Advanced NDE Training

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Welcome and Course Agenda

- Welcome and Course Agenda
- Day One – Introduction to NDE and Advanced NDE
- Day Two and Three – UT/AUT practical
- Day Four – RT/CR and MT/PT practical
- Day Five – ET practical

Training Objectives

- Course designed to familiarize participants with major advanced NDE methods and provide practical training
- Useful for technical personnel considering NDE for manufacturing and service processes
- On the completion of the course participants should:
  - Understand advanced NDE techniques and typical applications
  - Understand the inspection process and factors that affect it

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First Day Course Agenda

- NDE Overview
- Ultrasonics and Acoustic Emission
- Break
- Radiography
- Lunch Break
- Penetrant and Magnetic Particles
- Eddy Current
- Break
- NDE/AUT Qualifications

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Acronyms

- NDE - Nondestructive Evaluation
- NDT - Nondestructive Testing
- NDEx – Nondestructive Examination
- NDI - Nondestructive Inspection
- NDC - Nondestructive Characterization

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NDE Overview

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Introduction to Nondestructive Testing

Prepared by the Collaboration for NDT Education.
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Outline

- Introduction to NDT
- Overview of Six Most Common NDT Methods
- Selected Applications

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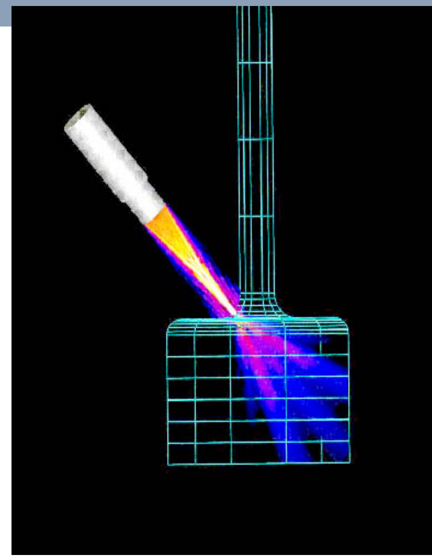
Definition of NDT

The use of noninvasive techniques to determine the integrity of a material, component or structure
or
quantitatively measure some characteristic of an object.



i.e. Inspect or measure without doing harm.

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Methods of NDT

Visual
Microwave
Thermography
Tap Testing
Magnetic Particle
X-ray
Acoustic Microscopy
Acoustic Emission
Magnetic Measurements
Liquid Penetrant
Ultrasonic
Replication
Laser Interferometry
Eddy Current
Flux Leakage

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What are Some Uses of NDE Methods?

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

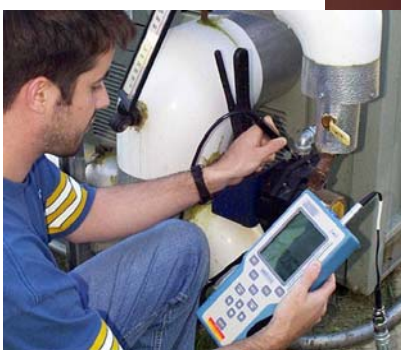
Fluorescent penetrant indication

When are NDE Methods Used?

- There are NDE application at almost any stage in the production or life cycle of a component.
  - To assist in product development
  - To screen or sort incoming materials
  - To monitor, improve or control manufacturing processes
  - To verify proper processing such as heat treating
  - To verify proper assembly
  - To inspect for in-service damage

Six Most Common NDT Methods

- Visual
- Liquid Penetrant
- Magnetic
- Ultrasonic
- Eddy Current
- X-ray



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Visual Inspection

Most basic and common inspection method.

Tools include fiberscopes, borescopes, magnifying glasses and mirrors.

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

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

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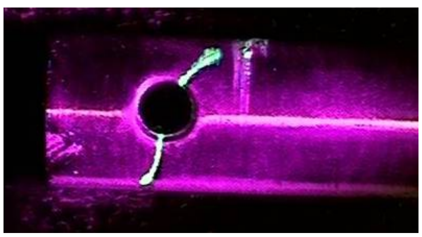
Liquid Penetrant Inspection

- A liquid with high surface wetting characteristics is applied to the surface of the part and allowed time to seep into surface breaking defects.
- The excess liquid is removed from the surface of the part.
- A developer (powder) is applied to pull the trapped penetrant out the defect and spread it on the surface where it can be seen.
- Visual inspection is the final step in the process. The penetrant used is often loaded with a fluorescent dye and the inspection is done under UV light to increase test sensitivity.



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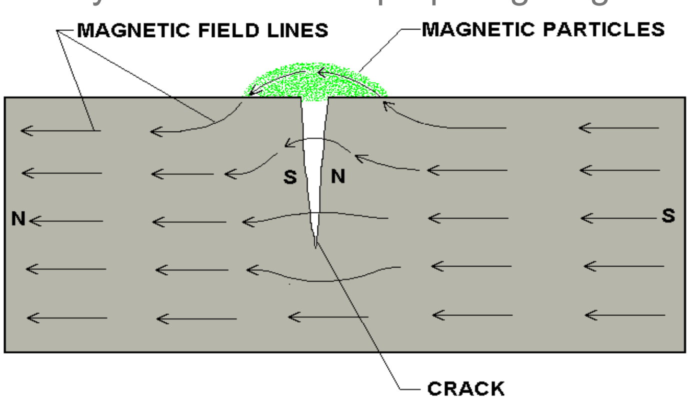
Magnetic Particle Inspection

The part is magnetized. Finely milled iron particles coated with a dye pigment are then applied to the specimen. These particles are attracted to magnetic flux leakage fields and will cluster to form an indication directly over the discontinuity. This indication can be visually detected under proper lighting conditions.



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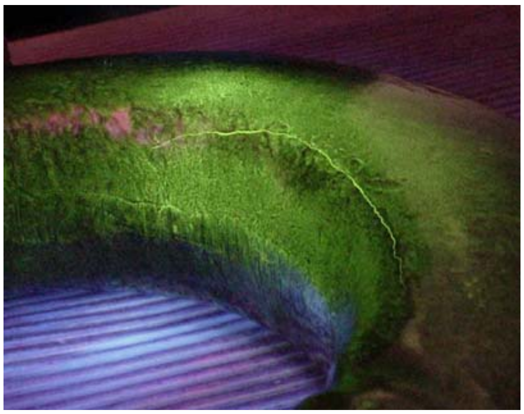
Magnetic Particle Crack Indications



