Nondestructive Testing in Science and Industry

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Chapter-1

Nondestructive Testing

Nondestructive testing or **Non-destructive testing** (**NDT**) is a wide group of analysis techniques used in science and 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. Because NDT does not permanently alter the article being inspected, it is a highly-valuable technique that can save both money and time in product evaluation, troubleshooting, and research. Common NDT methods include ultrasonic, magnetic-particle, liquid penetrant, radiographic, remote visual inspection (RVI), eddy-current testing, and low coherence interferometry . NDT is a commonly-used tool in forensic engineering, mechanical engineering, electrical engineering, civil engineering, systems engineering, aeronautical engineering, medicine, and art.

Methods

NDT methods may rely upon use of electromagnetic radiation, sound, and inherent properties of materials to examine samples. This includes some kinds of microscopy to examine external surfaces in detail, although sample preparation techniques for metallography, optical microscopy and electron microscopy are generally destructive as the surfaces must be made smooth through polishing or the sample must be electron transparent in thickness. The inside of a sample can be examined with penetrating electromagnetic radiation, such as X-rays or 3D X-rays for volumetric inspection. Sound waves are utilized in the case of ultrasonic testing. Contrast between a defect and the bulk of the sample may be enhanced for visual examination by the unaided eye by using liquids to penetrate fatigue cracks. One method (liquid penetrant testing) involves using dyes, fluorescent or non-fluorescing, in fluids for non-magnetic materials, usually metals. Another commonly used method for magnetic materials involves using a liquid suspension of fine iron particles applied to a part while it is in an externally applied magnetic field (magnetic-particle testing). Thermoelectric effect (or use of the Seebeck effect) uses thermal properties of an alloy to quickly and easily characterize many alloys.

The chemical test, or chemical spot test method, utilizes application of sensitive chemicals that can indicate the presence of individual alloying elements.

Applications

Weld verification
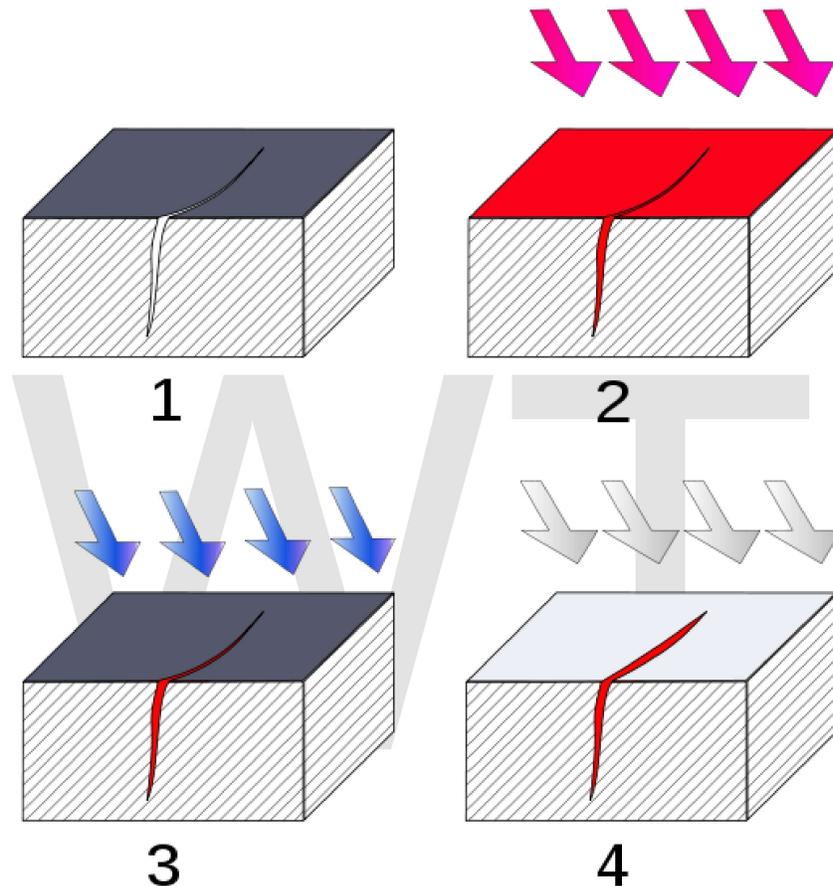
1. Section of material with a surface-breaking crack that is not visible to the naked eye.
2. Penetrant is applied to the surface.
3. Excess penetrant is removed.
4. Developer is applied, rendering the crack visible.

In manufacturing, welds are commonly used to join two or more metal surfaces. Because these connections may encounter loads and fatigue during product lifetime, there is a chance that they may fail if not created to proper specification. For example, the base metal must reach a certain temperature during the welding process, must cool at a specific rate, and must be welded with compatible materials or the joint may not be strong enough to hold the surfaces together, or cracks may form in the weld causing it to fail. The typical welding defects, lack of fusion of the weld to the base metal, cracks or

porosity inside the weld, and variations in weld density, could cause a structure to break or a pipeline to rupture.

Welds may be tested using NDT techniques such as industrial radiography using X-rays or gamma rays, ultrasonic testing, liquid penetrant testing or via eddy current. In a proper weld, these tests would indicate a lack of cracks in the radiograph, show clear passage of sound through the weld and back, or indicate a clear surface without penetrant captured in cracks.

Welding techniques may also be actively monitored with acoustic emission techniques before production to design the best set of parameters to use to properly join two materials.

Structural mechanics

Structures can be complex systems that undergo different loads during their lifetime. Some complex structures, such as the turbomachinery in a liquid-fuel rocket, can also cost millions of dollars. Engineers will commonly model these structures as coupled second-order systems, approximating dynamic structure components with springs, masses, and dampers. These sets of differential equations can be used to derive a transfer function that models the behavior of the system.

In NDT, the structure undergoes a dynamic input, such as the tap of a hammer or a controlled impulse. Key properties, such as displacement or acceleration at different points of the structure, are measured as the corresponding output. This output is recorded and compared to the corresponding output given by the transfer function and the known input. Differences may indicate an inappropriate model (which may alert engineers to unpredicted instabilities or performance outside of tolerances), failed components, or an inadequate control system.

Radiography in medicine
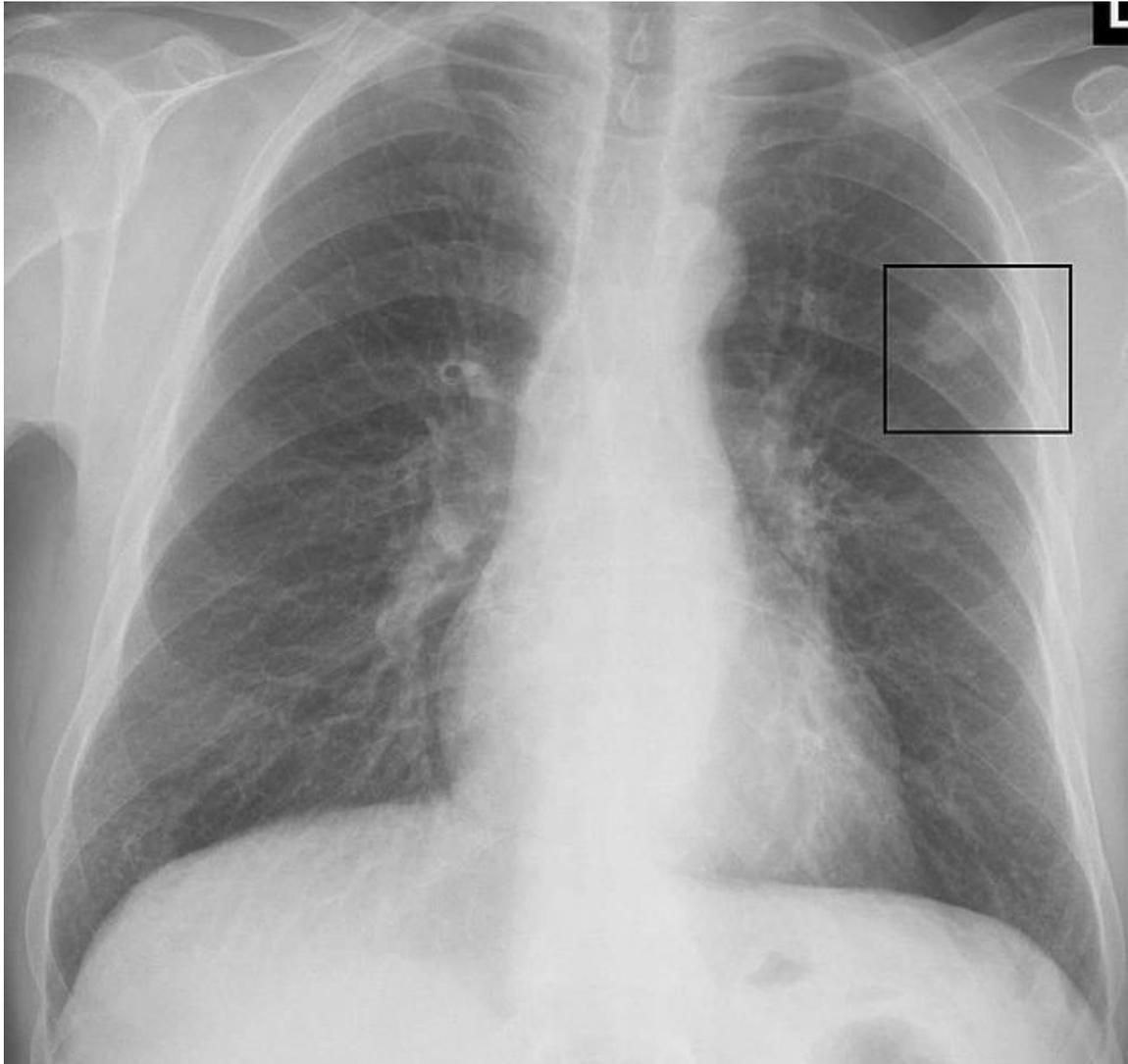
Chest radiography indicating a peripheres bronchialcarcinom.

As a system, the human body is difficult to model as a complete transfer function. Elements of the body, however, such as bones or molecules, have a known response to certain radiographic inputs, such as x-rays or magnetic resonance. Coupled with the controlled introduction of a known element, such as digested barium, radiography can be used to image parts or functions of the body by measuring and interpreting the response to the radiographic input. In this manner, many bone fractures and diseases may be detected and localized in preparation for treatment. X-rays may also be used to examine the interior of mechanical systems in manufacturing using NDT techniques, as well.

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

Applications

NDT is used in a variety of settings that covers a wide range of industrial activity.

- Automotive
  - Engine parts
  - Frame
- Aviation / Aerospace
  - Airframes
    - Spaceframes
  - Powerplants
    - Propellers

- - - Reciprocating Engines
    - Gas turbine engines
  - Rocketry
- Construction
  - Structures
  - Bridges
  - Cover Meter
- Maintenance, repair and operations
  - Bridges
- Manufacturing
  - Machine parts
  - Castings and Forgings
- Industrial plants such as Nuclear, Petrochemical, Power, Refineries, Pulp and Paper, Fabrication shops, Mine processing and their Risk Based Inspection programmes.
  - Pressure vessels
  - Storage tanks
  - Welds
  - Boilers
  - Heat exchangers
  - Turbine bores
  - In-plant Piping
- Miscellaneous
  - Pipelines
    - In-line Inspection using "pigs"
    - Pipeline integrity management
    - Leak Detection
  - Railways
    - Rail Inspection
    - Wheel Inspection
  - Tubular NDT, for Tubing material
  - Corrosion Under Insulation (CUI)
  - Amusement park rides
  - Submarines and other Naval warships
  - Medical imaging applications

Methods and techniques
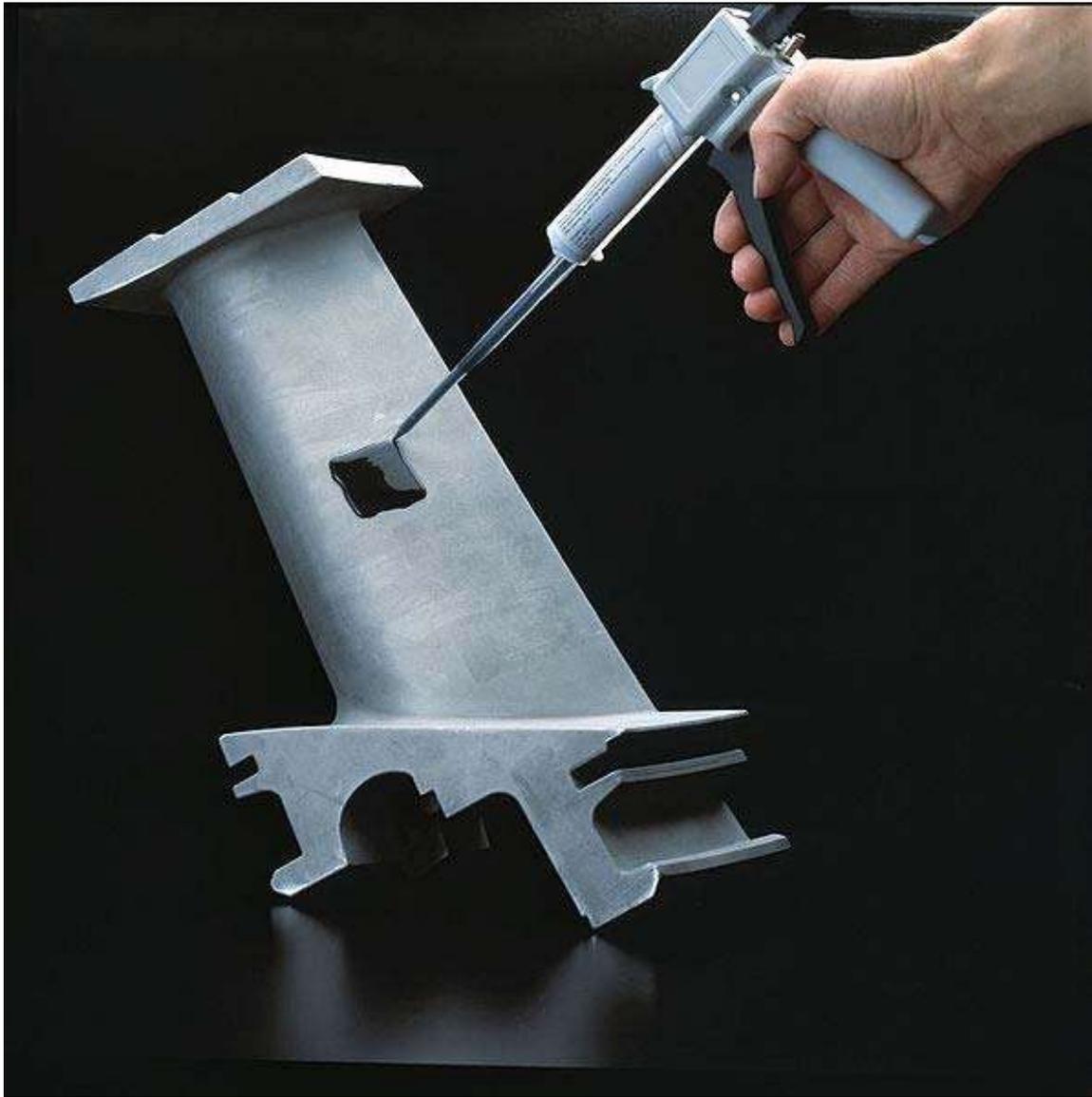
An example of a 3D replicating technique. The flexible high-resolution replicas allow surfaces to be examined and measured under laboratory conditions. A replica can be taken from all solid materials.

NDT is divided into various *methods* of nondestructive testing, each based on a particular scientific principle. These methods may be further subdivided into various *techniques*. The various methods and techniques, due to their particular natures, may lend themselves especially well to certain applications and be of little or no value at all in other applications. Therefore choosing the right method and technique is an important part of the performance of NDT.

- Acoustic emission testing (AE or AT)

- Blue Etch Anodize (BEA)
- Dye penetrant inspection Liquid penetrant testing (PT or LPI)
- Electromagnetic testing (ET)
    - Alternating current field measurement (ACFM)
    - Alternating current potential drop measurement (ACPD)
    - Barkhausen testing
    - Direct current potential drop measurement (DCPD)
    - Eddy-current testing (ECT)
    - Magnetic flux leakage testing (MFL) for pipelines, tank floors, and wire rope
    - Magnetic-particle inspection (MT or MPI)
    - Remote field testing (RFT)
- Ellipsometry
- Guided wave testing (GWT)
- Hardness testing
- Impulse excitation technique (IET)
- Infrared and thermal testing (IR)
    - Thermographic inspection
- Laser testing
    - Electronic speckle pattern interferometry
    - Holographic interferometry
    - Low coherence interferometry
    - Profilometry
    - Shearography
- Leak testing (LT) or Leak detection
    - Absolute pressure leak testing (pressure change)
    - Bubble testing
    - Halogen diode leak testing
    - Hydrogen leak testing
    - Mass spectrometer leak testing
    - Tracer-gas leak testing method Helium, Hydrogen and refrigerant gases
- Magnetic resonance imaging (MRI) and NMR spectroscopy
- Optical microscopy
- Positive Material Identification (PMI)
- Radiographic testing (RT)
    - Computed radiography
    - Digital radiography (real-time)
    - Neutron radiographic testing (NR)
    - SCAR (Small Controlled Area Radiography)
    - X-ray computed tomography (CT)
- Scanning electron microscopy
- Surface Temper Etch (Nital Etch)
- Ultrasonic testing (UT)
    - ART (Acoustic Resonance Technology)
    - Electro Magnetic Acoustic Transducer (EMAT) (non-contact)
    - Laser ultrasonics (LUT)

- o Internal rotary inspection system (IRIS) ultrasonics for tubes
- o Phased array ultrasonics
- o Time of flight diffraction ultrasonics (TOFD)
- o Time of Flight Ultrasonic Determination of 3D Elastic Constants (TOF)
- Visual inspection (VT)
    - o Pipeline video inspection
- Corroscan/C-scan
- IRIS - Internal Rotary Inspection System
- 3D Tomography
- Heat Exchanger Life Assessment System
- RTJ Flange Special Ultrasonic Testing

Personnel training, qualification and certification

Succeful and consistent application of nondestructive testing techniques depends heavily on personnel training and experience. Personnel involved in application of industrial NDT methods and interpretation of results should be certified, and in some idustrial sectors certification is enforced by law or by the applied codes and standards.

Definitions

The following definitions for *qualification* and *certification* are given in ISO 9712 and EN 473:

- **Certification:** "Procedure, used by the certification body to confirm that the qualification requirements for a method, level and sector have been fulfilled, leading to the issuing of a certificate".

- **Qualification:** "Demonstration of physical attributes, knowledge, skill, training and experience required to properly perform NDT tasks".

In US standards and codes, while a very similar definition of qualification is included in ASNT SNT-TC-1A, certification is simply defined as: "Written testimony of qualification".

Training

Non-Destructive Testing (NDT) training is provided for people working in many industries. It is generally necessary that the student successfully completes a theoretical training program (usually 40 hours of classroom training), as well as have performed several hundred hours of practical application of the particular method they wish to be trained in. At this point, they may pass a certification exam. Further, NDT Training has recently become available online. WorldSpec.org is one of the innovative companies that helped pioneer this new "era" in NDT Training.

Certification schemes

There are two approaches in personnel certification:

1. **Employer Based Certification**: Under this system the employer compiles their own *Written Practice*. The written practice defines the responsibilities of each level of certification, as implemented by the company, and describes the training, experience and examination requirements for each level of certification. In industrial sectors the written practices are usually based on recommended practice SNT-TC-1A of the American Society for Nondestructive Testing. ANSI standard CP-189 outlines requirements for any written practice that conforms to the standard.
2. **Personal Central Certification**: The concept of central certification is that an NDT operator can obtain certification from a central certification authority, that is recognised by most employers, third parties and/or government authorities. Industrial standards for central certification schemes are ISO 9712 and EN 473. Certification under these standards involves training, work experience under supervision and passing a written and practical examination set up by the independent certification authority.

In the United States employer based schemes are the norm, however central certification schemes exist as well. The most notable is *ASNT Level III* (established in 1976-1977), which is organized by the American Society for Nondestructive Testing for Level 3 NDT personnel.

NAVSEA 250-1500 is another US central certification scheme, specifically developed for use in the naval nuclear program.

Central certification is more widely used in the European Union, where certifications are issued by accredited bodies (independent organizations conforming to ISO 17024 and accredited by a national accreditation authority like UKAS). The Pressure Equipment Directive (97/23/EEC) actually enforces personnel certification to EN 473 for the initial testing of steam boilers and some categories of pressure vessels and piping. Certifications issued by a national NDT society which is a member of the European Federation of NDT (EFNDT) are mutually acceptable by the other member societies under a multilateral recognition agreement.

Canada also implements an ISO 9712 central certification scheme, which is administered by Natural Resources Canada, a government department.

The aerospace sector worldwide sticks to employer based schemes. In America it is based mostly on AIA-NAS-410 and in the European Union on the equivalent and very similar standard EN 4179

Levels of certification

Most NDT personnel certification schemes listed above specify three "levels" of qualification and/or certification, usually designated as *Level 1*, *Level 2* and *Level 3* (although some codes specify roman numerals, like *Level II*). The roles and responsibilities of personnel in each level are generally as follows (there are slight differences or variations between different codes and standards):

- **Level 1** are technicians qualified to perform only specific calibrations and tests under close supervision and direction by higher level personnel. They can only report test results. Normally they work following specific work instructions for testing procedures and rejection criteria.

- **Level 2** are engineers or experienced technicians who are able to set up and calibrate testing equipment, conduct the inspection according to codes and standards (instead of following work instructions) and compile work instructions for Level 1 technicians. They are also authorized to report, interpret, evaluate and document testing results. They can also supervise and train Level 1 technicians. In addition to testing methods, they must be familiar with applicable codes and standards and have some knowledge of the manufacture and service of tested products.

- **Level 3** are usually specialized engineers or very experienced technicians. They can establish NDT techniques and procedures and interpret codes and standards. They also direct NDT laboratories and have central role in personnel certification. They are expected to have wider knowledge covering materials, fabrication and product technology.

Terminology

Indication
> The response or evidence from an examination, such as a blip on the screen of an instrument. Indications are classified as *true* or *false*. *False indications* are those caused by factors not related to the principles of the testing method or by improper implementation of the method, like film damage in radiography, electrical interference in ultrasonic testing etc. *True indications* are further classified as *relevant* and *non relevant*. *Relevant indications* are those caused by flaws. *Non relevant indications* are those caused by known features of the tested object, like gaps, threads, case hardening etc.

Interpretation
> Determining if an indication is of a type to be investigated. For example, in electromagnetic testing, indications from metal loss are considered flaws because they should usually be investigated, but indications due to variations in the material properties may be harmless and nonrelevant.

