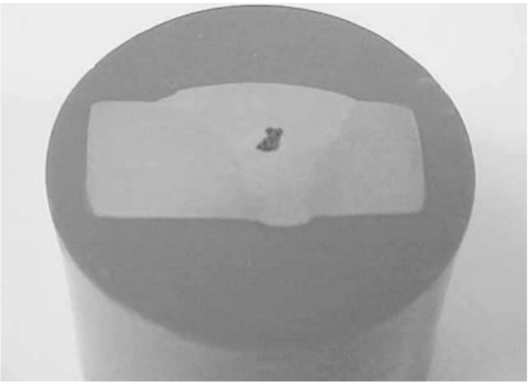
[f] Thermal tests possible.

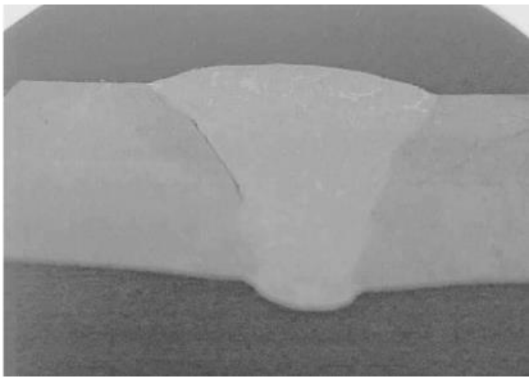
Note: Acoustic emission testing (AET) has not bee included in this guide because this method applies only to those discontinuities that propagate under applied loads.

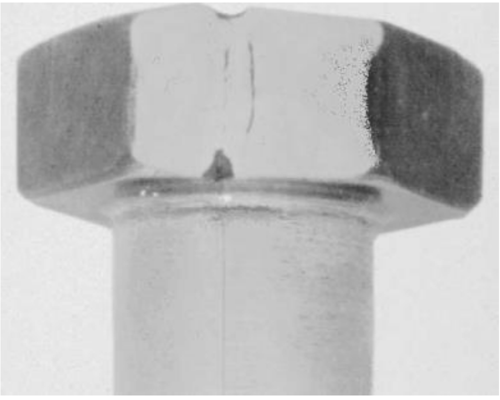

Lamination in plate edge

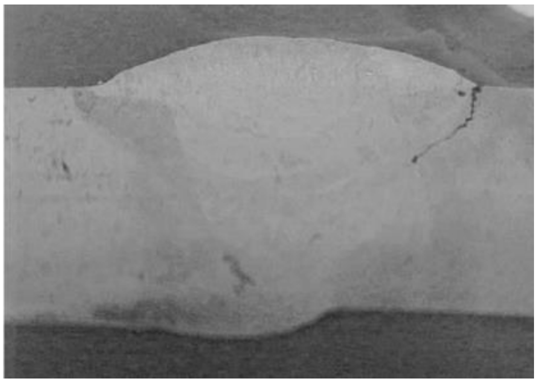

Forging lap

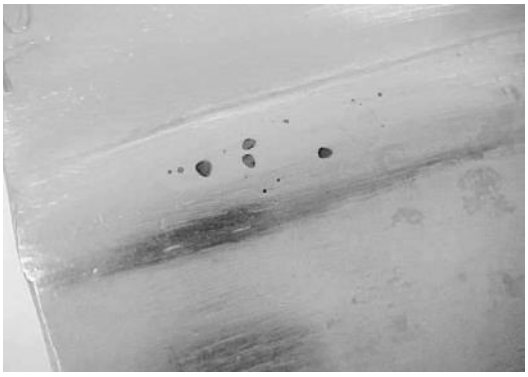

Sand and slag inclusions in a casting

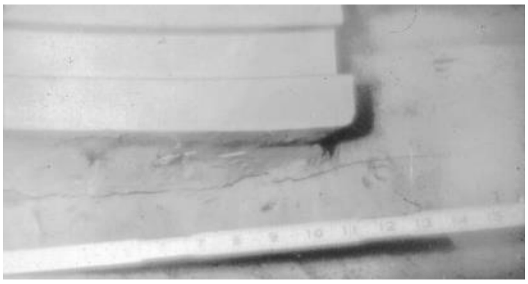

Slag inclusion in weld cross section


Lack of fusion

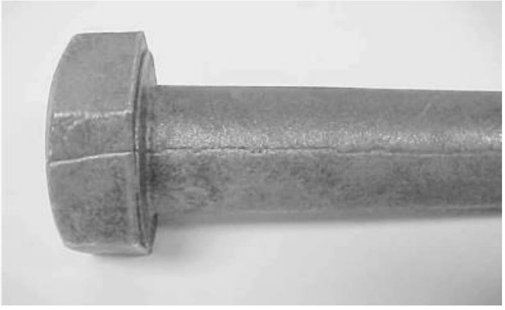

Seam in bolt

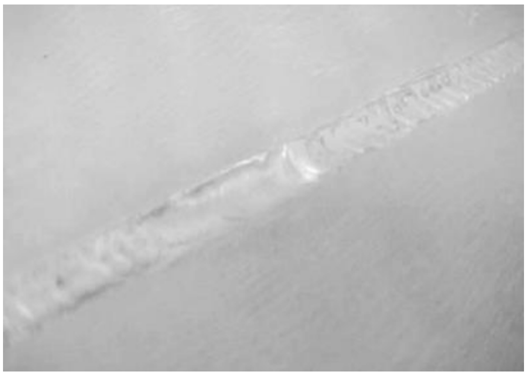

Toe crack in weld


Surface porosity in weld


Crack between two welds


Burst in bar


Crack in bolt



Lack of penetration in aluminum weld

CHARACTERISTICS OF STRENGTH. DESTRUCTIVE TESTING

What do the strength depends on?

Destructive Testing. Mechanical properties of materials.

Destructive and semi-destructive control.

Stress & strain.

How can we mesure the strain?

Tensometers (strain gauges) - gadgets for measuring of strain.

TENSION

In the course of operation or use, all the articles and structures are subjected to the action of external forces, which create stresses that inevitably cause deformation. To keep these stresses, and, consequently deformation within permissible limits it is necessary to select suitable materials for the Components of various designs and to apply the most effective heat treatment. i.e. a Comprehensive knowledge of the chief character tics of the semi- finished metal products & finished metal articles (such as strength, ductility, toughness etc) are essential for the purpose.

For this reason the specification of metals, used in the manufacture of various products and structure, are based on the results of mechanical tests or we say that the mechanical tests conducted on the specially prepared specimens (test pieces) of standard form and size on special machines to obtained the strength, ductility and toughness characteristics of the metal.

The conditions under which the mechanical test are conducted are of three types

1. **Static:** When the load is increased slowly and gradually and the metal is loaded by tension, compression, torsion or bending.
2. **Dynamic:** when the load increases rapidly as in impact
3. **Repeated or Fatigue:** (both static and impact type) . i.e. when the load repeatedly varies in the course of test either in value or both in value and direction Now let us consider the uniaxial tension test.

[For application where a force comes on and off the structure a number of times, the material cannot withstand the ultimate stress of a static tool. In such cases the ultimate strength depends on no. of times the force is applied as the material works at a particular stress level. Experiments one conducted to compute the number of cycles requires to break to specimen at a particular stress when fatigue or fluctuating load is acting. Such tests are known as fatigue tests]

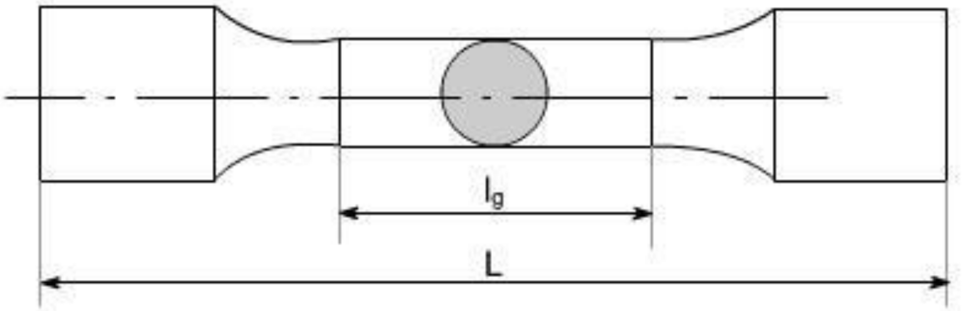
Uniaxial Tension Test: This test is of static type i.e. the load is increased comparatively slowly from zero to a certain value.

Standard specimen's are used for the tension test.

There are two types of standard specimen's which are generally used for this purpose, which have been shown below:

Specimen I:

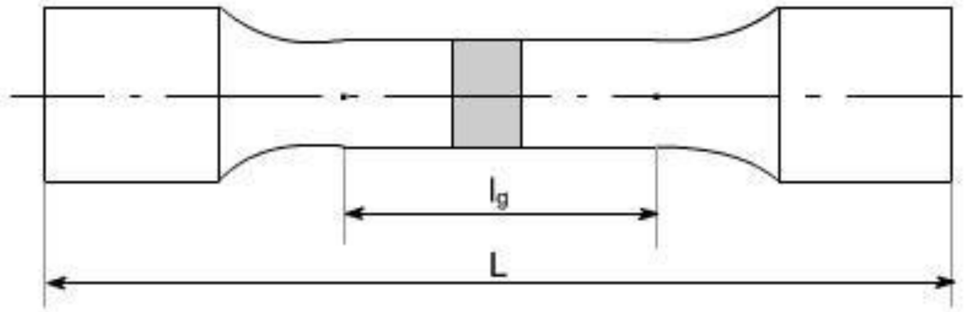
This specimen utilizes a circular X-section.



[specimen with circular X-section]

Specimen II:

This specimen utilizes a rectangular X-section.

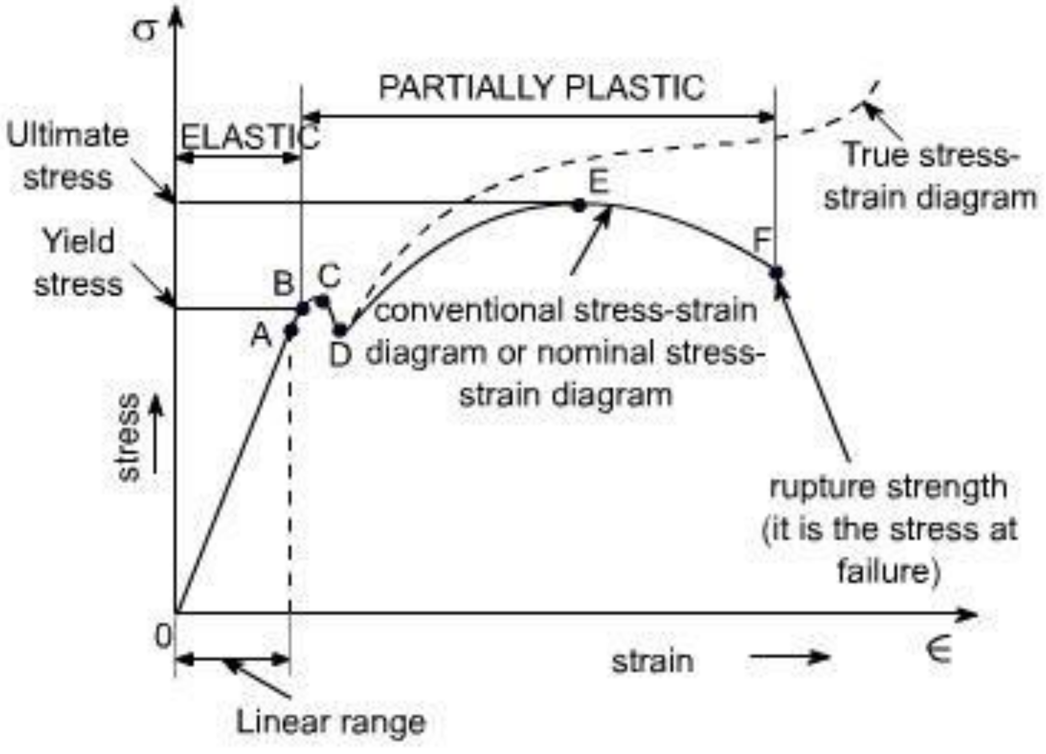


[specimen with rectangular X-section]

l_g = gauge length i.e. length of the specimen on which we want to determine the mechanical properties.The uniaxial tension test is carried out on tensile testing machine and the following steps are performed to conduct this test.

1. The ends of the specimen's are secured in the grips of the testing machine.
2. There is a unit for applying a load to the specimen with a hydraulic or mechanical drive.
3. There must be a some recording device by which you should be able to measure the final output in the form of Load or stress. So the testing machines are often equipped with the pendulum type lever, pressure gauge and hydraulic capsule and the stress Vs strain diagram is plotted which has the following shape.

A typical tensile test curve for the mild steel has been shown below



Nominal stress – Strain OR Conventional Stress – Strain diagrams:

Stresses are usually computed on the basis of the original area of the specimen; such stresses are often referred to as conventional or nominal stresses.

True stress – Strain Diagram:

Since when a material is subjected to a uniaxial load, some contraction or expansion always takes place. Thus, dividing the applied force by the corresponding actual area of the specimen at the same instant gives the so called true stress.

SALIENT POINTS OF THE GRAPH:

A. So it is evident form the graph that the strain is proportional to strain or elongation is proportional to the load giving a st.line relationship. This law of proportionality is valid upto a point A.

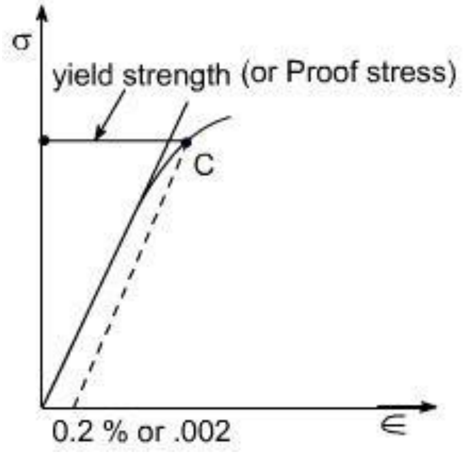
   or we can say that point A is some ultimate point when the linear nature of the graph ceases or there is a deviation from the linear nature. This point is known as **the limit of proportionality or the proportionality limit**.

B. For a short period beyond the point A, the material may still be elastic in the sense that the deformations are completely recovered when the load is removed. The limiting point B is termed as **Elastic Limit** .

C. **and (D)** - Beyond the elastic limit plastic deformation occurs and strains are not totally recoverable. There will be thus permanent deformation or permanent set when load is removed. These two points are termed as upper and lower yield points respectively. The stress at the yield point is called the yield strength.

   A study a stress – strain diagrams shows that the yield point is so near the proportional limit that for most purpose the two may be taken as one. However, it is much easier to locate the former. For material which do not posses a well define yield points, In order to find the yield point or yield strength, an offset method is applied.

In this method a line is drawn parallel to the straight line portion of initial stress diagram by off setting this by an amount equal to 0.2% of the strain as shown as below and this happens especially for the low carbon steel.



D. A further increase in the load will cause marked deformation in the whole volume of the metal. The maximum load which the specimen can with stand without failure is called the load at the ultimate strength.

The highest point ‘E' of the diagram corresponds to the ultimate strength of a material.

σ_u = Stress which the specimen can with stand without failure & is known as Ultimate Strength or Tensile Strength.

σ_u is equal to load at E divided by the original cross-sectional area of the bar.

E. Beyond point E, the bar begins to forms neck. The load falling from the maximum until fracture occurs at F.

[Beyond point E, the cross-sectional area of the specimen begins to reduce rapidly over a relatively small length of bar and the bar is said to form a neck. This necking takes place whilst the load reduces, and fracture of the bar finally occurs at point F]

Note: Owing to large reduction in area produced by the necking process the actual stress at fracture is often greater than the above value. Since the designers are interested in maximum loads which can be carried by the complete cross section, hence the stress at fracture is seldom of any practical value.

Percentage Elongation: '□δ ':

The ductility of a material in tension can be characterized by its elongation and by the reduction in area at the cross section where fracture occurs.

It is the ratio of the extension in length of the specimen after fracture to its initial gauge length, expressed in percent.

$$\delta = \frac{(l_1 - l_g)}{l_1} \times 100$$

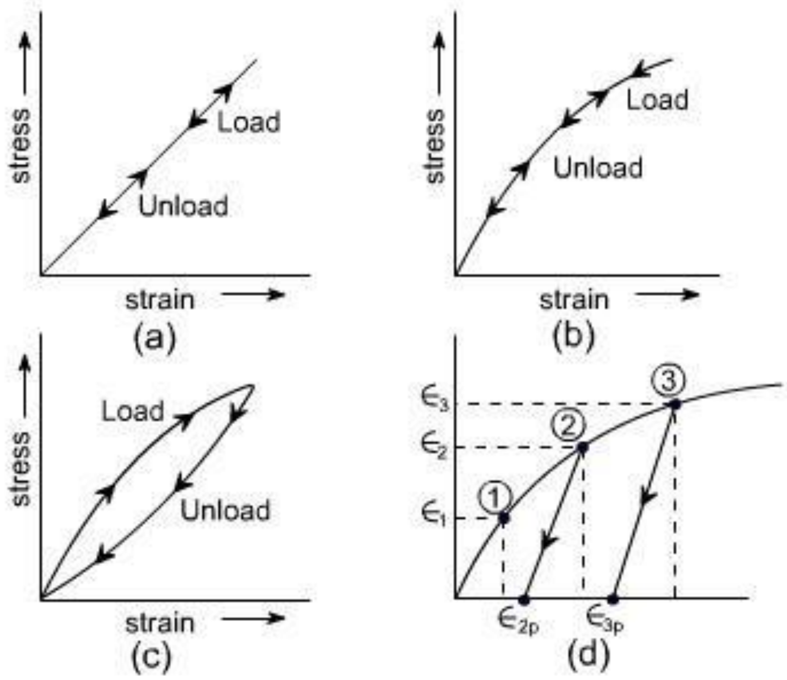
l_l = gauge length of specimen after fracture(or the distance between the gage marks at fracture)

l_g= gauge length before fracture(i.e. initial gauge length)

For 50 mm gage length, steel may here a % elongation δ of the order of 10% to 40%.

Elastic Action:

The elastic is an adjective meaning capable of recovering size and shape after deformation. Elastic range is the range of stress below the elastic limit.



Many engineering materials behave as indicated in Fig (a) however, some behaves as shown in figures in (b) and (c) while in elastic range. When a material behaves as in (c), the σ vs $\in$ is not single valued since the strain corresponding to any particular ' σ ' will depend upon loading history.

Fig (d): It illustrates the idea of elastic and plastic strain. If a material is stressed to level (1) and then relased the strain will return to zero beyond this plastic deformation remains.

If a material is stressed to level (2) and then released, the material will recover the amount $(\in_2 - \in_{2p})$, where $\in_{2p}$ is the plastic strain remaining after the load is removed. Similarly for level (3) the plastic strain will be $\in_{3p}$.

Ductile and Brittle Materials:

Based on this behaviour, the materials may be classified as ductile or brittle materials

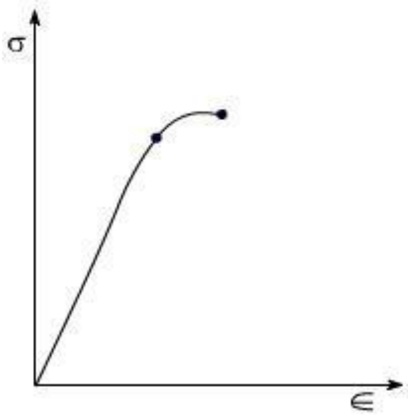
Ductile Materials:

It we just examine the earlier tension curve one can notice that the extension of the materials over the plastic range is considerably in excess of that associated with elastic loading. The Capacity of materials to allow these large deformations or large extensions without failure is termed as ductility. The materials with high ductility are termed as ductile materials.

Brittle Materials:

A brittle material is one which exhibits a relatively small extensions or deformations to fracture, so that the partially plastic region of the tensile test graph is much reduced.

This type of graph is shown by the cast iron or steels with high carbon contents or concrete.