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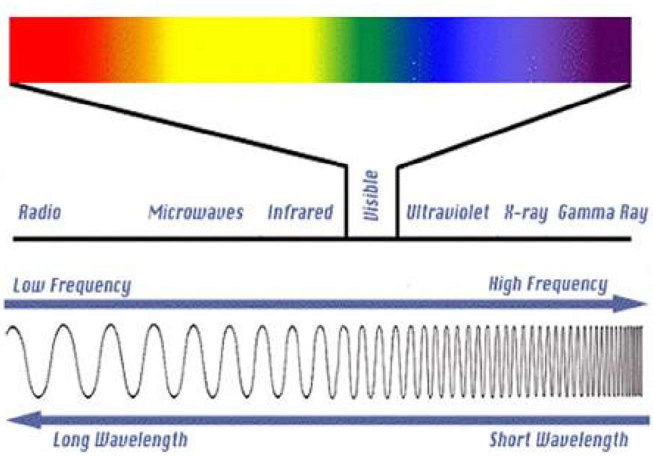
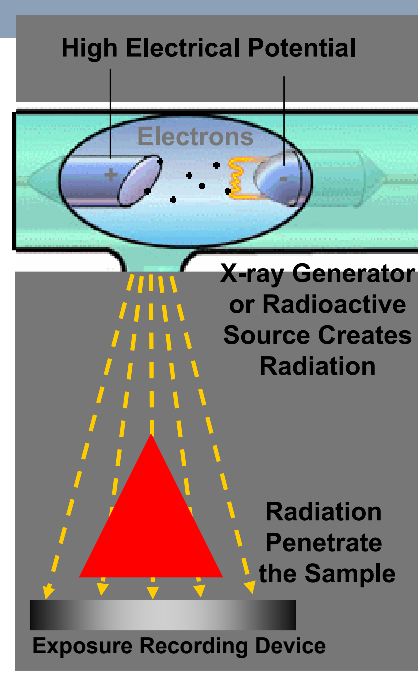
Radiography

The radiation used in radiography testing is a higher energy (shorter wavelength) version of the electromagnetic waves that we see as visible light. The radiation can come from an X-ray generator or a radioactive source.





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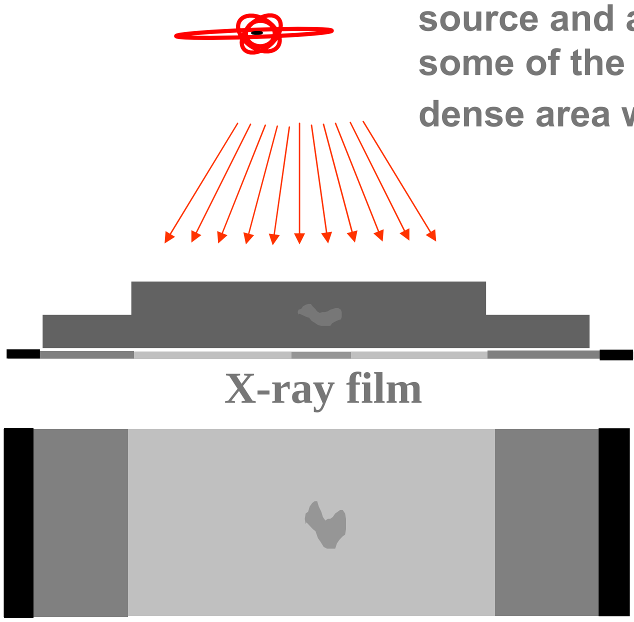
Film Radiography



Top view of developed film

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

The film darkness (density) will vary with the amount of radiation reaching the film through the test object.

= less exposure

= more exposure

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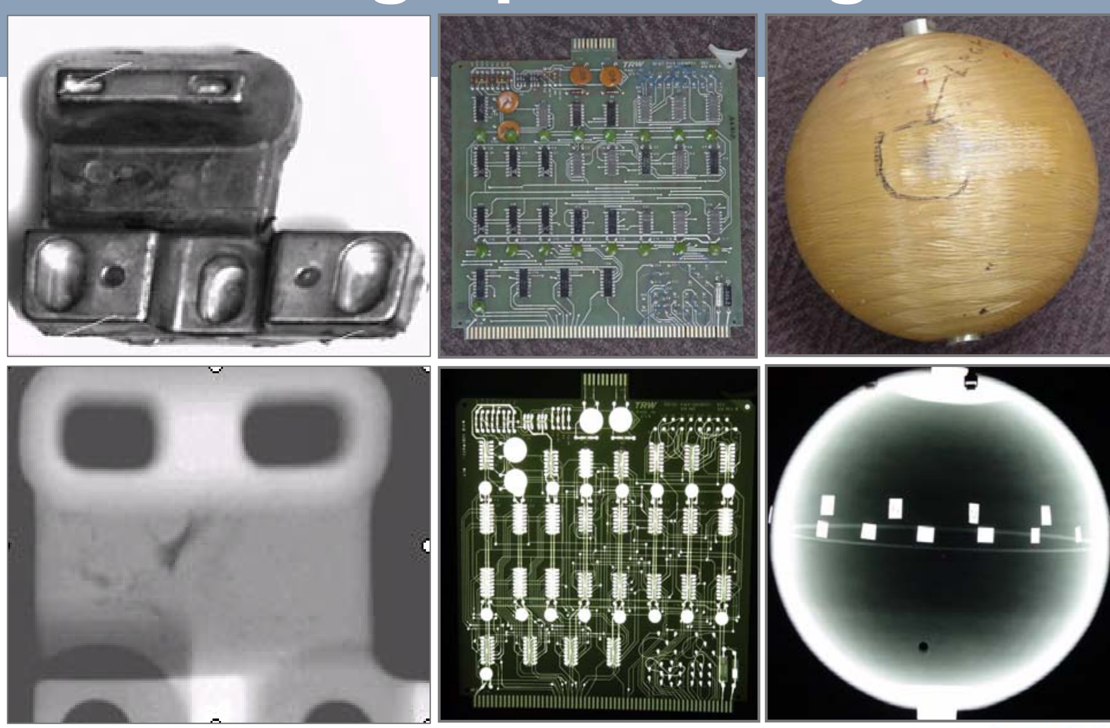
Radiographic Images