Flaw
> A type of discontinuity that must be investigated to see if it is rejectable. For example, porosity in a weld or metal loss.

Evaluation
>   Determining if a flaw is rejectable. For example, is porosity in a weld larger than acceptable by code?

Defect
>   A flaw that is rejectable — i.e. does not meet acceptance criteria. Defects are generally removed or repaired.

Penetrant testing
>   Non-destructive test typically comprising a penetrant, a method of excess removal and a developer to produce a visible indication of surface-breaking discontinuities.

Reliability and statistics

Defect detection tests are among the more commonly employed of non-destructive tests. The evaluation of NDT reliability commonly contains two statistical errors. First, most tests fail to define the objects that are called "sampling units" in statistics; it follows that the reliability of the tests cannot be established. Second, the literature usually misuses statistical terms in such a way as to make it sound as though sampling units *are* defined. These two errors may lead to incorrect estimates of probability of detection.

Chapter-2

Industrial Radiography

Industrial Radiography is the use of ionizing radiations to view objects in a way that cannot be seen otherwise. It is not to be confused with the use of ionizing radiation to change or modify objects; radiography's purpose is strictly for viewing. Industrial radiography has grown out of engineering, and is a major element of nondestructive testing (NDT). It is a method of inspecting materials for hidden flaws by using the ability of short X-rays and Gamma rays to penetrate various materials.

History

Radiography started in 1895 with the discovery of X-rays (later also called Röntgen rays after the man who first described their properties in detail), a type of electromagnetic radiation. Soon after the discovery of X-rays, radioactivity was discovered. By using radioactive sources such as radium, far higher photon energies could be obtained than those from *normal* X-ray machines. Soon these found various applications, with one of the earliest users being Loughborough University, from helping to fit shoes, more lasting medical uses and the examination of non-living objects. X-rays and gamma-rays were put to use very early, before the dangers of ionising radiation were discovered. After World War II new isotopes such as caesium-137, iridium-192 and cobalt-60 became available for industrial radiography, and the use of radium and radon decreased.

Applications

Inspection of products

GemX-160 - Portable Wireless Controlled Battery Powered X-ray Generator for use in Non Destructive Testing and Security.

Gamma radiation sources, most commonly Iridium-192 and Cobalt-60, are used to inspect a variety of materials. The vast majority of radiography concerns the testing and grading of welds on pressurized piping, pressure vessels, high-capacity storage containers, pipelines, and some structural welds. Other tested materials include concrete (locating rebar or conduit), welder's test coupons, machined parts, plate metal, or pipewall (locating anomalies due to corrosion or mechanical damage). Non-metal components such as ceramics used in the aerospace industries are also regularly tested. Theoretically, industrial radiographers could radiograph any solid, flat material (walls, ceilings, floors, square or rectangular containers) or any hollow cylindrical or spherical object.

For purposes of inspection, including weld inspection, there exist several exposure arrangements.

First, there is the panoramic, one of the four single wall exposure/single wall view (SWE/SWV) arrangements. This exposure is created when the radiographer places the

source of radiation at the center of a sphere, cone, or cylinder (including tanks, vessels, and piping). Depending upon client requirements, the radiographer would then place film cassettes on the outside of the surface to be examined. This exposure arrangement is ideal - when properly arranged and exposed, all portions of all exposed film will be of the same approximate density. It also has the advantage of taking less time than other arrangements since the source must only penetrate the total wall thickness (WT) once and must only travel the radius of the inspection item, not its full diameter. The major disadvantage of the panoramic is that it may be impractical to reach the center of the item (enclosed pipe) or the source may be too weak to perform in this arrangement (large vessels or tanks).

The second SWE/SWV arrangement is an interior placement of the source in an enclosed inspection item without having the source centered up. The source does not come in direct contact with the item, but is placed a distance away, depending on client requirements. The third is an exterior placement with similar characteristics. The fourth is reserved for flat objects, such as plate metal, and is also radiographed without the source coming in direct contact with the item. In each case, the radiographic film is located on the opposite side of the inspection item from the source. In all four cases, only one wall is exposed, and only one wall is viewed on the radiograph.

Of the other exposure arrangements, only the contact shot has the source located on the inspection item. This type of radiograph exposes both walls, but only resolves the image on the wall nearest the film. This exposure arrangement takes more time than a panoramic, as the source must penetrate the WT twice and travel the entire outside diameter of the pipe or vessel to reach the film on the opposite side. This is a double wall exposure/single wall view DWE/SWV arrangement. Another is the superimposure (wherein the source is placed on one side of the item, not in direct contact with it, with the film on the opposite side). This arrangement is usually reserved for very small diameter piping or parts. The last DWE/SWV exposure arrangement is the elliptical, in which the source is offset from the plane of the inspection item (usually a weld in pipe) and the elliptical image of the weld furthest from the source is cast onto the film.

The beam of radiation must be directed to the middle of the section under examination and must be normal to the material surface at that point, except in special techniques where known defects are best revealed by a different alignment of the beam. The length of weld under examination for each exposure shall be such that the thickness of the material at the diagnostic extremities, measured in the direction of the incident beam, does not exceed the actual thickness at that point by more than 6%. The specimen to be inspected is placed between the source of radiation and the detecting device, usually the film in a light tight holder or cassette, and the radiation is allowed to penetrate the part for the required length of time to be adequately recorded. Lead is often placed behind the film to reduce the 'back scattered' radiation which can lead to the film becoming over exposed.

The result is a two-dimensional projection of the part onto the film, producing a latent image of varying densities according to the amount of radiation reaching each area. It is

known as a radiograph, as distinct from a photograph produced by light. Because film is cumulative in its response (the exposure increasing as it absorbs more radiation), relatively weak radiation can be detected by prolonging the exposure until the film can record an image that will be visible after development. The radiograph is examined as a negative, without printing as a positive as in photography. This is because, in printing, some of the detail is always lost and no useful purpose is served.

Before commencing a radiographic examination, it is always advisable to examine the component with one's own eyes, to eliminate any possible external defects. If the surface of a weld is too irregular, it may be desirable to grind it to obtain a smooth finish, but this is likely to be limited to those cases in which the surface irregularities (which will be visible on the radiograph) may make detecting internal defects difficult.

After this visual examination, the operator will have a clear idea of the possibilities of access to the two faces of the weld, which is important both for the setting up of the equipment and for the choice of the most appropriate technique.

Airport security

Both hold luggage and carry-on hand luggage are normally examined by X-ray machines using X-ray radiography.

Non-intrusive Cargo Scanning (aka Non-Intrusive Inspection - NII)
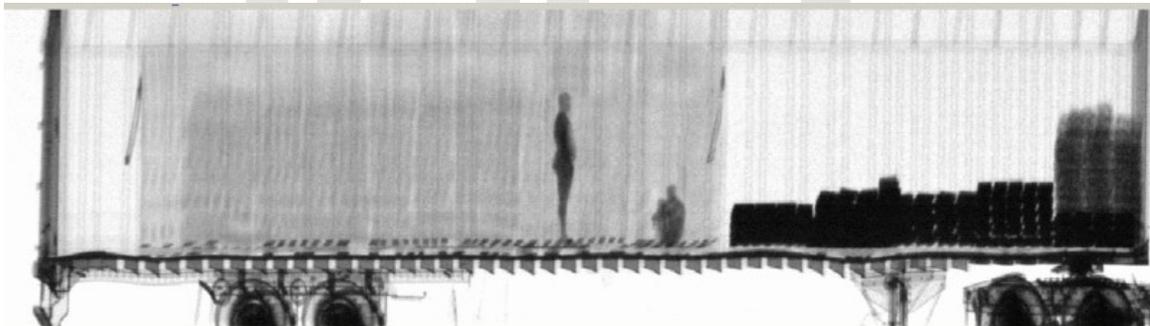
Gamma-ray Image of intermodal cargo container with stowaways

Gamma Radiography and High-Energy X-ray radiography are currently used to scan intermodal freight cargo containers in US and other countries. Also research is being done on adapting other types of radiography like Dual-Energy X-ray Radiography or Muon Radiography for scanning intermodal cargo containers.

Sources

X-ray sources

A high energy X-ray machine can be used. It is often important to use a high accelerating voltage to provide the electrons with a very high energy. This is because in a braking radiation source the maximum photon energy is determined by the energy of the charged particles. A recent development is the betatron, which is a device similar to a cyclotron that acts as a very intense photon source.

Radioisotope sources

These have the advantage that they do not need a supply of electrical power to function, but they do have the disadvantage that they can not be turned off. Also it is difficult using radioactivity to create a small and compact source that offers the photon flux possible with a normal sealed X-ray tube.

It might be possible to use Cs-137 as a photon source for radiography but this isotope is always diluted with inactive caesium isotopes. This makes it difficult to get a physically small source, and a large volume of the source makes it impossible to capture fine details in a radiographic examination.

Both cobalt-60 and caesium-137 have only a few gamma energies, which makes them close to monochromatic. The photon energy of cobalt-60 is higher than that of caesium-137, which allows cobalt sources to be used to examine thicker sections of metals than those that could be examined with Cs-137. Iridium-192 has a lower photon energy than cobalt-60 and its gamma spectrum is complex (many lines of very different energies), but this can be an advantage as this can give better contrast for the final photographs.

It has been known for many years that an inactive iridium or cobalt metal object can be machined to size. In the case of cobalt it is common to alloy it with nickel to improve the mechanical properties. In the case of iridium a thin wire or rod could be used. These precursor materials can then be placed in stainless steel containers that have been leak tested before being converted into radioactive sources. These objects can be processed by neutron activation to form gamma emitting radioisotopes. The stainless steel has only a small ability to be activated and the small activity due to ^{55}Fe and ^{63}Ni are unlikely to pose a problem in the final application because these isotopes are beta emitters, which have very weak gamma emission. The ^{59}Fe which might form has a short half life, so by allowing a cobalt source to stand for a year much of this isotope will decay away.

The source is often a very small object, which must be transported to the work site in a shielded container. It is normal to place the film in industrial radiography, clear the area where the work is to be done, add shielding (collimators) to reduce the size of the controlled area before exposing the radioactive source. A series of different designs have been developed for radiographic "cameras". Rather than the "camera" being a device that

accepts photons to record a picture, the "camera" in industrial radiography is the radioactive photon source.

Torch design of radiographic cameras

One design is best thought of as being like a torch. The radioactive source is placed inside a shielded box, a hinge allows part of the shielding to be opened exposing the source, allowing photons to exit the radiography camera.
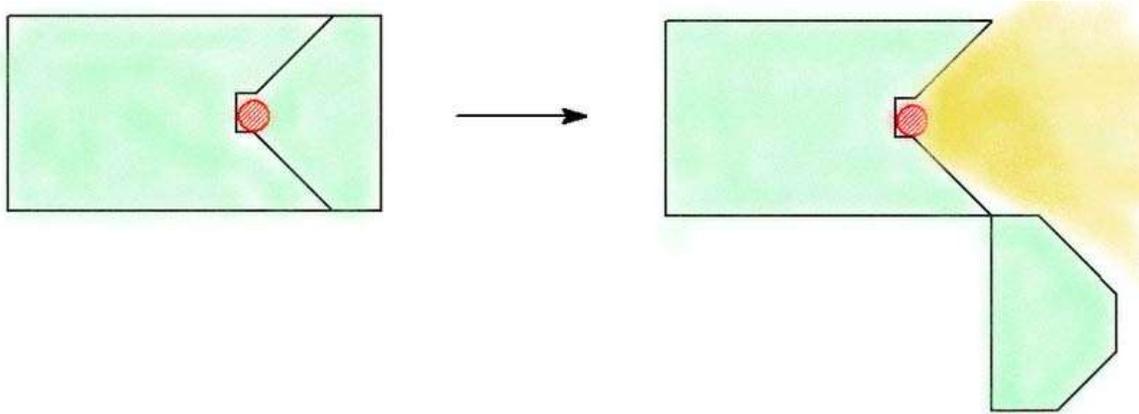
This torch-type camera uses a hinge. The radioactive source is in red, the shielding is blue/green, and the gamma rays are yellow.

Another design for a torch is where the source is placed in a metal wheel, which can turn inside the camera to move between the expose and storage positions.
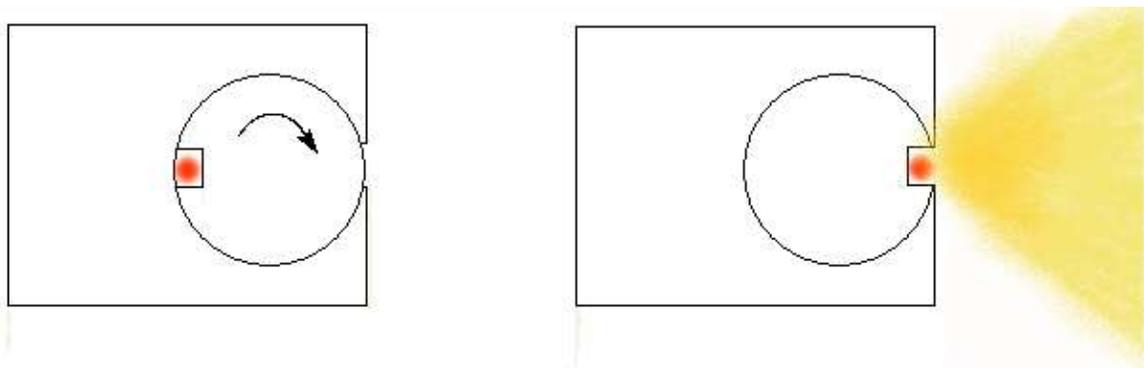
This torch-type camera uses a wheel design. The radioactive source is in red, and the gamma rays are yellow.

Cable based design of radiographic cameras

One group of designs use a radioactive source, which connects to a drive cable contained shielded exposure device. In one design of equipment the source is stored in a block of lead or depleted uranium shielding that has a S shaped tube-like hole through the block. In the safe position the source is in the centre of the block and is attached to a metal wire that extends in both directions, to use the source a guide tube is attached to one side of the device while a drive cable is attached to the other end of the short cable. Using a hand operated winch the source is then pushed out of the shield and along the source guide tube to the tip of the tube to expose the film, then cranked back into its fully-shielded position.
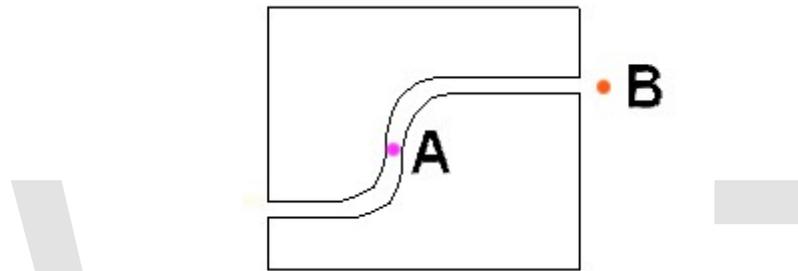
A diagram of the S shaped hole through a metal block; the source is stored at point A and is driven out on a cable through a hole to point B. It often goes a long way along a guide tube to where it is needed.

Contrast agents

Defects such as delaminations and planar cracks are difficult to detect using radiography, which is why penetrants are often used to enhance the contrast in the detection of such defects. Penetrants used include silver nitrate, zinc iodide, chloroform and diiodomethane. Choice of the penetrant is determined by the ease with which it can penetrate the cracks and also with which it can be removed. Diiodomethane has the advantages of high opacity, ease of penetration, and ease of removal because it evaporates relatively quickly. However, it can cause skin burns.

Neutrons

In some rare cases, radiography is done with neutrons. This type of radiography is called *neutron radiography* (NR, Nray, N-Ray) or *neutron imaging*. Neutron radiography can see very different things than X-rays, because neutrons can pass with ease through lead and steel but are stopped by plastics, water and oils. Neutron sources include radioactive (^{241}Am/Be and Cf) sources, electrically driven D-T reactions in vacuum tubes and conventional critical nuclear reactors. It might be possible to use a neutron amplifier to increase the neutron flux.

Since the amount of radiation emerging from the opposite side of the material can be detected and measured, variations in this amount (or intensity) of radiation are used to determine thickness or composition of material. Penetrating radiations are those restricted to that part of the electromagnetic spectrum of wavelength less than about 10 nanometres.

Safety

Industrial radiographers are in many locations required by governing authorities to use certain types of safety equipment and to work in pairs. Depending on location industrial radiographers may have been required to obtain permits, licences and/or undertake special training. Prior to conducting any testing the nearby area should always first be cleared of all other persons and measures taken to ensure that people do not accidentally enter into an area that may expose them to a large dose of radiation.

The safety equipment usually includes four basic items: a radiation survey meter (such as a Geiger/Mueller counter), an alarming dosimeter or rate meter, a gas-charged dosimeter, and a film badge or thermoluminescent dosimeter (TLD). The easiest way to remember what each of these items does is to compare them to gauges on an automobile.

The survey meter could be compared to the speedometer, as it measures the speed, or rate, at which radiation is being picked up. When properly calibrated, used, and maintained, it allows the radiographer to see the current exposure to radiation at the meter. It can usually be set for different intensities, and is used to prevent the radiographer from being overexposed to the radioactive source, as well as for verifying the boundary that radiographers are required to maintain around the exposed source during radiographic operations.

The alarming dosimeter could be most closely compared with the tachometer, as it alarms when the radiographer "redlines" or is exposed to too much radiation. When properly calibrated, activated, and worn on the radiographer's person, it will emit an alarm when the meter measures a radiation level in excess of a preset threshold. This device is intended to prevent the radiographer from inadvertently walking up on an exposed source.

The gas-charged dosimeter is like a trip meter in that it measures the total radiation received, but can be reset. It is designed to help the radiographer measure his/her total periodic dose of radiation. When properly calibrated, recharged, and worn on the radiographer's person, it can tell the radiographer at a glance how much radiation to which the device has been exposed since it was last recharged. Radiographers in many states are required to log their radiation exposures and generate an exposure report. In many countries personal dosimeters are not required to be used by radiographers as the dose rates they show are not always correctly recorded.

The film badge or TLD is more like a car's odometer. It is actually a specialized piece of radiographic film in a rugged container. It is meant to measure the radiographer's total exposure over time (usually a month) and is used by regulating authorities to monitor the

total exposure of certified radiographers in a certain jurisdiction. At the end of the month, the film badge is turned in and is processed. A report of the radiographer's total dose is generated and is kept on file.

When these safety devices are properly calibrated, maintained, and used, it is virtually impossible for a radiographer to be injured by a radioactive overexposure. Sadly, the elimination of just one of these devices can jeopardize the safety of the radiographer and all those who are nearby. Without the survey meter, the radiation received may be just below the threshold of the rate alarm, and it may be several hours before the radiographer checks the dosimeter, and up to a month or more before the film badge is developed to detect a low intensity overexposure. Without the rate alarm, one radiographer may inadvertently walk up on the source exposed by the other radiographer. Without the dosimeter, the radiographer may be unaware of an overexposure, or even a radiation burn, which may take weeks to result in noticeable injury. And without the film badge, the radiographer is deprived of an important tool designed to protect him or her from the effects of a long-term overexposure to occupationally-obtained radiation, and thus may suffer long-term health problems as a result.

There are three ways a radiographer will ensure they are not exposed to higher than required levels of radiation, time, distance, shielding. The less time that a person is exposed to radiation the lower their dose will be. The further a person is from a radioactive source the lower the level of radiation they receive, this is largely due to the inverse square law. Lastly the more a radioactive source is shielded by either better or greater amounts of shielding the lower the levels of radiation that will escape from the testing area. The most commanly used shielding materials in use are sand, lead (sheets or shot), steel, spent (non-radioactive uranium) tungsten and in suitable situations water.

Industrial radiography appears to have one of the worst safety profiles of the radiation professions, possibly because there are many operators using strong gamma sources (> 2 Ci) in remote sites with little supervision when compared with workers within the nuclear industry or within hospitals. Due to the levels of radiation present whilst they are working many radiographers are also required to work late at night when there are few other people present as most industrial radiography is carried out 'in the open' rather than in purpose built exposure booths or rooms. Fatigue, carelessness and lack of proper training are the three most comman factors attributed to industrial radiography accidents. Many of the "lost source" accidents commented on by the International Atomic Energy Agency involve radiography equipment. Lost source accidents have the potential to cause a considerable loss of human life. One scenario is that a passerby finds the radiography source and not knowing what it is, takes it home. The person shortly afterwards becomes ill and dies as a result of the radiation dose. The source remains in their home where it continues to irradiate other members of the household. Such an event occurred in March 1984 in Casablanca (Mohammedia), which is part of Morocco. This is related to the more famous Goiânia accident, where a related chain of events caused members of the public to be exposed to radiation sources.

Chapter-3

Ultrasonic Testing and Thermographic Inspection

Ultrasonic testing
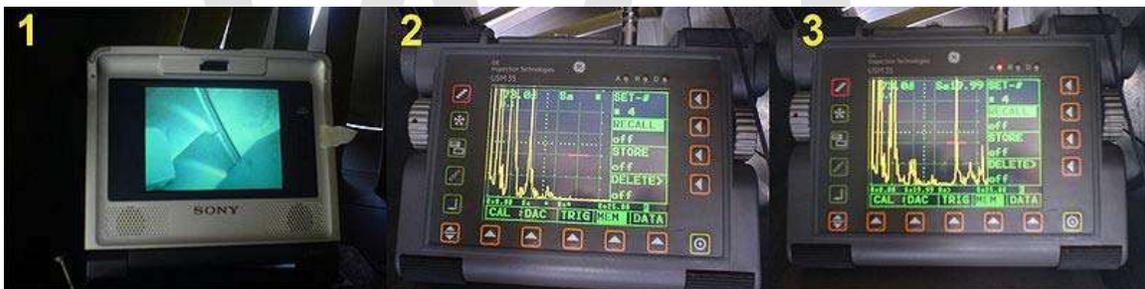
An example of Ultrasonic Testing (UT) on blade roots of a V2500 IAE aircraft engine.

Step 1: The UT probe is placed on the root of the blades to be inspected with the help of a special borescope tool.
Step 2: Instrument settings are input.
Step 3: The probe is scanned over the blade root. In this case, an indication (peak in the data) through the red line (or gate) indicates a good blade; an indication to the left of that range indicates a crack.

In **ultrasonic testing** (**UT**), very short ultrasonic pulse-waves with center frequencies ranging from 0.1-15 MHz and occasionally up to 50 MHz are launched into materials to detect internal flaws or to characterize materials. The technique is also commonly used to determine the thickness of the test object, for example, to monitor pipework corrosion.

Ultrasonic testing is often performed on steel and other metals and alloys, though it can also be used on concrete, wood and composites, albeit with less resolution. It is a form of

non-destructive testing used in many industries including aerospace, automotive and other transportation sectors.

How it works

In ultrasonic testing, an ultrasound transducer connected to a diagnostic machine is passed over the object being inspected. The transducer is typically separated from the test object by a couplant (such as oil) or by water, as in immersion testing.