Conditions Affecting Mechanical Properties:

The Mechanical properties depend on the test conditions

1. It has been established that lowering the temperature or increasing the rate of deformation considerably increases the resistance to plastic deformation. Thus, at low temperature (or higher rates of deformation), metals and alloys, which are ductile at normal room temperature may fail with brittle fracture.

2. Notches i.e. sharp charges in cross sections have a great effect on the mechanical properties of the metals. A Notch will cause a non – uniform distribution of stresses. They will always contribute lowering the ductility of the materials. A notch reduces the ultimate strength of the high strength materials. Because of the non – uniform distribution of the stress or due to stress concentration.

3. Grain Size: The grain size also affects the mechanical properties.

COMPRESSION

Compression Test: Machines used for compression testing are basically similar to those used for tensile testing often the same machine can be used to perform both tests.

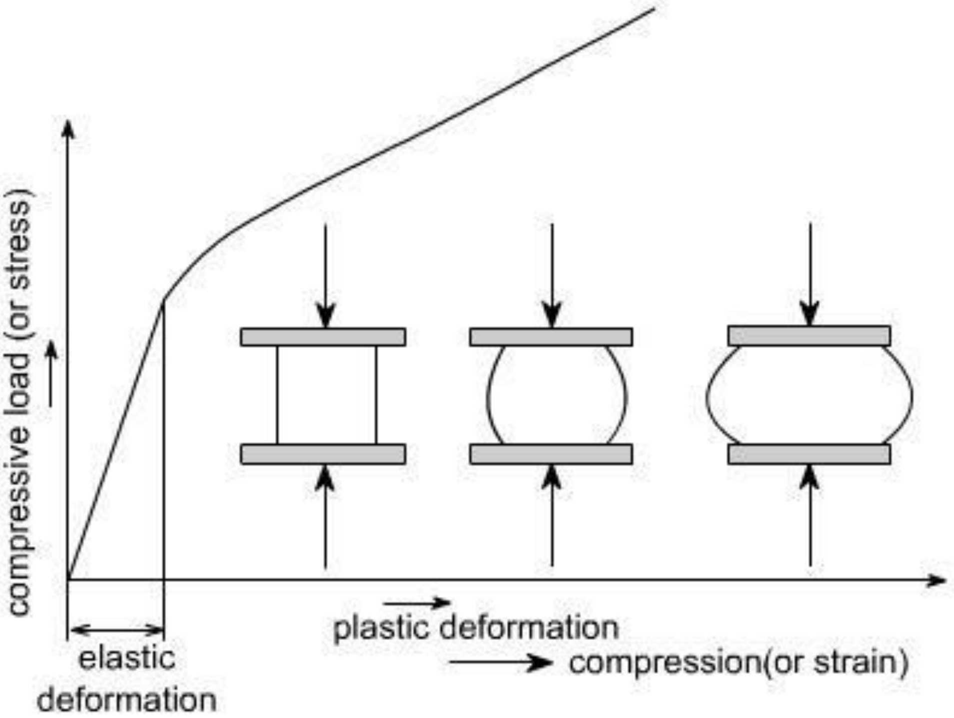
Shape of the specimen: The shapes of the specimen to be used for the different materials are as follows:

i. **For metals and certain plastics:** The specimen may be in the form of a cylinder

ii. **For building materials:** Such as concrete or stone the shape of the specimen may be in the form of a cube.

Shape of stress stain diagram

a. **Ductile materials:** For ductile material such as mild steel, the load Vs compression diagram would be as follows



1. The ductile materials such as steel, Aluminum, and copper have stress – strain diagrams similar to ones which we have for tensile test, there would be an elastic range which is then followed by a plastic region.

2. The ductile materials (steel, Aluminum, copper) proportional limits in compression test are very much close to those in tension.

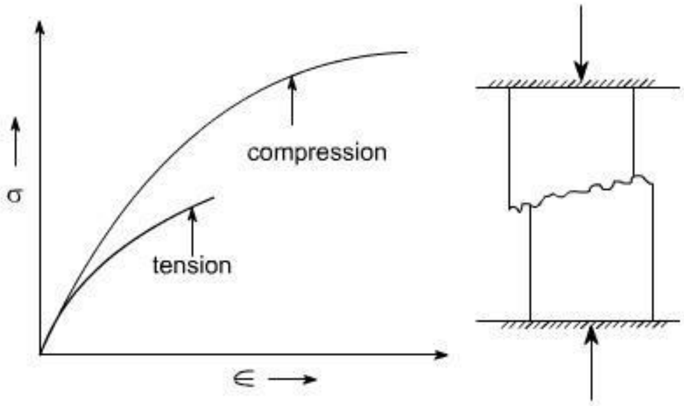
3. In tension test, a specimen is being stretched, necking may occur, and ultimately fracture fakes place. On the other hand when a small specimen of the ductile material is compressed, it begins to bulge on sides and becomes barrel shaped as shown in the figure above. With increasing load, the specimen is flattened out, thus offering increased resistance to further shortening (which means that the stress – strains curve goes upward) this effect is indicated in the diagram.

Brittle materials (in compression test)

Brittle materials in compression typically have an initial linear region followed by a region in which the shortening increases at a higher rate than does the load. Thus, the compression stress – strain diagram has a shape that is similar to the shape of the tensile diagram.

However, brittle materials usually reach much higher ultimate stresses in compression than in tension.

For cast iron, the shape may be like this



Brittle materials in compression behave elastically up to certain load, and then fail suddenly by splitting or by craking in the way as shown in figure. The brittle fracture is performed by separation and is not accompanied by noticeable plastic deformation.

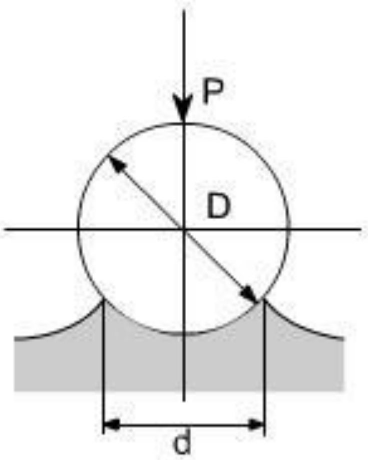
HARDNESS

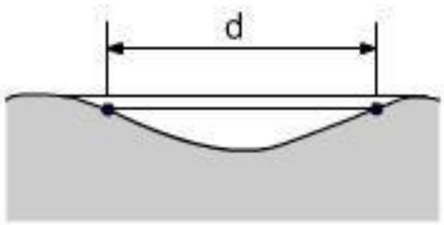
Hardness is the resistance of a metal to the penetration of another harder body which does not receive a permanent set.

Hardness Tests consists in measuring the resistance to plastic deformation of layers of metals near the surface of the specimen i.e. there are Ball indentation Tests.

BALL INDENTATION TESTS:

This method consists in pressing a hardened steel ball under a constant load P into a specially prepared flat surface on the test specimen as indicated in the figures below :





After removing the load an indentation remains on the surface of the test specimen. If area of the spherical surface in the indentation is denoted as F sq. mm. Brinell Hardness number is defined as :

Bhn = P / F

F is expressed in terms of D and d D = ball diameter

d = diametric of indentation and Brinell Hardness number is given ^{by}

$$Bhn = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}$$

Then is there is also **Vicker's Hardness Number** in which the ball is of conical shape.

HARDNESS TESTING:

The term ‘hardness' is one having a variety of meanings; a hard material is thought of as one whose surface resists indentation or scratching, and which has the ability to indent or cut other materials.

Hardness test: The hardness test is a comparative test and has been evolved mainly from the need to have some convenient method of measuring the resistance of materials to scratching, wear or in dentation this is also used to give a guide to overall strength of a materials, after as an inspection procedure, and has the advantage of being a non – destructive test, in that only small indentations are lift permanently on the surface of the specimen.

Four hardness tests are customarily used in industry namely

- Brinell
- Vickers
- Rockwell

The most widely used are the first two.

In the Brinell test the indenter is a hardened steel ball which is pressed into the surface using a known standard load. The diameter of resulting indentation is than measured using a microscope & scale.

Units:

The units of Brinell Hardness number in S.I Unit would have been N/mm^2 or MPa

To avoid the confusion which would have been caused of her wise Hardness numbers are quotes as kgf / mm^2

Brinell Hardness test:

In the Brinell hardness test, a hardened steel ball is pressed into the flat surface of a test piece using a specified force. The ball is then removed and the diameter of the resulting indentation is measured using a microscope.

The Brinell Hardness no. (BHN) is defined as

BHN = P / A

Where P = Force applied to the ball. A = curved area of the indentation
It may be shown that

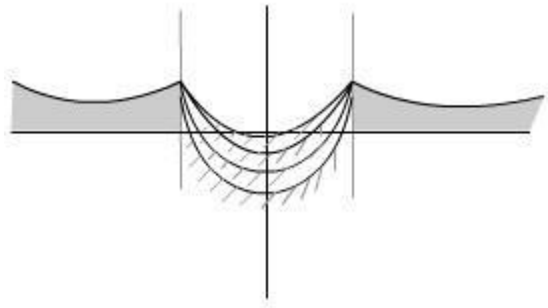
$$A = \frac{1}{2}\pi D\left[D - \sqrt{D^2 - d^2}\right]$$

D = diameter of the ball,

d = the diameter of the indentation.

In the Brinell Test, the ball diameter and applied load are constant and are selected to suit the composition of the metal, its hardness, and selected to suit the composition of the metal, its hardness, the thickness etc. Further, the hardness of the ball should be at least 1.7 times than the test specimen to prevent permanent set in the ball.

Disadvantage of Brinell Hardness Test: The main disadvantage of the Brinell Hardness test is that the Brinell hardness number is not independent of the applied load. This can be realized from. Considering the geometry of indentations for increasing loads. As the ball is pressed into the surface under increasing load the geometry of the indentation charges.



Here what we mean is that the geometry of the impression should not change w.r.t. load, however the size it impression may change.

Vickers Hardness test:

The Vicker's Hardness test follows a procedure exactly a identical with that of Brinell test, but uses a different indenter. The steel ball is replaced by a diamond, having the from of a square – based pyramid with an angle of 136^0 between opposite faces. This is pressed into the flat surface of the test piece using a specified force, and the diagonals of the resulting indentation measured is using a microscope. The Hardness, expressed as a Vicker's pyramid number is defined as the ratio F/A, where F is the force applied to the diamond and A is the surface area of the indentation.

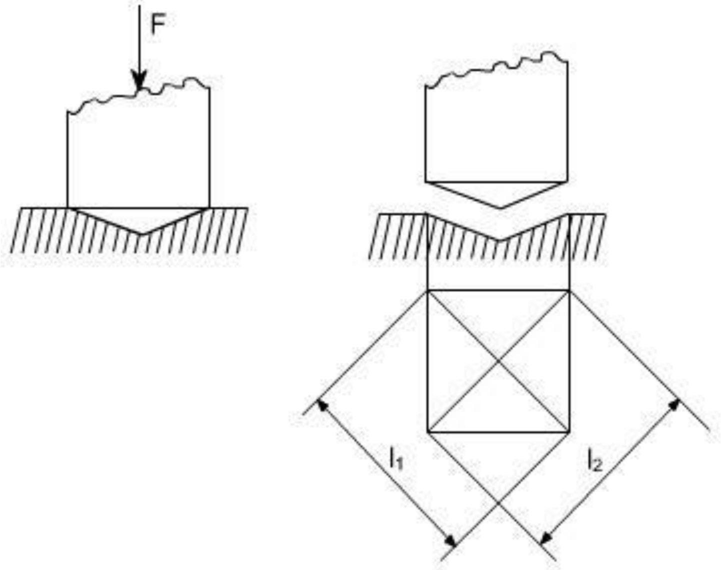
$$A = \frac{\frac{1}{2}l^2}{\sin\frac{1}{2}(136^0)}$$

$$= \frac{l^2}{.854v_x} \Rightarrow H_V = \frac{F}{\frac{l^2}{.854}}$$

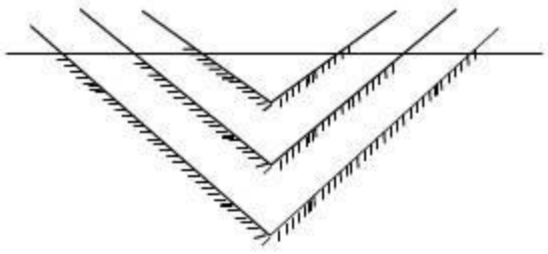
$$H_V = \frac{.854F}{l^2}$$

where l is the average lengthof the diagonal is $l = \frac{1}{2}(l_1 + l_2)$

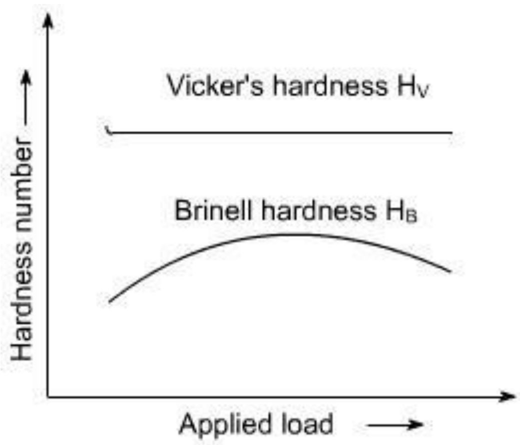
It may be shown that



In the Vicker Test the indenters of pyramidal or conical shape are used & this overcomes the disadvantage which is faced in Brinell test i.e. as the load increases, the geometry of the indentation's does not change



The Variation of Hardness number with load is given below.



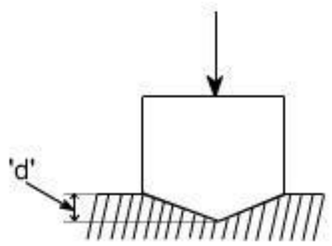
Advantage: Apart from the convenience the vicker's test has certain advantages over the Brinell test.

(i) Harder material can be tested and indentation can be smaller & therefore less obtrusive or damaging.

Upto a 300 kgf /mm^2 both tests give the same hardness number but above too the Brinell test is unreliable.

Rockwell Hardness Test :

The Rockwell Hardness test also uses an indenter when is pressed into the flat surface of the test piece, but differs from the Brinell and Vicker's test in that the measurement of hardness is based on the depth of penetration, not on the surface area of indentation. The indenter may be a conical diamond of 120^{0} included angle, with a rounded apex. It is brought into contact with the test piece, and a force F is applied.

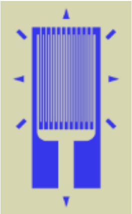


Advantages :

Rockwell tests are widely applied in industry due to rapidity and simplicity with which they may be performed, high accuracy, and due to the small size of the impressions produced on the surface.

STRAIN GAUGE

A strain gauge (also spelled strain gage) is a device used to measure strain on an object. Invented by Edward E. Simmons and Arthur C. Ruge in 1938, the most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. The gauge is attached to the object by a suitable adhesive, such as cyanoacrylate. As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor.



Typical foil strain gauge; the blue region is conductive and resistance is measured from one large blue pad to the other. The gauge is far more sensitive to strain in the vertical direction than in the horizontal direction. The markings outside the active area help to align the gauge during installation

PHYSICAL OPERATION

A strain gauge takes advantage of the physical property of electrical conductance and its dependence on the conductor's geometry. When an electrical conductor is stretched within the limits of its elasticity such that it does not break or permanently deform, it will become narrower and longer, which increases its electrical resistance end-to-end. Conversely, when a conductor is compressed such that it does not buckle, it will broaden and shorten, which decreases its electrical resistance end-to-end. From the measured electrical resistance of the strain gauge, the amount of induced stress may be inferred.

A typical strain gauge arranges a long, thin conductive strip in a zig-zag pattern of parallel lines. This does not increase the sensitivity, since the percentage change in resistance for a given strain for the entire zig-zag is the same as for any single trace. A single linear trace would have to be extremely thin, hence liable to overheating (which would change its resistance and cause it to expand), or would need to be operated at a much lower voltage, making it difficult to measure resistance changes accurately.

Gauge factor

The gauge factor is defined as:

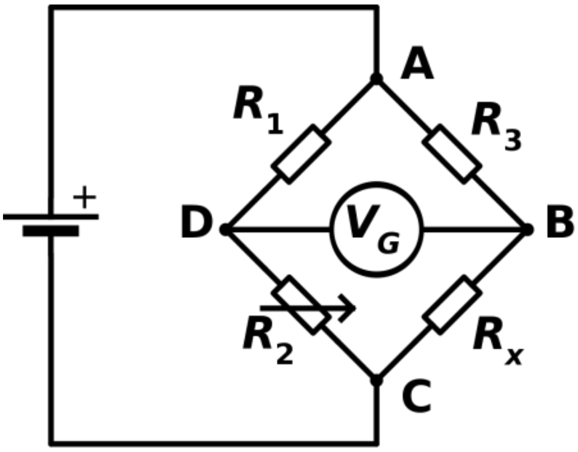
$$GF = \frac{\Delta R / R_G}{\epsilon}$$

where

ΔR is the change in resistance caused by strain,

R_G is the resistance of the undeformed gauge, and

ϵ is strain.



For common metallic foil gauges, the gauge factor is usually a little over 2. For a single active gauge and three dummy resistors of the same resistance about the active gauge in a balanced Wheatstone bridge configuration, the output sensor voltage SV from the bridge is approximately:

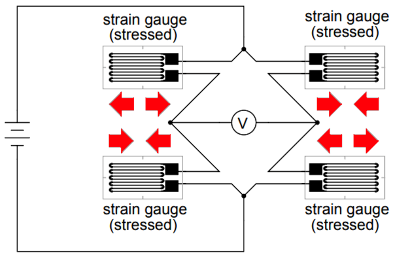
$$SV = EV \frac{GF \cdot \epsilon}{4}$$

where

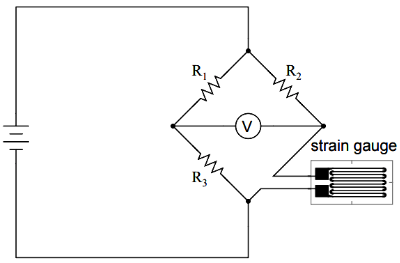
EV is the bridge excitation voltage.

Foil gauges typically have active areas of about 2–10 mm^2 in size. With careful installation, the correct gauge, and the correct adhesive, strains up to at least 10% can be measured.

Full-bridge strain gauge circuit



Quarter-bridge strain gauge circuit



IN PRACTICE

An excitation voltage is applied to input leads of the gauge network, and a voltage reading is taken from the output leads. Typical input voltages are 5 V or 12 V and typical output readings are in millivolts.

Foil strain gauges are used in many situations. Different applications place different requirements on the gauge. In most cases the orientation of the strain gauge is significant.

Gauges attached to a load cell would normally be expected to remain stable over a period of years, if not decades; while those used to measure response in a dynamic experiment may only need to remain attached to the object for a few days, be energized for less than an hour, and operate for less than a second.

Strain gauges are attached to the substrate with a special glue. The type of glue depends on the required lifetime of the measurement system. For short term measurements (up to some weeks) cyanoacrylate glue is appropriate, for long lasting installation epoxy glue is required. Usually epoxy glue requires high temperature curing (at about 80-100 °C). The preparation of the surface where the strain gauge is to be glued is of the utmost importance. The surface must be smoothed (e.g. with very fine sand paper), deoiled with solvents, the solvent traces must then be removed and the strain gauge must be glued immediately after this to avoid oxidation or pollution of the prepared area. If these steps are not followed the strain gauge binding to the surface may be unreliable and unpredictable measurement errors may be generated.

Strain gauge based technology is used commonly in the manufacture of pressure sensors. The gauges used in pressure sensors themselves are commonly made from silicon, polysilicon, metal film, thick film, and bonded foil.

APPLICATIONS

Structural Health Monitoring

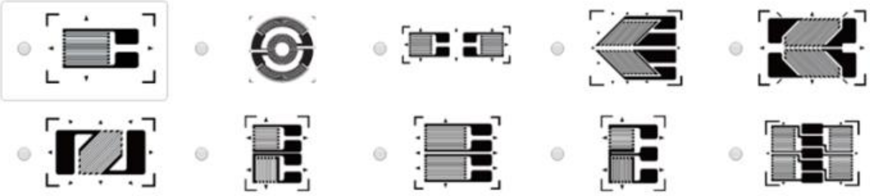
Structural health monitoring (SHM) is used to monitor structures after their completion. To prevent failures, strain gauges are used to detect and locate damages and creep. A specific example is the monitoring of bridge cables increasing safety by detecting possible damages. Also, the bridge's behavior to unusual loads can be analyzed such as special heavy-duty transports.