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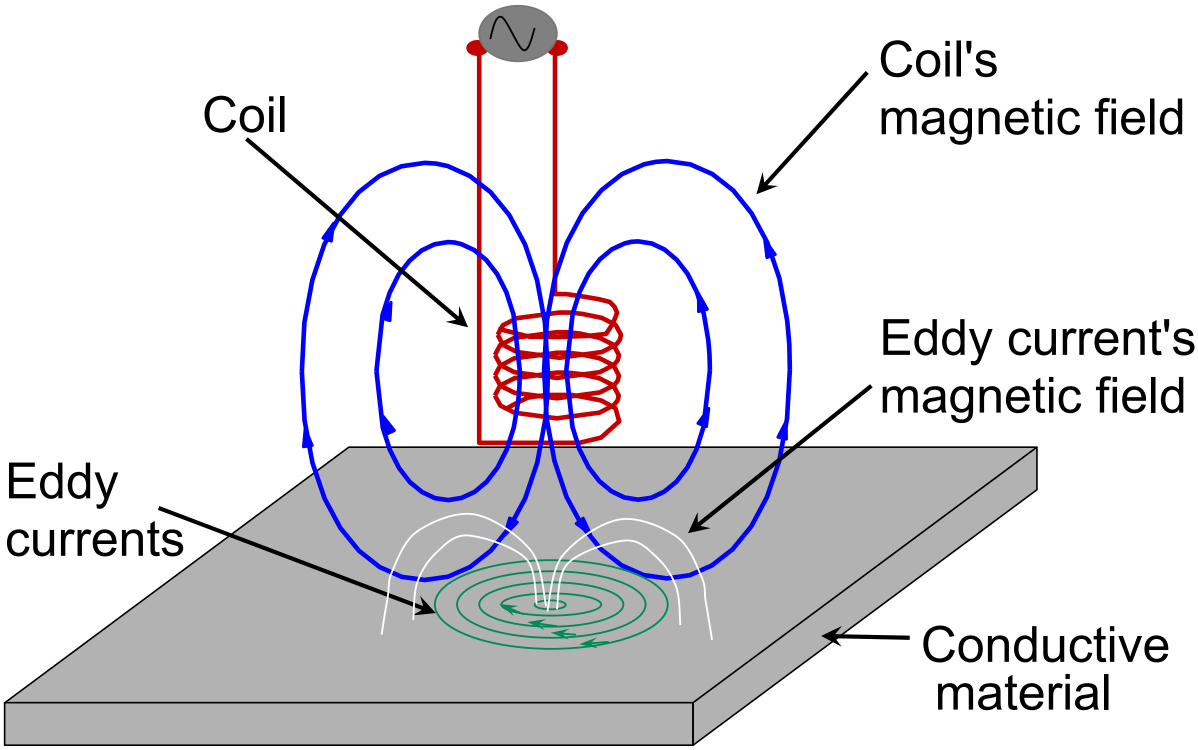
Eddy Current Testing



Eddy Current Testing

- Eddy current testing is particularly well suited for detecting surface cracks but can also be used to make electrical conductivity and coating thickness measurements. Here a small surface probe is scanned over the part surface in an attempt to detect a crack.

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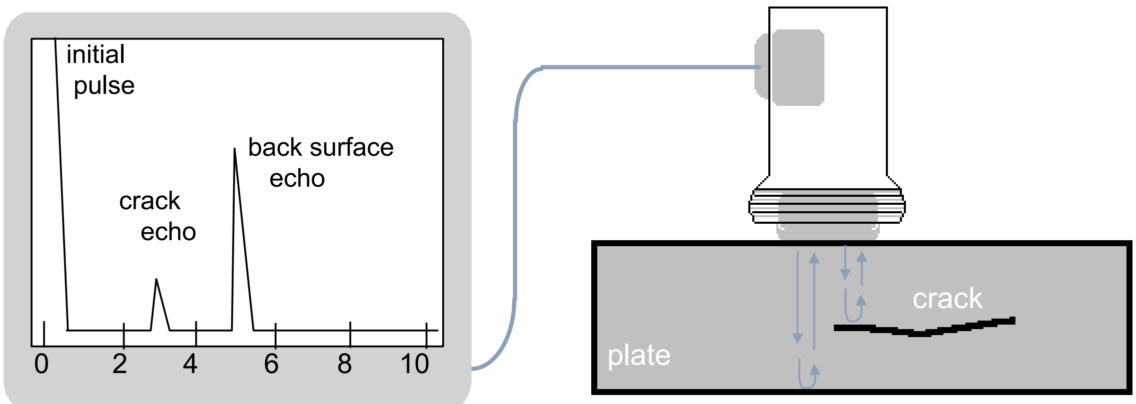
Ultrasonic Inspection (Pulse-Echo)

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

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



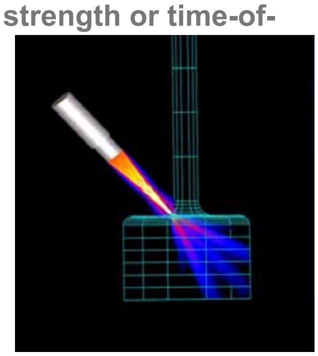
Oscilloscope, or flaw detector screen

Ultrasonic Imaging

High resolution images can be produced by plotting signal strength or time-of-flight using a computer-controlled scanning system.

Gray scale image produced using the sound reflected from the front surface of the coin

Gray scale image produced using the sound reflected from the back surface of the coin (inspected from "heads" side)

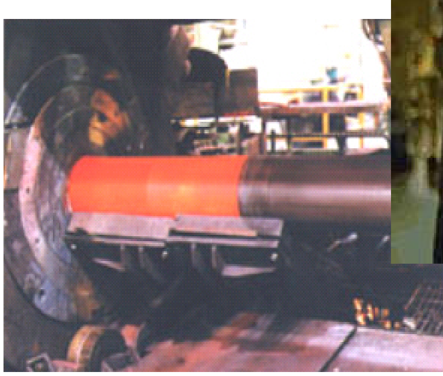


Common Application of NDT

- Inspection of Raw Products
- Inspection Following Secondary Processing
- In-Services Damage Inspection

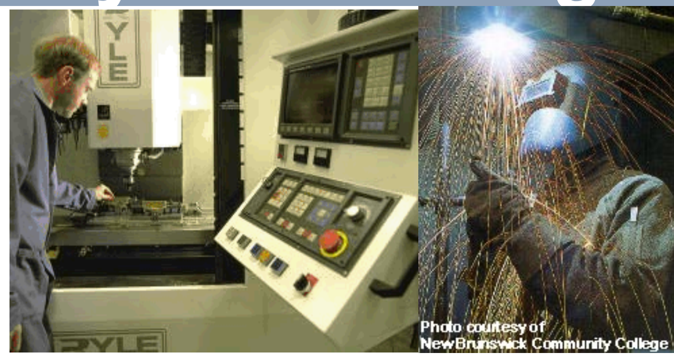
Inspection of Raw Products

- Forgings,
- Castings,
- Extrusions,
- etc.



Inspection Following Secondary Processing

- Machining
- Welding
- Grinding
- Heat treating
- Plating
- etc.



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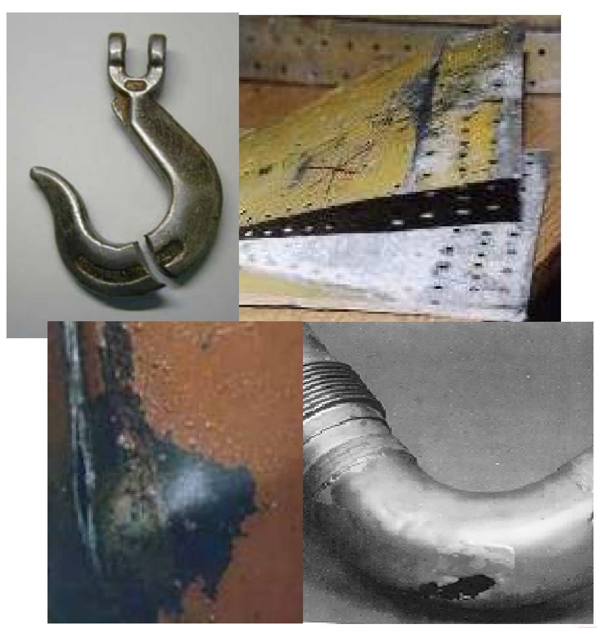
Inspection For In-Service Damage

- Cracking
- Corrosion
- Erosion/Wear
- Heat Damage
- etc.