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

At a construction site, a technician tests a pipeline weld for defects using an ultrasonic phased array instrument. The scanner, which consists of a frame with magnetic wheels, holds the probe in contact with the pipe by a spring. The wet area is the ultrasonic couplant that allows the sound to pass into the pipe wall.
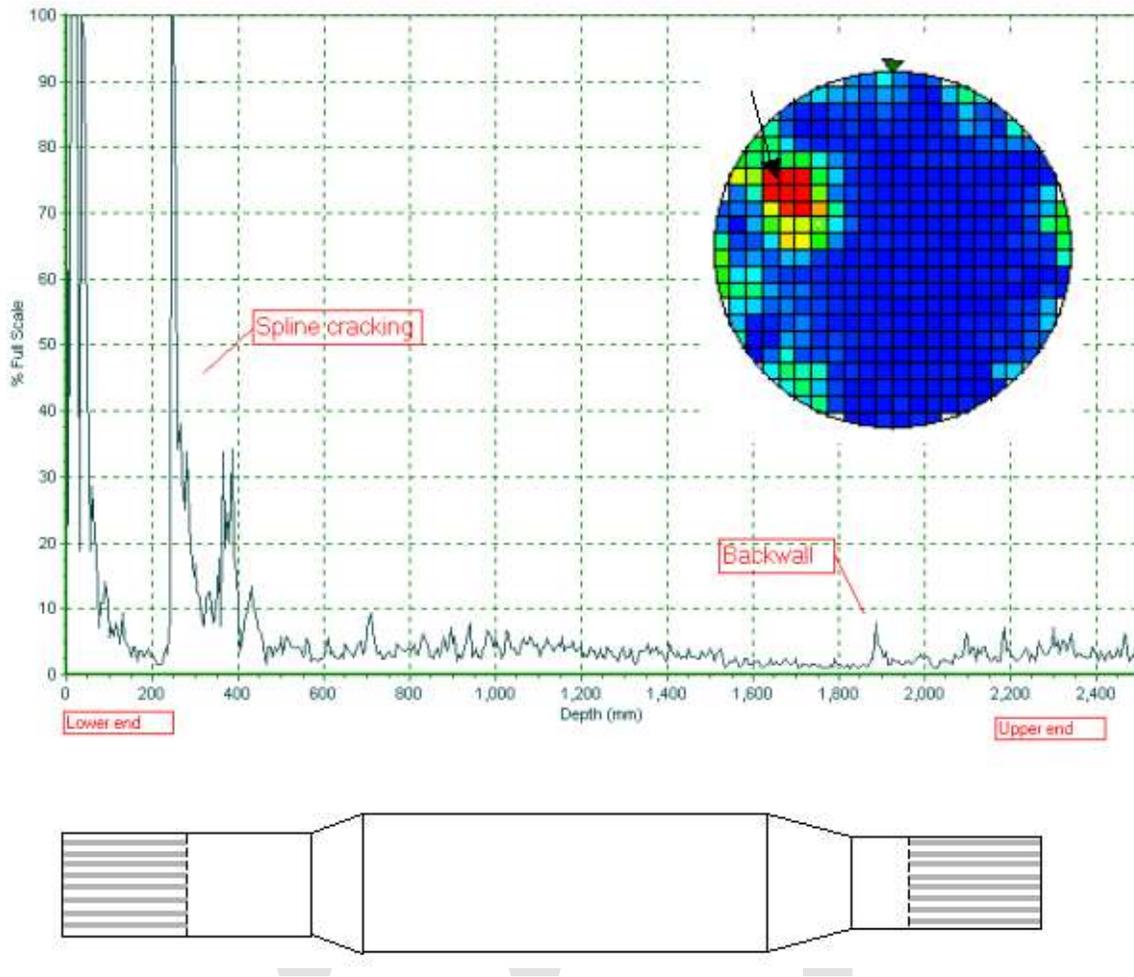
Non-destructive testing of a swing shaft showing spline cracking

Features

Advantages

1. High penetrating power, which allows the detection of flaws deep in the part.
2. High sensitivity, permitting the detection of extremely small flaws.
3. Only one surface need be accessible.
4. Greater accuracy than other nondestructive methods in determining the depth of internal flaws and the thickness of parts with parallel surfaces.
5. Some capability of estimating the size, orientation, shape and nature of defects.
6. Nonhazardous to operations or to nearby personnel and has no effect on equipment and materials in the vicinity.
7. Capable of portable or highly automated operation.

Disadvantages

1. Manual operation requires careful attention by experienced technicians
2. Extensive technical knowledge is required for the development of inspection procedures.
3. Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.
4. Surface must be prepared by cleaning and removing loose scale, paint, etc., although paint that is properly bonded to a surface need not be removed.
5. Couplants are needed to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected unless a non-contact technique is used. Non-contact techniques include Laser and Electro Magnetic Acoustic Transducers (EMAT).
6. Inspected items must be water resistant, when using water based couplants that do not contain rust inhibitors.

Thermographic inspection

Thermographic inspection refers to the nondestructive testing of parts, materials or systems through the imaging of the thermal patterns at the object's surface. Strictly speaking, the term **thermography** alone, refers to all thermographic inspection techniques regardless of the physical phenomena used to monitor the thermal changes. For instance, the application of a temperature sensitive coating to a surface in order to measure its temperature is a thermographic inspection contact technique based on heat conduction where there is no infrared sensor involved. **Infrared thermography** on the other hand, is a nondestructive, nonintrusive, noncontact mapping of thermal patterns or "thermograms", on the surface of objects through the use of some kind of infrared detector.

In addition, there are two approaches in thermographic inspection: (1) *passive*, in which the features of interest are naturally at a higher or lower temperature than the background, for example: the surveillance of people on a scene; and (2) active, in which an energy source is required to produce a thermal contrast between the feature of interest and the background, for example: an aircraft part with internal flaws.

When compared with other classical nondestructive testing techniques such as ultrasonic testing or radiographic testing, thermographic inspection is safe, nonintrusive and noncontact, allowing the detection of relatively shallow subsurface defects (a few millimeters in depth) under large surfaces (typically 30x30 cm2 at once, although inspection of larger surfaces is possible) and in a fast manner (from a fraction of a second to a few minutes depending in the configuration).

There are many other terms widely used all referring to infrared thermography, the adoption of one or other term depends on the author's background and preferences. For

instance, Video Thermography and Thermal Imaging draw attention to the fact that a sequence of images is acquired and is possible to see it as a movie. Pulse-Echo Thermography and Thermal Wave Imaging ,,, are adopted to emphasize the wave nature of heat. Pulsed Video Thermography ,, Transient Thermography ,,, and Flash Thermography , are used when the specimen is stimulated using a short energy pulse.

Techniques
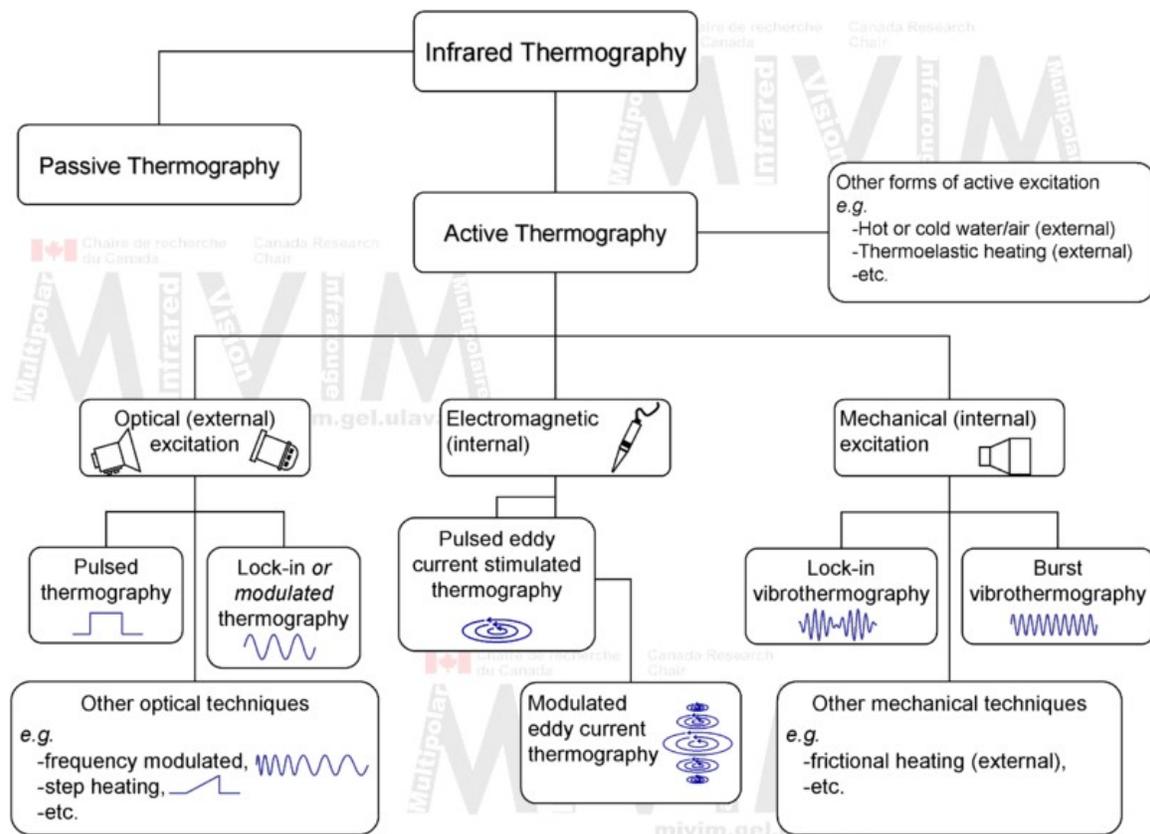
Infrared thermgography techniques

A wide variety of energy sources can be used to induce a thermal contrast between defective and non-defective zones that can be divided in external, if the energy is delivered to the surface and then propagated through the material until it encounters a flaw; or internal, if the energy is injected into the specimen in order to stimulate exclusively the defects. Typically, external excitation is performed with optical devices such as photographic flashes (for heat pulsed stimulation) or halogen lamps (for periodic heating), whereas internal excitation can be achieved by means of mechanical oscillations, with a sonic or ultrasonic transducer for both burst and amplitude modulated stimulation. As depicted in the figure, there are three classical active thermographic techniques based on these two excitation modes: lock-in (or modulated) thermography and pulsed thermography, which are optical techniques applied externally; and

vibrothermography, which uses ultrasonic waves (amplitude modulated or pulses) to excite internal features. YAKA

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Chapter-4

Magnetic-particle Inspection

Magnetic particle inspection (**MPI**) is a non-destructive testing (NDT) process for detecting surface and subsurface discontinuities in ferroelectric materials such as iron, nickel, cobalt, and some of their alloys. The process puts a magnetic field into the part. The piece can be magnetized by direct or indirect magnetization. Direct magnetization occurs when the electric current is passed through the test object and a magnetic field is formed in the material. Indirect magnetization occurs when no electric current is passed through the test object, but a magnetic field is applied from an outside source. The magnetic lines of force are perpendicular to the direction of the electric current which may be either alternating current (AC) or some form of direct current (DC) (rectified AC).

The presence of a surface or subsurface discontinuity in the material allows the magnetic flux to leak. Ferrous iron particles are applied to the part. The particles may be dry or in a wet suspension. If an area of flux leakage is present the particles will be attracted to this area. The particles will build up at the area of leakage and form what is known as an indication. The indication can then be evaluated to determine what it is, what may have caused it, and what action should be taken if any.

Types of electrical currents used

There are several types of electrical currents used in MPI. For a proper current to be selected one needs to consider the part geometry, material, the type of discontinuity you're looking for, and how far the magnetic field needs to penetrate into the part.

- Alternating current (AC) commonly used to detect surface discontinuities. Using AC to detect subsurface discontinuities is limited due to what is known as the skin effect, where the current runs along the surface of the part. Because the current alternates in polarity at 50 to 60 cycles per second it does not penetrate much past the surface of the test object. This means the magnetic domains will only be

aligned equal to the distance AC current penetration into the part. The Frequency of the Alternating Current decides how deep the penetration.

- Direct current (DC, full wave DC) Used to detect sub surface discontinuities where AC can not penetrate deep enough to magnetize the part at the depth needed. The amount of magnetic penetration depends on the amount of current passed through the part. DC is also limited on very large cross sectional parts how effective it will magnetize the part.

- Half wave DC (HWDC, pulsating DC) work similar to full wave DC with sightly more magnetic penetration into the part. HWDC is known to have the most penetrating ability in magnetic particle testing. HWDC is advantageous for inspection process because it actually helps move the magnetic particles over the test object so that they have the opportunity to come in contact with areas of magnetic flux leakage. The increase in particle mobility is caused by the pulsating current which vibrates the test piece and particles.

Each method of magnetizing has its pros and cons. AC is generally always best for discontinuities open to the surface and some form of DC for subsurface.

Equipment

A wet horizontal MPI machine with a 36 in (910 mm) coil
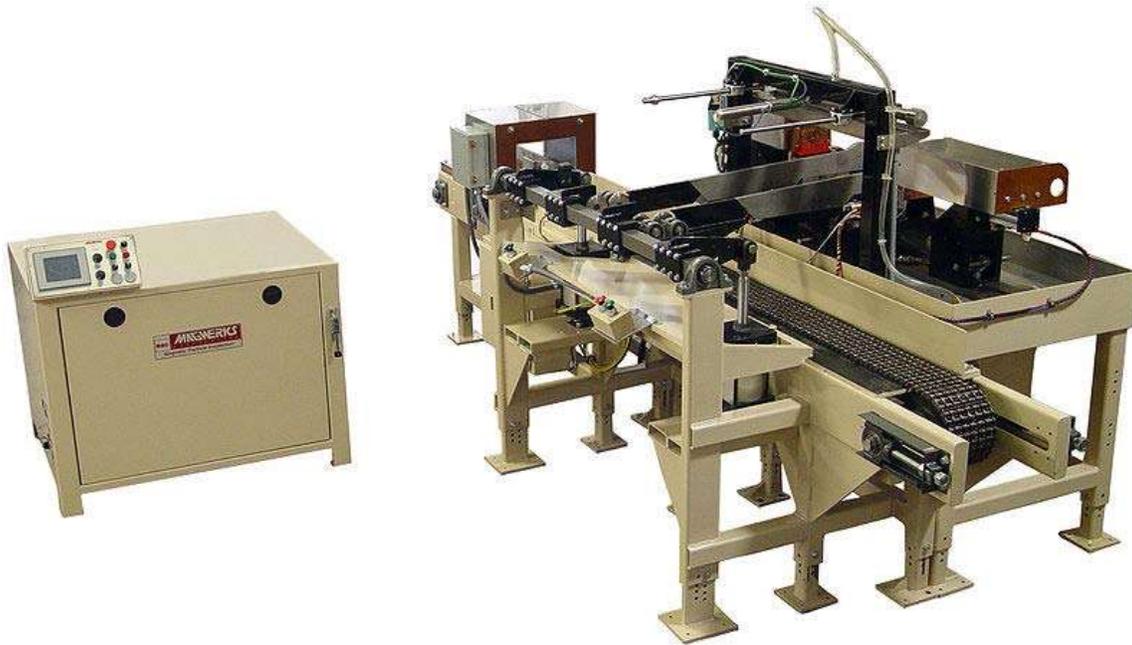
An automatic wet horizontal MPI machine with an external power supply, conveyor, and demagnetizing system; its used to inspect engine cranks.

- A wet horizontal MPI machine is the most commonly used mass production inspection machine. The machine has a head and tail stock where the part is placed to magnetize it. In between the head and tail stock is typically an induction coil, which is used to change the orientation of the magnetic field by 90° from head stock. Most of the equipment is customized and built for a specific application.
- Mobile power packs: Are custom built magnetizing power supplies used in wire wrapping applications.
- Magnetic yoke: is a hand held devices that induces a magnetic field between two poles. Common applications are for outdoor use, remote locations, and weld inspection. The draw back of magnetic yokes are they only induce a magnetic field between the poles so inspection is time consuming are on large parts. For proper inspection the yoke needs to be rotated 90 degrees for every inspection area to detect horizontal and vertical discontinuities. Yokes subsurface detection is limited. These systems used dry magnetic powders, wet powders, or aerosol cans.

Demagnetizing parts

A pull through AC demagnetizing unit

After the part has been magnetized its needs to be demagnetized. This requires special equipment that works the opposite of magnetizing equipment. Magnetizing is normally done with high current pulse that very quickly reaches a peak current and instantaneously turns off leaving the part magnetized. To demagnetize a part the current or magnetic field needed, has to be equal or greater than the current or magnetic field used to magnetized the part, the current or magnetic field then is slowly reduced to zero leaving the part demagnetized.

- AC demagnetizing
    - Pull through AC demagnetizing coils: seen in Fig 3 are AC powered devices that generate a high magnetic field where the part is slowly pulled through by hand or on a conveyor. The act of pulling the part through and away from coil's magnetic field slows drops the magnetic field in the part. Note many AC demagnetizing coils have power cycles of several seconds so the part must be passed through the coil and be several feet (meters) away before the demagnetizing cycle finishes or the part will have residue magnetism.
    - AC step down demagnetizing: This is built in only a few MPI equipment, the process is where the part is subjected to equal or greater AC current, the current is reduced by X amps in several sequential pulses till zero

current is reached. The number of steps required to demagnetizing a part is a function of amount current to magnetize the part.

- Reversing DC demagnetizing: The simply reverses the current flow of magnetizing pulse canceling the magnetic flow. Note: This is built in the MPI equipment by the manufacturer.

Magnetic particle powder

The particles used to detect cracks is commonly iron oxide for both dry and wet systems.

- Wet system particle range in size from <0.5 to 10 micrometres for use with water or oil carriers. Particles used in wet systems have pigments applied that fluoresce at 365 nm (Ultraviolet A) requiring 1000 µW/cm2 (10 W/m2) at the surface of the part for proper inspection. If the particles do not have the correct light applied in a **Dark Room** the particles can not be detected/seen. Its industry practices to use UV goggles/glasses to filter the UV light and amplify the visible light spectrum normally Green and Yellow created by the fluorescing particles. Green and Yellow fluorescence was chosen because the human eye reacts best to these colors.
- Dry particle powders range in size from 5 to 170 micrometres, designed to be seen in white light conditions. The particles are not designed to be used in wet environments. Dry powders are normally applied using hand operated air powder applicators
- Aerosol applied particles are similar to wet systems, sold in premixed aerosol cans similar to hair spray.

Magnetic particle carriers

It is common industry practices to use specifically designed oil and water-based carriers for magnetic particles. Deodorized kerosene, and mineral spirits have not been commonly used in the industry for 40 years. It is very dangerous to use kerosene or mineral spirits as a carrier to due to their low flash points, and inhalation of fumes by the operators.

Inspection

The following are general steps for inspecting on a wet horizontal machine:

1. Part is cleaned of oil and other contaminants
2. Necessary calculations done to know the amount of current required to magnetize the part.
3. The magnetizing pulse is applied for 5 seconds during which the operator washes the part with the particle, stopping before the magnetic pulse is completed. Failure to Stop prior to end of the magnetic pulse will wash away indications.
4. UV light is applied the operator looks for indications of defects that are 0 to +/- 45 degrees from path the current flowed through the part. Defects only appear that are 45 to 90 degrees the magnetic field. The easiest way to quickly figure out

which way the magnetic field is running is grab the part with either hand between the head stocks laying your thumb against the part (do not wrap your thumb around the part) this is called either left or right thumb rule or right hand grip rule. The direction thumb points tell us the direction current is flowing, the Magnetic field will be running 90 degrees from the current path. On complex geometry like a engine crank the operator needs to visualize the changing direction of the current and magnetic field created. The current starts at 0 degrees then 45 degrees to 90 degree back to 45 degrees to 0 then -45 to -90 to -45 to 0 and repeats this for crankpin. So inspection can be time consuming to carefully look for indications that are only 45 to 90 degrees from the magnetic field.

5. The part is either accepted or rejected based on pre-defined accept and reject criteria
6. The part is demagnetized
7. Depending on requirements the orientation of the magnetic field may need to be changed 90 degrees to inspect for defects that can not be detected from steps 3 to 5. The most common way is change magnetic field orientation is to a use Coil Shot. in Fig 1 a 36 inch Coil can be seen then steps 4, 5, and 6 are repeated

Chapter-5

Automated Optical Inspection

Automated optical inspection (AOI) is an automated visual inspection of a wide range of products, such as printed circuit boards (PCBs), LCDs, transistors, automotive parts, lids and labels on product packages or agricultural products (seed corn or fruits). In case of PCB-inspection, a camera autonomously scans the device under test (DUT) for variety of surface feature defects such as scratches and stains, open circuits, short circuits, thinning of the solder as well as missing components, incorrect components, and incorrectly placed components. Agricultural inspections might check for variations in part color, perhaps to find ripe fruit. AOI is a type of white box testing. It is commonly used in the manufacturing process because it is a non-contact test method. AOI is able to perform most of the visual checks performed previously by manual operators, and far more swiftly and accurately. AOI systems are implemented at many stages through the manufacturing process. They are used for inspecting parts that have limited and known variations. For defect or flaw detection, the AOI system looks for differences from a perfect part. There are systems capable of bare board inspection, Solder Paste inspection (SPI), as well as inspecting the component placement prior to reflow, the post-reflow component conditions, and post-reflow solder joints. These inspection devices all have some common attributes that affect capability, accuracy, and reliability.

In this way AOI can be used to detect problems early in the production process. Since faults cost more to fix later in the production process, it is essential to notice problems early. For example, problems in the solder and assembly area of a PCB can be seen early in the production process and information used to feedback quickly to previous stages, avoiding the production of too many boards with the same problem.

Low costs and programming efforts make AOI a practical and powerful quality tool for both prototypes and high-volume assembles. It is often paired with the testing provided by boundary scan test, in-circuit test, x-ray test, and functional test. In many cases, smaller circuit board designs are driving up the demand for AOI versus in-circuit test.

Process

A machine vision or an AOI system can acquire millions of data points (pixels) in a fraction of a second. These data points are used for visual inspection and precision measurement.

AOI visually scans the surface of the PCB. The board is lit by several light sources and observed by a scanner or by a number of high definition cameras. This enables the monitoring of all areas of the board, even those hidden in one direction by other components. It should be noted that each manufacturer of AOI systems utilizes different inspection algorithms and lighting techniques, each of these systems may have varying strengths and weaknesses depending upon the item/product it is inspecting.

Light source

Lighting preprocesses the image to amplify features that need to be inspected and suppress noise. Advances in lighting have improved the capabilities of vision systems, in part by reducing the computation required by the vision computer. In essence this means that the lighting combinations ideally will improve the image quality to improve the efficiency of the AOI system's decision making process. Most AOI systems will have predefined lighting combinations depending upon the mode of operation and type of product being inspected, these combinations will require no user interaction and the system software/algorithms will manipulate and choose the best image for analysis. However some customization is often required and with that these systems will provide interfacing for the end user.