Aviation

In aviation, strain gauges are the standard approach to measuring the structural load and calculating wind deflection. Strain gauges are fixed in several locations on the aircraft. However, deflection measurement systems have been shown to measure reliable strains remotely. This reduces instrumentation weight on the aircraft and thus is replacing the strain gauge.

GEOMETRIES OF STRAIN GAUGES

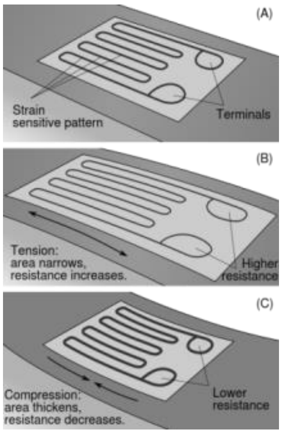
- The following different kind of strain gauges are available in the market:
- Linear strain gauges
- Membrane Rosette strain gauges
- Double linear strain gauges
- Full bridge strain gauges
- Shear strain gauges
- Half bridge strain gauges
- Column strain gauges
- 45°-Rosette (3 measuring directions)
- 90°-Rosette (2 measuring directions).

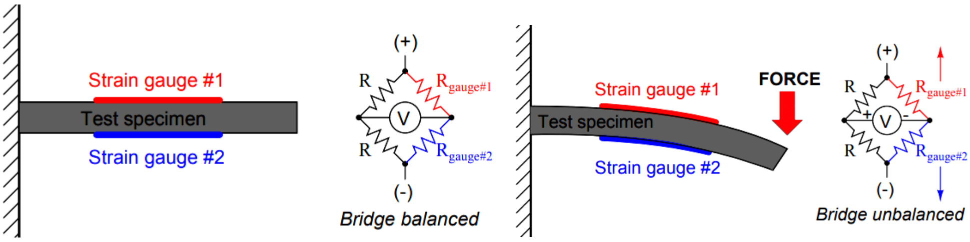


EXAMPLE OF STRAIN GAUGE

With no force applied to the test specimen, both strain gauges have equal resistance and the bridge circuit is balanced.

However, when a downward force is applied to the free end of the specimen, it will bend downward, stretching gauge #1 and compressing gauge #2 at the same time.





Visualization of the working concept behind the strain gauge on a beam under exaggerated bending

NDT METHODS

1. VISUAL INSPECTION

Most basic and common inspection method.

Tools include fiberscopes, borescopes, magnifying glasses and mirrors.

Portable video inspection unit with zoom allows inspection of large tanks and vessels, railroad tank cars, sewer lines.

Robotic crawlers permit observation in hazardous or tight areas, such as air ducts, reactors, pipelines.

2. MAGNETIC PARTICLE INSPECTION (MPI)

2.1 Introduction

- A nondestructive testing method used for defect detection. Fast and relatively easy to apply and part surface preparation is not as critical as for some other NDT methods. – MPI one of the most widely utilized nondestructive testing methods.

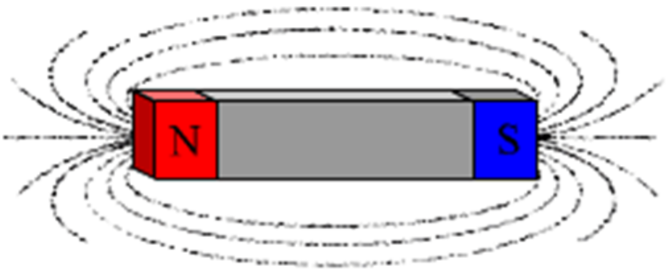
- MPI uses magnetic fields and small magnetic particles, such as iron filings to detect flaws in components. The only requirement from an inspectability standpoint is that the component being inspected must be made of a ferromagnetic material such as iron, nickel, cobalt, or some of their alloys. Ferromagnetic materials are materials that can be magnetized to a level that will allow the inspection to be affective.

- The method is used to inspect a variety of product forms such as castings, forgings, and weldments. Many different industries use magnetic particle inspection for determining a component's fitness-for-use. Some examples of industries that use magnetic particle inspection are the structural steel, automotive, petrochemical, power generation, and aerospace industries. Underwater inspection is another area where magnetic particle inspection may be used to test such things as offshore structures and underwater pipelines.

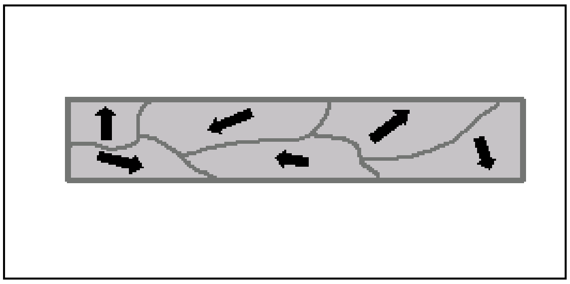
2.2 Basic Principles

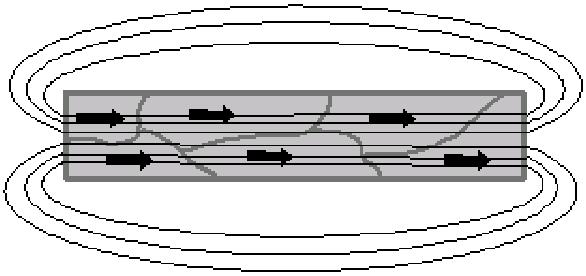
In theory, magnetic particle inspection (MPI) is a relatively simple concept. It can be considered as a combination of two nondestructive testing methods: magnetic flux leakage testing and visual testing.

Consider a bar magnet. It has a magnetic field in and around the magnet. Any place that a magnetic line of force exits or enters the magnet is called a pole. A pole where a magnetic line of force exits the magnet is called a north pole and a pole where a line of force enters the magnet is called a south pole.



Ferromagnetic materials become magnetized when the magnetic domains within the material are aligned. This can be done by placing the material in a strong external magnetic field or by passes electrical current through the material. Some or all of the domains can become aligned. The more domains that are aligned, the stronger the magnetic field in the material. When all of the domains are aligned, the material is said to be magnetically saturated. When a material is magnetically saturated, no additional amount of external magnetization force will cause an increase in its internal level of magnetization.

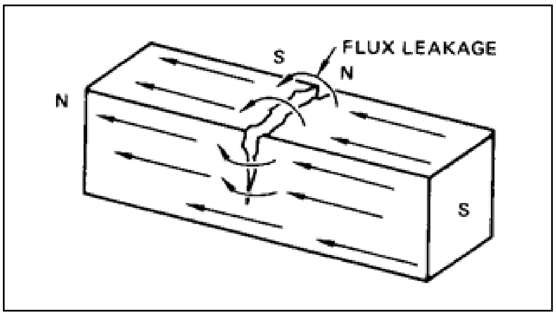




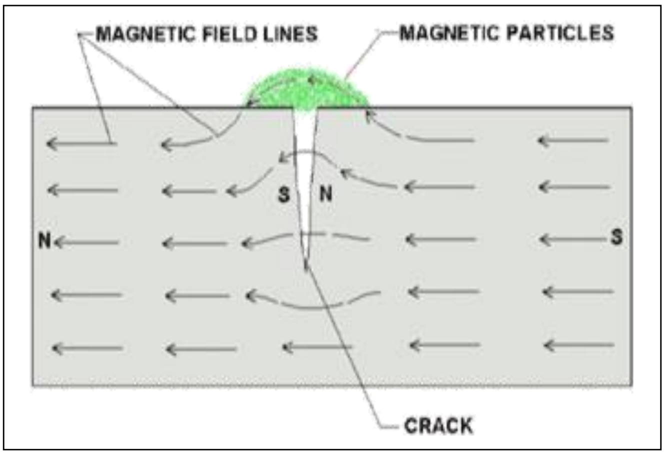
Unmagnetized material	Magnetized material

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 reenters the at the south pole. The magnetic field spreads out when it encounter the small air gap created by the crack because the air can not 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, it is called a flux leakage field.



If iron particles are sprinkled on a cracked magnet, the particles will be attracted to and cluster not only at the poles at 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.



MPI

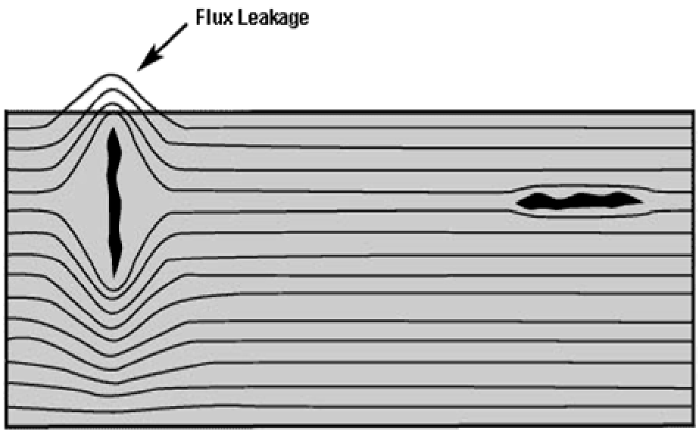
- The magnetic flux line close to the surface of a ferromagnetic material tends to follow the surface profile of the material

- Discontinuities (cracks or voids) of the material perpendicular to the flux lines cause fringing of the magnetic flux lines, i.e. flux leakage

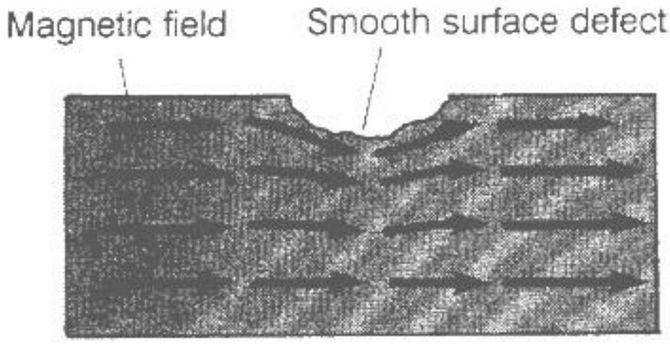
- The leakage field can attract other ferromagnetic particles

The magnetic particles form a ridge many times wider than the crack itself, thus making the otherwise invisible crack visible.

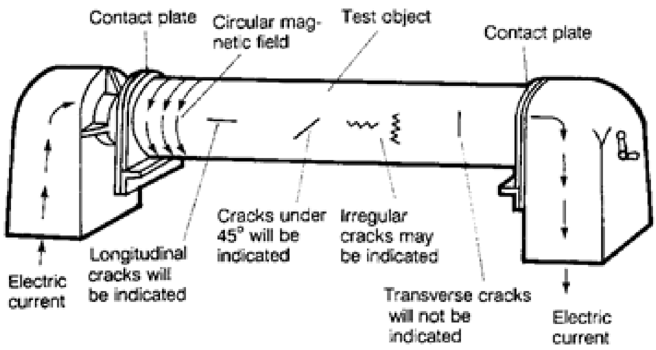
Cracks just below the surface can also be revealed



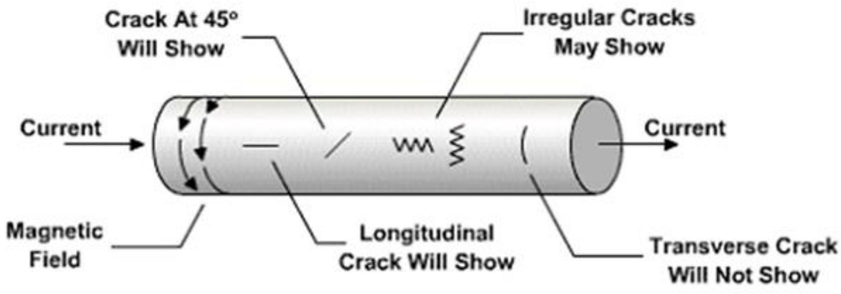
MPI is not sensitive to shallow and smooth surface defects



The effectiveness of MPI depends strongly on the orientation of the crack related to the flux lines



Stationary bench unit. The importance of the orientation of a defect in relation to the magnetic field lines is shown.



2.3. TESTING PROCEDURE OF MPI

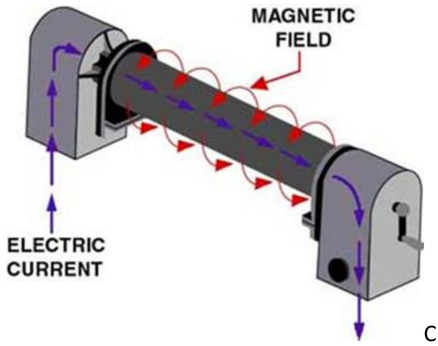
- Cleaning
- Demagnetization

- Contrast dyes (e.g. white paint for dark particles)
- Magnetizing the object
- Addition of magnetic particles
- Illumination during inspection (e.g. UV lamp)
- Interpretation
- Demagnetization - prevent accumulation of iron particles or influence to sensitive instruments

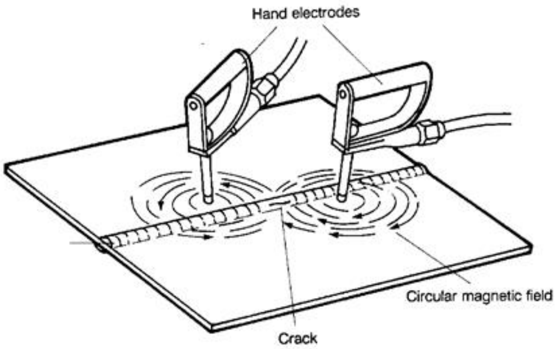
Magnetizing the object

There are a variety of methods that can be used to establish a magnetic field in a component for evaluation using magnetic particle inspection. It is common to classify the magnetizing methods as either *direct* or *indirect*.

Direct magnetization: current is passed directly through the component.



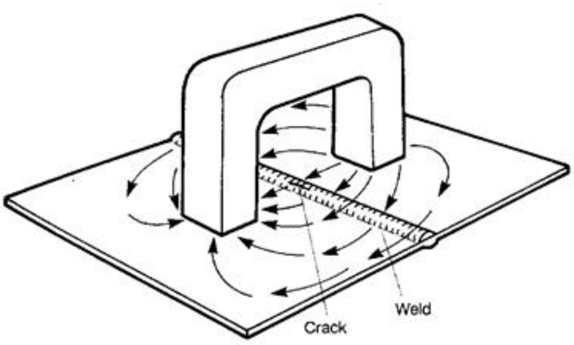
Clamping the component between two electrical contacts in a special piece of equipment



Magnetization using hand held electrodes.

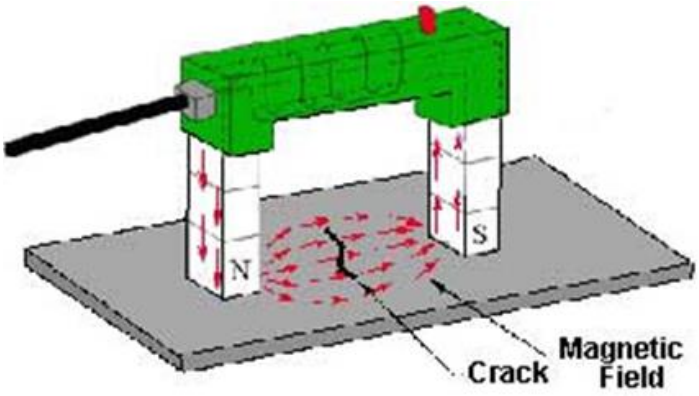
Using clams or prods, which are attached or placed in contact with the component

Indirect magnetization: using a strong external magnetic field to establish a magnetic field within the component

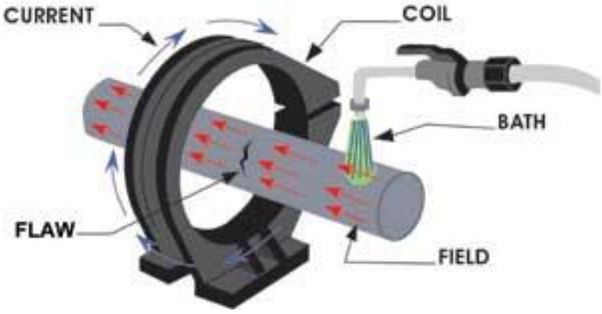


Magnetization using a permanent magnet.

(a) permanent magnets

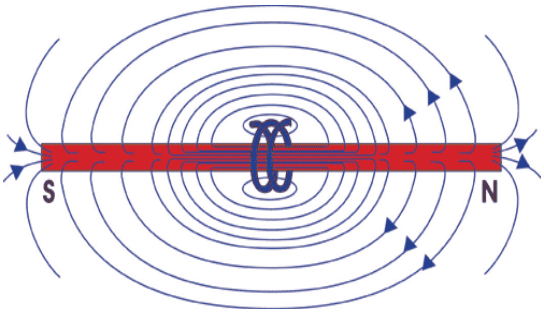


(b) electromagnets

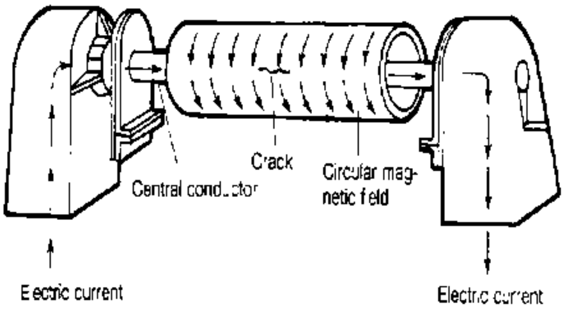


(c) coil shot

Longitudinal magnetization: achieved by means of permanent magnet or electromagnet



Circumferential magnetization: achieved by sending an electric current through the object



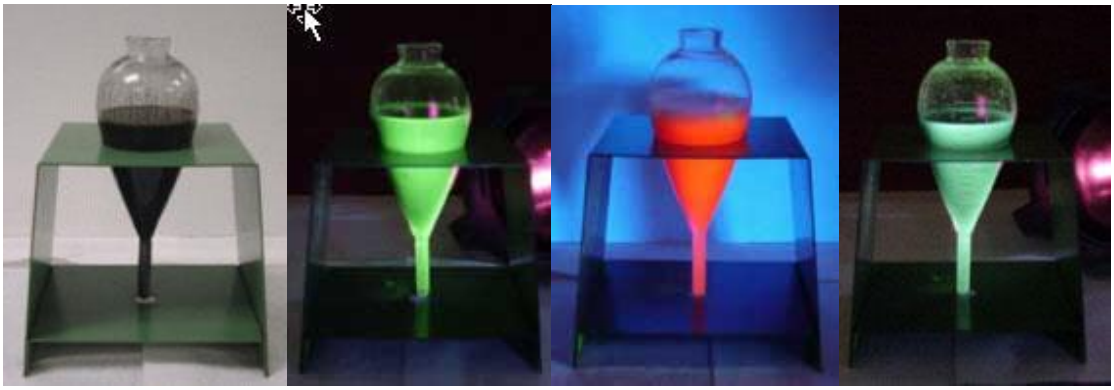
Circumferential magnetization of a pipe by means of a central conductor.