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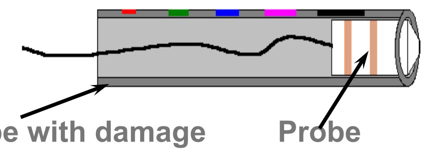
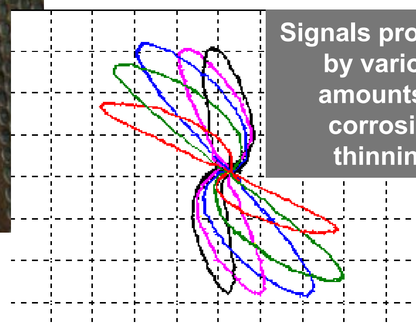
Power Plant Inspection

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

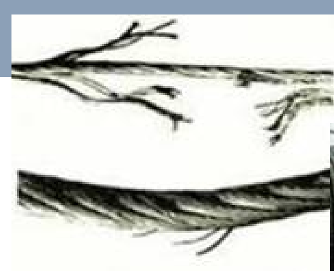


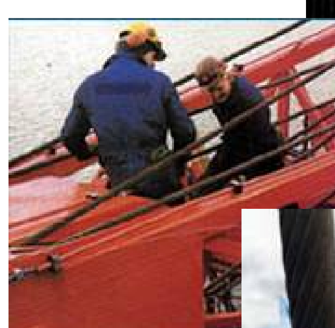


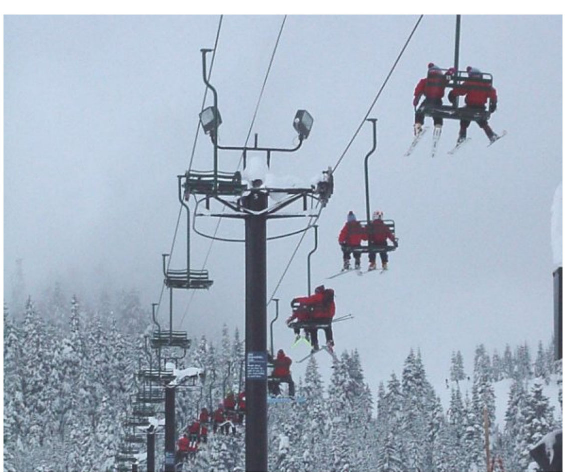
Signals produced by various amounts of corrosion thinning.

Wire Rope Inspection

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

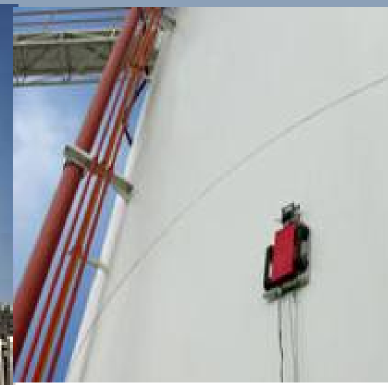




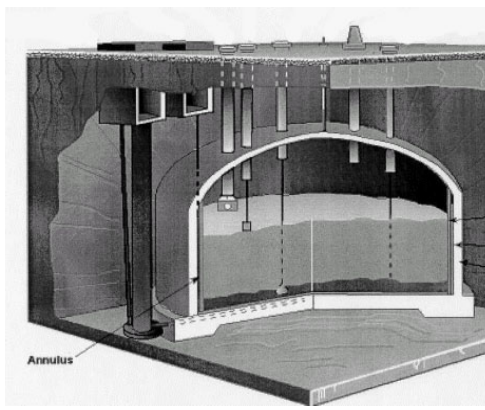


Storage Tank Inspection

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



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



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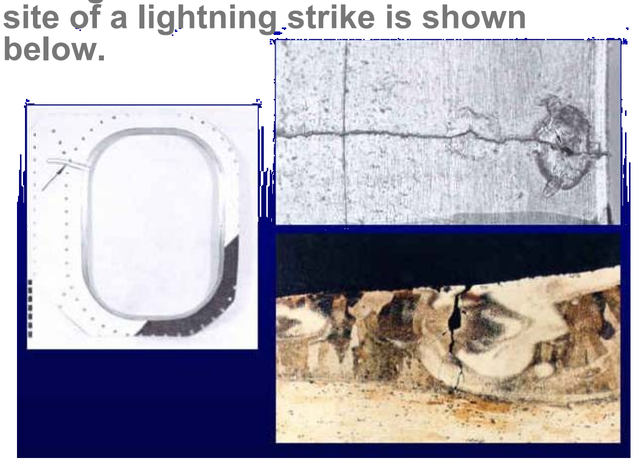
Aircraft Inspection

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



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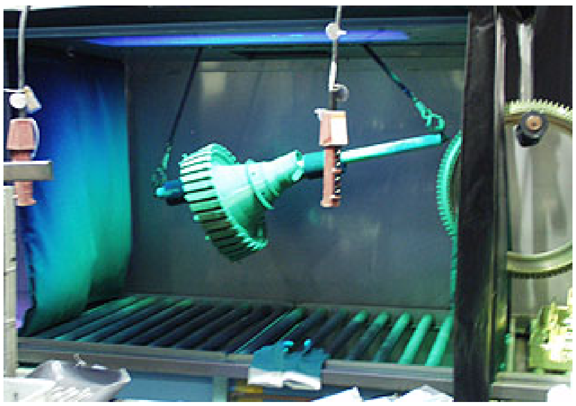
Jet Engine Inspection

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



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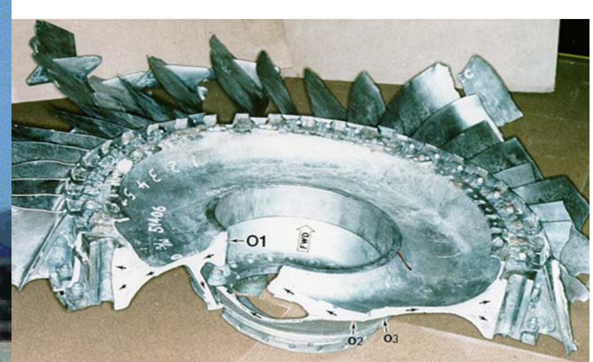
Crash of United Flight 232

Sioux City, Iowa, July 19, 1989

A defect that went undetected in an engine disk was responsible for the crash of United Flight 232.



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Pressure Vessel Inspection

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

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Rail Inspection

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

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Bridge Inspection

- The US has 578,000 highway bridges.
- Corrosion, cracking and other damage can all affect a bridge's performance.
- The collapse of the Silver Bridge in 1967 resulted in loss of 47 lives.
- Bridges get a visual inspection about every 2 years.
- Some bridges are fitted with acoustic emission sensors that "listen" for sounds of cracks growing.