The test engineer has the option to choose which light source to use for the lighting: a LED, fluorescent light, or in certain industries other light sources such as IR or UV. This depends on the area to be inspected, industry, and other variables. Some users believe that LED light measures post-print solder brick height more accurately than a fluorescent light source. This accuracy also makes LED light a good tool for post-reflow solder joint inspection. Fluorescent light, on the other hand is excellent for inspection of component placement pre-reflow but is typically used for location inspection only. The problem with it is that because of the frequent light changes the fluorescent lamps can degrade quickly. For these above reasons LED lighting has become very popular among most AOI companies in the PCB industry.

The adoption of standard LED-based lighting has improved AOI systems because it is very stable and easily controlled when compared to older incandescent and fluorescent lighting. LEDs are not perfect: they become darker with age, but this can be easily compensated for by increasing the current to the LED or group of LEDs.

Another lighting method projects a pattern of light on an object, often by using a laser with a holographic lens or a white light source with an attached projection grid. The distortions of this structured light pattern can be measured and processed to recover the object's 3D structure. AOI systems using structured light can, for example, compare

complex objects such as engine blocks or PCBs to the designed shape in CAD files. These techniques in the PCB industry are referred to as laser triangulation and phase shift profilometry Profilometer respectively. Both are valid techniques for acquiring three dimensional (3-D) information from the PCB

The position of the light sources and laser inside the machine are important. Angles of approach are calculated into the inspection algorithms providing enhanced accuracy of the measurements. Also the angle of approach can be particularly important in certain applications because surrounding objects may interfere with the light approach to the target object. An example would be a tall component on a circuit board that blocks the visual approach of the light/camera system to the target component or solder deposit for example.

Capturing an image

If a scanner is used it has to scan the surface of the PCB from above only once. If image cameras are used, one must first determine the number of cameras needed. There are systems with only one camera which scans the DUT from above and systems with a couple of cameras from all sides. To be able to scan the device from all points of view, the cameras should be able to move in both X- and Y-direction controlled by software. To program this software the test engineer must have the CAD data.

Then the type of cameras must be chosen. There are several types in use today. Streaming video 2D frame grabbers are common. They utilize a motion capture video camera that extracts one frame from a streaming video and creates a still image. However, the system sacrifices image quality for speed and efficiency. A second type of camera imaging system is the Line Scan Still Image Camera. In this system, a still camera is placed relatively close to the target. Because of this, this system requires a very good lighting system. Unfortunately, the image can be distorted by subsystem imperfections such as transporter movement. This makes obtaining precise positioning and measurements difficult when compared to other types of systems. A benefit of the Line Scan Still Image Camera is the image acquisition speed, which is faster than a CCD camera.

Another camera imaging system is the 2D Charge-coupled device or CCD. The CCD is used for high-end and special applications such as space and military technologies. This system creates high precision still images in color that are more accurate than other systems.

Each industry is different in how image acquisition signals are transferred to the camera. It can be hardware driven via a mechanical signal such as a proximity sensor, laser interruption, drive system encoder position, or software. Regardless of the signal the AOI system interprets the signal which triggers the vision assembly (which could be a single frame grabber and camera combination or more advanced as already discussed) that the object is in a known location and to begin image acquisition. The vision computer then triggers the camera/cameras to simultaneously acquire images of the device.

Programming

The AOI system takes time to "learn" the object which in the PCB industry is typically a circuit board. Several methods of learning exist but the two most common are image matching and algorithm based. Image matching is when a "golden board" is introduced to the system and the attributes of each component, solder deposit, etc. are learned into the system. This could include but not limited to color, white pixel count, dark pixel count, transition points, and relative position of transition points. Image based systems require a few example products typically to learn all possible variations. The other method is algorithm based programming; this is where the user can apply rules and measurement algorithms for inspection. Algorithm based programming typically also requires product examples for programming but not usually as many as image based programming. There are pros and cons for each technique which can include setup time, complexity of the system, program transportability, time to generate a program, and call effectiveness.

The AOI system needs to be able to add the learned information acquired from the above inspection techniques to its memory. It has to "remember" the different types of components, their positions and also to check the quality of the soldered joints. It must be able to recognize and adapt to differences in the appearances of the board resulting from normal process variations, but must be able to recognize any that affect performance. To achieve this it is normal to run a number of good boards (golden boards) through the system before full production starts so that the system can "learn" the board. Currently the best AOI machines can be set up relatively quickly and then they are reliably able to inspect boards. This can be done by offline programming. This reduces production downtime, and the programmer has time to enter accurate parameters without stopping an assembly line. These systems also have a component database that saves data so that it does not have to be entered every time a new board is produced.

In case of automotive parts inspection for example, the system should know what features to measure or for sorting agricultural products the color of ripe fruit should be known.

Data collection

To obtain the necessary data one can use 3D software imaging or LED light measurements, which are common methods for measuring solder joint parameters. Typical systems use both methods to obtain accurate measurements. These systems use a directed light source or refracting light to measure height, area, and volume. The vision computer and its software analyze data (images) and calculate statistical process control (SPC) results in these areas. The results of the inspection are used to reject defective parts.

To reduce the computation required by the vision computer so that parts are quickly inspected it is a good idea to use a type of mechanical restraint known as staging or fixturing. The part is positioned in a known location and variability in where the parts are and how they look is decreased.

Other data collection concerns are factory software integration of inspection results, how long to keep the data/measurements, and what data is available. Each AOI system is going to vary in what is available and each industry and customer will have varying needs. For example military and aerospace industries may have the need to store data for years or until the expected end of life (EOL) of a product while commercial manufacturing such as mobile phones may only require data for a few weeks or possibly even just for that day or shift.

System memory

System memory is also important. Upgradeable systems that have the capacity for expanded memory are desirable. Databases expand every day particularly with the increase in lead-free components, solders, boards and assemblies that are rapidly entering the industry.

System speed

System speed is influenced largely by the size and complexity of the boards being inspected and the level of inspection. Control over the pace of the production line can be influenced by the AOI system. Since one hundred percent inspection is not always necessary, valuable time can be saved by dialing in the appropriate inspection level.

System accuracy

The accuracy for finding defects such as missing components, skewed components, reversed components, or wrong valued components depends not only on the capability of the inspection system but also on the accuracy of the program supplied by the user.

Accuracy of inspection is becoming even more important with the smaller devices especially in the PCB industry devices such as 0201 and 01005 resistors and capacitors are so small that the human eye can not detect their presence or absence on a PCB.

Types of AOI machines

Stand-alone and inline AOI systems

When using Stand-alone machines the PCB has to be inserted into and after the test taken out of the machine manually. Inline systems on the other hand are part of the production line so the PCBs move into and go out of the machine automatically.

Closed- and open-top AOI systems

Inside Open-top machines the artificial light is distracted by light sources different than the ones used by the system itself (e.g. sunlight). Closed-top machines eliminate any light pollution because they are closed from all sides. In this way only artificial light is available inside the machine making these type of systems much more efficient.

AOI and combined AOI/AXI systems

Today's AOI systems have the capability to inspect visible solder joints on capacitors, resistors, and other components. However, without additional capabilities such as Automated x-ray inspection (AXI), ball grid array (BGA) and "J" leaded components are limited to polarity, missing, and placement error detection. That is why Combined AOI/AXI systems can provide the necessary mixture for high-performance and are becoming more and more popular.

Inspection in surface-mount technology

The growing demand for Surface-mount technology equipment is reducing the need for expensive rework and repair while increasing throughput. As PCB assembly manufacturers aim for a zero-tolerance regime, the demand for pre-solder paste and pre-reflow optical inspection equipment that detect faults such as poor quality solder joints, tombstoning, and other post reflow defects is expected to rise significantly. Technological improvements in AOI equipment have resulted in higher throughput, repeatability, and reliability as well as increasing quality and production yields for the PCB assembly manufacturers.

AOI's for a PCB board with components may inspect the following features:

- Area Defects
- Billboarding
- Component offset
- Component polarity
- Component presence/absence
- Component skew
- Excessive solder joints
- Flipped component
- Height Defects
- Insufficient paste around Leads
- Insufficient solder joints
- Lifted leads
- No-population tests
- Paste registration
- Severely damaged components
- Solder bridges
- Tombstoning
- Volume defects
- Wrong part

Bare PCB inspection

AOI for a bare PCB board inspection may detect these features:

- Line width violations.
- Spacing violation.
- Access copper.
- Missing pad. I.e. a feature that should be on the board is missing.
- Shorts circuits.
- Cuts.
- Hole breakage. I.e. a drilled hole (via) is outside of its **landing pad**.

The triggering of a defects report may be either rule based (e.g. no lines on the board should be smaller than 50μ) or CAD based in which the board is locally compared with the intended design.

This inspection is much more reliable and repeatable than manual visual inspection.

Chapter-6

Tracer-gas Leak Testing method and Dye Penetrant Inspection

Tracer-gas leak testing method

Tracer-gas leak testing method is a nondestructive testing method.

Types

Several tracer-gas leak testing methods exist among which the methods of choice are:

- Helium mass spectrometer or helium leak detection, providing the highest sensitivity
- Hydrogen leak testing or hydrogen leak detection, providing the best mobility
- Refrigerant gas leak detection, for refrigeration applications.

Method selection

The nature of the product or the process and the process gases will set the leak rate requirement:

Typical leak rates		
System	**Allowed Leak Rate**	**Comments**
Chemical process equipment	10^{-1} to 1 mbar l/s	high process flows
Beverage can	low 10^{-5} to 10^{-6} mbar l/s	retention of CO_2
Vacuum pumped system	10^{-5} to 10^{-7} mbar l/s	permanent pumping
IC-package	10-7 to 10^{-8} mbar l/s	lifetime control

Airbag cartridge	10^{-8} mbar l/s	lifetime control
Pacemaker	10^{-9} mbar l/s	Bio compatibilty
Closed vacuum system	10^{-9} mbar l/s	X-Ray tube

Based on the target leak rate the table below wil help to choose the most suitable method.

Leak test performances

mbar l/s	10^2	10^1	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}
Bubble test in water	----	----	----	----	>										
Bubble test soapy water	----	----	----	----	----	----	>								
Pressure decay	----	----	----	----	----	>									
Acoustic (US)	----	----	----	----	----	>									
Vacuum decay	----	----	----	----	----	>									
Corona tester	----	----	----	----	----	>									
Thermal conductivity	----	----	----	----	----	----	----	>							
Halogen sniffer*	----	----	----	----	----	----	----	>							
Hydrogen sniffer	----	----	----	----	----	----	----	----	->						
Helium sniffer	----	----	----	----	----	----	----	----	->						
Halogen detector*	----	----	----	----	----	----	----	----	>						
Dye penetrant	----	----	----	----	----	----	----	----	----	----	>>				
Radio-isotope	----	----	----	----	----	----	----	----	----	----	----	----	>>>>		
Mass spectrometer	----	----	----	----	----	----	----	----	----	----	----	----	----	----	>>>>>>
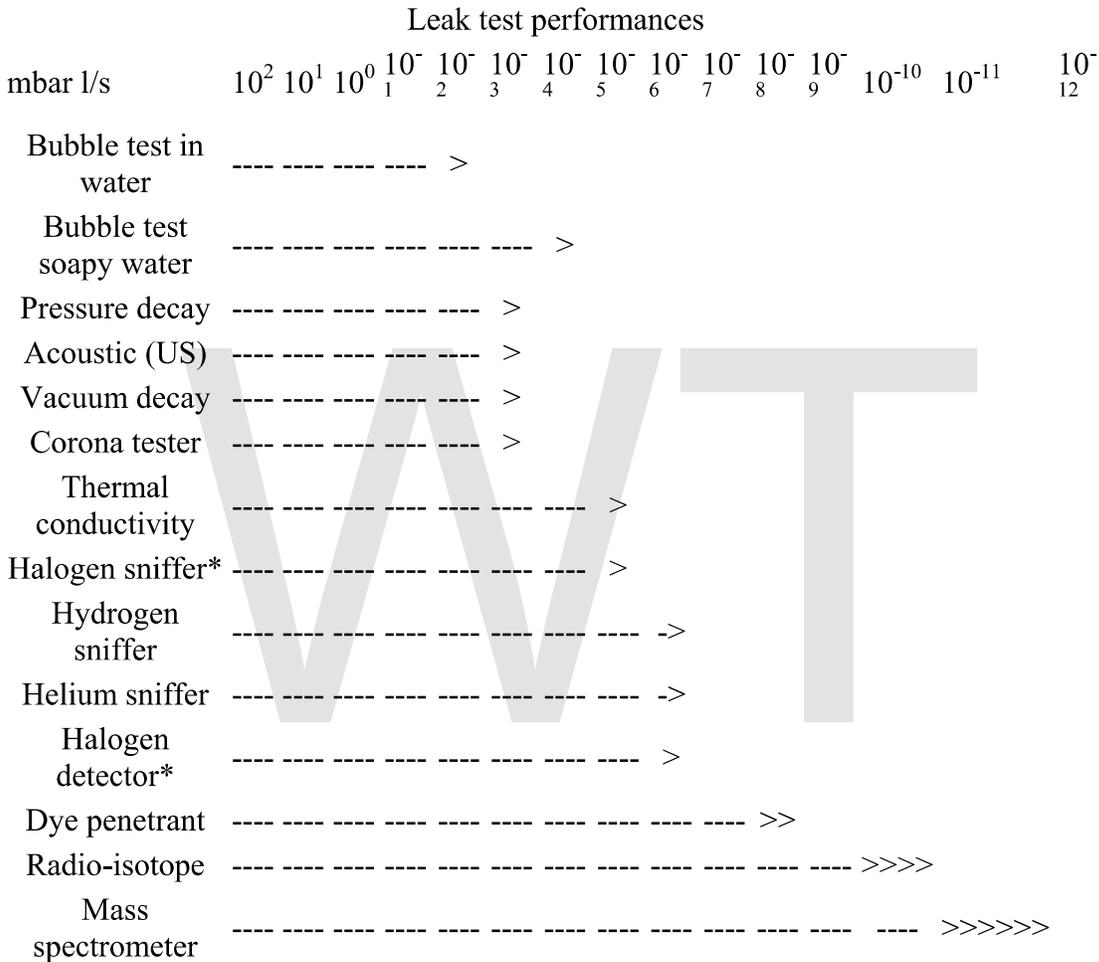
- Restriction of use (F-Gas Directive)

Typical applications of **tracer gas leak testing** include:

- Chemical plant
- Petrochemical plant: hydrocracker , vapocracker, catalytic reforming, steam reforming are all Hydrogen based processes were Hydrogen leak testing will be very appropriate,
- Semiconductor industry; all processes taking place in a process chamber at atmospheric pressure or under vacuum; Diffusion, Oxidation, LPCVD , PECVD,

PVD, Etch, Ion Implant, typically the later that implies vacuum will require Helium leak testing, while the other will make good use of Hydrogen leak testing,

- Automotive: with airbag being the most demanding leak testing application (small gas tank, very high pressure, long shelf life) and air conditioning system (for best efficiency), fuel system (for low emission), exhaust system (for lowest pollution), engine and transmission (for no oil dripage), rims to keep tyre safe,
- Medical: to ensure safe and long life implant (pacemaker) or a safe catheter
- Airplane: to quickly and safely locate fuel leaks , to check oxygen distribution devices and cabin pressurization systems
- Refrigeration and air conditioning systems-residential, commercial or industrial- in order to deliver best efficiency at the lowest loss rate of refrigerant gases (ozone depletion)
- Power distribution for high voltage circuit breaker using SF_6 as a dielectric
- Drinking water distribution grid as today average leakage rate or efficiency is above 25%, wasting precious resources, water and power.
- Sewage water collecting network as leaks can contaminate drinking water collection process;

Another element of consideration is the dimension of the part to be tested as well as to take into consideration the law of physics, specially the rules that govern the flow of gas at different pressure.

Dye penetrant inspection
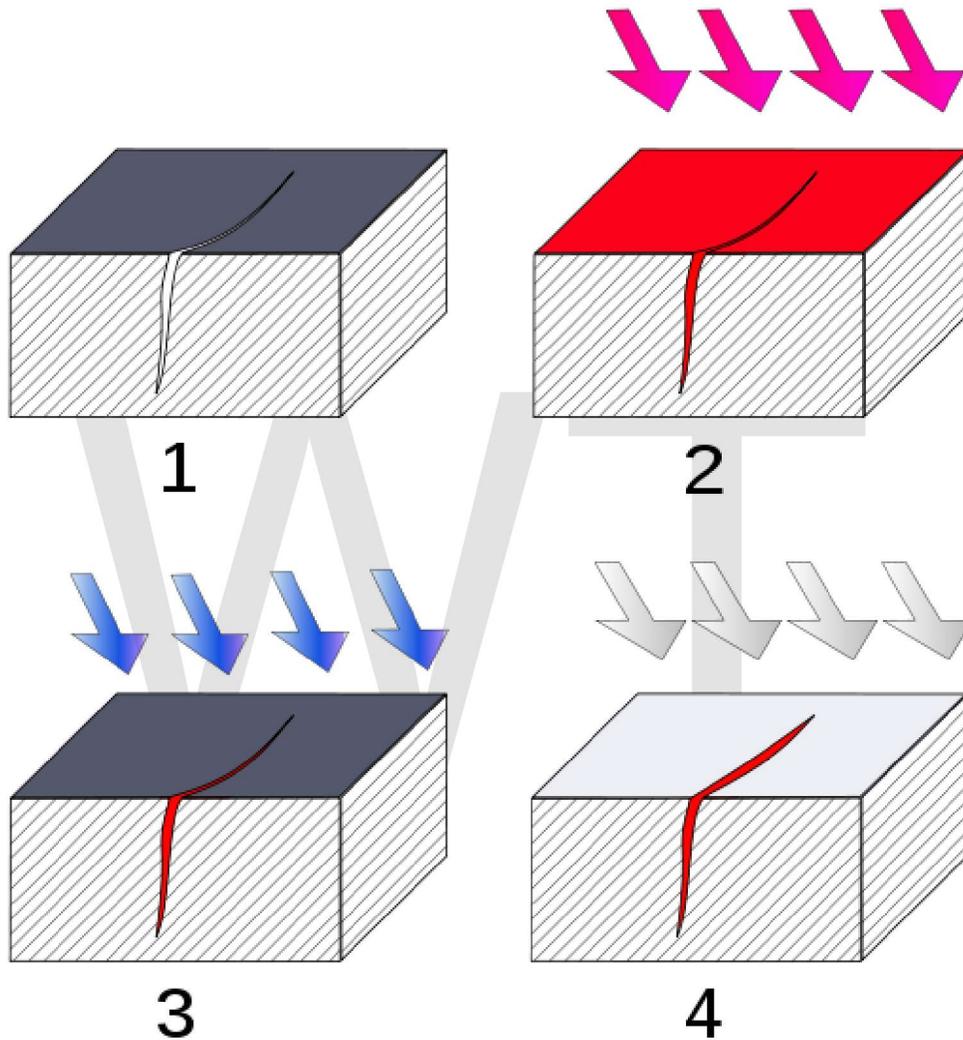
1. Section of material with a surface-breaking crack that is not visible to the naked eye.
2. Penetrant is applied to the surface.
3. Excess penetrant is removed.
4. Developer is applied, rendering the crack visible.

Dye penetrant inspection (**DPI**), also called **liquid penetrant inspection** (**LPI**) or **penetrant testing** (**PT**), is a widely applied and low-cost inspection method used to locate surface-breaking defects in all non-porous materials (metals, plastics, or ceramics). The penetrant may be applied to all non-ferrous materials and ferrous materials, *but for*

inspection of ferrous components magnetic-particle inspection is also preferred for its subsurface detection capability. LPI is used to detect casting, forging and welding surface defects such as cracks,suface porosities, and leaks in new products, and fatigue cracks on in-service components.

Principles

DPI is based upon capillary action, where low surface tension fluid penetrates into clean and dry surface-breaking discontinuities. Penetrant may be applied to the test component by dipping, spraying, or brushing. After adequate penetration time has been allowed, the excess penetrant is removed, a developer is applied. The developer helps to draw penetrant out of the flaw where a visible indication becomes visible to the inspector. Inspection is performed under ultraviolet or white light, depending upon the type of dye used - fluorescent or nonfluorescent (visible).

Materials

Penetrants are classified into sensitivity levels. Visible penetrants are typically red in color, and represent the lowest sensitivity. Fluorescent penetrants contain two or more dyes that fluoresce when excited by ultraviolet (UV-A) radiation (also known as black light). Since Fluorescent penetrant inspection is performed in a darkened environment, and the excited dyes emit brilliant yellow-green light that contrasts strongly against the dark background, this material is more sensitive to small defects.

When selecting a sensitivity level one must consider many factors, including the environment under which the test will be performed, the surface finish of the specimen, and the size of defects sought. One must also assure that the test chemicals are compatible with the sample so that the examination will not cause permanent staining, or degradation. This technique can be quite portable, because in its simplest form the inspection requires only 3 aerosol spray cans, some lint free clothes, and adequate visible light. Stationary systems with dedicated application, wash, and development stations, are more costly and complicated, but result in better sensitivity and higher sample through-put.

Inspection steps

Below are the main steps of Liquid Penetrant Inspection:

1. Pre-cleaning:

The test surface is cleaned to remove any dirt, paint, oil, grease or any loose scale that could either keep penetrant out of a defect, or cause irrelevant or false indications. Cleaning methods may include solvents, alkaline cleaning steps, vapor degreasing, or media blasting. The end goal of this step is a clean surface where any defects present are open to the surface, dry, and free of contamination. Note that if media blasting is used, it

may "work over" small discontinuities in the part, and an etching bath is recommended as a post-bath treatment.

2. Application of Penetrant:

The penetrant is then applied to the surface of the item being tested. The penetrant is allowed time to soak into any flaws (generally 5 to 30 minutes)is called dwell time. The dwell time mainly depends upon the penetrant being used, material being testing and the size of flaws sought. As expected, smaller flaws require a longer penetration time. Due to their incompatible nature one must be careful not to apply solvent-based penetrant to a surface which is to be inspected with a water-washable penetrant.

3. Excess Penetrant Removal:

The excess penetrant is then removed from the surface. The removal method is controlled by the type of penetrant used. Water-washable, solvent-removable, lipophilic post-emulsifiable, or hydrophilic post-emulsifiable are the common choices. Emulsifiers represent the highest sensitivity level, and chemically interact with the oily penetrant to make it removable with a water spray. When using solvent remover and lint-free cloth it is important to not spray the solvent on the test surface directly, because this can remove the penetrant from the flaws. If excess penetrant is not properly removed, once the developer is applied, it may leave a background in the developed area that can mask indications or defects. In addition, this may also produce false indications severely hindering your ability to do a proper inspection.