Magnetic particles

Pulverized iron oxide (Fe3O4) or carbonyl iron powder can be used

Coloured or even fluorescent magnetic powder can be used to increase visibility

Powder can either be used dry or suspended in liquid



Some Standards for MPI Procedure

British Standards

- BS M.35: Aerospace Series: Magnetic Particle Flaw Detection of Materials and Components
- BS 4397: Methods for magnetic particle testing of welds

ASTM Standards

- ASTM E 709-80: Standard Practice for Magnetic Particle Examination
- ASTM E 125-63: Standard reference photographs for magnetic particle indications on ferrous castings

ГОСТ Р 56512-2015 КОНТРОЛЬ НЕРАЗРУШАЮЩИЙ. Магнитопорошковый метод. Типовые технологические процессы. Non-destructive testing. Method of magneting particle testing. Standard technological processes

2.4 Advantages of MPI

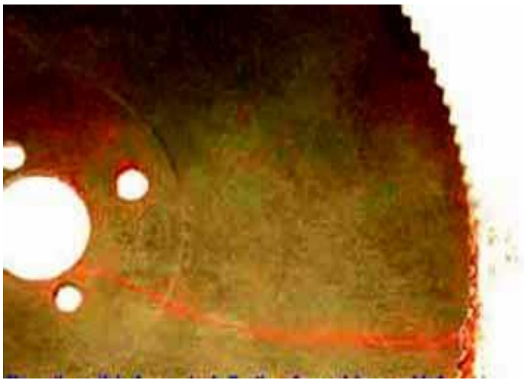
- One of the most dependable and sensitive methods for surface defects
- fast, simple and inexpensive
- direct, visible indication on surface
- unaffected by possible deposits, e.g. oil, grease or other metals chips, in the cracks
- can be used on painted objects
- surface preparation not required
- results readily documented with photo or tape impression

2.5 Limitations of MPI

- Only good for ferromagnetic materials
- sub-surface defects will not always be indicated
- relative direction between the magnetic field and the defect line is important
- objects must be demagnetized before and after the examination
- the current magnetization may cause burn scars on the item examined

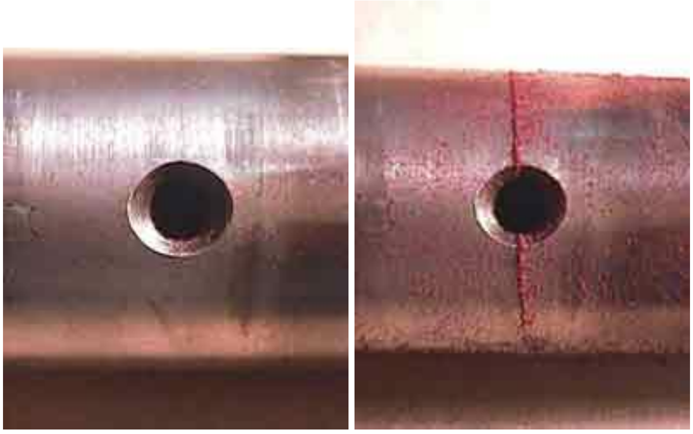
Examples

Examples of visible dry magnetic particle indications



Indication of a crack in a saw blade

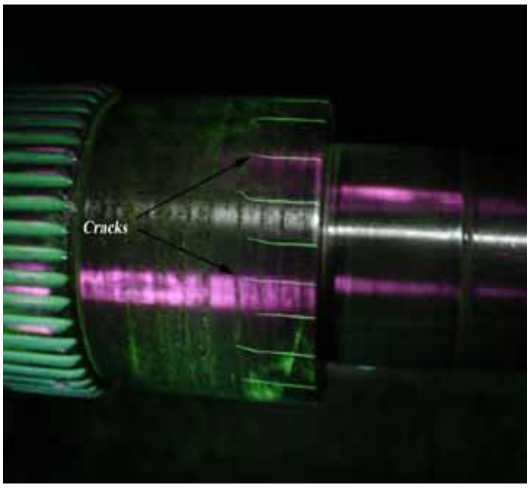
Indication of cracks in a weldment



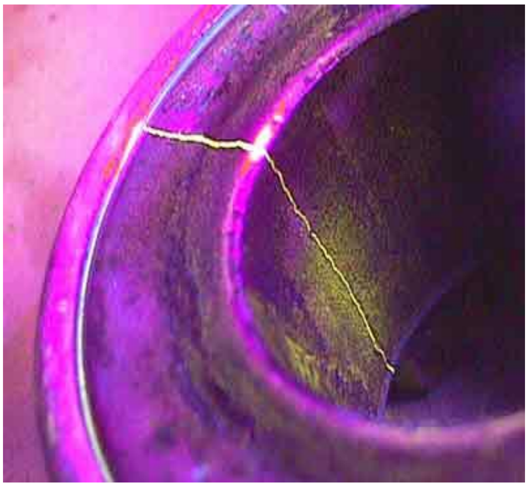
Before and after inspection pictures of cracks emanating from a hole


Indication of cracks running between attachment holes in a hinge

Examples of Fluorescent Wet Magnetic Particle Indications



Magnetic particle wet fluorescent indication of a cracks in a drive shaft


Magnetic particle wet fluorescent indication of a crack in a bearing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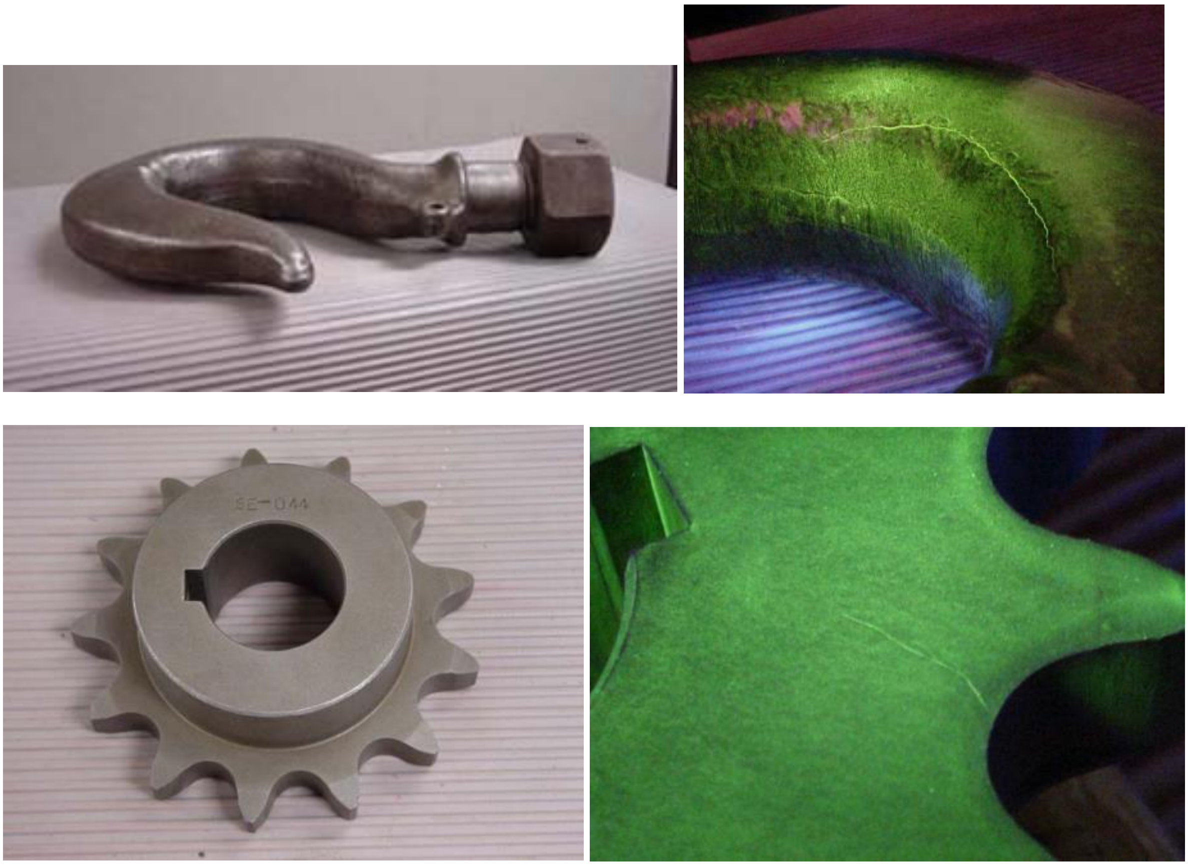
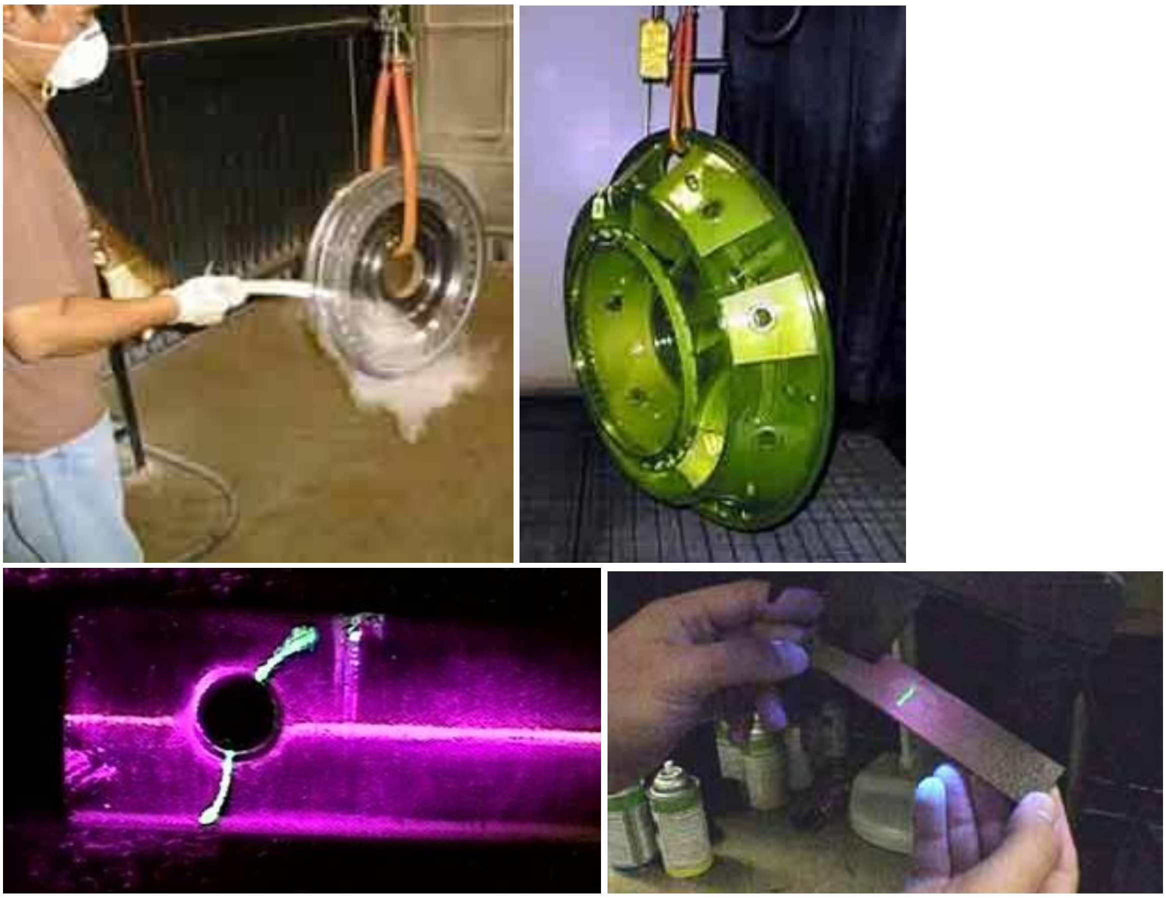
Magnetic particle wet fluorescent indication of a cracks at a fastener hole



3. DYE PENETRANT INSPECTION

Liquid penetrant inspection (LPI) is one of the most widely used nondestructive evaluation (NDE) methods. Its popularity can be attributed to two main factors, which are its relative ease of use and its flexibility. LPI can be used to inspect almost any material provided that its surface is not extremely rough or porous. Materials that are commonly inspected using LPI include metals (aluminum, copper, steel, titanium, etc.), glass, many ceramic materials, rubber, and plastics.



3.1 INTRODUCTION

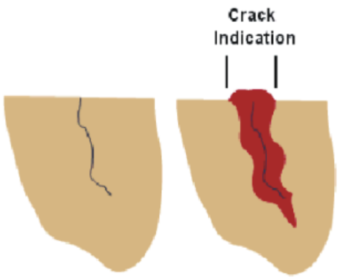
- Liquid penetration inspection is a method that is used to reveal surface breaking flaws by bleedout of a colored or fluorescent dye from the flaw.
- The technique is based on the ability of a liquid to be drawn into a "clean" surface breaking flaw by capillary action.
- After a period of time called the "dwell," excess surface penetrant is removed and a developer applied. This acts as a "blotter." It draws the penetrant from the flaw to reveal its presence.
- Colored (contrast) penetrants require good white light while fluorescent penetrants need to be used in darkened conditions with an ultraviolet "black light". Unlike MPI, this method can be used in non-ferromagnetic materials and even non-metals
- Modern methods can reveal cracks 2µm wide
- Standard: ASTM E165-80 Liquid Penetrant Inspection Method
  ГОСТ Р ИСО 3452-1-2011Контроль неразрушающий. ПРОНИКАЮЩИЙ КОНТРОЛЬ. Часть 1. Основные требования. Non-destructive testing. Penetrant testing. Part 1. Basic requirements
-

Why Liquid Penetrant Inspection?

To improves the detectability of flaws

There are basically two ways that a penetrant inspection process makes flaws more easily seen.

1. LPI produces a flaw indication that is much larger and easier for the eye to detect than the flaw itself.
2. LPI produces a flaw indication with a high level of contrast between the indication and the background



The advantage that a liquid penetrant inspection (LPI) offers over an unaided visual inspection is that it makes defects easier to see for the inspector.

The advantage that a liquid penetrant inspection (LPI) offers over an unaided visual inspection is that it makes defects easier to see for the inspector. There are basically two ways that a penetrant inspection process makes flaws more easily seen. First, LPI produces a flaw indication that is much larger and easier for the eye to detect than the flaw itself. Many flaws are so small or narrow that they are undetectable by the unaided eye. Due to the physical features of the eye, there is a threshold below which objects cannot be resolved. This threshold of visual acuity is around 0.003 inch for a person with 20/20 vision.

The second way that LPI improves the detectability of a flaw is that it produces a flaw indication with a high level of contrast between the indication and the background which also helps to make the indication more easily seen. When a visible dye penetrant inspection is performed, the penetrant materials are formulated using a bright red dye that provides for a high level of contrast between the white developer that serves as a background as well as to pull the trapped penetrant from the flaw. When a fluorescent penetrant inspection is performed, the penetrant materials are formulated to glow brightly and to give off light at a wavelength that the eye is most sensitive to under dim lighting conditions.

3.2 BASIC PROCESSING STEPS OF LPI

1. **Surface Preparation:** One of the most critical steps of a liquid penetrant inspection is the surface preparation. The surface must be free of oil, grease, water, or other contaminants that may prevent penetrant from entering flaws. The sample may also require etching if mechanical operations such as machining, sanding, or grit blasting have been performed. These and other mechanical operations can smear the surface of the sample, thus closing the defects.

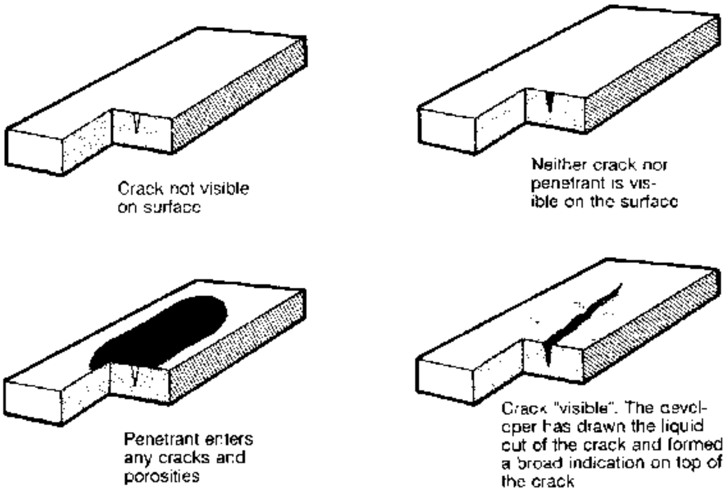
2. **Penetrant Application:** Once the surface has been thoroughly cleaned and dried, the penetrant material is applied by spraying, brushing, or immersing the parts in a penetrant bath.

3. **Penetrant Dwell:** The penetrant is left on the surface for a sufficient time to allow as much penetrant as possible to be drawn from or to seep into a defect. The times vary depending on the application, penetrant materials used, the material, the form of the material being inspected, and the type of defect being inspected. Generally, there is no harm in using a longer penetrant dwell time as long as the penetrant is not allowed to dry.

4. **Excess Penetrant Removal:** This is the most delicate part of the inspection procedure because the excess penetrant must be removed from the surface of the sample while removing as little penetrant

as possible from defects. Depending on the penetrant system used, this step may involve cleaning with a solvent, direct rinsing with water, or first treated with an emulsifier and then rinsing with water.

5. **Developer Application:** A thin layer of developer is then applied to the sample to draw penetrant trapped in flaws back to the surface where it will be visible. Developers come in a variety of forms that may be applied by dusting (dry powdered), dipping, or spraying (wet developers).
6. **Indication Development:** The developer is allowed to stand on the part surface for a period of time sufficient to permit the extraction of the trapped penetrant out of any surface flaws. This development time is usually a minimum of 10 minutes and significantly longer times may be necessary for tight cracks.
7. **Inspection:** Inspection is then performed under appropriate lighting to detect indications from any flaws which may be present.
8. **Clean Surface:** The final step in the process is to thoroughly clean the part surface to remove the developer from the parts that were found to be acceptable.



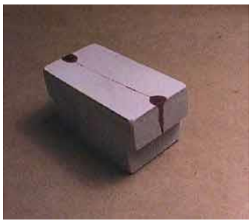
The procedure used when performing an examination with a penetrant.
1. *Pre-clean, remove grease and dry the component.*
2. *Penetrant is applied to the component and acts for a brief period.*
3. *Excess penetrant is completely removed from the surface.*
4. *A developer is applied and dried off. Inspect for indication of defects.*

Penetrant testing materials

A penetrant must possess a number of important characteristics. A penetrant must

- spread easily over the surface of the material being inspected to provide complete and even coverage,
- be drawn into surface breaking defects by capillary action,
- remain in the defect but remove easily from the surface of the part,
- remain fluid so it can be drawn back to the surface of the part through the drying and developing steps,
- be highly visible or fluoresce brightly to produce easy to see indications,
- must not be harmful to the material being tested or the inspector.

Penetrant Types



Dye penetrants

- The liquids are coloured so that they provide good contrast against the developer
- Usually red liquid against white developer
- Observation performed in ordinary daylight or good indoor illumination

Fluorescent penetrants

- Liquid contain additives to give fluorescence under UV
- Object should be shielded from visible light during inspection
- Fluorescent indications are easy to see in the dark

Further classification

According to the method used to remove the excess penetrant from the part, the penetrants can be classified into:

- Method A - Water Washable
- Method B - Post Emulsifiable, Lipophilic
- Method C - Solvent Removable
- Method D - Post Emulsifiable, Hydrophilic

Based on the strength or detectability of the indication that is produced for a number of very small and tight fatigue cracks, penetrants can be classified into five sensitivity levels are shown below:

- Level ½ - Ultra Low Sensitivity
- Level 1 - Low Sensitivity
- Level 2 - Medium Sensitivity
- Level 3 - High Sensitivity
- Level 4 - Ultra-High Sensitivity

Developer

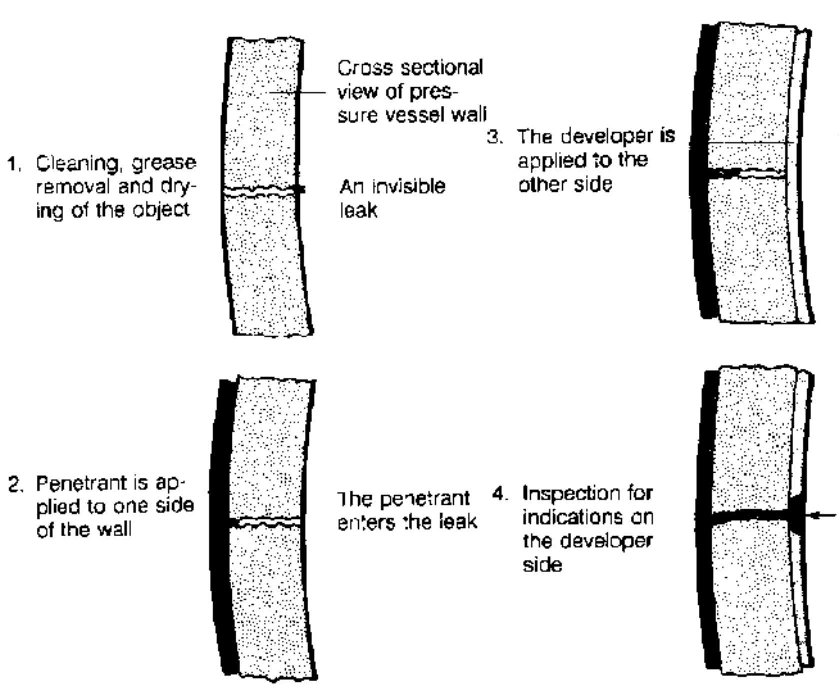
The role of the developer is to pull the trapped penetrant material out of defects and to spread the developer out on the surface of the part so it can be seen by an inspector. The fine developer particles both reflect and refract the incident ultraviolet light, allowing more of it to interact with the penetrant, causing more efficient fluorescence. The developer also allows more light to be emitted through the same mechanism. This is why indications are brighter than the penetrant itself under UV light. Another function that some developers performs is to create a white background so there is a greater degree of contrast between the indication and the surrounding background.