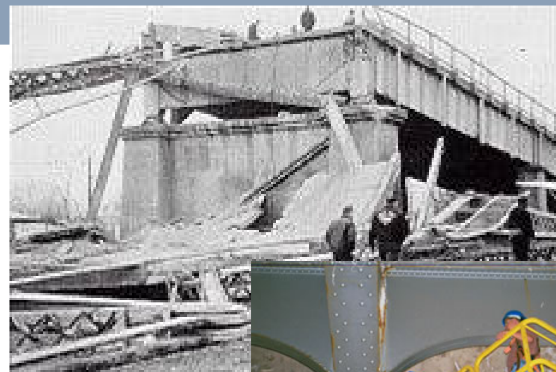

Photo Courtesy of Physical Acoustics Corporations

Pipeline Inspection

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

Photo Courtesy of Inuktun

Remote visual inspection using a robotic crawler.

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

Photo Courtesy of Yxlon International

Radiography of weld joints.

Special Measurements

Boeing employees in Philadelphia were given the privilege of evaluating the Liberty Bell for damage using NDT techniques. Eddy current methods were used to measure the electrical conductivity of the Bell's bronze casing at various points to evaluate its uniformity.

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For More Information on NDT

The Collaboration for NDT Education

www.ndt-ed.org

The American Society for Nondestructive Testing

www.asnt.org

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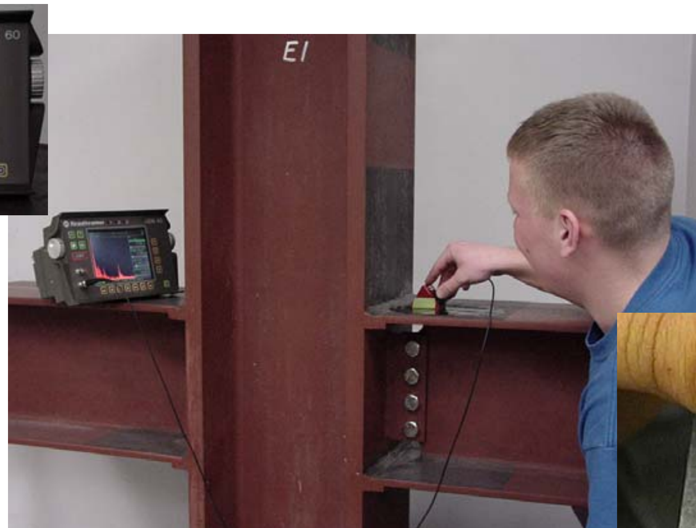
Ultrasonic Testing

Ultrasonic Testing



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Introduction

- This module presents an introduction to the NDT method of ultrasonic testing.
- Ultrasonic testing uses high frequency sound energy to conduct examinations and make measurements.
- Ultrasonic examinations can be conducted on a wide variety of material forms including castings, forgings, welds, and composites.
- A considerable amount of information about the part being examined can be collected, such as the presence of discontinuities, part or coating thickness; and acoustical properties can often be correlated to certain properties of the material.

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Outline

- Applications
- Basic Principles of sound generation
- Pulse echo and through transmission testing
- Inspection applications
- Equipment
  - Transducers
  - Instrumentation
  - Reference Standards
- Data presentation
- Advantages and Limitations
- Glossary of terms

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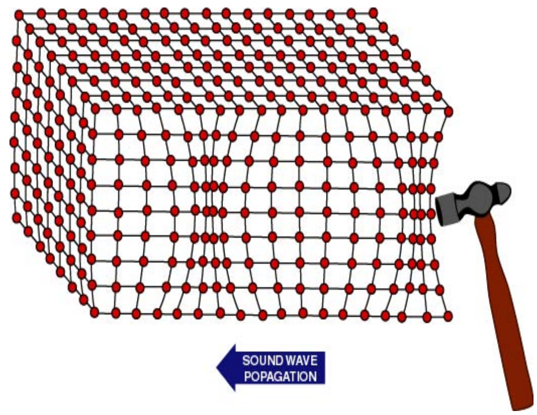
Basic Principles of Sound

- Sound is produced by a vibrating body and travels in the form of a wave.
- Sound waves travel through materials by vibrating the particles that make up the material.
- The pitch of the sound is determined by the frequency of the wave (vibrations or cycles completed in a certain period of time).
- Ultrasound is sound with a pitch too high to be detected by the human ear.



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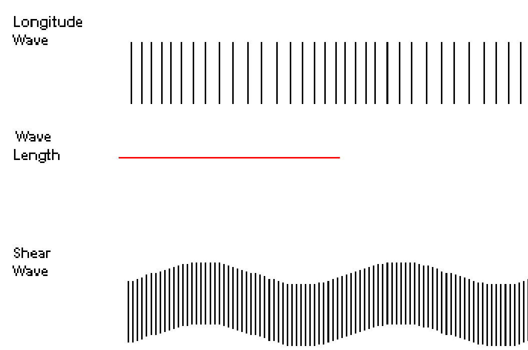
Basic Principles of Sound (cont.)

- The measurement of sound waves from crest to crest determines its wavelength (λ).
- The time is takes a sound wave to travel a distance of one complete wavelength is the same amount of time it takes the source to execute one complete vibration.
- The sound wavelength is inversely proportional to its frequency. ($\lambda = 1/f$)
- Several wave modes of vibration are used in ultrasonic inspection. The most common are longitudinal, shear, and Rayleigh (surface) waves.



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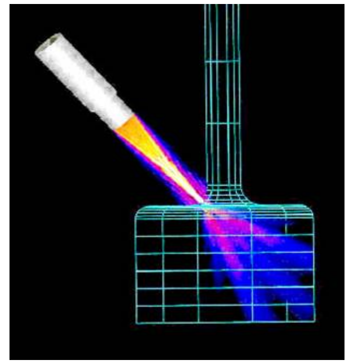
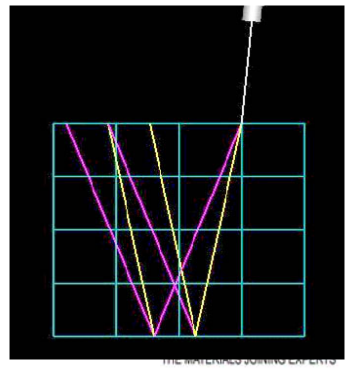
Basic Principles of Sound (cont.)