4. Application of Developer:

After excess penetrant has been removed a white developer is applied to the sample. Several developer types are available, including: non-aqueous wet developer, dry powder, water suspendable, and water soluble. Choice of developer is governed by penetrant compatibility (one can't use water-soluble or suspendable developer with water-washable penetrant), and by inspection conditions. When using non-aqueous wet developer (NAWD) or dry powder, the sample must be dried prior to application, while soluble and suspendable developers are applied with the part still wet from the previous step. NAWD is commercially available in aerosol spray cans, and may employ acetone, isopropyl alcohol, or a propellant that is a combination of the two. Developer should form a semi-transparent, even coating on the surface.

The developer draws penetrant from defects out onto the surface to form a visible indication, commonly known as bleed-out. Any areas that bleed-out can indicate the location, orientation and possible types of defects on the surface. Interpreting the results and characterizing defects from the indications found may require some training and/or experience [the indication size is not the actual size of the defect]

5. Inspection:

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

6. Post Cleaning:

The test surface is often cleaned after inspection and recording of defects, especially if post-inspection coating processes are scheduled.

Advantages and disadvantages

The main advantages of DPI are the speed of the test and the low cost. The main disadvantages are that it only detects surface flaws and it does not work on very rough surfaces. Also, on certain surfaces a great enough color contrast cannot be achieved or the dye will stain the workpiece.

Limited training is required for the operator — although experience is quite valuable. Proper cleaning is necessary to assure that surface contaminants have been removed and any defects present are clean and dry. Some cleaning methods have been shown to be detrimental to test sensitivity, so acid etching to remove metal smearing and re-open the defect may be necessary.

Chapter-7

Computed Radiography and Fluorescent Penetrant Inspection

Computed radiography

Computed Radiography (CR) uses very similar equipment to conventional radiography except that in place of a film to create the image, an imaging plate (IP) made of photostimulable phosphor is used. The imaging plate housed in a special cassette and placed under the body part or object to be examined and the x-ray exposure is made. Hence, instead of taking an exposed film into a darkroom for developing in chemical tanks or an automatic film processor, the imaging plate is run through a special laser scanner, or CR reader, that reads and digitizes the image. The digital image can then be viewed and enhanced using software that has functions very similar to other conventional digital image-processing software, such as contrast, brightness, filtration and zoom.

Differences from Direct Radiography

CeReO - Computed Radiography Scanner

Computed radiography (CR) is often distinguished from Direct Radiography (DR). CR and DR have many similarities. Both CR and DR use a medium to capture x-ray energy and both produce a digital image that can be enhanced for soft copy diagnosis or further review. Both CR and DR can also present an image within seconds of exposure. CR generally involves the use of a cassette that houses the imaging plate, similar to traditional film-screen systems, to record the image whereas DR typically captures the image directly onto a flat panel detector without the use of a cassette. Image processing or enhancement can be applied on DR images as well as CR images due to the digital format of each. There are many different types of DR detectors in use in medicine and industry. Each type has its own merits and distinctions and may be applied to certain imaging requirements based on these attributes.

CR and DR should not be confused with Fluoroscopy, where there is a continuous beam of radiation, and the images appear on the screen like on a TV. This is the system many people are familiar with, where the image of the article being x-rayed is viewed in real time on a monitor or display. Many people think airports use Fluoroscopes for baggage inspection, when in fact LDA's (Linear Diode Arrays) are universally used to generate static images of luggage content. LDA's are also used in a wide variety of other screening and imaging applications, and are also presented in a digital format. Modern fluorosopes use a device called an image intensifier to enhance the analog output of the real time x-ray image, where it is picked up by either a video or CCD camera and digitally enhanced to reduce the noise inherent in the system.

Imaging plate

The CR imaging plate (IP) contains photostimulable storage phosphors, which store the radiation level received at each point in local electron energies. When the plate is put through the scanner, the scanning laser beam causes the electrons to relax to lower energy levels, emitting light that is detected by a photo-multiplier tube, which is then converted to an electronic signal. The electronic signal is then converted to discrete (digital) values and placed into the image processor pixel map.

Imaging plates can theoretically be re-used thousands of times if they are handled carefully. IP handling under industrial conditions, however, may result in damage after a few hundred uses. An image can be erased by simply exposing the plate to a room-level fluorescent light. Most laser scanners automatically erase the image plate after laser scanning is complete. The imaging plate can then be re-used. Reusable phosphor plates are environmentally safe but need to be disposed of according to local regulations.

Industrial applications

Common applications for computed radiography include:

- corrosion surveys on pipes, often through insulation;
- Examination of valves for erosion;
- Information shots on industrial components; e.g. checking to see if a valve is closed properly, or checking for obstructions in valves and pipes;
- Examination of boiler water walls;
- Weld examination for all AWS & ASME code applications including Sect. III & XI
- Automotive casting inspection
- High pressure braze joint inspection (aerospace)
- Wax pattern core integrity verification in investment casting foundries
- Best when used with Se75 for small core piping due to internal scatter created by Ir192's wavelength
- Code work for Nuclear Applications on all size piping

Medical applications

Computed Radiography systems are the most common in medical applications because they have proven reliability over more than two decades, flexibility to address a variety of clinical applications and lower costs to take multiple exam rooms digital. DR in the form of a portable detector starts at around $150,000.00, while a basic low volume CR can start as low as $30,000.00 (but higher volume, hospital-grade applications can be higher.) DR systems are generally sold as a full x-ray room replacements and tied to a single x-ray generator. CR IPs can be retrofitted to existing exam rooms and used in multiple x-ray sites since IPs are processed through a CR reader (scanner) that can be shared between multiple exam rooms.

Advantages

- No silver based film or chemicals are required to process film.
- Reduced film storage costs because images can be stored digitally.

- Computed radiography often requires fewer retakes due to under- or over-exposure which results in lower overall dose to the patient.
- Image acquisition is much faster - image previews can be available in less than 15 seconds.
- By adjusting image brightness and/or contrast, a wide range of thicknesses may be examined in one exposure, unlike conventional film based radiography, which may require a different exposure or multiple film speeds in one exposure to cover wide thickness range in a component.
- Images can be enhanced digitally to aid in interpretation.
- Images can be stored on disk or transmitted for off-site review.
- Ever growing technology makes the CR more affordable than ever today. With Chemicals, dark room storage and staff to organize them, you could own a CR for the same monthly cost while being environmentally conscious, depending upon the size of the Radiographic Operation.

Disadvantages

- In medical applications, manual handling of the cassette housing the IP is considered a disadvantage versus DR but it also offers more flexibility for patient positioning.
- CR is still not an approved method for higher quality radiologic applications (aerospace), due to the possibility of digital manipulation to the captured image, the inherent geometric unsharpness and resultant lower spatial resolution as compared to film (radiographic) images, SNR (signal vs. noise)issues and sensitivity to scattered radiation, and the general lack of procedural consensus among primes and OEM's.
- There also are no quality (image resolution)standards for general radiography, only for mammography (21 CFR 900.12 (e)), however, competition among manufacturers has raised the bar and newer CR technologies with increased detective quantum efficiency (DQE) and higher spatial resolution have emerged.
- Imaging plates (IPs) are expensive and can be damaged if the system being used requires manual handling of the IPs. Theoretically, IPs may be reused thousands of times, but constant use will always result in damage to the IP and image artifacts, eventually to the point of necessary replacement.

Products

- VMI Virtual Media Integradtion
- Oy. Ajat Ltd. CdTe CMOS imaging systems
- Viztek OPAL CR
- DÜRR DENTAL VistaScan Combi Plus
- DÜRR DENTAL VistaScan Perio Plus
- DÜRR DENTAL VistaScan Mini Plus
- DÜRR NDT HD-CR 35 NDT, HD-CR 43 NDT
- DÜRR MEDICAL CR 35 MED, CR 43 MED, CR 35 VET, CR 43 VET, CR 7 VET

- Hamamatsu Photonics (PMT)
- CONSORZIO REGIONALE MEDITEC
- Radlink CR PRO Series Systems
- Carestream Classic CR System (formerly Kodak)
- Carestream Elite CR System (formerly Kodak)
- Carestream Directview Max CR
- Carestream Vita CR
- Carestream Vita SE CR
- Carestream 975 / 950 / 900 / 850 / 825 / 800 CR System (formerly Kodak)
- Carestream Point of Care CR 360 / 140 / 120 (formerly Kodak)
- OREX ACL-4 / ACL-2
- CR-TECH CR 5020S
- FujiFilm FCR Capsula X
- FujiFilm FCR Capsula XL II
- FujiFilm FCR XG 5000
- FujiFilm FCR XG-1
- FujiFilm Profect CS (Mammography)
- FujiFilm Profect One (Mammography)
- iCRco 3600
- iCRco 3600sf
- Konica ImagePilot CR
- Konica Regius 190 / 170 / 150
- Konica Xpress CR
- Konica IQue CR
- Philips PCR Eleva S
- Agfa CR 30-X
- Agfa CR 35-X
- Agfa CR 75-X
- Agfa CR 85-X
- Agfa DX-S

Fluorescent penetrant inspection

Fluorescent Penetrant Inspection (FPI) is a type of **dye penetrant inspection** in which a fluorescent dye is applied to the surface of a non-porous material in order to detect defects that may compromise the integrity or quality of the part in question. Noted for its low cost, simple process, FPI is used widely in a variety of industries.

Materials

There are many types of dye used in penetrant inspections. FPI operations use a dye much more sensitive to smaller flaws than penetrants used in other DPI procedures. This is because of the nature of the fluorescent penetrant that is applied. With its brilliant yellow glow caused by its reaction with ultraviolet radiation, FPI dye sharply contrasts

with the dark background. A vivid reference to even minute flaws is easily observed by a skilled inspector.

Because of its sensitivity to such small defects, FPI is ideal for most metals which tend to have small, tight pores and smooth surfaces. Defects can vary but are typically tiny cracks caused by processes used to shape and form the metal. It is not unusual for a part to be inspected several times before it is finished (an inspection often follows each significant forming operation).

Selection of inspection type is, of course, largely based on the material in question. FPI is a nondestructive inspection process which means that the part is not in any way damaged by the test process. Thus, it is of great importance that a dye and process are selected that ensure the part is not subjected to anything that may cause damage or staining.

Inspection Steps

See the following main steps in a Fluorescent Penetrant Inspection:

1. Initial Cleaning:

Before the dye can be applied to the surface of the material in question one must ensure that the surface is free of any contamination such as paint, oil, dirt, or scale that may fill a defect or falsely indicate a flaw. Methods such as sand blasting or chemical etching can be used to rid the surface of undesired contaminates and ensure good penetration when the dye is applied. Even if the part has already been through a previous DPI operation it is imperative that it is cleaned again. Most dyes are not compatible and therefore will thwart any attempt to identify defects that are already penetrated by any other dye. This process of cleaning is critical because if the surface of the part is not properly prepared to receive the dye, defective product may be moved on for further processing. This can cause lost time and money in reworking, overprocessing, or even scrapping a finished part at final inspection.

2. Penetrant Application:

The fluorescent penetrant is applied to the surface and allowed time to seep into flaws or defects in the material. Time varies by material and the size of the flaws that are intended to be identified but is generally around 30 minutes. It requires much less time to penetrate larger defects because the dye is able to soak in much faster. The opposite is true for smaller flaws.

3. Excess Dye Removal:

Penetrant on the outer surface of the material is next removed. This highly controlled process is necessary in order to ensure that the dye is removed only from the surface of the material and not from any identified flaws. Various chemicals can be used for such a

process and vary by specific penetrant types. Typically, the cleaner is applied to a cloth that is used to carefully clean the surface.

4. Developer Application:

Having removed excess penetrant a contrasting developer may be applied to the surface. This serves as a background against which flaws can more readily be detected. The developer also causes penetrant that is still in any defects to surface and bleed. These two attributes allow defects to be easily detected upon inspection. Time is then allowed for the developer to achieve desired results before inspection.

5. Inspection:

In the case of fluorescent inspection, the inspector will use ultraviolet radiation with an intensity appropriate to the intent of the inspection operation. This must take place in a dark room to ensure good contrast between the glow emitted by the penetrant in the defected areas and the unlit surface of the material. The inspector carefully examines all surfaces in question and records any concerns. Areas in question may be marked so that location of defects can be identified easily without the use of the UV lighting. The inspection should occur at a given point in time after the application of the developer. Too short a time and the flaws may not be fully blotted, too long and the blotting may make proper interpretation difficult.

6. Final Cleaning:

Upon successful inspection of the product, it is returned for a final cleaning before it is either shipped, moved on to another process, or deemed defective and reworked or scrapped. Note that a flawed part may never be cleaned if it is considered not to be cost effective.

Advantages

- Highly sensitive fluorescent penetrant is ideal for even the smallest imperfections
- Little training is needed for the operator/ inspector
- Low cost and potentially high volume

Potential Disadvantages

- Requires adequate cleaning (neglect of this step can have costly repercussions)
- Test materials can be damaged if compatibility is not ensured
- Dyes stain clothe and skin and must be treated with care

Penetrant dyes stain cloth, skin and other porous surfaces brought into contact. One should verify compatibility on the test material, especially when considering the testing of plastic components. Further information on inspection steps may be found in industry

standards (e.g. the American Welding Society, American Society for Testing and Materials, the British Standards Institute, and the Society for Automotive Engineers).

Chapter-8

Industrial CT Scanning

Industrial CT (Industrial Computed Tomography) scanning is a process which uses X-ray equipment to produce 3D representations of components both externally and internally. Industrial CT scanning has been used in many areas of industry for internal inspection of components. Some of the key uses for CT scanning have been flaw detection, failure analysis, metrology, assembly analysis and reverse engineering applications.

Advantages

There are many advantages to using CT scanning over traditional techniques such as CMM's, or 3D laser scanners. Some of the main points include:

• A non-destructive test for inspection and metrology

• Inspection and analysis costs from first article to production are significantly reduced

• Design requirements for both internal and external components are validated quickly and accurately

• Product quality is improved to reduce the risk of recalls

• Internal complex features can be precisely measured without destructive testing

• Parts are scanned in a free-state environment without fixturing applying stresses which could damage delicate parts or display warping not present in the part

• For the first time, rapid prototyping of the internal components can be completed without the daunting task of creating the CAD file from scratch

- Development costs are reduced in creating the first CAD model

Types of Scanners

Fan/Line beam scanners-Translate Line scanners are the first generation of industrial CT Scanners. X-rays are produced and the beam is collimated to create a line. The X-ray line beam is then translated across the part and data is collected by the detector. The data is then reconstructed to create a 3-D Volume rendering of the part.
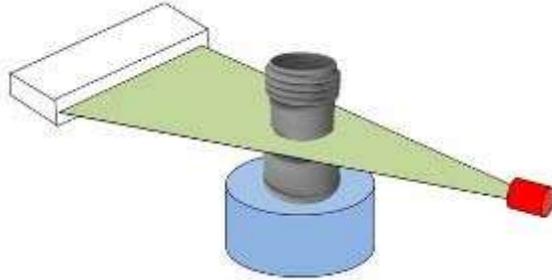
Cone beam scanners-Rotate

During the CT scan the part is placed on a rotary table. As the part rotates the cone of X-rays produce about 1300 2D images which are collected by the detector. The 2D images are then processed to create a 3D Volume rendering of the external and internal geometries of the part.
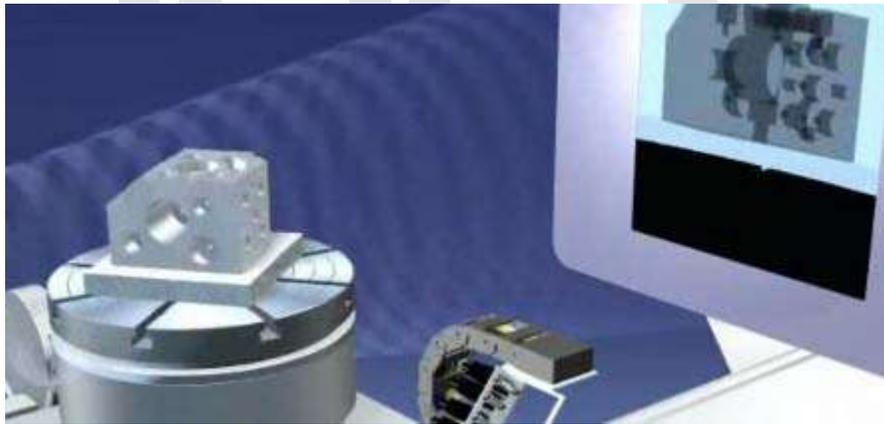
History

Industrial CT scanning technology was introduced in 1972 with the invention of the CT scanner by G. Hounsfield. The invention earned him a Nobel Prize in medicine, which he shared with Allan Cormack.

Many advances in CT scanning have allowed for its use in the industrial field for metrology in addition to the visual inspection primarily used in the medical field.(medical CT scan)

Analysis/Inspection Techniques Using Industrial CT Scanning
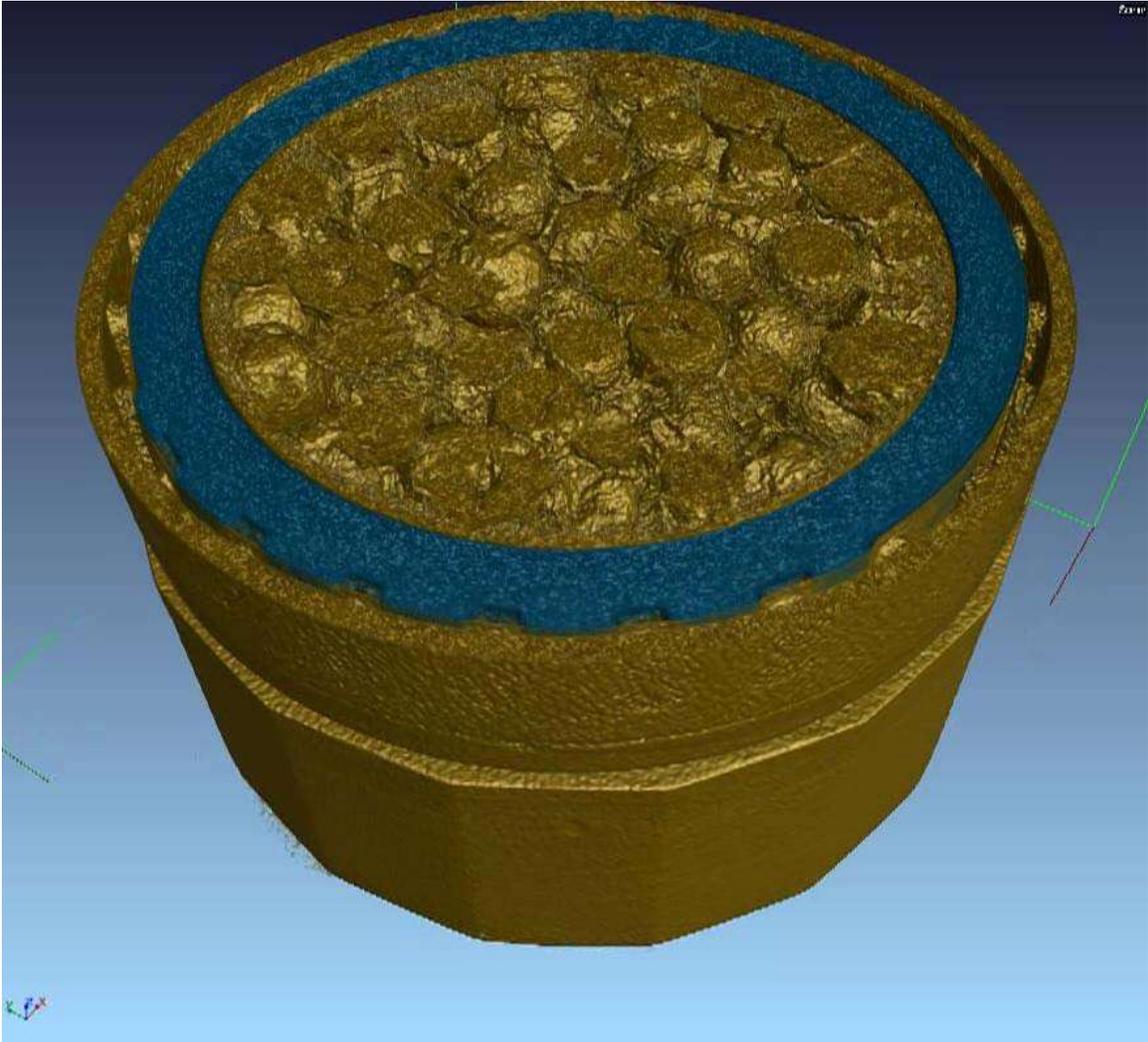
Various inspection techniques include:

Part to CAD comparisons, part to part comparisons, assembly / defect analysis, void analysis, wall thickness analysis, and generation of CAD data for reverse engineering requirements and GD&T (geometric dimensioning and tolerance) analysis to meet PPAP (production part approval process) requirements.
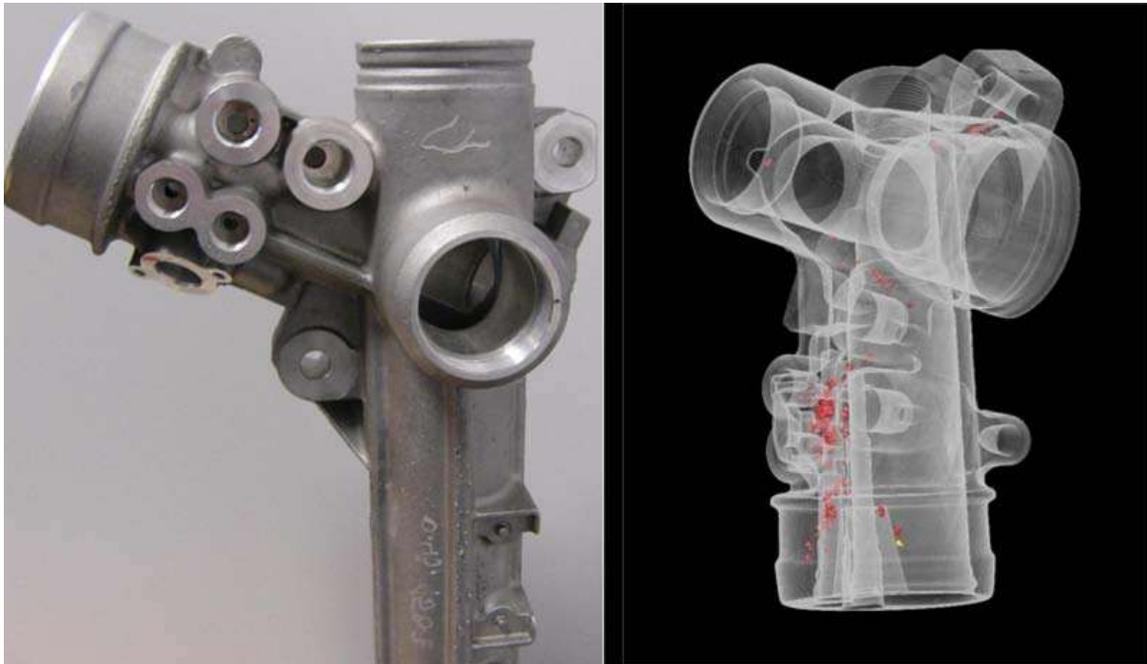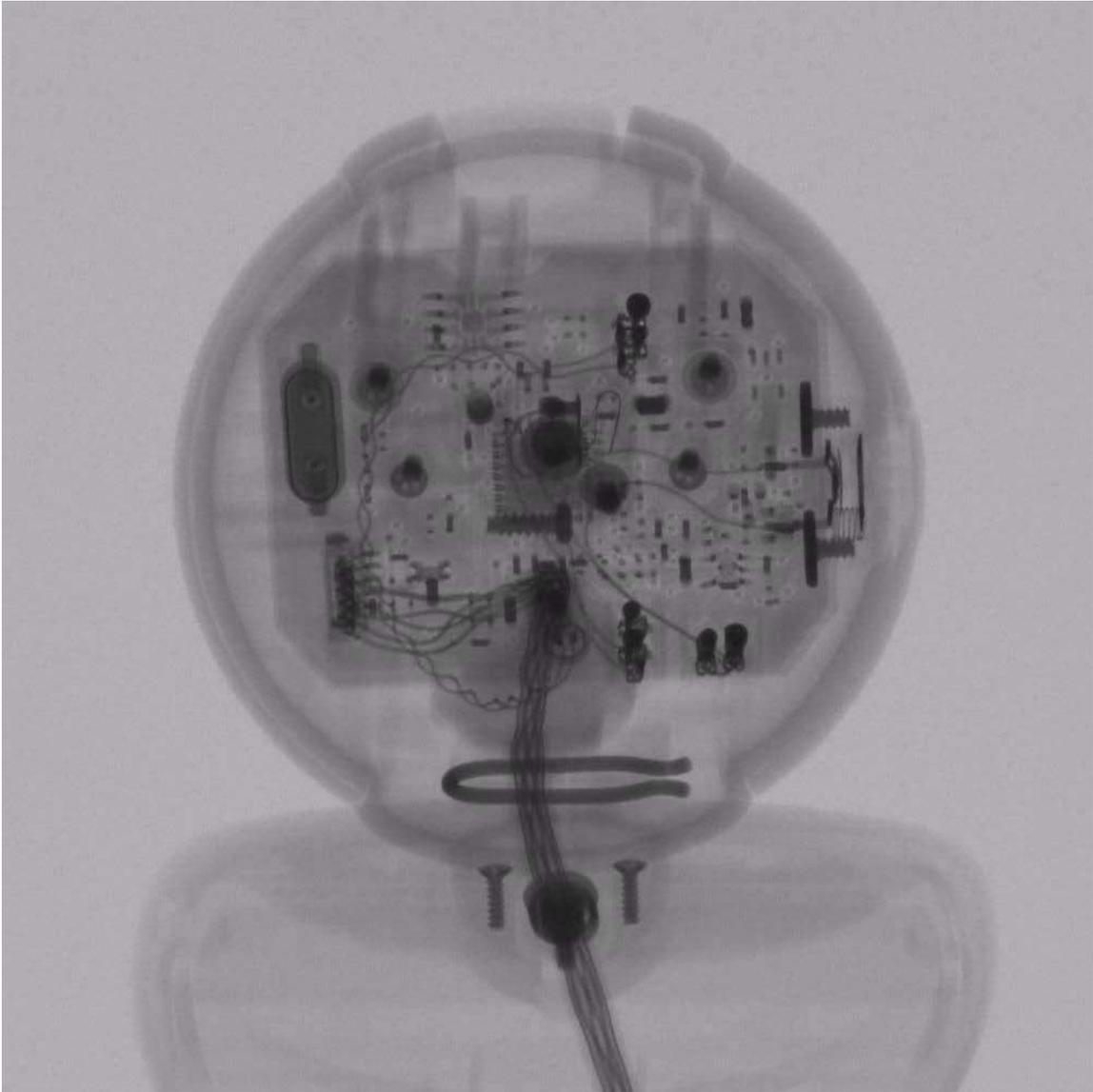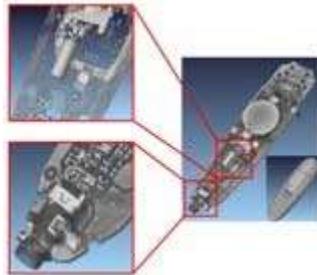
Flight through a 3D reconstruction of a disposable pepper grinder. Glass in blue

CT transmission images of a Logitech C500 webcam.

Assembly

One of the most recognized forms of analysis using CT is assembly or visual analysis. CT scanning has been largely used for medical purposes as an imaging tool to supplement medical ultrasonography and X-rays as well as for screening for disease and preventative medicine. For industrial CT scanning, the ability to see inside a component is beneficial since internal components can be seen in their functioning position. Also, devices can be analyzed without disassembly. Some software programs for industrial CT scanning allow for measurements to be taken from the CT dataset volume rendering. These measurements are useful for determining the clearances between assembled parts or simply a dimension of an individual feature.

Part comparisons (part to part or part to CAD)
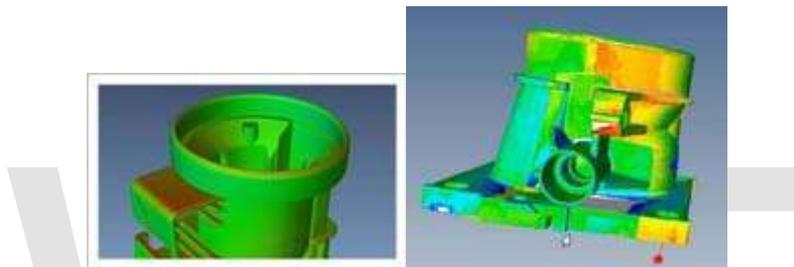
In today's market parts can be manufactured around the world: designed in one country, machined in another and assembled in a third. Verification of the part to the original CAD design is critical, especially if the part is to be used in an assembly. Industrial computed tomography allows for a comparison of parts to one another or parts to CAD data. The deviations for both external and internal geometries can be shown on the surface colour map chromatically on the 3D representation or by whisker plots in the 2D windows. This process is beneficial when comparing the same part from various suppliers, studying the differences in parts from one cavity to another cavity from the same mould, or verifying the design to the part.

Void analysis

Traditionally, determining an object's porosity would require destructive testing. CT scanning can detect internal features and flaws without destroying the part. Industrial CT scanning (3D X-ray) is used to detect flaws inside a part such as porosity, an inclusion, or a crack before a failure can occur. In some software programs the porosity within a part is categorized by colour based on their respective sizes.

Metal casting and moulded plastic components are typically prone to porosity because of cooling processes, transitions between thick and thin walls, and material properties. Void analysis can be used to locate, measure, and analyze voids inside plastic or metal components.

Generation of CAD data for reverse engineering requirements

A CAD file can be generated from the CT data set, which is particularly useful in reverse engineering applications and product development. Exported CAD file formats are recognized by many software such as CAD, FEA, Fluid Dynamics and Mold Flow software. The CAD file created by CT scanning not only shows the external components, but the internal as well. This allows for first-time rapid prototyping of internal components without the daunting task of creating an entirely new CAD file.

GD&T (Geometric dimensioning and tolerancing) analysis to meet PPAP (Production Part Approval Process) requirements

Traditionally, without destructive testing, full metrology has only been performed on the exterior dimensions of components. If a highly detailed component requires inspection, the conventional method of inspection would be to fixture the part to create specified datum reference plane and go through a timely CMM touch-probe inspection process or use a vision system to map exterior surfaces. Past internal inspection methods would require using a 2D X-ray of the component or the use of destructive testing. Industrial CT scanning allows for full metrology of the CT datasets allowing for an analysis of GD&T points to meet the PPAP requirement.

Chapter-9

Radiographic Testing and Phased Array Ultrasonics

Radiographic testing

Radiographic Testing (RT), or **industrial radiography**, is a nondestructive testing (NDT) method of inspecting materials for hidden flaws by using the ability of short wavelength electromagnetic radiation (high energy photons) to penetrate various materials.

Either an X-ray machine or a radioactive source (Ir-192, Co-60, or in rare cases Cs-137) can be used as a source of photons. Neutron radiographic testing (NR) is a variant of radiographic testing which uses neutrons instead of photons to penetrate materials. This can see very different things from X-rays, because neutrons can pass with ease through lead and steel but are stopped by plastics, water and oils.

Since the amount of radiation emerging from the opposite side of the material can be detected and measured, variations in this amount (or intensity) of radiation are used to determine thickness or composition of material. Penetrating radiations are those restricted to that part of the electromagnetic spectrum of wavelength less than about 10 nanometres.

Inspection of welds

The beam of radiation must be directed to the middle of the section under examination and must be normal to the material surface at that point, except in special techniques where known defects are best revealed by a different alignment of the beam. The length of weld under examination for each exposure shall be such that the thickness of the material at the diagnostic extremities, measured in the direction of the incident beam, does not exceed the actual thickness at that point by more than 6%. The specimen to be inspected is placed between the source of radiation and the detecting device, usually the film in a light tight holder or cassette, and the radiation is allowed to penetrate the part for the required length of time to be adequately recorded.

The result is a two-dimensional projection of the part onto the film, producing a latent image of varying densities according to the amount of radiation reaching each area. It is known as a radiograph, as distinct from a photograph produced by light. Because film is cumulative in its response (the exposure increasing as it absorbs more radiation), relatively weak radiation can be detected by prolonging the exposure until the film can record an image that will be visible after development. The radiograph is examined as a negative, without printing as a positive as in photography. This is because, in printing, some of the detail is always lost and no useful purpose is served.

Before commencing a radiographic examination, it is always advisable to examine the component with one's own eyes, to eliminate any possible external defects. If the surface of a weld is too irregular, it may be desirable to grind it to obtain a smooth finish, but this is likely to be limited to those cases in which the surface irregularities (which will be visible on the radiograph) may make detecting internal defects difficult.

After this visual examination, the operator will have a clear idea of the possibilities of access to the two faces of the weld, which is important both for the setting up of the equipment and for the choice of the most appropriate technique.

Defects such as delaminations and planar cracks are difficult to detect using radiography, which is why penetrants are often used to enhance the contrast in the detection of such defects. Penetrants used include silver nitrate, zinc iodide, chloroform and diiodomethane. Choice of the penetrant is determined by the ease with which it can penetrate the cracks and also with which it can be removed. Diiodomethane has the advantages of high opacity, ease of penetration, and ease of removal because it evaporates relatively quickly. However, it can cause skin burns.

Safety

Industrial radiography appears to have one of the worst safety profiles of the radiation professions, possibly because there are many operators using strong gamma sources (> 2 Ci) in remote sites with little supervision when compared with workers within the nuclear industry or within hospitals.

Phased array ultrasonics
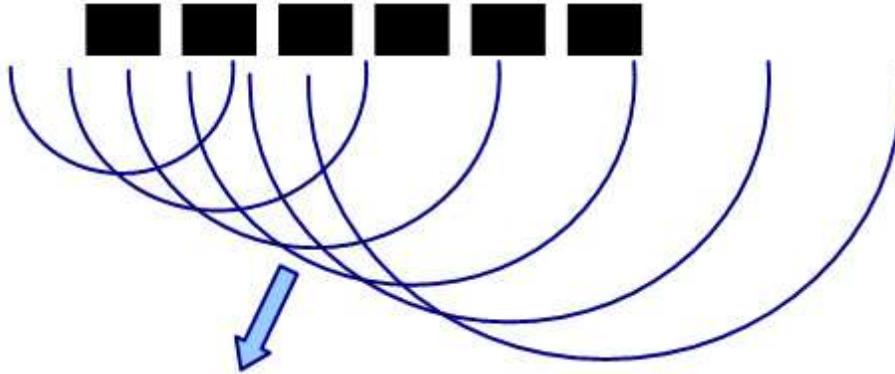
Principle of operation of phased array (PA). The PA probe consists of many small elements, each of which can be pulsed separately. In the figure the element on the right is pulsed first, and emits a pressure wave that spreads out like a ripple on a pond (largest semicircle). The second to right element is pulsed next, and emits a ripple that is slightly smaller than the first because it was started later. The process continues down the line until all the elements have been pulsed. The multiple waves add up to one single wave front travelling at a set angle. In other words, the beam angle can be set just by programming the pulse timings.
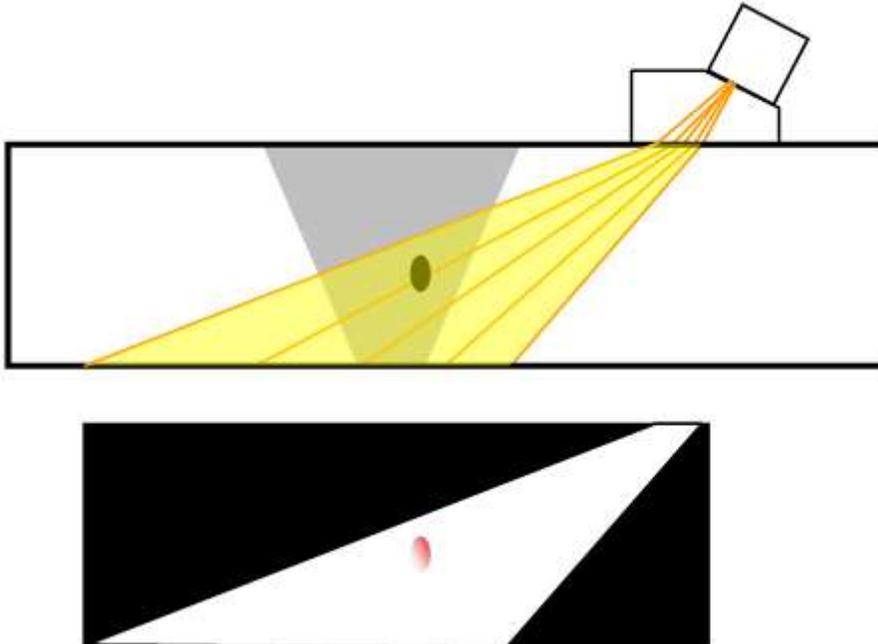
Weld examination by phased array. TOP: The phased array probe emits a series of beams to flood the weld with sound. BOTTOM: The flaw in the weld appears as a red indication on the instrument screen.

Phased Array (PA) ultrasonics is an advanced method of ultrasonic testing that has applications in medical imaging and industrial nondestructive testing. In medicine a common application of phased array is the imaging of the heart (images of the fetus in the womb are usually made by curvilinear array, a multi-element probe that does not actually phase the signals). When applied to metals the PA image shows a slice view that may reveal defects hidden inside a structure or weld.

Principle of operation

The PA probe consists of many small ultrasonic elements, each of which can be pulsed individually. By varying the timing, for instance by pulsing the elements one by one in sequence along a row, a pattern of constructive interference is set up that results in a beam at a set angle. In other words, the beam can be steered electronically. The beam is swept like a search-light through the tissue or object being examined, and the data from multiple beams are put together to make a visual image showing a slice through the object.

Features of phased array

- The method most commonly used for medical ultrasonography.
- Multiple probe elements produce a steerable, tightly focused, high-resolution beam.
- Produces an image that shows a slice through the object.
- Compared to conventional, single-element ultrasonic inspection systems, PA instruments and probes are more complex and expensive.
- In industry, PA technicians require more experience and training than conventional technicians.

At a construction site, a technician tests a pipeline weld for defects using an ultrasonic phased array instrument. The scanner, which consists of a frame with magnetic wheels, holds the probe in contact with the pipe by a spring. The wet area is the ultrasonic couplant that allows the sound to pass into the pipe wall.

Chapter-10

Magnetic Flux Leakage & Infrared and Thermal Testing

Magnetic flux leakage

Magnetic flux leakage (**MFL**) is a magnetic method of nondestructive testing that is used to detect corrosion and pitting in steel structures, most commonly pipelines and storage tanks. The basic principle is that a powerful magnet is used to magnetize the steel. At areas where there is corrosion or missing metal, the magnetic field "leaks" from the steel. In an MFL tool, a magnetic detector is placed between the poles of the magnet to detect the leakage field. Analysts interpret the chart recording of the leakage field to identify damaged areas and hopefully to estimate the depth of metal loss.

Introduction to pipeline examination

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

The reliable supply and transportation of product in a safe and cost-effective manner is a primary goal of most pipeline operating companies and managing the integrity of the pipeline is paramount in maintaining this objective. In-line-inspection programs are one of the most effective means of obtaining data that can be used as a fundamental base for

an Integrity Management Program. There are many types of ILI tools that detect various pipeline defects, but high-resolution MFL tools are becoming more prevalent as its applications are surpassing those to which it was originally designed. Originally designed for detecting areas of metal loss, the modern High Resolution MFL tool is proving to be able to accurately assess the severity of corrosion features, define dents, wrinkles, buckles, and, in some cases, cracks. Having a device that can perform simultaneous tasks reliably is more efficient and ultimately provides cost saving benefits.

MFL pipeline inspection tools

In the field, a device that travels inside a pipeline to clean or inspect it is typically known as a "PIG". There is no history to back up this term as an acronym as it was first derived from the squealing pig-like sound made as the tool passed by. In some countries a pig is known as a "Diablo", literally translated to mean "the Devil" relating to the shuddering sound the tool would make as it passed beneath people's feet. The pigs are built to match the diameter of a pipeline and use the very product being carried to end users to transport them. Pigs have been used in pipelines for many years and have many uses. Some separate one product from another, some clean and some inspect. An MFL tool is known as an "intelligent" or "smart" inspection pig because it contains electronics and collects data real-time while travelling through the pipeline. Sophisticated electronics on board allow this tool to accurately detect features as small as 1 cm by 1 cm.

Typically, an MFL tool consists of two or more bodies. One body is the magnetizer with the magnets and sensors and the other bodies contain the electronics and batteries. The magnetizer body houses the sensors that are located between powerful "rare-earth" magnets. The magnets are mounted between the brushes and tool body to create a magnetic circuit along with the pipe wall. As the tool travels along the pipe, the sensors detect interruptions in the magnetic circuit. Interruptions are typically caused by metal loss and which in most cases is corrosion. Mechanical damage such as shovel gouges can also be detected. The metal loss in a magnetic circuit is analogous to a rock in a stream. Magnetism needs metal to flow and in the absence of it, the flow of magnetism will go around, over or under to maintain its relative path from one magnet to another, similar to the flow of water around a rock in a stream. The sensors detect the changes in the magnetic field in the three directions (axial ,radial, or circumferential) to characterize the anomaly. An MFL tool can take sensor readings based on either the distance the tool travels or on increments of time. The choice depends on many factors such as the length of the run, the speed that the tool intends to travel, and the number of stops or outages that the tool may experience.

The second body is called an Electronics Can. This section can be split into a number of bodies depending on the size of the tool. This can, as the name suggests, contains the electronics or "brains" of the smart pig. The Electronics Can also contains the batteries and is some cases an IMU (Inertial Measurement Unit) to tie location information to GPS coordinates. On the very rear of the tool are odometer wheels that travel along the inside of the pipeline to measure the distance and speed of the tool.

MFL principle

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

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

Signal analysis

The primary purpose of an MFL tool is to detect corrosion in a pipeline. To more accurately predict the dimensions (length, width and depth) of a corrosion feature, extensive testing is performed before the tool enters an operational pipeline. Using a known collection of measured defects, tools can be trained and tested to accurately interpret MFL signals. Defects can be simulated using a variety of methods.

Creating and therefore knowing the actual dimensions of a feature makes it relatively easy to make simple correlations of signals to actual anomalies found in a pipeline. When signals in an actual pipeline inspection have similar characteristics to the signals found during testing it is logical to assume that the features would be similar. The algorithms and neural nets designed for calculating the dimensions of a corrosion feature are complicated and often they are closely guarded trade secrets. An anomaly is often reported in a simplified fashion as a cubic feature with an estimated length, width and depth. In this way, the effective area of metal loss can be calculated and used in acknowledged formulas to predict the estimated burst pressure of the pipe due to the detected anomaly.

Another important factor in the ongoing improvement of sizing algorithms is customer feedback to the ILI vendors. Every anomaly in a pipeline is unique and it is impossible to replicate in the shop what exists in all cases in the field. Open lines of communication

usually exist between the inspection companies and the pipeline operators as to what was reported and what was actually visually observed in an excavation.

After an inspection, the collected data is downloaded and compiled so that an analyst is able to accurately interpret the collected signals. Most pipeline inspection companies have proprietary software designed to view their own tool's collected data. The three components of the MFL vector field are viewed independently and collectively to identify and classify corrosion features. Metal loss features have unique signals that analysts are trained to identify.

Estimation of corrosion growth rate

High-resolution MFL tools collect data approximately every 2 mm along the axis of a pipe and this superior resolution allows for a comprehensive analysis of collected signals. Pipeline Integrity Management programs have specific intervals for inspecting pipeline segments and by employing high-resolution MFL tools an exceptional corrosion growth analysis can be conducted. This type of analysis proves extremely useful in forecasting the inspection intervals.

Other features that an MFL tool can identify

Although primarily used to detect corrosion, MFL tools can also be used to detect features that they were not originally designed to identify. When an MFL tool encounters a geometric deformity such as a dent, wrinkle or buckle, a very distinct signal is created due to the plastic deformation of the pipe wall.

Crack detection

There are cases where large non-axial oriented cracks have been found in a pipeline that was inspected by a magnetic flux leakage tool. To an experienced MFL data analyst, a dent is easily recognizable by trademark "horseshoe" signal in the radial component of the vector field. What is not easily identifiable to an MFL tool is the signature that a crack leaves.

Summary

MFL technology has evolved to a state that now makes it an integral part of any cost effective pipeline integrity program. Although high-resolution MFL tools are designed to successfully detect, locate and characterize corrosion, a pipeline operator should not dismiss the ability of an MFL tool to identify and characterize dents, wrinkles, corrosion growth, mechanical damage and even some cracks.

Infrared and thermal testing

Infrared and thermal testing is one of many Nondestructive testing techniques designated by the American Society for Nondestructive Testing (ASNT). Infrared Thermography is the science of measuring and mapping surface temperatures.

"Infrared thermography, a nondestructive, remote sensing technique, has proved to be an effective, convenient, and economical method of testing concrete. 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. As a testing technique, some of its most important qualities are that (1) it is accurate; (2) it is repeatable; (3) it need not inconvenience the public; and (4) it is economical."