Developer Types

- Dry powder developer –the least sensitive but inexpensive
- Water soluble – consist of a group of chemicals that are dissolved in water and form a developer layer when the water is evaporated away.
- Water suspendible – consist of insoluble developer particles suspended in water.
- Nonaqueous – suspend the developer in a volatile solvent and are typically applied with a spray gun.

Using dye and developer from different manufacturers should be avoided.

3.3 FINDING LEAKS WITH DYE PENETRANT



Leakage testing using dye penetrant.

1) *Cleaning, grease removal and drying of the component.*
2) *Penetration liquid is applied to one side of the component.*
3) *The developer is applied to the other side.*
4) *Inspection for indications on the developer side.*

3.4 ADVANTAGES & DISADVANTAGES

Primary Advantages

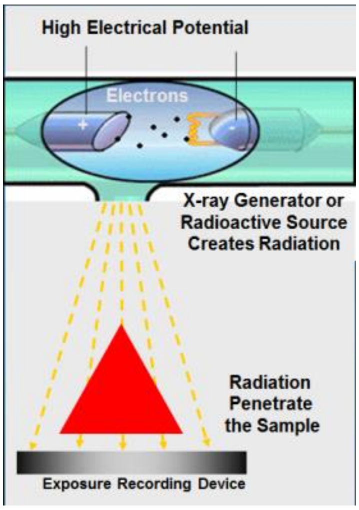
- The method has high sensitive to small surface discontinuities.
- The method has few material limitations, i.e. metallic and nonmetallic, magnetic and nonmagnetic, and conductive and nonconductive materials may be inspected.
- Large areas and large volumes of parts/materials can be inspected rapidly and at low cost.
- Parts with complex geometric shapes are routinely inspected.
- Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.
- Aerosol spray cans make penetrant materials very portable.
- Penetrant materials and associated equipment are relatively inexpensive.

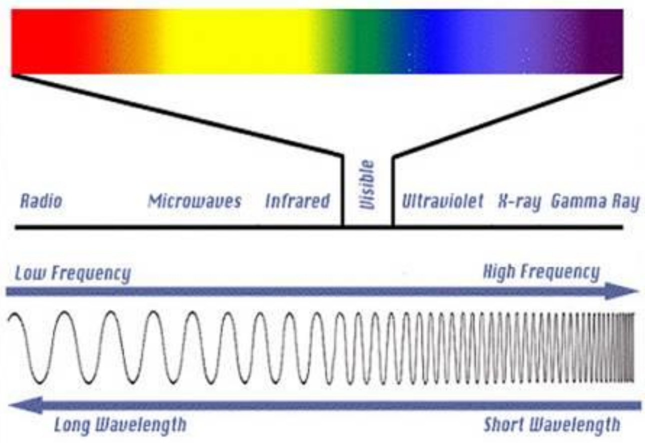
Primary Disadvantages

- Only surface breaking defects can be detected.
- Only materials with a relative nonporous surface can be inspected.
- Precleaning is critical as contaminants can mask defects.
- Metal smearing from machining, grinding, and grit or vapor blasting must be removed prior to LPI.
- 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.

4. RADIOGRAPHY

Radiography involves the use of penetrating gamma- or X-radiation to examine material's and product's defects and internal features. An X-ray machine or radioactive isotope is used as a source of radiation. Radiation is directed through a part and onto film or other media. The resulting shadowgraph shows the internal features and soundness of the part. Material thickness and density changes are indicated as lighter or darker areas on the film. The darker areas in the radiograph below represent internal voids in the component.





4.1 RADIATION SOURCES

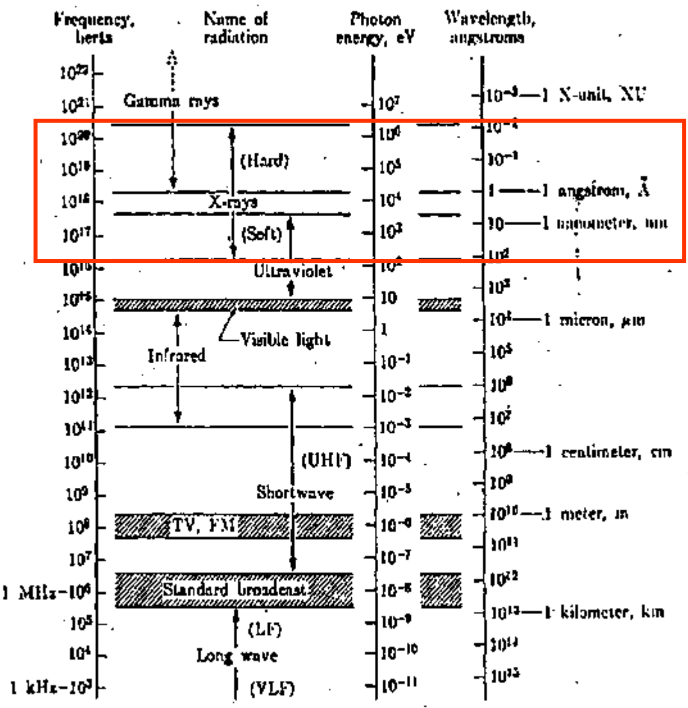
X-rays or gamma radiation is used

4.1.1 x-ray source

- X-rays are electromagnetic radiation with very short wavelength (≈ 10^{-8} -10^{-12} m)
- The energy of the x-ray can be calculated with the equation

***E* = *h*ν = *hc*/λ**

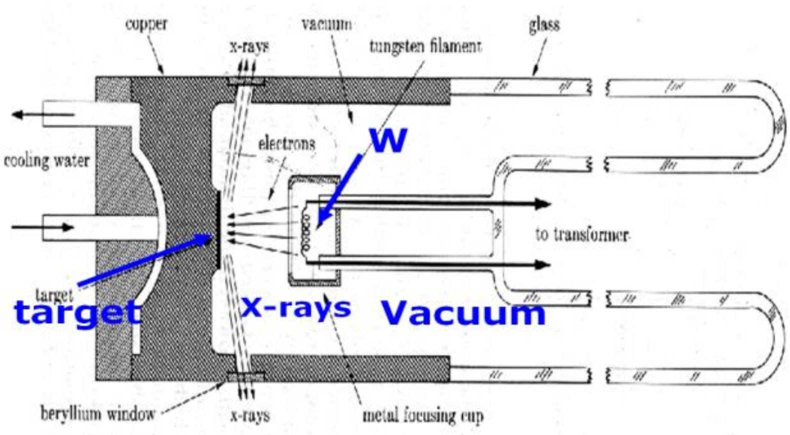
e.g. the x-ray photon with wavelength 1Å has energy 12.5 keV



Production of X-rays

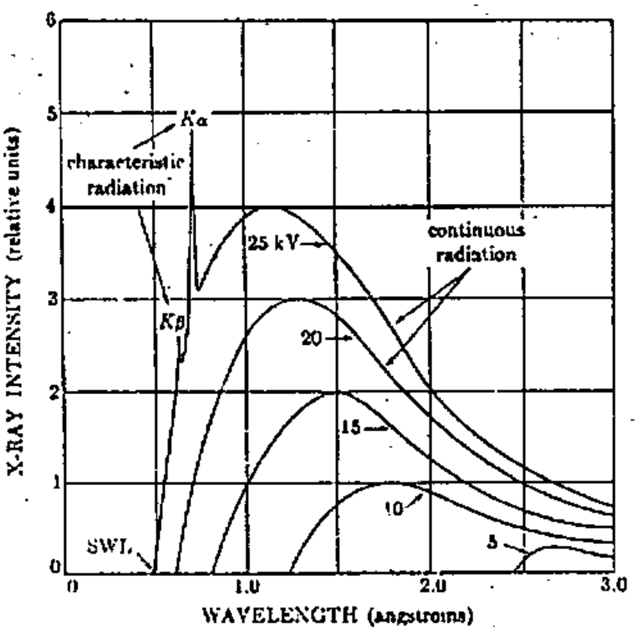
X-rays are produced whenever high-speed electrons collide with a metal target.

A source of electrons – hot W filament, a high accelerating voltage (30-50kV) between the cathode (W) and the anode and a metal target. The anode is a water-cooled block of Cu containing desired target metal.

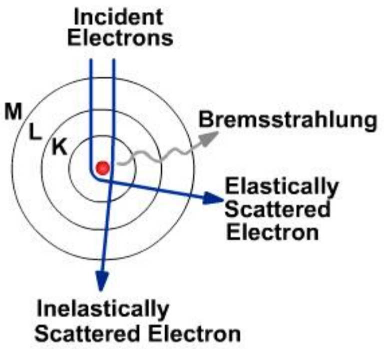


X-ray Spectrum

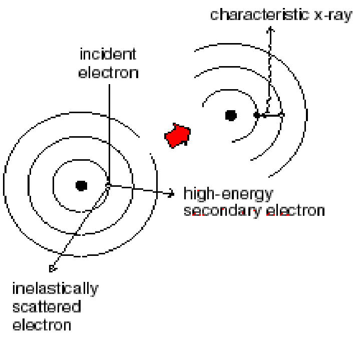
- A spectrum of x-ray is produced as a result of the interaction between the incoming electrons and the inner shell electrons of the target element.
- Two components of the spectrum can be identified, namely, **<u>the continuous spectrum</u>** and **<u>the characteristic spectrum</u>**.



SWL - short-wavelength limit



- Fast moving e^- will then be deflected or decelerated and EM radiation will be emitted.
- The energy of the radiation depends on the severity of the deceleration, which is more or less random, and thus has a continuous distribution.
- These radiation is called **white radiation** or **bremsstrahlung** (German word for ‘braking radiation’).



- If an incoming electron has sufficient kinetic energy for knocking out an electron of the K shell (the inner-most shell), it may excite the atom to an high-energy state (K state).
- One of the outer electron falls into the K-shell vacancy, emitting the excess energy as a x-ray photon -- **K-shell emission Radiation**.

Absorption of x-ray

- All x-rays are absorbed to some extent in passing through matter due to **electron ejection** or **scattering**.
- The absorption follows the equation

$$I = I_0 e^{-\mu x} = I_0 e^{-\left(\frac{\mu}{\rho}\right)\rho x}$$

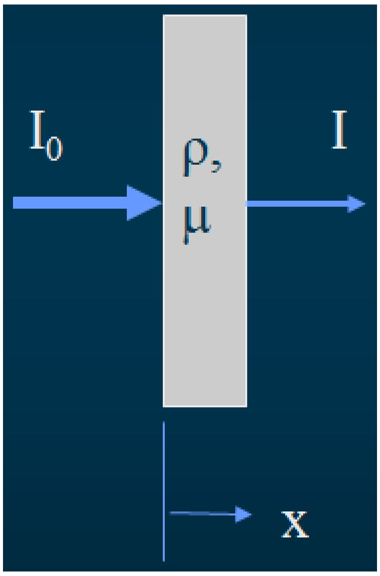
where I is the transmitted intensity;

x is the thickness of the matter;

μ is the linear absorption coefficient (element dependent);

ρ is the density of the matter;

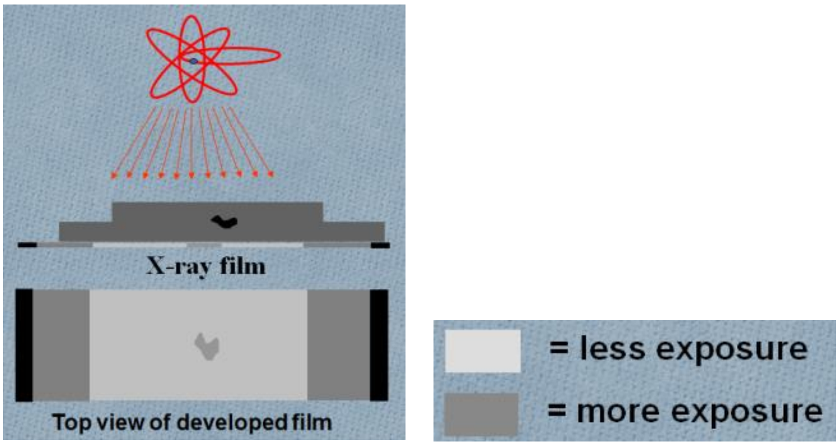
(μ/ρ) is the mass absorption coefficient (cm^2/gm).



4.2 Film Radiography

The part is placed between the radiation source and a piece of film. The part will stop some of the radiation. Thicker and more dense area will stop more of the radiation.

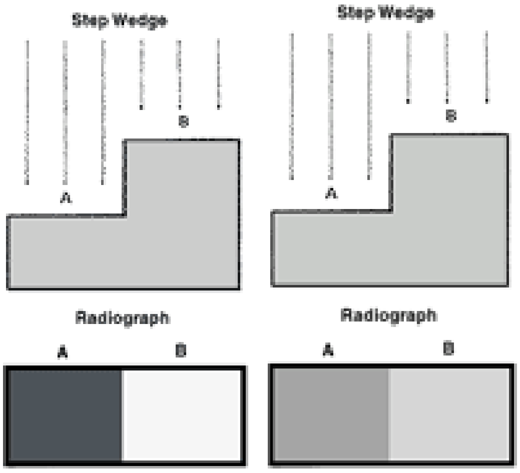
- The film darkness (density) will vary with the amount of radiation reaching the film through the test object.
- Defects, such as voids, cracks, inclusions, etc., can be detected.



Contrast and Definition

Contrast

The first subjective criteria for determining radiographic quality is radiographic contrast. Essentially, radiographic contrast is the degree of density difference between adjacent areas on a radiograph.

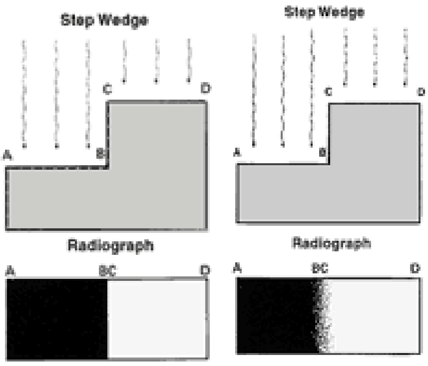


low kilovoltage **high kilovoltage**

Definition

Radiographic definition is the abruptness of change in going from one density to another.

High definition: the detail portrayed in the radiograph is equivalent to physical change present in the part. Hence, the imaging system produced a faithful visual reproduction.



good **poor**

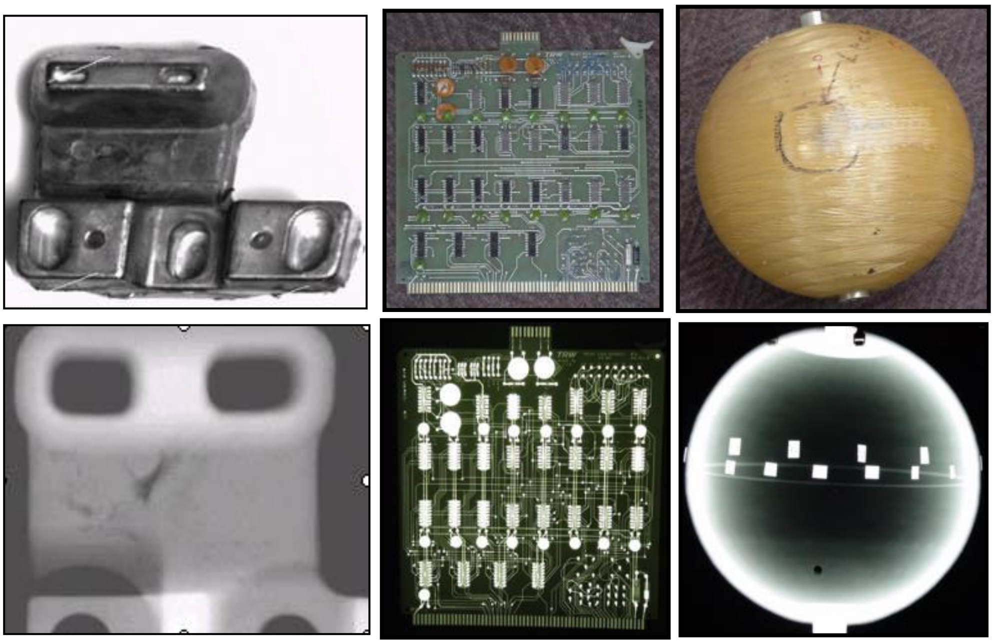
4.3 AREAS OF APPLICATION

- Can be used in any situation when one wishes to view the interior of an object
- To check for internal faults and construction defects, e.g. faulty welding
- To 'see' through what is inside an object
- To perform measurements of size, e.g. thickness measurements of pipes

Standards (https://litas.ru/blog/stati/reglament-na-radiograficheskie-metody-nk/)

- ГОСТ ISO 17636-1- 2017 НЕРАЗРУШАЮЩИЙ КОНТРОЛЬ СВАРНЫХ СОЕДИНЕНИЙ. РАДИОГРАФИЧЕСКИЙ КОНТРОЛЬ/ Часть 1 Способы рентгено- и гаммаграфического контроля с применением пленки
- (ISO 17636-1:2013, Non-destructive testing of welds — Radiographic testing — Part 1: X- and gamma-ray techniques with film , IDT)
- ГОСТ Р 50.05.07-2018. Система оценки соответствия в области использования атомной энергии. Оценка соответствия в форме контроля. Унифицированные методики. Радиографический контроль/ Conformity assessment system for the use of nuclear energy. Conformity assessment in the form of examination. Unified procedures. Radiographic examination
- ASTM E94-84a Radiographic Testing
- ASTM E1032-85 Radiographic Examination of Weldments
- ASTM E1030-84 Radiographic Testing of Metallic Castings

Radiographic Images

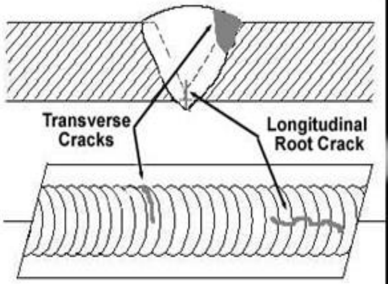


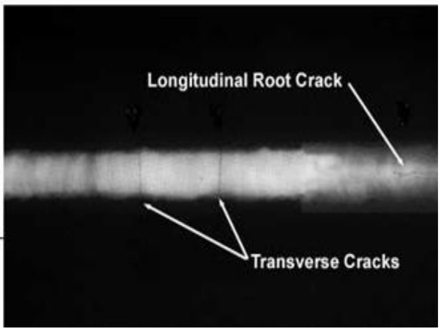
4.4 LIMITATIONS OF RADIOGRAPHY

- There is an upper limit of thickness through which the radiation can penetrate, e.g. γ-ray from Co-60 can penetrate up to 150mm of steel
- The operator must have access to both sides of an object
- Highly skilled operator is required because of the potential health hazard of the energetic radiations

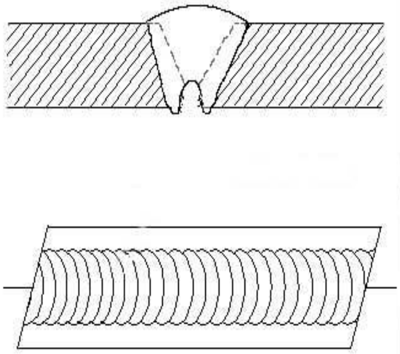
- Relative expensive equipment

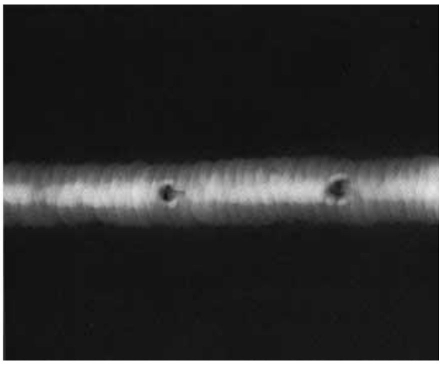
4.5 EXAMPLES OF RADIOGRAPHS



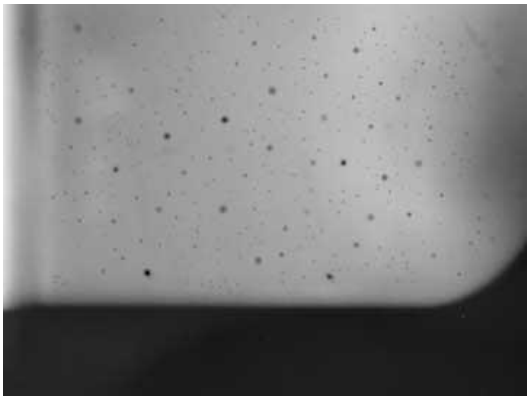


Cracking can be detected in a radiograph only the crack is propagating in a direction that produced a change in thickness that is parallel to the x-ray beam. Cracks will appear as jagged and often very faint irregular lines. Cracks can sometimes appearing as "tails" on inclusions or porosity.