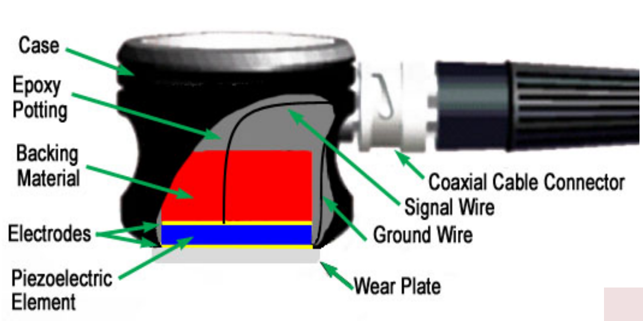
- Ultrasonic waves are very similar to light waves in that they can be reflected, refracted, and focused.
- Reflection and refraction occurs when sound waves interact with interfaces of differing acoustic properties.
- In solid materials, the vibrational energy can be split into different wave modes when the wave encounters an interface at an angle other than 90 degrees.
- Ultrasonic reflections from the presence of discontinuities or geometric features enables detection and location.
- The velocity of sound in a given material is constant and can only be altered by a change in the mode of energy.





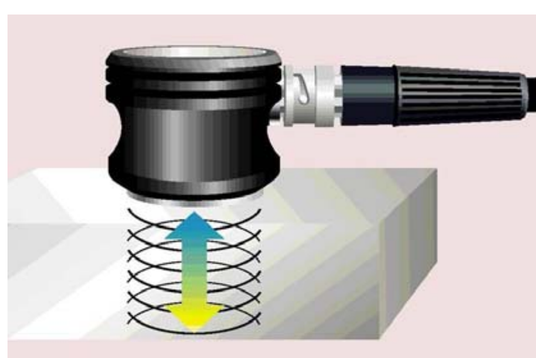
Ultrasound Generation

Ultrasound is generated with a transducer.



A piezoelectric element in the transducer converts electrical energy into mechanical vibrations (sound), and vice versa.

The transducer is capable of both transmitting and receiving sound energy.



Principles of Ultrasonic Inspection

- Ultrasonic waves are introduced into a material where they travel in a straight line and at a constant speed until they encounter a surface.
- At surface interfaces some of the wave energy is reflected and some is transmitted.
- The amount of reflected or transmitted energy can be detected and provides information about the size of the reflector.
- The travel time of the sound can be measured and this provides information on the distance that the sound has traveled.

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Test Techniques

- Ultrasonic testing is a very versatile inspection method, and inspections can be accomplished in a number of different ways.
- Ultrasonic inspection techniques are commonly divided into three primary classifications.
  - **Pulse-echo and Through Transmission** (Relates to whether reflected or transmitted energy is used)
  - **Normal Beam and Angle Beam** (Relates to the angle that the sound energy enters the test article)
  - **Contact and Immersion** (Relates to the method of coupling the transducer to the test article)

Each of these techniques will be discussed briefly in the following slides.

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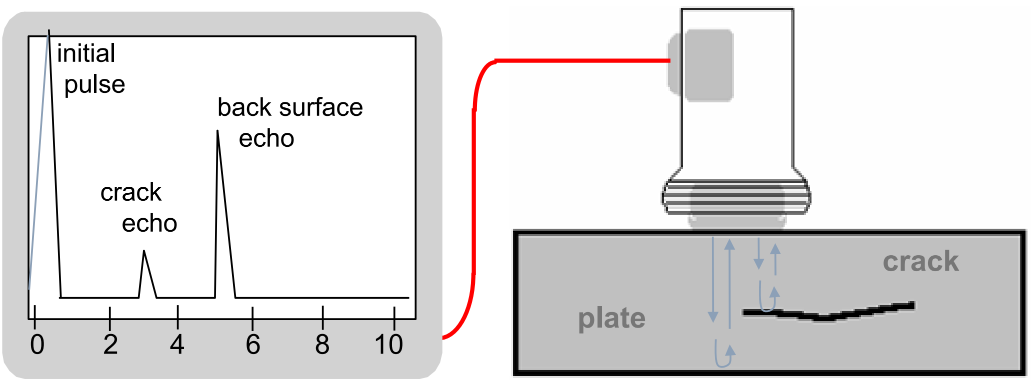
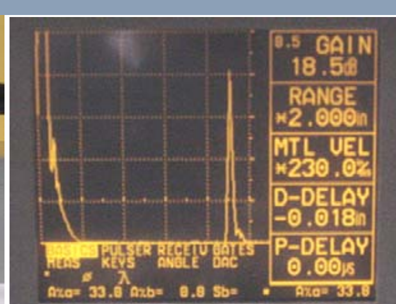
Test Techniques - Pulse-Echo

- In pulse-echo testing, a transducer sends out a pulse of energy and the same or a second transducer listens for reflected energy (an echo).
- Reflections occur due to the presence of discontinuities and the surfaces of the test article.
- The amount of reflected sound energy is displayed versus time, which provides the inspector information about the size and the location of features that reflect the sound.



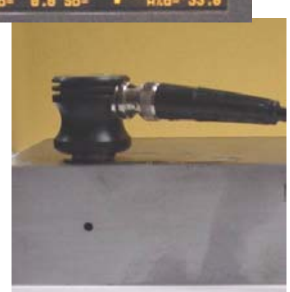
UT Instrument Screen

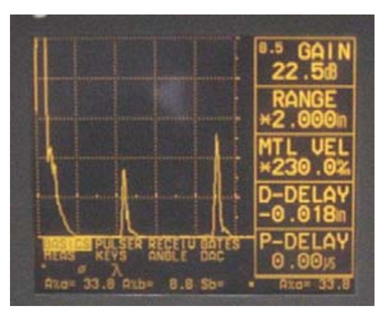
Test Techniques - Pulse-Echo (cont’d)



Digital display showing signal generated from sound reflecting off back surface.

Digital display showing the presence of a reflector midway through material, with lower amplitude back surface reflector.

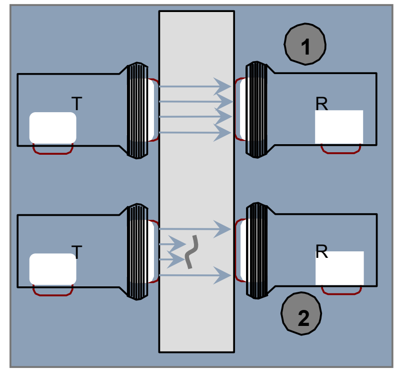


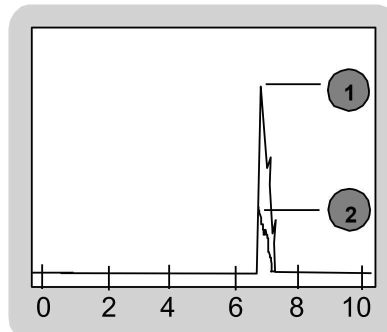


The pulse-echo technique allows testing when access to only one side of the material is possible, and it allows the location of reflectors to be precisely determined.