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. Infrared thermographic testing may be performed during day or night, depending on environmental conditions and the desired results.

All objects emit electromagnetic radiation of a wavelength dependent on the object's temperature. The frequency of the radiation is inversely proportional to the temperature. 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 & white computer display monitor.

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. These "hot spots" are usually measured in the range of 40 °C to 150 °C (70 to 270 °F) above ambient temperatures. But, when engineers use its patented proprietary systems to locate subsurface targets such as Underground Storage Tanks (USTs), pipelines, pipeline leaks and their plumes, and in this project, hidden tunnels, we are looking for temperature patterns typically in the range of 0.01 °C to 1 °C above or below ambient temperatures.

After the thermal data is processed, it can be displayed on a monitor in multiple shades of gray scale or color. The colors displayed on the thermogram are arbitrarily set by the Thermographer to best illustrate the infrared data being analyzed.

In this roofing investigation application, infrared thermographic data was collected during daytime hours, on both sunny and rainy days. This data collection time allowed for solar heating of the roof, and any entrapped water within the roofing system, during the daylight hours. IR data was observed until the roof had sufficiently warmed to allow detection of the entrapped wet areas because of their ability to collect and store more heat than the dry insulated areas. The wet areas would also transfer the heat at a faster rate than the dry insulated roof areas. At this point in time, the wet areas showed up as warmer roof surface temperatures than the surrounding dry background areas of the roof.

During the rainy day, with minimum solar loading, any entrapped leak plumes would become evident because of their cooler temperature as compared to the dry roof areas

An infrared thermographic scanning system measures surface temperatures only. But the surface temperatures that are measured on the surface of the ground, above a buried pipeline, are, to a great extent, dependent upon the subsurface conditions.

The subsurface configuration effects are based upon the theory that energy cannot be stopped from flowing from warmer to cooler areas, it can only be slowed down by the insulating effects of the material through which it is flowing. Various types of construction materials have different insulating abilities. In addition, differing types of pipeline defects have different insulating values.

Background

There are three ways of transferring energy: 1) conduction; 2) convection; and 3) radiation. Good solid backfill should have the least resistance to conduction of energy and the convection gas radiation effects should be negligible. The various types of problems associated with soil erosion and poor backfill surrounding buried pipelines increase the insulating ability of the soil, by reducing the energy conduction properties, without substantially increasing the convection effects. This is because dead air spaces do not allow the formation of convection currents.

In order to have an energy flow, there must be an energy source. Since buried pipeline testing can involve large areas, the heat source has to be low cost and able to give the ground surface above the pipeline an even distribution of heat. The sun fulfills both of these requirements. The ground surface reacts, storing or transmitting the energy received.

Pipeline testing

For pipelines carrying fluids at temperatures above or below the ambient ground temperatures (i.e., steam, oil, liquefied gases, or chemicals), an alternative is to use the heat sinking ability of the earth to draw heat from the pipeline under test. The crucial point to remember is that the energy must be flowing through the ground and fluids.

Ground cover must be evaluated for temperature differentials (i.e., anomalies such as high grass or surface debris), as to how it may effect the surface condition of the test area. Of the three methods of energy transfer, radiation is the method that has the most profound effect upon the ability of the surface to transfer energy. The ability of a material to radiate energy is measured by the emissivity of the material. This is defined as the ability of the material to release energy as compared to a perfect blackbody radiator. This is strictly a surface property. It normally exhibits itself in higher values for rough surfaces and lower values for smooth surfaces. For example, rough concrete may have an emissivity of 0.95 while a shiny piece of tinfoil may have an emissivity of only 0.05. In practical terms, this means that when looking at large areas of ground cover, the engineer

in charge of testing must be aware of differing surface textures caused by such things as broom roughed spots, tire rubber tracks, oil spots, loose sand and dirt on the surface and the height of grassy areas.

Chapter-11

Automatic Test Equipment

Automatic or **Automated Test Equipment** (**ATE**) is any apparatus that performs tests on a device, known as the Device Under Test (DUT), using automation to quickly perform measurements and evaluate the test results. An ATE can be a simple computer controlled digital multimeter, or a complicated system containing dozens of complex test instruments (real or simulated electronic test equipment) capable of automatically testing and diagnosing faults in sophisticated electronic packaged parts or on Wafer testing, including System-On-Chips and Integrated circuits.

Keithley Instruments Series 4200 CVU

Where ATE is Used

ATE is widely used in the electronic manufacturing industry to test electronic components and systems after being fabricated. ATE is also used to test avionics and the electronic modules in automobiles. It is used in military applications like radar and wireless communication.

ATE in the Semiconductor Industry

Semiconductor ATE, named for testing semiconductor devices, can test a wide range of electronic devices and systems, from simple components (resistors, capacitors, and inductors) to integrated circuits (ICs), printed circuit boards (PCBs), and complex, completely-assembled electronic systems. ATE systems are designed to reduce the amount of test time needed to verify that a particular device works or to quickly find its faults before the part has a chance to be used in a final consumer product. To reduce manufacturing costs and improve yield, semiconductor devices should to be tested after being fabricated to prevent even a small number of defective devices ending up with consumer.

Components of ATE

The Semiconductor ATE architecture consists of master controller (usually a computer) that synchronizes one or more source and capture instruments (listed below). Historically, custom-designed controllers or relays were used by ATE systems. The Device Under Test (DUT) is physically connected to the ATE by another robotic machine called a Handler or Prober and through a customized Interface Test Adapter (ITA) or "fixture" that adapts the ATE's resources to the DUT.

Industrial PC

The Industrial PC is nothing but a normal desktop computer packaged in 19-inch rack standards with sufficient PCI / PCIe slots for accommodating the Signal simulator/sensing cards. This takes up the role of a controller in the ATE. Development of test applications and result storage is managed in this PC. Most modern semiconductor ATEs include multiple computer controlled instruments to source or measure a wide range of parameters. The instruments may include Digital Power Supplies (DPS), Parametric Measurement Units (PMU), Arbitrary Waveform Generators (AWG), Digitizers, Digital IOs, and utility supplies. The instruments perform different measurements on the DUT, and the instruments are synchronized so that they source and measure waveforms at the proper times. Based on the requirement of response-time, real-time systems are also considered for simulation and signal capturing.

Mass interconnect

The Mass interconnect is a connector interface between test instruments (PXI, VXI, LXI, GPIB, SCXI, & PCI) and devices/units under test (D/UUT). This section acts as a nodal point for signals going in/out between ATE and D/UUT.

Example: Simple Voltage Measurement

For example, to measure a voltage of a particular semiconductor device, the Digital Signal Processing instruments in the ATE measure the voltage directly and send the results to a computer for signal processing, where the desired value is computed. This

example shows that conventional instruments, like a Ammeter, may not be used in many ATEs due to the limited number of measurements the instrument could make, and the time it would take to use the instruments to make the measurement. One key advantage to using DSP to measure the parameters is time. If we have to calculate the peak voltage of an electrical signal and other parameters of the signal, then we have to employ a peak detector instruments as well as other instruments to test the other parameters. If DSP-based instruments are used, however, then a sample of the signal is made and the other parameters can be computed from the single measurement.

Test Parameter Requirements vs Test Time

Not all devices are tested equally. Testing adds costs, so low cost components are rarely tested completely, whereas medical or high costs components (where reliability is important) are frequently tested.

But testing the device for all parameters may or may not be required depending on the device functionality and end user. For example if the device finds application in medical or life saving products then many of its parameters must be tested, and some of the parameters must be guaranteed. But deciding on the parameters to be tested is a complex decision based on cost vs yield. If the device is a complex digital device, with thousands of gates, then test fault coverage has to be calculated. Here again the decision is complex based on test economics, based on frequency, number and type of I/Os in the device and the end-use application.

Handler or Prober and Device Test Adapter

ATE can be used on packaged parts (typical IC 'chip') or directly on the Silicon Wafer. Packaged parts use a handler to place the device on a customized interface board, whereas silicon wafers are tested directly with high precision probes. The ATE systems interact with the handler or prober to test the DUT.

Packaged Part ATE with Handlers

ATE systems typically interface with an automated placement tool, called a "handler", that physically places the Device Under Test (DUT) on an Interface Test Adapter (ITA) so that it can be measured by the equipment. There may also be an Interface Test Adapter (ITA), a device just making electronic connections between the ATE and the Device Under Test (also called Unit Under Test or UUT), but also it might contain an additional circuitry to adapt signals between the ATE and the DUT and has physical facilities to mount the DUT. Finally, a socket is used to bridge the connection between the ITA and the DUT. A socket must survive the rigorous demands of a production floor, so they are usually replaced frequently.

Simple electrical interface diagram: ATE -> ITA -> DUT (package) <- Handler

Silicon Wafer ATE with Probers

Wafer based ATEs typically use a device called a Prober that moves across a silicon wafer to test the device.

Simple electrical interface diagram: ATE -> Prober -> Wafer (DUT)

Multi-site

One way to improve test time is to test multiple devices at once. ATE systems can now support having multiple "sites" where the ATE resources are shared by each site. Some resources can be used in parallel, others must be serialized to each DUT.

Programming ATE

The ATE computer uses modern computer languages (like C, C++, Java, LabVIEW or Smalltalk) with additional statements to control the ATE equipment through standard and proprietary Application Programming Interfaces (API). Also some dedicated computer languages exists, like Abbreviated Test Language for All Systems (ATLAS). Automatic test equipment can also be automated using a Test execution engine such as National Instruments' TestStand, and Hiatronics' Hiatronic Development Suite.

Test Data (STDF)

Many ATE platforms used in the semiconductor industry output data using Standard Test Data Format (STDF)

ATE Diagnostics

Automatic test equipment diagnostics is the part of an ATE test that determines the faulty components. ATE tests perform two basic functions. The first is to test whether or not the Device Under Test is working correctly. The second is when the DUT is not working correctly, to diagnose the reason. The diagnostic portion can be the most difficult and costly portion of the test. It is typical for ATE to reduce a failure to a cluster or ambiguity group of components. One method to help reduce these ambiguity groups is the addition of analog signature analysis testing to the ATE system. Diagnostics are often aided by the use of flying probe testing.

Test Equipment Switching

The addition of a high-speed switching system to a test system's configuration allows for faster, more cost-effective testing of multiple devices, and is designed to reduce both test errors and costs. Designing a test system's switching configuration requires an understanding of the signals to be switched and the tests to be performed, as well as the switching hardware form factors available.

Test Equipment Platforms

Several modular electronic instrumentation platforms are currently in common use for configuring automated electronic test and measurement systems. These systems are widely employed for incoming inspection, quality assurance, and production testing of electronic devices and subassemblies. Industry-standard communication interfaces link signal sources with measurement instruments in "rack-and-stack" or chassis-/mainframe-based systems, often under the control of a custom software application running on an external PC.

GPIB/IEEE-488

The General Purpose Interface Bus (GPIB) is an IEEE-488 (a standard created by the Institute of Electrical and Electronics Engineers) standard parallel interface used for attaching sensors and programmable instruments to a computer. GPIB is a digital 8-bit parallel communications interface capable of achieving data transfers of more than 8 Mbytes/s. It allows daisy-chaining up to 14 instruments to a system controller using a 24-pin connector. It is one of the most common I/O interfaces present in instruments and is designed specifically for instrument control applications. The IEEE-488 specifications standardized this bus and defined its electrical, mechanical, and functional specifications, while also defining its basic software communication rules. GPIB works best for applications in industrial settings that require a rugged connection for instrument control.

The original GPIB standard was developed in the late 1960s by Hewlett-Packard to connect and control the programmable instruments the company manufactured. The introduction of digital controllers and programmable test equipment created a need for a standard, high-speed interface for communication between instruments and controllers from various vendors. In 1975, the IEEE published ANSI/IEEE Standard 488-1975, IEEE Standard Digital Interface for Programmable Instrumentation, which contained the electrical, mechanical, and functional specifications of an interfacing system. This standard was subsequently revised in 1978 (IEEE-488.1) and 1990 (IEEE-488.2). The IEEE 488.2 specification includes the Standard Commands for Programmable Instrumentation (SCPI), which define specific commands that each instrument class must obey. SCPI ensures compatibility and configurability among these instruments.

The IEEE-488 bus has long been popular because it is simple to use and takes advantage of a large selection of programmable instruments and stimuli. Large systems, however, have the following limitations:

- **Driver fanout** capacity limits the system to 14 devices plus a controller.
- **Cable length** limits the controller-device distance to two meters per device or 20 meters total, whichever is less. This imposes transmission problems on systems spread out in a room or on systems that require remote measurements.
- **Primary addresses** limit the system to 30 devices with primary addresses. Modern instruments rarely use secondary addresses so this puts a 30-device limit on system size.

LAN eXtensions for Instrumentation (LXI)

The LXI Standard defines the communication protocols for instrumentation and data acquisition systems using Ethernet. These systems are based on small, modular instruments, using low-cost, open-standard LAN (Ethernet). LXI-compliant instruments offer the size and integration advantages of modular instruments without the cost and form factor constraints of card-cage architectures. Through the use of Ethernet communications, the LXI Standard allows for flexible packaging, high-speed I/O, and standardized use of LAN connectivity in a broad range of commercial, industrial, aerospace, and military applications. Every LXI-compliant instrument includes an Interchangeable Virtual Instrument (IVI) driver to simplify communication with non-LXI instruments, so LXI-compliant devices can communicate with devices that are not themselves LXI compliant (i.e., instruments that employ GPIB, VXI, PXI, etc.). This simplifies building and operating hybrid configurations of instruments.

LXI instruments sometimes employ scripting using embedded test script processors for configuring test and measurement applications. Script-based instruments provide architectural flexibility, improved performance, and lower cost for many applications. Scripting enhances the benefits of LXI instruments, and LXI offers features that both enable and enhance scripting. Although the current LXI standards for instrumentation do not require that instruments be programmable or implement scripting, several features in the LXI specification anticipate programmable instruments and provide useful functionality that enhances scripting's capabilities on LXI-compliant instruments.

VME eXtensions for Instrumentation (VXI)

The VXI bus architecture is an open standard platform for automated test based on the VMEbus. Introduced in 1987, VXI uses all Eurocard form factors and adds trigger lines, a local bus, and other functions suited for measurement applications. VXI systems are based on a mainframe or chassis with up to 13 slots into which various VXI instrument modules can be installed. The chassis also provides all the power supply and cooling requirements for the chassis and the instruments it contains. VXI bus modules are typically 6U in height.

PCI eXtensions for Instrumentation (PXI)

PXI is a peripheral bus specialized for data acquisition and real-time control systems. Introduced in 1997, PXI uses the CompactPCI 3U and 6U form factors and adds trigger lines, a local bus, and other functions suited for measurement applications. PXI hardware and software specifications are developed and maintained by the PXI Systems Alliance. More than 50 manufacturers around the world produce PXI hardware.

Universal Serial Bus (USB)

The USB connects peripheral devices, such as keyboards and mice, to PCs. The USB is a Plug and Play bus that can handle up to 127 devices on one port, and has a theoretical

maximum throughput of 480 Mb/s (high-speed USB defined by the USB 2.0 specification). Because USB ports are standard features of PCs, they are a natural evolution of conventional serial port technology. However, it is not widely used in building industrial test and measurement systems for a number of reasons; for example, USB cables are not industrial grade, are noise sensitive, can accidentally become detached, and the maximum distance between the controller and the device is 30 m. Like RS-232, USB is useful for applications in a laboratory setting that do not require a rugged bus connection.

RS-232

RS-232 is a specification for serial communication that is popular in analytical and scientific instruments, as well for controlling peripherals such as printers. Unlike GPIB, with the RS-232 interface, it is possible to connect and control only one device at a time. RS-232 is also a relatively slow interface with typical data rates of less than 20 kbytes/s. RS-232 is best suited for laboratory applications compatible with a slower, less rugged connection.

Test Script Processors and a Channel Expansion Bus

One of the most recently developed test system platforms employs instrumentation equipped with onboard test script processors combined with a high-speed bus. In this approach, one "master" instrument runs a test script (a small program) that controls the operation of the various "slave" instruments in the test system, to which it is linked via a high-speed LAN-based trigger synchronization and inter-unit communication bus. Scripting is writing programs in a scripting language to coordinate a sequence of actions.

This approach is optimized for small message transfers that are characteristic of test and measurement applications. With very little network overhead and a 100Mbit/sec data rate, it is significantly faster than GPIB and 100BaseT Ethernet in real applications.

The advantage of this platform is that all connected instruments behave as one tightly integrated multi-channel system, so users can scale their test system to fit their required channel counts cost-effectively. A system configured on this type of platform can stand alone as a complete measurement and automation solution, with the master unit controlling sourcing, measuring, pass/fail decisions, test sequence flow control, binning, and the component handler or prober. Support for dedicated trigger lines means that synchronous operations between multiple instruments equipped with onboard Test Script Processors that are linked by this high speed bus can be achieved without the need for additional trigger connections.

Chapter-12

Check Weigher and Shearography

Check weigher

Example checkweigher. Product passes on the conveyor belt where it is weighed

A **checkweigher** is an automatic machine for checking the weight of packaged commodities. It is normally found at the offgoing end of a production process and is used to ensure that the weight of a pack of the commodity is within specified limits. Any packs that are outside the tolerance are taken out of line automatically.

A checkweigher can weigh in excess of 500 items per minute (depending on carton size and accuracy requirements).

Checkweighers often incorporate additional checking devices such as metal detectors and X-ray machines to enable other attributes of the pack to be checked and acted upon accordingly.

A typical machine

A checkweigher incorporates a series of conveyor belts. Checkweighers are known also as belt weighers, in-motion scales, conveyor scales, dynamic scales, and in-line scales. In filler applications, they are known as check scales. Typically, there are three belts or chain beds:

- An infeed belt that may change the speed of the package and to bring it up or down to a speed required for weighing. The infeed is also sometimes used as an indexer, which sets the gap between products to an optimal distance for weighing. It sometimes has special belts or chains to position the product for weighing.

- A weigh belt. This is typically mounted on a weight transducer which can typically be a strain-gauge load cell or a servo-balance (also known as a force-balance), or sometimes known as a split-beam. Some older machines may pause the weigh bed belt before taking the weight measurement. This may limit line speed and throughput.

- A reject belt that provides a method of removing an out-of-tolerance package from the conveyor line. The reject can vary by application. Some require an air-amplifier to blow small products off the belt, but heavier applications require a linear or radial actuator. Some fragile products are rejected by "dropping" the bed so that the product can slide gently into a bin or other conveyor.

For high-speed precision scales, a load cell using electromagnetic force restoration(EMFR) is appropriate. This kind of system charges an inductive coil, effectively floating the weigh bed in an electromagnetic field. When the weight is added, the movement of a ferrous material through that coil causes a loss of ElectroMagnetic Force. A precision circuit charges the coil back to its original charge. The amount added to the coil is precisely measured. The voltage produced is filtered and sampled into digital data. That voltage is then passed through a Digital Signal Processor (DSP) filter and ring-buffer to further reduce ambient and digital noise and delivered to a computerized controller.

It is usual for a built-in computer to take many weight readings from the transducer over the time that the package is on the weigh bed to ensure an accurate weight reading.

Calibration is critical. A lab scale, which usually is in an isolated chamber pressurized with dry nitrogen(pressurized at sea level) can weigh an object within plus or minus

100th of a gram, but ambient air pressure is a factor. This is straightforward when there is no motion, but in motion there is a factor that is not obvious-noise from the motion of a weigh belt, vibration, air-conditioning or refrigeration which can cause drafts. Torque on a load cell causes erratic readings.

A dynamic, in-motion checkweigher takes samples, and analyzes them to form an accurate weight over a given time period. In most cases, there is a trigger from an optical(or ultrasonic) device to signal the passing of a package. Once the trigger fires, there is a delay set to allow the package to move to the "sweet spot" (center) of the weigh bed to sample the weight. The weight is sampled for a given duration. If either of these times are wrong, the weight will be wrong. There seems to be no scientific method to predict these timings. Some systems have a "graphing" feature to do this, but it is generally more of an empirical method that works best.

- A reject conveyor to enable the out-of-tolerance packages to be removed from the normal flow while still moving at the conveyor velocity. The reject mechanism can be one of several types. Among these are a simple pneumatic pusher to push the reject pack sideways from the belt, a diverting arm to sweep the pack sideways and a reject belt that lowers or lifts to divert the pack vertically. A typical checkweigher usually has a bin to collect the out-of-tolerance packs.

Tolerance methods

There are several tolerance methods:

- The traditional "minimum weight" system where weights below a specified weight are rejected. Normally the minimum weight is the weight that is printed on the pack or a weight level that exceeds that to allow for weight losses after production such as evaporation of commodities that have a moisture content. The larger wholesale companies have mandated that any product shipped to them have accurate weight checks such that a customer can be confident that they are getting the amount of product for which they paid. These wholesalers charge large fees for inaccurately filled packages.

- The European Average Weight System which follows three specified rules known as the "Packers Rules".
- Other published standards and regulations such as NIST Handbook 133

Data Collection

There is also a requirement under the European Average Weight System that data collected by checkweighers is archived and is available for inspection. Most modern checkweighers are therefore equipped with communications ports to enable the actual pack weights and derived data to be uploaded to a host computer. This data can also be used for management information enabling processes to be fine-tuned and production performance monitored.

Checkweighers that are equipped with high speed communications such as Ethernet ports are capable of integrating themselves in to groups such that a group of production lines that are producing identical products can be considered as one production line for the purposes of weight control. For example, a line that is running with a low average weight can be complemented by another that is running with a high average weight such that the aggregate of the two lines will still comply with rules.

An alternative is to program the checkweigher to check bands of different weight tolerances. For instance, the total valid weight is 100 grams ±15 grams. This means that the product can weigh 85 g - 115 g. However, it is obvious that if you are producing 10,000 packs a day, and most of your packs are 110 g, you are losing 100 kg of product. If you try to run closer to 85 g, you may have a high rejection rate.

EXAMPLE: A checkweigher is programmed to indicate 5 zones with resolution to 1 g:

1. Under Reject.... the product weighs 84.9 g or less
2. Under OK........ the product weighs 85 g, but less than 95 g
3. Valid........... the product weighs 96 g, but less than 105 g
4. Over OK......... the product weighs 105 g, and less than 114 g
5. Over Reject..... the product weighs over the 115 g limit

With a check weigher programmed as a zone checkweigher, the data collection over the networks, as well as local statistics, can indicate the need to check the settings on the upstream equipment to better control flow into the packaging. In some cases the dynamic scale sends a signal to a filler, for instance, in real-time, controlling the actual flow into a barrel, can, bag, etc. In many cases a checkweigher has a light-tree with different lights to indicate the variation of the zone weight of each product.