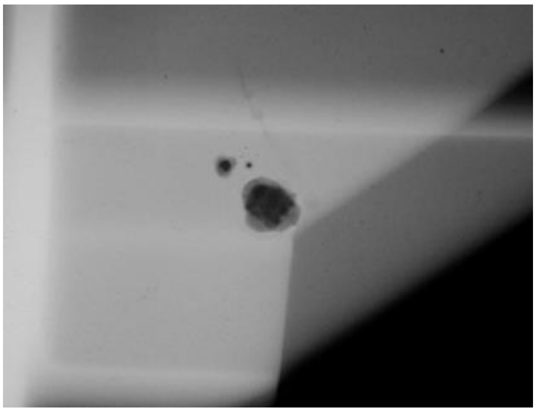




Burn through (icicles) results when too much heat causes excessive weld metal to penetrate the weld zone. Lumps of metal sag through the weld creating a thick globular condition on the back of the weld. On a radiograph, burn through appears as dark spots surrounded by light globular areas.



Gas porosity or blow holes are caused by accumulated gas or air which is trapped by the metal. These discontinuities are usually smooth-walled rounded cavities of a spherical, elongated or flattened shape



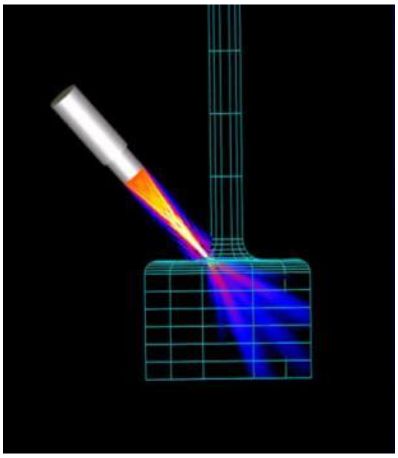
Sand inclusions and dross are nonmetallic oxides, appearing on the radiograph as irregular, dark blotches.

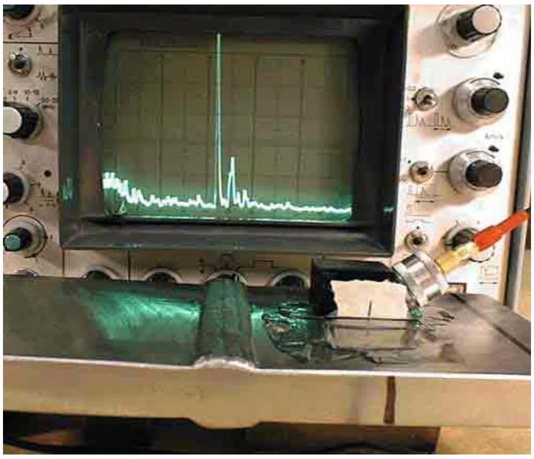
5. ULTRASONIC TESTING

INTRODUCTION

In ultrasonic testing, high-frequency sound waves are transmitted into a material to detect imperfections or to locate changes in material properties.

The most commonly used ultrasonic testing technique is pulse echo, whereby sound is introduced into a test object and reflections (echoes) from internal imperfections or the part's geometrical surfaces are returned to a receiver. The time interval between the transmission and reception of pulses give clues to the internal structure of the material.

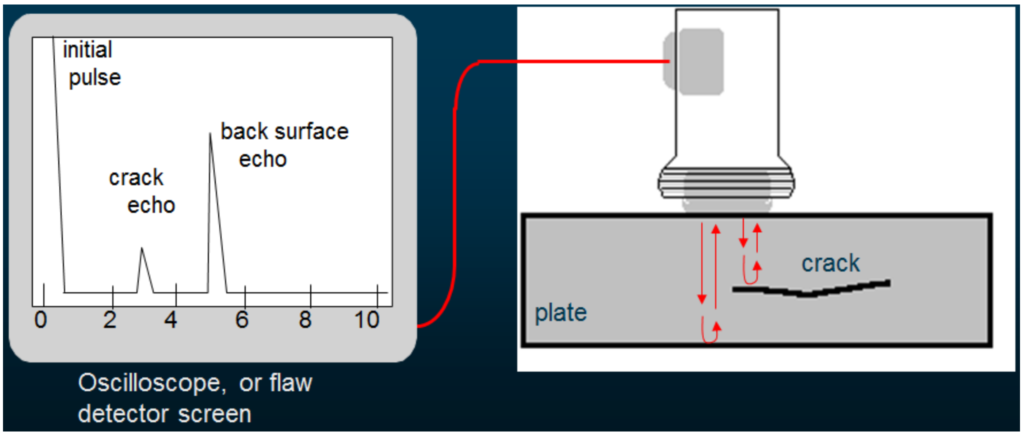




ULTRASONIC INSPECTION (PULSE-ECHO)

High frequency sound waves are introduced into a material and they are reflected back from surfaces or flaws.

Reflected sound energy is displayed versus time, and inspector can visualize a cross section of the specimen showing the depth of features that reflect sound.



GENERATION OF ULTRASONIC WAVES

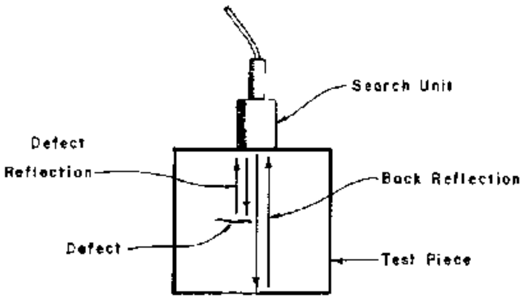
- Piezoelectric transducers are used for converting electrical pulses to mechanical vibrations and vice versa
- Commonly used piezoelectric materials are quartz, Li_2SO_4, and polarized ceramics such as $BaTiO_3$ and $PbZrO_3$.
- Usually the transducers generate ultrasonic waves with frequencies in the range 2.25 to 5.0 MHz

NORMAL BEAM INSPECTION

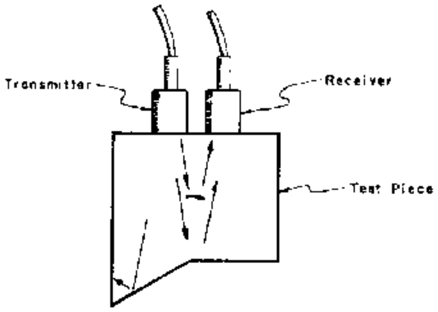
Pulse-echo ultrasonic measurements can determine the location of a discontinuity in a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through a thickness of material, reflect from the back or the surface of a discontinuity, and be returned to the transducer. In most applications, this time interval is a few microseconds or less.

$d = vt/2$ or $v = 2d/t$

where **d** is the distance from the surface to the discontinuity in the test piece, **v** is the velocity of sound waves in the material, and **t** is the measured round-trip transit time.

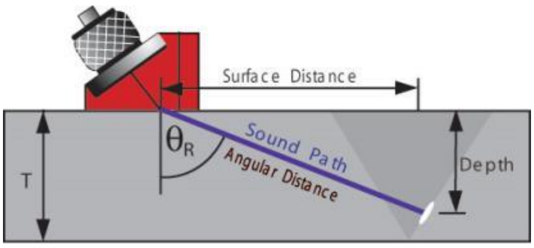


Single search unit pulse-echo reflection technique.



Two search units being used to inspect irregularly shaped test object.

ANGLES BEAM INSPECTION



θ_R = Angle of Refraction

T = Material Thickness

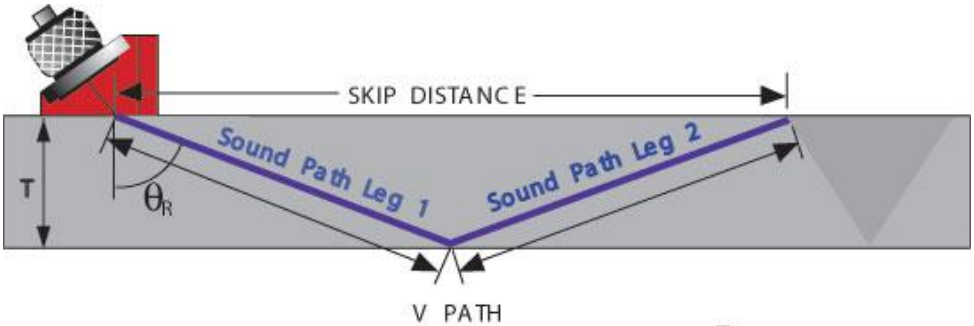
Surface Distance = $\sin\theta_R$ x Sound Path

Depth (1st Leg) = $\cos\theta_R$ x Sound Path

Angle Beam Transducers and wedges are typically used to introduce a refracted shear wave into the test material. An angled sound path allows the sound beam to come in from the side, thereby improving detectability of flaws in and around welded areas.

- Can be used for testing flat sheet and plate or pipe and tubing
- Angle beam units are designed to induce vibrations in Lamb, longitudinal, and shear wave modes

The geometry of the sample below allows the sound beam to be reflected from the back wall to improve detectability of flaws in and around welded areas.



θ_R = Refracted Angle

T = Material Thickness

Skip Distance = 2T x $\tan\theta_R$

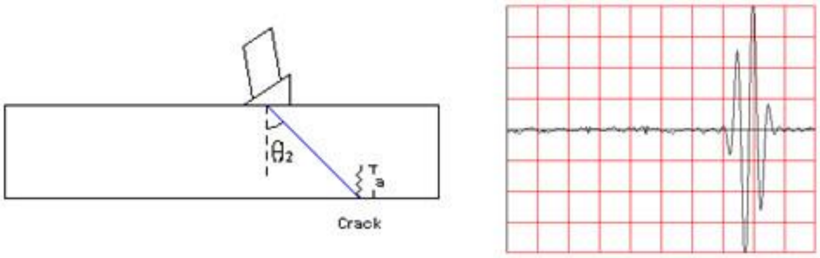
$$\text{Leg} = \frac{T}{\cos\theta_R}$$

$$\text{V-Path} = \frac{2T}{\cos\theta_R}$$

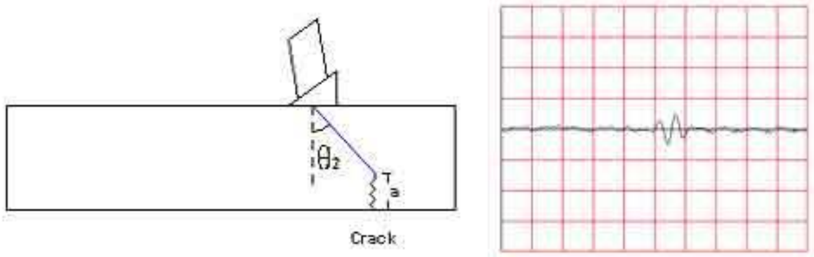
CRACK TIP DIFFRACTION

When the geometry of the part is relatively uncomplicated and the orientation of a flaw is well known, the length **(*a*)** of a crack can be determined by a technique known as tip diffraction. One common application of the tip diffraction technique is to determine the length of a crack originating from on the backside of a flat plate.

When an angle beam transducer is scanned over the area of the flaw, the principle echo comes from the base of the crack to locate the position of the flaw (Image 1).

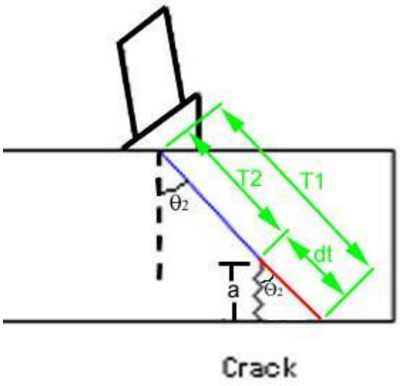


A second, much weaker echo comes from the tip of the crack and since the distance traveled by the ultrasound is less, the second signal appears earlier in time on the scope (Image 2).



Crack height ***(a)*** is a function of the ultrasound velocity ***(v)*** in the material, the incident angle **(θ_2)** and the difference in arrival times between the two signal **(dt)**.

The variable **dt** is really the difference in time but can easily be converted to a distance by dividing the time in half (to get the one-way travel time) and multiplying this value by the velocity of the sound in the material. Using trigonometry an equation for estimating crack height from these variables can be derived.



$$a = \text{Cos}\,\Theta \text{ X (Distance dt)} \qquad a = \text{Cos}\,\Theta \text{ X } \frac{(dt \times v)}{2}$$

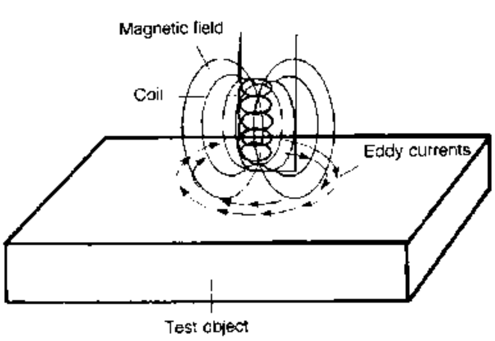
6. EDDY CURRENT TESTING

Electrical currents are generated in a conductive material by an induced alternating magnetic field. The electrical currents are called **eddy currents** because the flow in circles at and just below the surface of the material. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the material's conductive and permeability properties, can be detected with the proper equipment.

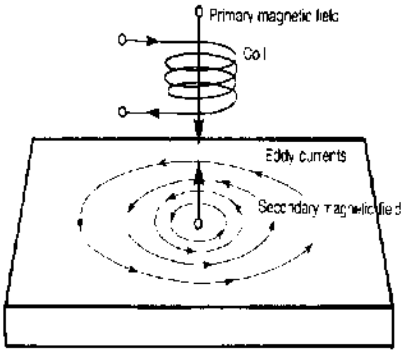
- Eddy current testing can be used on all electrically conducting materials with a reasonably smooth surface.
- The test equipment consists of a generator (AC power supply), a test coil and recording equipment, e.g. a galvanometer or an oscilloscope
- Used for crack detection, material thickness measurement (corrosion detection), sorting materials, coating thickness measurement, metal detection, etc.

6.1. Principle of Eddy Current Testing

- When a AC passes through a test coil, a primary magnetic field is set up around the coil
- The AC primary field induces eddy current in the test object held below the test coil
- A secondary magnetic field arises due to the eddy current

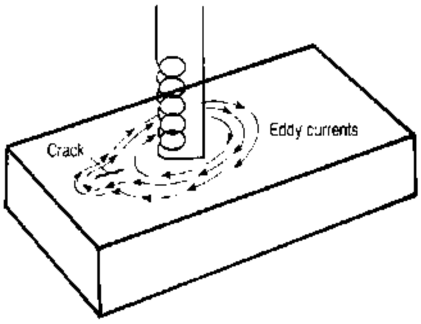


Induction of eddy currents.



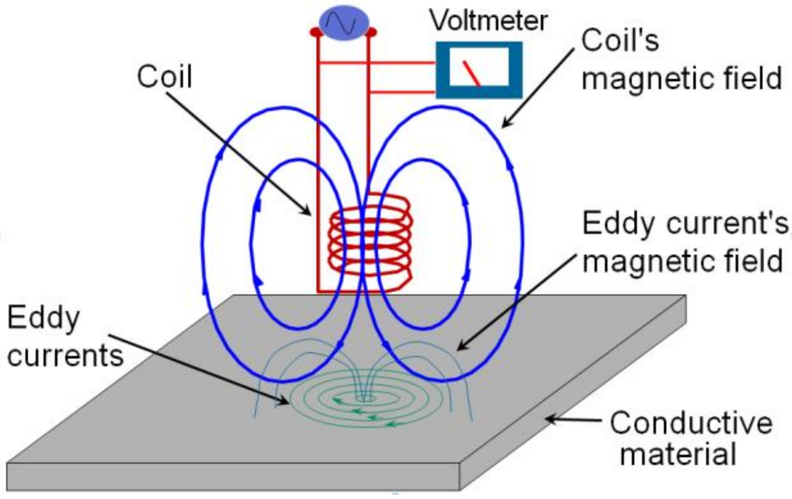
The primary magnetic field H_p and the secondary magnetic field H_s

- The strength of the secondary field depends on electrical and magnetic properties, structural integrity, etc., of the test object
- If cracks or other inhomogeneities are present, the eddy current, and hence the secondary field is affected.



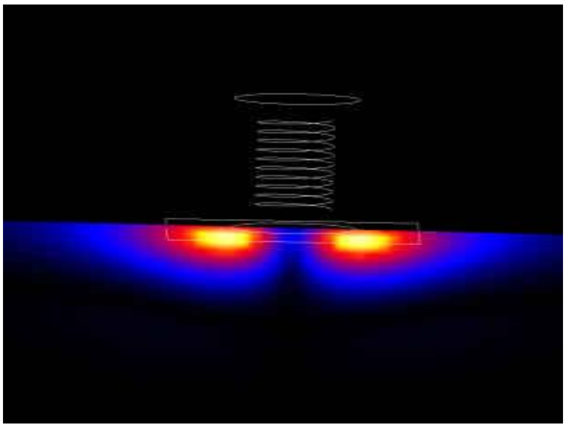
Changes in the magnetic field during passage of a crack.

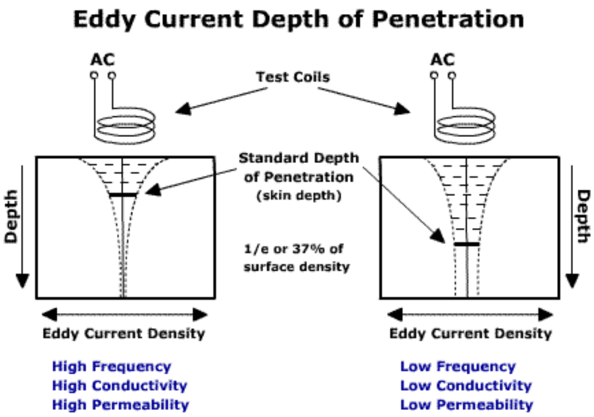
6.2. EDDY CURRENT INSTRUMENTS



Depth of Penetration

Eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux. They normally travel parallel to the coil's winding and flow is limited to the area of the inducing magnetic field. Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil as shown in the image. Eddy current density decreases exponentially with depth. This phenomenon is known as the skin effect.