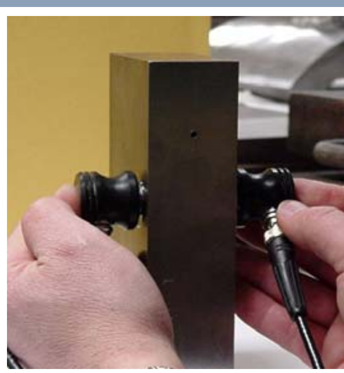
Test Techniques – Through-Transmission

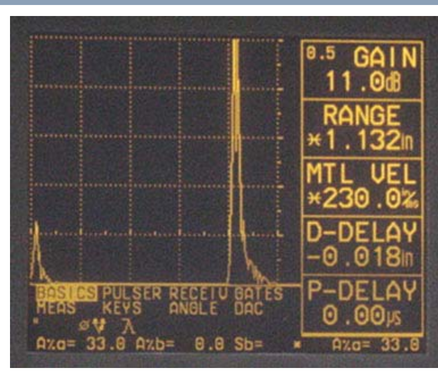
- Two transducers located on opposing sides of the test specimen are used. One transducer acts as a transmitter, the other as a receiver.
- Discontinuities in the sound path will result in a partial or total loss of sound being transmitted and be indicated by a decrease in the received signal amplitude.
- Through transmission is useful in detecting discontinuities that are not good reflectors, and when signal strength is weak. It does not provide depth information.



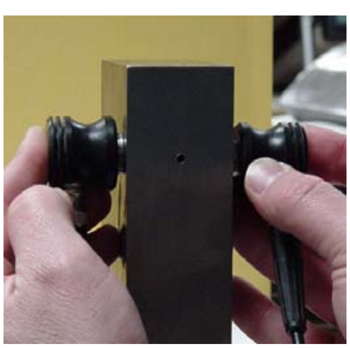


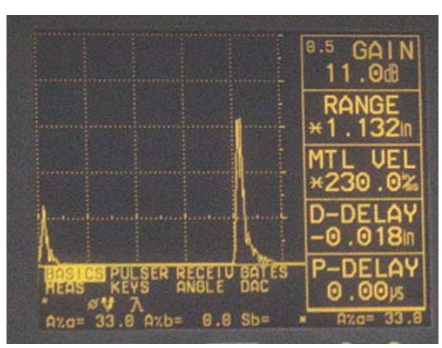
Test Techniques – Through-Transmission





Digital display showing received sound through material thickness.





Digital display showing loss of received signal due to presence of a discontinuity in the sound field.

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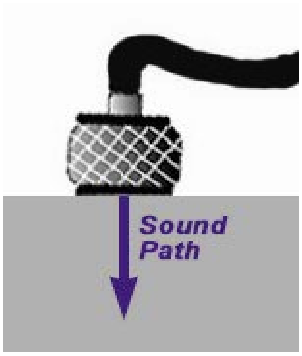
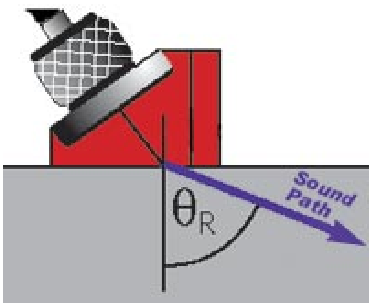
Test Techniques – Normal and Angle Beam





- In normal beam testing, the sound beam is introduced into the test article at 90 degree to the surface.
- In angle beam testing, the sound beam is introduced into the test article at some angle other than 90.
- The choice between normal and angle beam inspection usually depends on two considerations:
  - The orientation of the feature of interest – the sound should be directed to produce the largest reflection from the feature.
  - Obstructions on the surface of the part that must be worked around.

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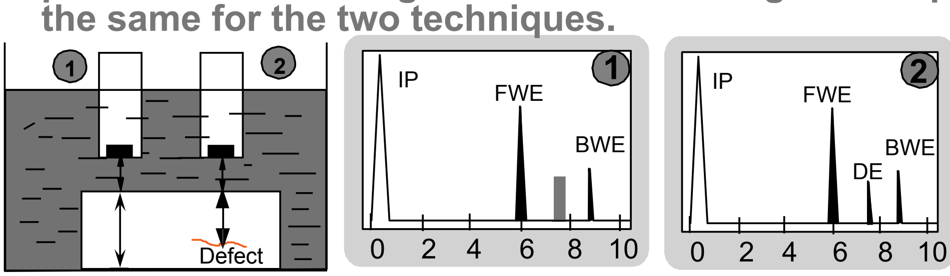
Test Techniques – Contact Vs Immersion

- To get useful levels of sound energy into a material, the air between the transducer and the test article must be removed. This is referred to as coupling.
- In contact testing (shown on the previous slides) a couplant such as water, oil or a gel is applied between the transducer and the part.
- In immersion testing, the part and the transducer are place in a water bath. This arrangement allows better movement of the transducer while maintaining consistent coupling.
- With immersion testing, an echo from the front surface of the part is seen in the signal but otherwise signal interpretation is the same for the two techniques.



IP = Initial Pulse
FWE = Front Wall Echo
DE = Defect Echo
BWE = Back Wall Echo

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Inspection Applications

Some of the applications for which ultrasonic testing may be employed include:

- Flaw detection (cracks, inclusions, porosity, etc.)
- Erosion & corrosion thickness gauging
- Assessment of bond integrity in adhesively joined and brazed components
- Estimation of void content in composites and plastics
- Measurement of case hardening depth in steels
- Estimation of grain size in metals

On the following slides are examples of some common applications of ultrasonic inspection.

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Thickness Gauging

- Ultrasonic thickness gauging is routinely utilized in the petrochemical and utility industries to determine various degrees of corrosion/erosion.
- Applications include piping systems, storage and containment facilities, and pressure vessels.

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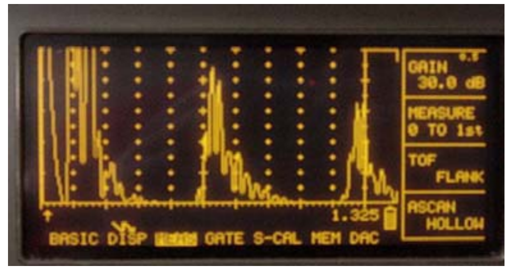
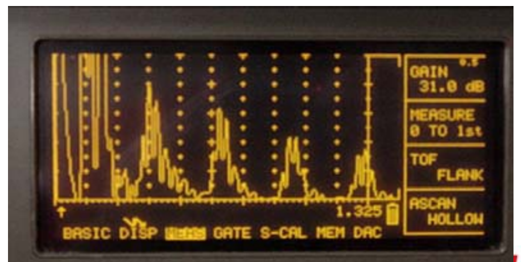
Flaw Detection - Delaminations

Contact, pulse-echo inspection for delaminations on 36” rolled beam.



Signal showing multiple back surface echoes in an unflawed area.



Additional echoes indicate delaminations in the member.