Application considerations

Speed and accuracy that can be achieved by a checkweigher is influenced by the following:

- Pack length
- Pack weight
- Line speed required
- Pack content (solid or liquid)
- Motor technology
- Stabilization time of the weight transducer
- Airflow causing readings in error
- Vibrations from machinery causing unnecessary rejects
- Sensitivity to temperature, as the load cells *can* be temperature sensitive
- Quality control tape
- Band with the principles of quality control weight
- Weighing tape quality control principles
- Automatic weighing tape

- Weight control tape
- Food weight control tape
- Drug for weight control tape
- Detergent industry for the quality control tape
- Weight control tape for chemical industry
- Weight control tape for the pasta industry
- Flour weight control tape for the industry

Applications

In-motion scales are dynamic machines that can be designed to perform thousands of tasks. Some are used as simple caseweighers at the end of the conveyor line to ensure the overall finished package product is within its target weight.

An in motion conveyor checkweigher can be used to detect missing pieces of a kit, such as a cell phone package that is missing the manual, or other collateral. Checkweighers are typically used on the incoming conveyor chain, and the output pre-packaging conveyor chain in a poultry processing plant. The bird is weighed when it comes onto the conveyor, then after processing and washing at the end, the network computer can determine whether or not the bird absorbed too much water, which as it is further processed, will be drained, making the bird under its target weight.

A high speed conveyor scale can be used to change the pacing, or pitch of the products on the line by speeding, or slowing the product speed to change the distance between packs before reaching a different speed going into a conveyor machine that is boxing multiple packs into a box.

A checkweigher can be used to count packs, and the aggregate (total) weight of the boxes going onto a pallet for shipment, including the ability to read each package's weight and cubic dimensions. The controller computer can print a shipping label and a bar-code label to identify the weight, the cubic dimensions, ship-to address, and other data for machine ID through the shipment of the product. A receiving checkweigher for the shipment can read the label with a bar code scanner, and determine if the shipment is as it was before the transportation carrier received it from the shipper's loading dock, and determine if a box is missing, or something was pilfered or broken in transit.

Checkweighers are also used for Quality management. For instance, raw material for machining a bearing is weighed prior to beginning the process, and after the process, the quality inspector expects that a certain amount of metal was removed in the finishing process. The finished bearings are checkweighed, and bearings over- or underweight are rejected for physical inspection. This is a benefit to the inspector, since he can have a high confidence that the ones not rejected are within machining tolerance.A common usage is for throttling plastic extruders such that a bottle used to package detergent meets that requirements of the finished packager.

Quality management can use a checkweigher for Nondestructive testing to verify finished goods using common Evaluation methods to detect pieces missing from a "finished" product, such as grease from a bearing, or a missing roller within the housing.

Checkweighers can be built with metal detectors, x-ray machines, open-flap detection, bar-code scanners, holographic scanners, temperature sensors, vision inspectors, timing screws to set the timing and spacing between product, indexing gates and concentrator ducts to line up the product into a designated area on the conveyor. An industrial motion checkweigher can sort products from a fraction of a gram to many, many kilograms. In English units, is this from less than 100th of an ounce to as much as 500 lbs or more. Specialized checkweighers can weigh commercial aircraft, and even find their center-of-gravity.

Checkweighers can be very high speed, processing products weighing fractions of a gram at over 100m/m (meters per minute, such as pharmaceuticals, and 200 lb bags of produce at over 100fpm(feet per minute). They can be designed in many shapes and sizes, hung from ceilings, raised on mezzanines, operated in ovens or in refrigerators. Their conveying medium can be industrial belting, low-static belting, chains similar to bicycle chains(but much smaller), or interlocked chain belts of any width. They can have chain belts made of special materials, different polymers, metals, etc.

Checkweighers are used in cleanrooms, dry atmosphere environments, wet environments, produce barns, food processing, drug processing, etc. Checkweighers are specified by the kind of environment, and the kind of cleaning will be used. Typically, a checkweigher for produce is made of mild steel, and one that will be cleaned with harsh chemicals, such as bleach, will be made with all stainless steel parts, even the Load cells. These machines are labeled "full washdown", and must have every part and component specified to survive the washdown environment.

Checkweighers are operated in some applications for extremely long periods of time-24/7 year round. Generally, conveyor lines are not stopped unless there is maintenance required, or there is an emergency stop, called an E-stop. Checkweighers operating in high density conveyor lines may have numerous special equipments in their design to ensure that if an E-stop occurs, all power going to all motors is removed until the E-stop is cleared and reset.

Shearography

Shearography or **speckle pattern shearing interferometry** is a measuring and testing method similar to holographic interferometry. It uses coherent light or coherent soundwaves to provide information about the quality of different materials in nondestructive testing, strain measurement, and vibration analysis. Shearography is extensively used in production and development in aerospace, wind rotor blades, automotive, and materials research areas. Advantages of shearography are the large area

testing capabilities (up to 1 m² per minute), non-contact properties, its relative insensitivity to environmental disturbances, and its good performance on honeycomb materials, which is a big challenge for traditional nondestructive testing methods. Electronic speckle pattern interferometry is one form of shearography.

Shearing function

When a surface area is illuminated with a highly coherent laser light, a stochastical interference pattern is created. This interference pattern is called a speckle, and is projected on a rigid camera's CCD chip. Analogous with Electronic speckle pattern interferometry (ESPI), to obtain results from the speckle we need to compare it with a known reference light. Shearography uses the test object itself as the known reference; it shears the image so a double image is created. The superposition of the two images, a shear image, represents the surface of the test object at this unloaded state. This makes the method much more insensible to external vibrations and noise. By applying a small load, the material will deform. A nonuniform material quality will generate a nonuniform movement of the surface of the test object. A new shearing image is recorded at the loaded state and is compared with the sheared image before load. If a flaw is present, it will be seen.

Phase-shift technology

To increase the sensitivity of the measurement method, a real-time phase shift process is used in the sensor. This contains a stepping mirror that shifts the reference beam, which is then processed with a best fit-algorithm and presents the information in real time.

Applications

The main applications are in composite nondestructive testing, where typical flaws are:

- Disbonds
- Delaminations
- Wrinkles
- Porosity
- Foreign objects
- Impact damages

Industries where Shearography is used are:

- Aerospace
- Space
- Boats
- Wind power
- Automotive
- Tires

Chapter-13

Impulse Excitation Technique and Guided Wave Testing

Impulse excitation technique

Practical

The **impulse excitation technique** is a nondestructive test method that uses natural frequency, dimensions and mass of a test-piece to determine Young's modulus, Shear modulus, Poisson's ratio and damping coefficient. Dimensions and mass of a test-piece can be easily measured. Natural frequency is determined by gently tapping the test-piece and analyzing the vibration. Tapping can be done using a small hammer or an automated tapping device. There are different ways to detect vibrations in the test-piece: piezoelectric sensor, microphone, laservibrometer or accelerometer. To optimize the results a microphone or a laservibrometer can be used as there is no contact between the test-piece and the sensor. Laservibrometers are preferred to measure signals with extreme frequencies. These kinds of signals are usually only induced in very thin test-pieces.

Flexure mode
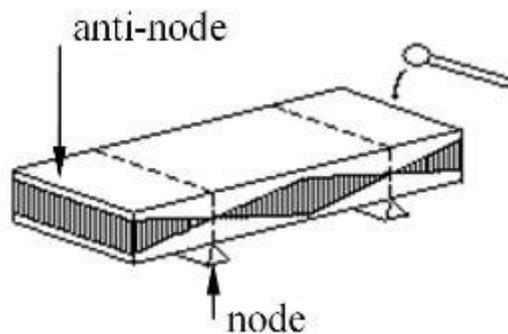
Test-piece vibrating in flexure mode

This figure gives an example of a test-piece vibrating in the flexure mode. The induced vibration is also referred to as the out-of plane vibration. The in-plane vibration is the vibration vibrating vertically on the out-of plane vibration. The natural frequency of this vibration is measured to calculate Young's modulus. To damp the test-piece as little as possible it has to be supported at the nodes. The test-piece is mechanically excited at one of the anti-nodes to cause maximum vibration.

Torsion mode
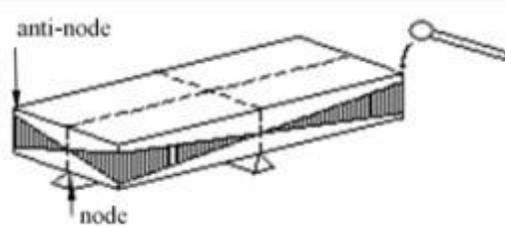
Test-piece vibrating in the torsion mode

This figure gives an example of a test-piece vibrating in the torsion mode. The natural frequency of this vibration is measured to calculate the Shear modulus. To damp the test-piece as little as possible it has to be supported in the nods. The test-piece is mechanically excited at one of the anti-nodes to cause maximum vibration.

Signal conditioning and calculating result

After the signal is induced it has to be amplified and filtered. The resulting signal can than be introduced in a software package where it is logged. Software packages use algorithms to calculate Young's modulus, Shear modulus, Poisson's ratio and damping coefficient. The basic formulas used in these algorithms are discussed in the theory section. Most software packages visualize the signal and show a graphic of the obtained frequencies.

Area of application

There is a wide range of untested applications in which impulse excitation techniques (IET) could be used. Today IET is mostly used in research and quality control. The advantage of IET in research projects is that it gives an in depth look into the internal structure of materials. Physical properties like damping and Young's modulus can be used for example to map out thermal shock behaviour of certain materials. Some machines even have the possibility to do measurements at very high temperatures, up to 1750 °C, or in vacuum conditions. This can be an advantage in understanding the physical properties of certain materials. Applications in quality control work differently. Most of these applications need a reference piece they can relate to. Engine blocks for example can be tested by tapping them and comparing the recorded signal with a pre-recorded signal of another engine block of which there is certainty its properties are satisfactory.

From a material point of view most materials that have enough stiffness to vibrate can be measured using IET.

Theory

Rectangular bar

Young's modulus

$$E = 0.9465 \left(\frac{m f_f^2}{b} \right) \left(\frac{L^3}{t^3} \right) T$$

Where

$$T = 1 + 6.858 \left(\frac{t}{L} \right)^2$$

E is Young's modulus
m is mass
f_f is natural frequency in flexure dimension
b is width
L is length
t is thickness
The above formula can be used should L/t ≥ 20

Shear modulus

$$G = \frac{4 L m f_t^2}{bt} \left(\frac{B}{1 + A} \right)$$

Where

$$B = \left(\frac{b/t + t/b}{4 \left(t/b \right) - 2.52 \left(t/b \right)^2 + 0.21 \left(t/b \right)^6} \right)$$

$$A = \left(\frac{0.5062 - 0.8776 \left(b/t \right) + 0.3504 \left(b/t \right)^2 - 0.0078 \left(b/t \right)^3}{12.03 \left(b/t \right) + 9.892 \left(b/t \right)^2} \right)$$

Note we assume that b≥t
f_t is the natural frequency in the torsion mode
m is mass
b is width
L is length
t is thickness

Cylindrical rod

Young's modulus

$$E = 1.6067 \left(\frac{L^3}{d^4} \right) m f_f^2 T'$$

Where

$$T' = 1 + 4.939 \left(\frac{d}{L} \right)^2$$

E is Young's modulus
m is mass
f_f is the natural frequency in flexure dimension
d is diameter
L is length
The above formula can be used should L/t ≥ 20

Shear modulus

$$G = 16 \left(\frac{L}{\pi d^2} \right) m f_t^2$$

Where
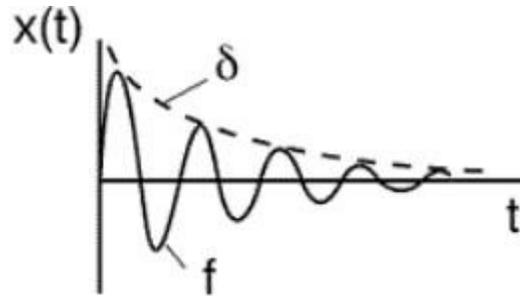
f_t is the natural frequency in the torsion mode
m is mass
d is diameter
L is length

Poisson ratio

If Young's modulus and Shear modulus are known Poisson's ratio can be calculated.

$$\nu = \left(\frac{E}{2G} \right) - 1$$

Damping coefficient

The signal induced in the test-piece is described as a damped sine. The damping of this sine can be determined by checking the force of consecutive amplitudes.

Damped sine

$$x(t) = Ae^{-\delta t} \sin(\omega t + \phi)$$

Where

$f = 1/T = \omega/(2\pi)$ the natural frequency
$\delta = kt$ the logarithmic decrement
k the exponential damping of the vibration signal

Accuracy

Accuracy is determined by the quality of support of the test-piece and the correctness of measurement of the test-piece's dimensions and mass. It is possible to do measurements within an accuracy rate of 0,1%. The best way to support a test-piece is to use nylon fibers, but most systems use polyurethane foam strips as support. This makes it very difficult to measure small test-pieces because the damping effect of the support is too big.

Guided wave testing
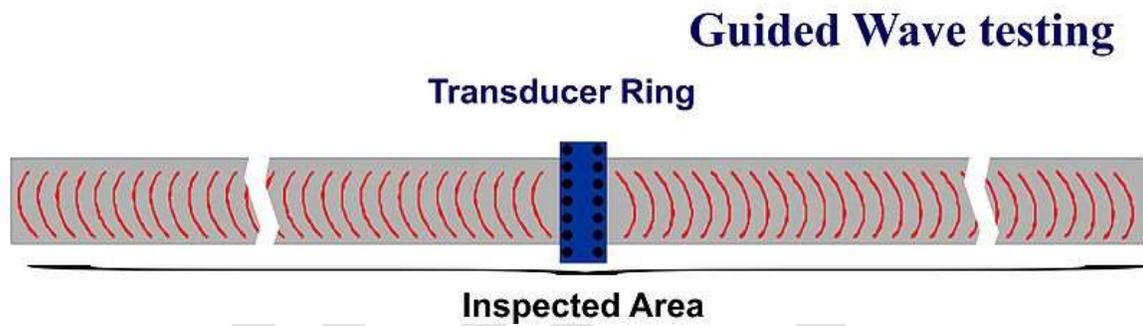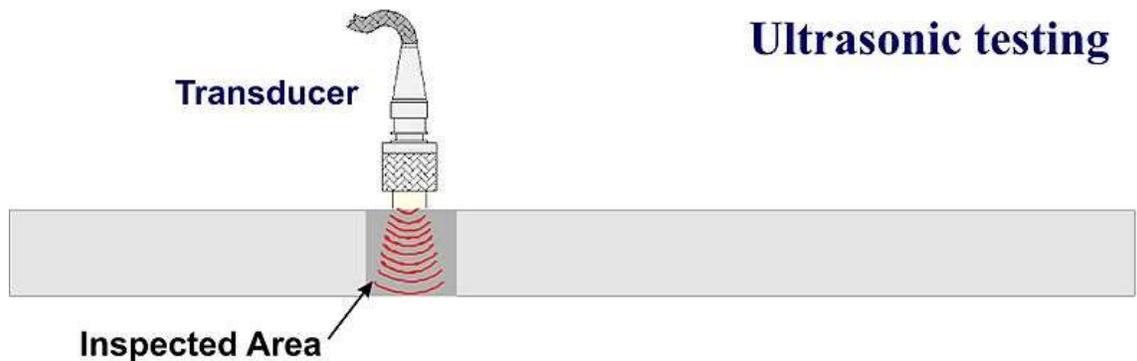
This illustrates the difference in concept between conventional UT and guided wave testing (GWT).

Guided Wave testing (GWT) is one of latest methods in the field of non-destructive evaluation. The method employs mechanical stress waves that propagate along an elongated structure while guided by its boundaries. This allows the waves to travel a long distance with little loss in energy. Nowadays, GWT is widely used to inspect and screen many engineering structures, particularly for the inspection of metallic pipelines around the world. In some cases, hundreds of meters can be inspected from a single location. There are also some applications for inspecting rail tracks, rods and metal plate structures.

Although Guided wave testing is also commonly known as Guided Wave Ultrasonic Testing (GWUT) or Long Range Ultrasonic Testing (LRUT), it is fundamentally very different to conventional ultrasonic testing. Guided wave testing uses very low ultrasonic frequencies compared to those used in conventional UT, typically between 10~100kHz. Higher frequencies can be used in some cases, but detection range is significantly reduced.

History

The study of guided waves propagating in a structure can be traced back to as early as the 1920s, mainly inspired by the field of seismology. Since then, there has been an increased effort on the analytical study of guided wave propagation in cylindrical structures. It was only in the early 1990s that guided wave testing was considered as a practical method for the non-destructive testing of engineering structures. Today, GWT is applied as an integrated health monitoring program in the oil, gas and chemical industries.

How it works (Pipeline Inspections)

An example of pipeline inspection using guided wave testing (GWT). Mechanical stress wave is generated via transducer array mounted around the pipe surface. The electrical

signal is driven by the portable electronic unit. After the collection, the result is displayed on the computer for further analysis.
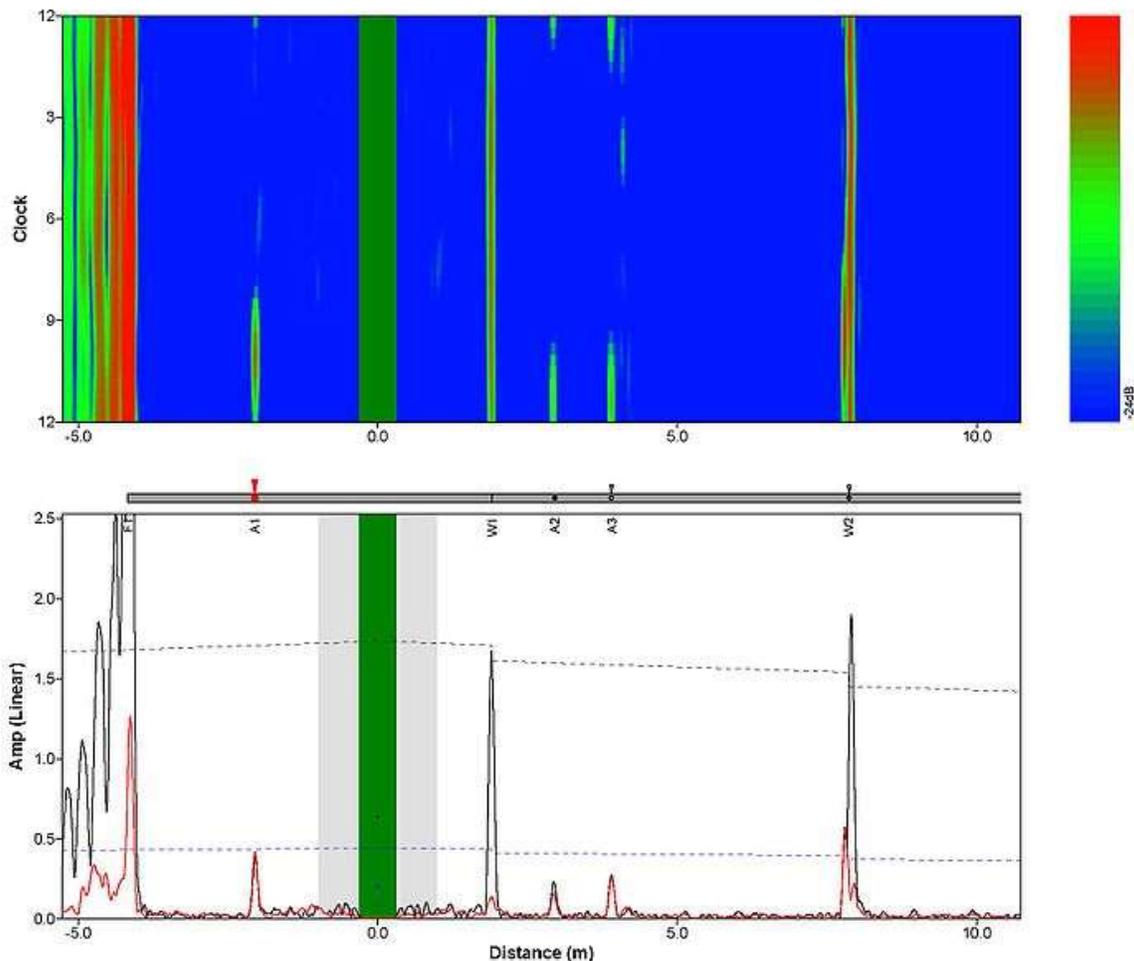
A typical example of the GWT data showing both the A-scan type (bottom) and the C-scan type (top) results. The green band indicates the position of the transducer array.

Unlike conventional ultrasonics, there are an infinite number of guided wave modes that exist for a pipe geometry, and they can be generally grouped into three families, namely the torsional, longitudinal and flexural modes. The acoustic properties of these wave modes are a function of the pipe geometry, the material and the frequency. Predicting these properties of the wave modes often relies on heavy mathematical modeling which are typically presented in graphical plots called Dispersion curves.

In Guided Wave Testing of pipelines, an array of low frequency transducers is attached around the circumference of the pipe to generate an axially symmetric wave that propagate along the pipe in both the forward and backward directions of the transducer array. The Torsional wave mode is most commonly used, although there is limited use of

the longitudinal mode. The equipment operates in a pulse-echo configuration where the array of transducers is used for both the excitation and detection of the signals.

At location where there is a change of cross-section or a change in local stiffness of the pipe, an echo is generated. Based on the arrival time of the echoes, and the predicted speed of the wave mode at a particular frequency, the distance of a feature in relation to the position of the transducer array can be accurately calculated. GWT uses a system of distance amplitude curves (DAC) to correct for attenuation and amplitude drops when estimating the cross-section change (CSC) from a reflection at a certain distance. The DACs are usually calibrated against a series of echoes with known signal amplitude such as weld echoes.

Once the DAC levels are set, the signal amplitude correlates well to the CSC of a defect. GWT does not measure the remaining wall thickness directly, but it is possible to group the defect severity in several categories. One method of doing this is to exploit the mode conversion phenomenon of the excitation signal where some energy of the axially symmetric wave mode is converted to the flexural modes at a pipe feature. The amount of mode conversion provides an accurate estimate of the circumferential extent of the defect, and together with the CSC, operators could establish the severity category.

A typical result of GWT is displayed in an A-scan style with the reflection amplitude against the distance from the transducer array position. In the past few years, some advanced systems have started to offer C-scan type results where the orientation of each feature can be easily interpreted. This has shown to be extremely useful when inspecting large size pipelines.

Features

Advantages

1. 100% Volumetric coverage - full coverage within the inspection range.
2. Long range inspection - potential to achieve hundreds of meters of inspection range.
3. Limited access - insulated line with minimal insulation removal, corrosion under supports without need for lifting, inspection at elevated locations with minimal need for scaffolding, and inspection of road crossings and buried pipes.
4. Data is fully recorded.
5. Fully automated data collection protocols.

Disadvantages

1. Interpretation of data is highly operator dependent.
2. Difficult to find small pitting defects.
3. Not very effective at inspecting areas close to accessories.
4. Needs good procedure