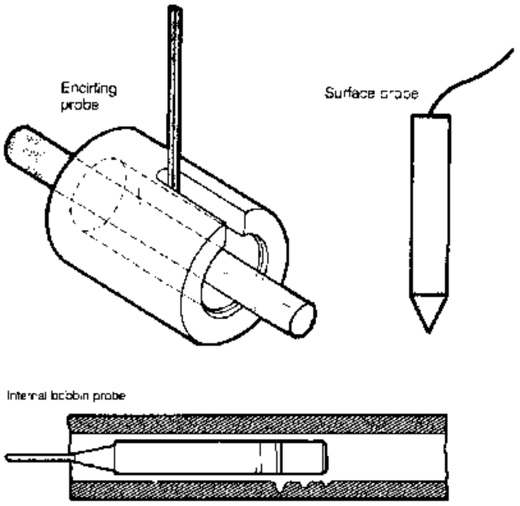




The depth at which eddy current density has decreased to 1/e, or about 37% of the surface density, is called the standard depth of penetration (δ).

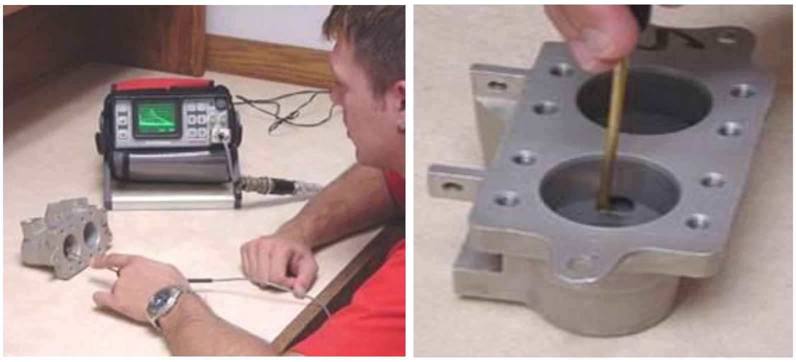
Three Major Types of Probes

- The test coils are commonly used in three configurations
  - Surface probe
  - Internal bobbin probe
  - Encircling probe



6.3. APPLICATIONS

- Crack Detection
- Material Thickness Measurements
- Coating Thickness Measurements
- Conductivity Measurements For:
- Material Identification
- Heat Damage Detection
- Case Depth Determination
- Heat Treatment Monitoring



6.4. ADVANTAGES & LIMITATIONSOF ET

Advantages of ET

- Sensitive to small cracks and other defects
- Detects surface and near surface defects
- Inspection gives immediate results
- Equipment is very portable
- Method can be used for much more than flaw detection
- Minimum part preparation is required
- Test probe does not need to contact the part
- Inspects complex shapes and sizes of conductive materials

Limitations of ET

- Only conductive materials can be inspected
- Surface must be accessible to the probe
- Skill and training required is more extensive than other techniques
- Surface finish and and roughness may interfere
- Reference standards needed for setup
- Depth of penetration is limited
- Flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable

7. OVERVIEW ON ACOUSTIC EMISSION TESTING

When materials are cracking, deforming or otherwise becoming damaged, they produce a kind of sound. Sometimes, these sounds are loud and obvious. Other times, they are much more subtle, and to detect them, you need to use specialized equipment. Detecting these subtler sounds through acoustic emission testing (AET) can reveal cracks and other defects that are forming which may cause significant issues, such as equipment failure, in the future if not corrected.

WHAT ARE ACOUSTIC EMISSIONS?

The term acoustic emission (AE) refers to the creation of transient elastic waves due to rapid energy release from localized sources in a material. These acoustic waves are emitted by solid materials when they experience deformation or damage. AE is associated with a permanent alteration of the microstructure of a material. A simplified explanation is that AE is the sound produced when a material becomes damaged, although other types of waves, in addition to sound waves, may also be involved.

Various events can generate AE, including:

- The dislocation movement causes by plastic deformation or yielding
- The formation and extension of cracks in an object under stress
- Phase transformation
- Thermal stresses
- Cracking during cooldown
- Stress build-up
- Twinning, a form of crystalline distortion
- Matrix cracking
- Fiber breakage
- Debonding

AE can occur in various types of materials, including metals, plastics, polymers, concrete and wood. The characteristics of an acoustic emission depend on various factors, including the event that caused the AE and the material involved. Matrix cracking, for example, tends to produce a low amplitude emission, while crack propagation produces a higher amplitude emission.

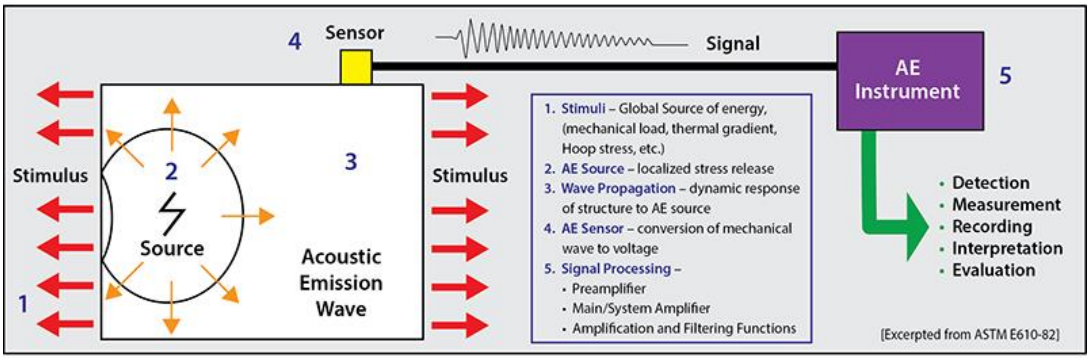
WHAT IS ACOUSTIC EMISSION TESTING?

The term acoustic emission testing (AET) refers to the process of detecting and recording AE using specialized equipment. AET is a type of nondestructive test (NDT) that has various uses, including ensuring the structural integrity of vessels, monitoring weld quality and more. The process involves using sensors to detect AE and then converting the waves into electrical signals so that they can be recorded. You can then analyze the results to assess a material’s condition and locate any defects. The recorded information can provide potentially valuable information about the origin and significance of a defect in a structure.

There are several slightly different methods used for acoustic emission testing. Some of the main methods include:

- **Global screening:** One method is used to screen all components and involves increasing stress levels to slightly above normal using thermal or pressure gradients to reveal stress risers and cracks. For example, you might increase the pressure in a reactor to 110% of the typical maximum operating pressure. Raising the pressure should reveal active defects that are not apparent under normal operating conditions but will likely continue to worsen over time.
- **Monitoring during Normal Operating Conditions:** Another method involves monitoring known flaws or detecting unknown flaws that can’t easily be discovered by increasing stress levels. With this method, the AE signals result from actual damage progression or crack propagation. For example, you might monitor coke drums over time for thermally induced fatigue cracks. In this method, rather than artificially increasing the load for the purpose of testing, you use AET to monitor a vessel for significant damage progression.

- **Proof tests:** The goal of a proof test is to show that a given structure can handle loads up to a certain amount. In the test, you increase the load to the required amount. If successful, the test will not record any significant emissions.
- **Failure tests:** A failure test aims to determine the load at which a structure begins to fail. It involves gradually increasing the load until the system begins to record emissions that indicate failure is beginning to occur.
- **Fatigue tests:** Fatigue tests involve applying a cyclic load to a structure to estimate its working lifetime.



SETTING UP THE EQUIPMENT

For testing a small component, you may only use one acoustic emission sensor. Typically, however, multiple sensors are used and spread across the surface of the object. This is, in part, because different sensors may pick up different signal characteristics for the same emission event, especially in complex structures. When setting up sensors, it's typically ideal that each area of interest is within the acoustic range of at least three sensors. Often, a pattern of interlocking triangles or interlocking rectangles is used to set up sensors.

It's also important to use a fluid couplant to help the sensor obtain a stronger signal, which it does by increasing the surface area that is transmitting the force. Various types of fluid couplants can be used, including resins, greases and sealants. Different types of couplants may work best in different applications. Couplants can also help bond the sensor to the surface, and tape, magnetic hold-downs, springs or other items are used to further secure the sensors.

The sensors are connected to a low-noise preamplifier and a main amplifier, as well as additional electronic equipment used to filter and isolate the sound. These devices help make the reading clearer and easier to analyze accurately. Shielding is also important for reducing electrical noise. The sensors and other equipment are connected using coaxial cables to a computer that records the readings.

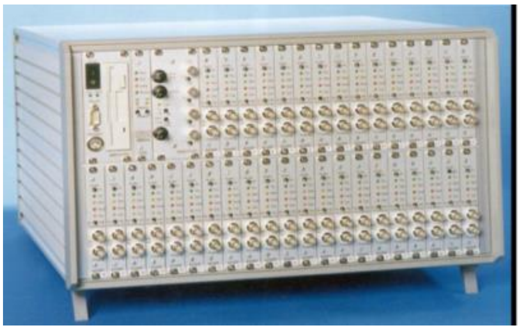
RUNNING THE TEST

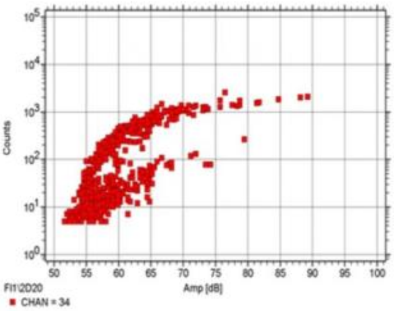
After setting up the equipment, the test is begun by applying the required load. For example, the test may require increasing the pressure in a vessel to slightly above the normal operating pressure. The system may also continue to operate as usual if the test aims to monitor performance under normal operating conditions. Once the test begins, the AET system will record any AE above a pre-determined threshold, along with the exact time it occurred. The system will record data related to emission count, signal length, peak amplitude, emission strength and other chosen parameters. The distance between the emission source and the sensor affects the recorded emission strength, so the strength recorded by multiple sensors is often averaged to help estimate the strength of each emission.

Various techniques can be used in acoustic emission testing. The ideal equipment setup and testing process depend on the type of structure being tested, the material being tested, the type of test being conducted and other factors.

ANALYZING THE RESULTS

Once the test is complete, the results are analyzed. Alternatively, for some types of tests, you can conduct analysis while the test is taking place. Analysis involves looking for the occurrence of AE, measuring the rate of each emission and determining the location of any defects. With modern computer systems, the results of the test show up as a graph, which helps in interpreting the results. By measuring the arrival time of an AE signal to each sensor, you can determine the defect's location using triangulation. After locating the flaw, you can perform additional inspection or begin taking steps toward correcting the flaw.





WHAT ARE THE APPLICATIONS OF ACOUSTIC EMISSION TESTING?

AET is very versatile and has many applications across a variety of industries. It's also used as a research tool. Some of the applications of AET include:

- Detection of active sources, including yielding, crack propagation, fatigue, creep, fiber delamination, fiber fracture, and corrosion.
- Structural integrity evaluation
- In-field inspection
- Weld quality monitoring
- Production quality control
- Leak detection
- Monitoring chemical reactions and phase changes
- Laboratory and research and development (R&D) studies

WHO USES ACOUSTIC EMISSION TESTING?

A wide variety of industries can use AET, including:

- **Aerospace:** The aerospace sector can use AET to assess aging aircraft, motors and fuel storage tanks.
- **Alternative energy sources:** AET is useful for testing the structural integrity of alternative energy infrastructure such as wind turbines.
- **Automotive:** Automotive manufacturers may use AET to assess vehicle components, as well as factory equipment.
- **Chemical and refinery:** Companies in the chemical and refinery sector can use AET to test for defects in plant equipment and vessels.
- **Infrastructure:** AET is valuable for testing the structural integrity of bridges, tunnels, dams and other types of infrastructure.
- **Manufacturing:** Manufacturers can use AET to test a wide range of manufacturing equipment types, as well as ensure product quality of certain types of goods.
- **Materials research and development:** Those working in materials research and development can use AET to test the integrity of new and existing materials in various applications.
- **Nuclear power:** AET can be used to inspect nuclear components, such as lift beams, valves and steam lines.
- **Offshore drilling:** AET can provide early detection of faults in offshore drilling platforms and pipelines.
- **Oil and gas:** Oil and gas companies can use AET to test pipelines, vessels and processing equipment.
- **Power distribution:** AET can be used for partial discharge detection in power transformers.
- **Pressure vessels and piping:** Manufacturers of pressure vessels may use AET to ensure product quality. Users of this equipment may also use AET to test the condition of their equipment.
- **Process technology:** Process technology professionals in the fields of wastewater treatment, chemical processing, power generation and more can use AET to test the integrity of system components.
- **Pulp and paper:** AET is used in the pulp and paper industry for testing the integrity of vessels, tanks, piping, tubing and other equipment used in manufacturing operations.

- **Transportation:** AET is useful for testing various types of transportation equipment, including railroad tank cars, marine vessels, motors, tube trailers and more.

WHAT ARE THE ADVANTAGES OF AET?

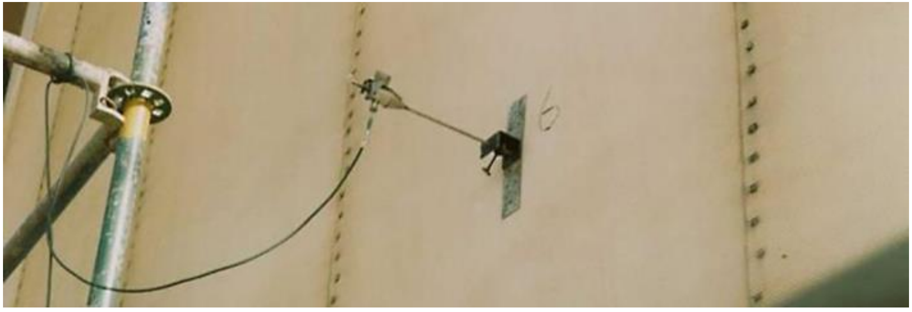
AET can be used for the early detection of flaws as well as real-time monitoring. It is a high-sensitivity test method and offers advantages including:

- **Early damage detection:** Because AET detects the growth of cracks and flaws and is a highly sensitive test method, it can detect relatively small (micro) defects early on. This early detection enables you to repair flaws before they cause significant issues.
- **Global, simultaneous inspection:** With AET, you can inspect an entire unit or system simultaneously, including pressure vessels, reactors, piping and other components. This results in a more efficient, cost-effective testing process and enables you to test even large systems relatively quickly.
- **No need for shutdown:** AET can often be performed on a unit while it is in operation, avoiding the need for a shutdown. You can also perform AET during an in-service over-pressurization or scheduled cool-down. Avoiding a shutdown can reduce costs significantly and help keep productivity levels consistent.
- **Identification of only active defects:** AET only identifies active defects — those that are growing. This feature means that only flaws that are likely to cause significant issues in the future are identified, while stable cracks and old fabrications defects are not. This enables you to focus on the most significant issues, saving your company time and money.
- **Immediate indication of risk:** With AET, you get an immediate indication of the strength of a given component and the risk of failure, enabling you to respond quickly if needed.
- **Minimal disruption to insulation:** Typically, only small holes in insulation are required to mount sensors. You may also be able to place permanent sensors underneath insulation.
- **Compliance assistance:** Several standards recognize AET, and it can help ensure compliance with local, state and federal regulations.
- **Reduced costs:** Using AET can reduce costs significantly by avoiding downtime, reducing test time, requiring minimal disruption to insulation and identifying only the defects that may cause significant issues in the future if not corrected.

WHAT ARE THE LIMITATIONS OF AET?

Like any test method, AET also has some limitations, which means it may not be the right choice for every application. In some cases, organizations may benefit from supplementing AET with other test methods. Some of the disadvantages of AET include that it:

- **Can only provide qualitative results:** AET can only provide qualitative results, not quantitative results. It can detect that a flaw exists, but determining the size and depth of a crack, for example, requires other test methods, such as ultrasonic testing.
- **Can only find active flaws:** The fact that AET only identifies active flaws can be an advantage, but, in some cases, you may also want to identify stagnant defects. AET would not work for this purpose. It’s also possible that AET may not detect relatively minor active flaws if the loading is not enough to result in an acoustic event.
- **Loud environments present challenges:** It can be more challenging to get accurate results from AET when it is performed in loud service environments. To filter out excess noise, signal discrimination and noise reduction techniques and technologies are required.
- **Requires specific skills and knowledge:** Performing AET requires an experienced, knowledgeable and skilled operator. It also involves the use of relatively complex and expensive hardware and software.



AET STANDARDS

Various organizations, including standards organizations, industry organizations and government agencies, publish standards or oversee regulations related to acoustic emission testing. These documents offer guidance for conducting AET. Conducting AET according to the requirements in these documents can also help organizations earn and maintain compliance with the relevant standards and regulations. Some of the organizations that publish standards and other documents related to AET include:

- **The International Organization for Standardization (ISO):** ISO has published various standards related to AET, which include standards for calibrating AE sensors, classifying active cracks in concrete structures and using AET for leak detection.
- **The American Society of Mechanical Engineers (ASME):** ASME has released numerous publications that discuss AET and covers requirements for AET in ASME Sec V Articles 11, 12 and 13.
- **The American Society for Testing and Materials (ASTM):** ASTM has also published various standards related to AET, including standards for Acoustic Emission Monitoring of Structures During Controlled Stimulation, Continuous Monitoring of Acoustic Emission from Metal Pressure Boundaries, testing aerial personnel devices and more.
- **The European Committee for Standardization (CEN):** CEN standards related to AET include standards for testing liquified petroleum gas equipment, calibrating AE transducers and testing metallic industrial piping.
- **The Japanese Standards Association (JSA):** JIS Z 2342:2003 from JAS describes methods for acoustic emission testing of pressure vessels.
- **The American Society for Nondestructive Testing (ASNT):** ASNT SNT-TC1A from ASNT describes requirements for qualification and certification of personnel in nondestructive testing, including AET.
- **The Committee on Acoustic Emission from Reinforced Plastics (CARP):** CARP has published various documents on using AET to test piping, tanks, pressure vessels and other objects made of reinforced plastics.
- **The Institute of Electrical and Electronics Engineers (IEEE):** IEEE has published PC57.127/D10.0, which is a guide for detecting and locating AE due to partial discharges in oil-immersed power reactors and transformers.
- **The Electric Power Research Institute (EPRI):** EPRI has published various guidelines, research papers and other technical documents related to AET, including guidelines for evaluating seam-welded high-energy piping.
- **The American Petroleum Institute (API):** API discusses AET in various documents, including ANSI/API 510, its pressure vessel inspection code.
- **The Compressed Gas Association (CGA):** CGA's C-18 describes methods for requalifying seamless steel tubes used for compressed gas with AET.
- **ГОСТ 27655-88.** ГОСТ 27655-88 Акустическая эмиссия. Термины, определения и обозначения Acoustic emission. Terms, definitions and symbols 07.11.2012 07.11.2012 01.01.1989.
- **ГОСТ Р 52727-2007** Техническая диагностика. Акустико-эмиссионная диагностика. Общие требования
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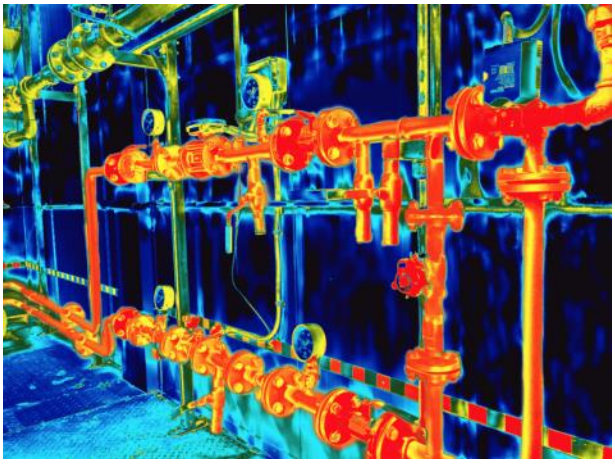
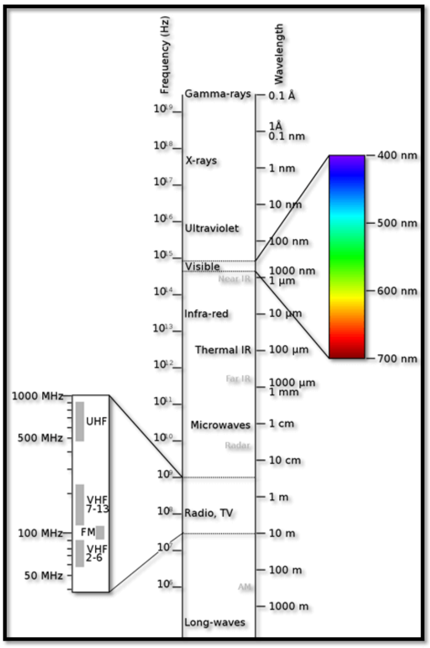
8. INTRODUCTION TO IR & THERMAL TESTING



All objects emit electromagnetic radiation of a wavelength-dependent on the object's temperature. The wavelength of the radiation is inversely proportional to the temperature. Infrared and thermal testing involves temperature and heat flow measurement to predict or diagnose the failure. This may involve contact or non-contact devices or a combination of both. Infrared thermography is the non-destructive, nonintrusive, noncontact mapping of thermal patterns on the surface of objects. it is the science of measuring and mapping surface temperatures. Infrared and thermal testing is one of many non-destructive testing techniques designated by the American Society for Nondestructive Testing (ASNT). Here in this article, we will have an introduction to IR(Infrared) & Thermal Testing.

WHAT IS INFRARED :

Infrared (IR), is electromagnetic radiation (EMR) with wavelengths longer than those of visible light. In an Electromagnetic spectrum, Infrared radiation extends from the nominal red edge of the visible spectrum at 700 nanometers (nm) to 1 millimeter (mm). This range of wavelengths corresponds to a frequency range of approximately 430 THz down to 300 GHz.



Electromagnetic spectrum
https://commons.wikimedia.org/w/index.php?curid=22428451

General

Thermography, infrared is the process of displaying variations of apparent temperature (variations of temperature or emissivity, or both) over the surface of an object or a scene by measuring variations in infrared radiance.

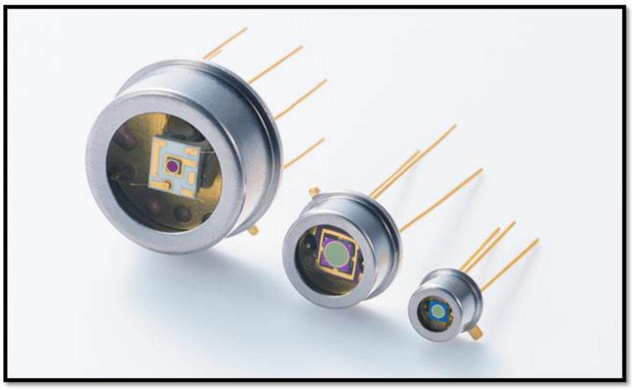
There are two basic types of thermography; passive thermography and active thermography

- **passive thermography**: refers to examination of an object or system during its normal operational mode, without the application of any additional energy source for the express purpose of generating a thermal gradient in the object or system;
- **active thermography**: refers to the examination of an object upon the intentional application of an external energy source. The energy source (active or passive) may be a source of heat, mechanical energy (vibration or fatigue testing), electrical current, or any other form of energy.

System Components

An infrared thermographic scanning system can measure and view temperature patterns based upon temperature differences as small as a few hundredths of a degree Celsius.

In infrared thermography, the radiation is detected and measured with infrared imagers (radiometers). The imagers contain an infrared detector that converts the emitting radiation into electrical signals that are displayed on a color or black and white computer display monitor. In thermal detectors, the incident radiation heats the surface. This heating affects properties of the heated material such as electrical conductivity, which in turn causes the signal output to vary.



Infrared detectors

Types of Detectors :

- Pyroelectric detectors
- Photonic Detectors
- Photoemissive Photonic Detectors
- Quantum detectors

infrared sensing device—one of a wide class of instruments used to display or record, or both information related to the thermal radiation received from any object surfaces viewed by the instrument. The instrument varies in complexity from spot radiometers to two-dimensional real-time imaging systems.

infrared imaging system—an apparatus that converts the two-dimensional spatial variations in infrared radiance from any object surface into a two-dimensional thermogram of the same scene, in which variations in radiance are displayed in gradations of gray tone or in color.

radiometer—an instrument for measuring the intensity of radiant energy. In infrared thermography, an apparatus that measures the average apparent temperature of the surface subtended by its field of view.

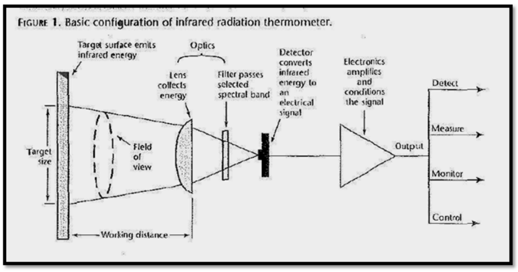


FIGURE 1. Basic configuration of infrared radiation thermometer.

Basic configuration of IR Radiation thermometer

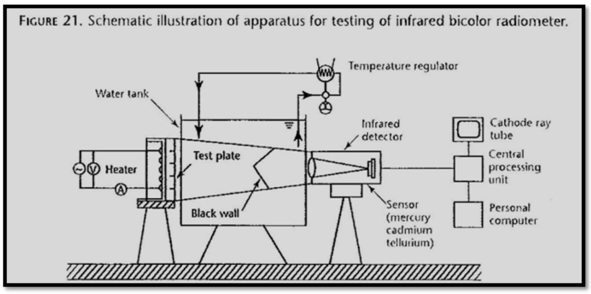


FIGURE 21. Schematic illustration of apparatus for testing of infrared bicolor radiometer.

Infrared Bicolor Radiometer

Inframetrics 760 Infrared Camera/Thermal Imaging Radiometer

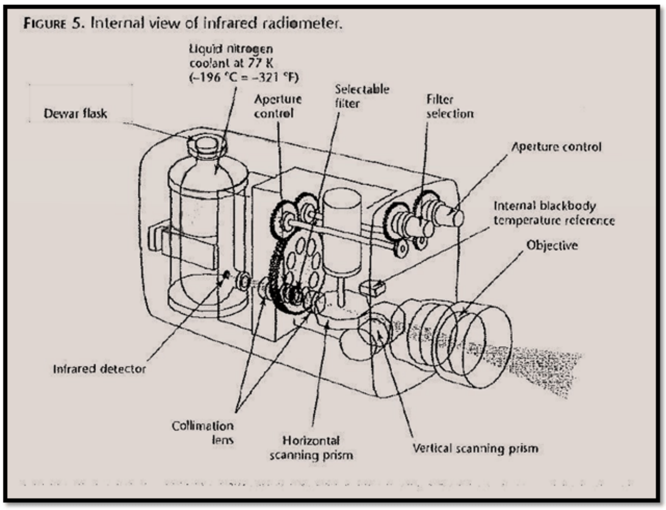


FIGURE 5. Internal view of infrared radiometer.

Internal view of Infrared Radiometer

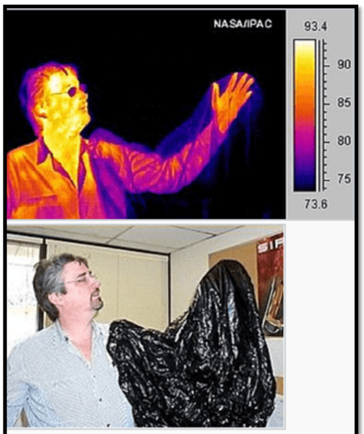
Fluke Tir3/ft-20 IR Flexcam Thermal Imager With Fusion

THERMOGRAM

a visual image that maps the apparent temperature pattern of an object or scene into a corresponding contrast or color pattern. It is a recording of the thermal image. The thermogram can be made in the form of a photograph from a camera, recorded on a videotape, or a file on any digital storage medium. The colors visible in the thermogram image are conventionally assigned to the individual temperature values. The thermogram image may also contain isotherms. The thermogram may also take the form of a curve versus time printed on paper by the thermograph.

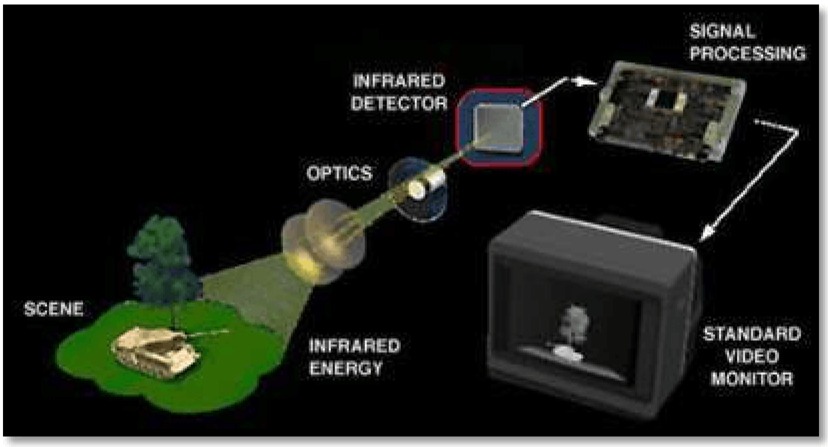
In any thermogram, the brighter colors (red, orange, and yellow) indicate warmer temperatures (more heat and infrared radiation emitted) while the purples and dark blue/black indicate cooler temperatures (less heat and infrared radiation emitted). In this image, the bright yellow area indicates warn regions.

Thermal image of steam locomotive made by IR camera



A comparison of a thermal image (top) and an ordinary photograph (bottom). The plastic bag is mostly transparent to long-wavelength infrared, but the man's glasses are opaque.

HOW THERMAL IMAGING WORKS?



working of a thermal imaging system

- A special lens focuses the infrared light emitted by all of the objects in view. The focused light is scanned by a phased array of infrared-detector elements.
- The detector elements create a very detailed temperature pattern called a thermogram.
- The thermogram created by the detector elements is translated into electric impulses.
- The impulses are sent to a signal-processing unit, a circuit board with a dedicated chip that translates the information from the elements into data for the display.

- The signal-processing unit sends the information to the display, where it appears in various colors depending on the intensity of the infrared emission. The combination of all the impulses from all of the elements creates the image.

Test specifications for IR and thermal testing

A thermographic specification must anticipate a number of issues that arise during testing.

Test condition requirements –

1. The heat stimulation requirements (energy and duration) to detect the target discontinuities must be determined.
2. The required heating rate depends on the thermal and surface process and efficiency and on equipment characteristics such as speed and sensitivity.
3. The inspector needs to know whether a stripplable paint or coating is needed because of the low emissivity of the test surface. Whether the customer will allow a coating?
4. The profile of time versus temperature required to reveal the target discontinuities must be determined. **Emissivity** is defined as the ratio of the energy radiated from a material's surface to that radiated from a perfect emitter, known as a **blackbody**, at the same temperature and wavelength and under the same viewing conditions. It is a dimensionless number between **0 (for a perfect reflector)** and **1 (for a perfect emitter)**.

Selection on Heat source

- Issues include portability, accessibility, cost, availability, power requirements, safety, and heating requirements.
- If the optimum heat source is neither particle nor available, determine an alternative.
- Does the application require testing from one side or from two sides?

Selection of Detector:

Technical specifications for the detector include noise equivalent temperature differential, scan rate, field of view, and standoff, specifications must be made for the imaging system if used and for detection algorithms if the detection process is automated.

Mechanical Considerations:

- The best positions for recording devices, monitors, electrical connections, and personnel need to be determined.
- Fixturing may be needed to support the heat source, camera, or other equipment.
- Camera positioning may be determined by distance, fixturing, lens choice, and spatial or thermal resolution required to detect the target discontinuities.

INTERPRETATION:

Interpretation can be complex because of the presence of unknown materials (inserts, repairs) or time-dependent contrast reversal because of thermal capacitance (mass) or other thermal property interactions. Discontinuities may be detected primarily through pattern recognition or image interpretation by an experienced operator. Beware of the possibility of false or missed discontinuity findings caused by reflections and emissivity variations (spatial or because of viewing angle) ; by surface curvature, viewing angle, or field of view; or by environmental interference with the heat pulse from wind, sunlight, moisture or personnel.

STANDARDS AND SPECIFICATIONS FOR INFRARED AND THERMAL TESTING:

Standards and specifications exist in three basic areas :

- **Equipment**: standards for equipment and materials include electronic and optical equipment. standardized reference objects such as blackbodies would also fit in this category.
- **Processes and personnel**: the American society for testing and materials and other organizations publish standards for test techniques. Other standards are for quality assurance procedures and are not specific to a test method or even to inspection in general.
- **Personnel**: the American society for nondestructive testing(**ASNT**) has been a world leader in the qualification and certification of nondestructive testing personnel for many years.

APPLICATIONS

Infrared thermography, a nondestructive, remote sensing technique, has proved to be an effective, convenient, and economical method of testing concrete.
A typical application for regularly available IR Thermographic equipment is looking for “hot spots” in electrical equipment, which illustrates high resistance areas in electrical circuits.
It can detect internal voids, delaminations, and cracks in concrete structures such as bridge decks, highway pavements, garage floors, parking lot pavements, and building walls, locating loose electrical connections, failing transformers, improper bushing and bearing lubrication, overloaded motors or pumps, coupling misalignment, and other applications where a change in temperature will indicate an undesirable condition.

As a testing technique, some of its most important qualities are that

- it is accurate;
- it is repeatable;
- it need not inconvenience the public; and
- it is economical.”

References

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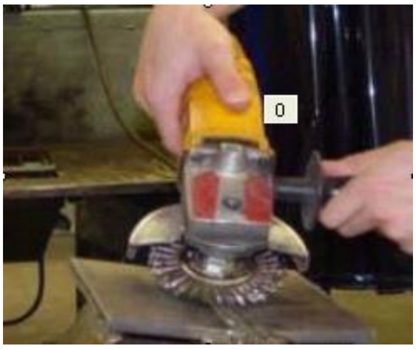
- ГОСТ Р 53698 Контроль неразрушающий. Методы тепловые. Термины и определения
- ASME BPVC Sec-V ARTICLE 30, SE-1316
- NDT Hand Book Infrared and Thermal Testing.

COMMON APPLICATION OF NDT

- Inspection of Raw Products
    - Forgings,
    - Castings,
    - Extrusions,
    - etc.
    -

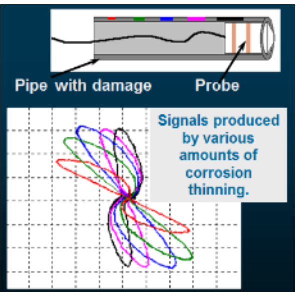
- Inspection Following Secondary Processing
    - Machining
    - Welding
    - Grinding
    - Heat treating
    - Plating
    - etc.



- In-Services Damage Inspection
    - Cracking
    - Corrosion
    - Erosion/Wear
    - Heat Damage
    - etc.

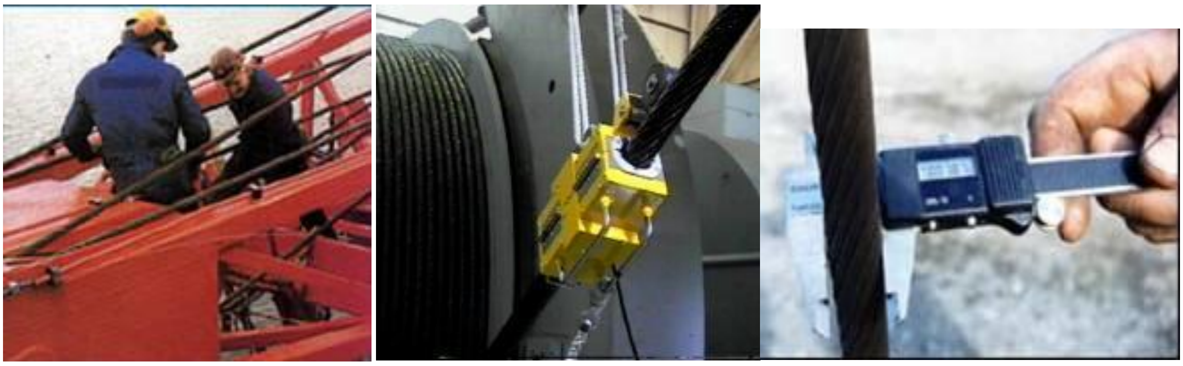
Power Plant Inspection

Periodically, power plants are shutdown for inspection. Inspectors feed eddy current probes into heat exchanger tubes to check for corrosion damage.



Wire Rope Inspection

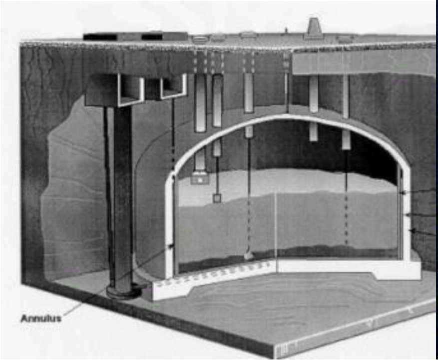
Electromagnetic devices and visual inspections are used to find broken wires and other damage to the wire rope that is used in chairlifts, cranes and other lifting devices.



Storage Tank Inspection

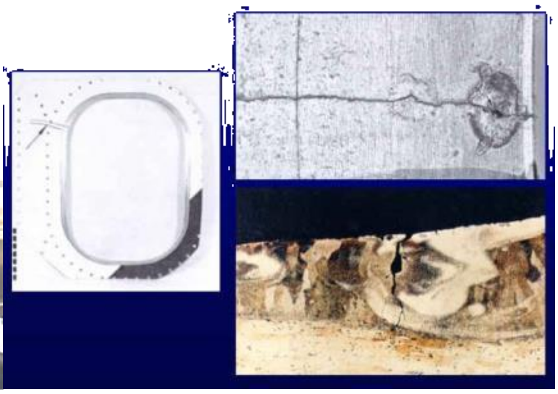
Robotic crawlers use ultrasound to inspect the walls of large above ground tanks for signs of thinning due to corrosion.

Cameras on long articulating arms are used to inspect underground storage tanks for damage.



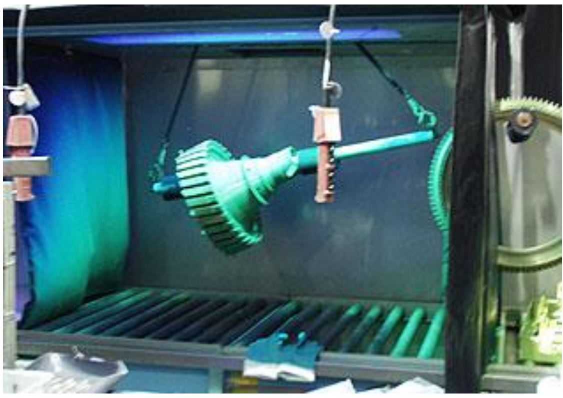
Aircraft Inspection

- **Nondestructive testing is used extensively during the manufacturing of aircraft.**
- **NDT is also used to find cracks and corrosion damage during operation of the aircraft.**
- **A fatigue crack that started at the site of a lightning strike is shown below.**



Jet Engine Inspection

- **Aircraft engines are overhauled after being in service for a period of time.**
- **They are completely disassembled, cleaned, inspected and then reassembled.**
- **Fluorescent penetrant inspection is used to check many of the parts for cracking.**



Pressure Vessel Inspection

The failure of a pressure vessel can result in the rapid release of a large amount of energy. To protect against this dangerous event, the tanks are inspected using radiography and ultrasonic testing.

Rail Inspection

Special cars are used to inspect thousands of miles of rail to find cracks that could lead to a derailment.

Bridge Inspection

- **Corrosion, cracking and other damage can all affect a bridge's performance.**
- **Bridges get a visual inspection about every 2 years.**
- **Some bridges are fitted with acoustic emission sensors that "listen" for sounds of cracks growing.**

Pipeline Inspection

NDT is used to inspect pipelines to prevent leaks that could damage the environment. Visual inspection, radiography and electromagnetic testing are some of the NDT methods used.

Remote visual inspection using a robotic crawler.

Magnetic flux leakage inspection. This device, known as a pig, is placed in the pipeline and collects data on the condition of the pipe as it is pushed along by whatever is being transported.

Radiography of weld joints.