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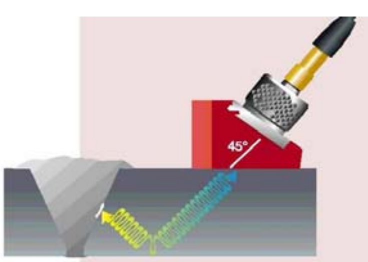
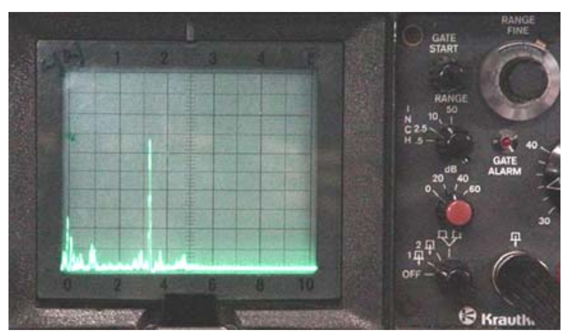
Flaw Detection in Welds

- One of the most widely used methods of inspecting weldments is ultrasonic inspection.
- Full penetration groove welds lend themselves readily to angle beam shear wave examination.





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Equipment

Equipment for ultrasonic testing is very diversified. Proper selection is important to insure accurate inspection data as desired for specific applications.

In general, there are three basic components that comprise an ultrasonic test system:

- Instrumentation
- Transducers
- Calibration Standards

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Transducers

- Transducers are manufactured in a variety of forms, shapes and sizes for varying applications.
- Transducers are categorized in a number of ways which include:
  - Contact or immersion
  - Single or dual element
  - Normal or angle beam
- In selecting a transducer for a given application, it is important to choose the desired frequency, bandwidth, size, and in some cases focusing which optimizes the inspection capabilities.

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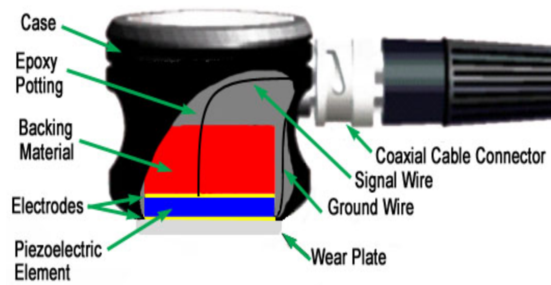
Contact Transducers

Contact transducers are designed to withstand rigorous use, and usually have a wear plate on the bottom surface to protect the piezoelectric element from contact with the surface of the test article.

Many incorporate ergonomic designs for ease of grip while scanning along the surface.



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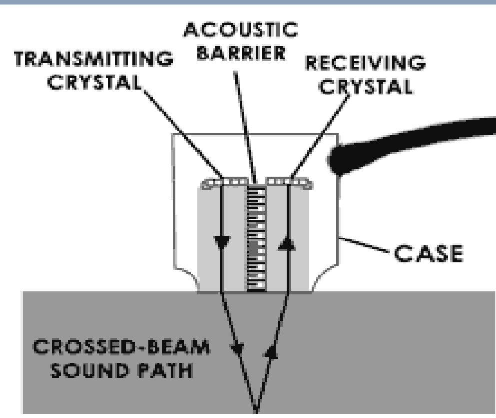
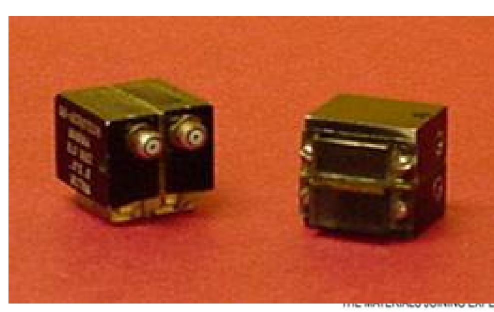
Contact Transducers (cont.)

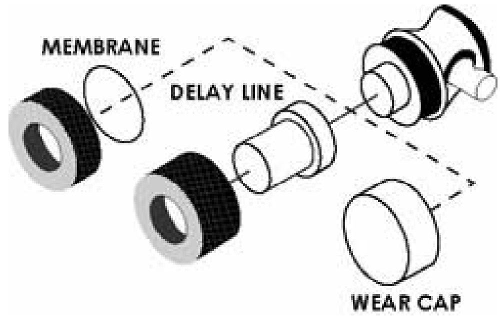
- Contact transducers are available with two piezoelectric crystals in one housing. These transducers are called dual element transducers.
- One crystal acts as a transmitter, the other as a receiver.
- This arrangement improves near surface resolution because the second transducer does not need to complete a transmit function before listening for echoes.
- Dual elements are commonly employed in thickness gauging of thin materials.

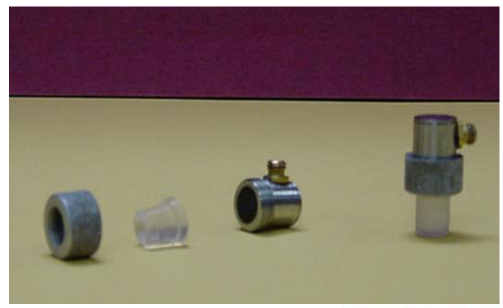




Contact Transducers (cont.)

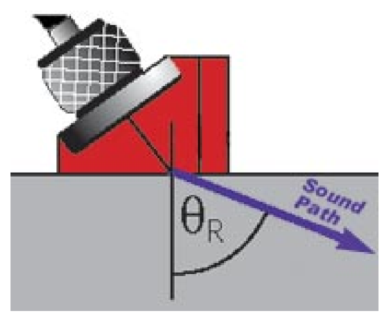
- A way to improve near surface resolution with a single element transducer is through the use of a delay line.
- Delay line transducers have a plastic piece that is a sound path that provides a time delay between the sound generation and reception of reflected energy.
- Interchangeable pieces make it possible to configure the transducer with insulating wear caps or flexible membranes that conform to rough surfaces.
- Common applications include thickness gauging and high temperature measurements.

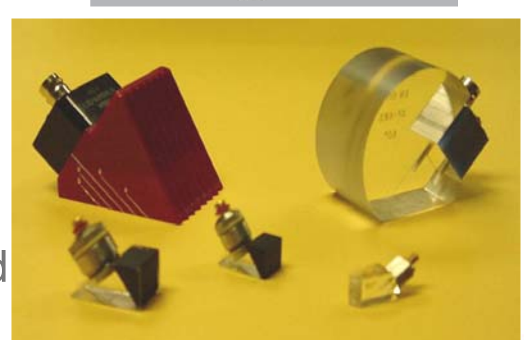




Transducers (cont.)

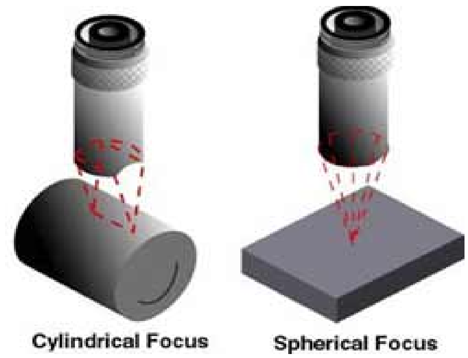
- Angle beam transducers incorporate wedges to introduce a refracted shear wave into a material.
- The incident wedge angle is used with the material velocity to determine the desired refracted shear wave according to Snell's Law)
- Transducers can use fixed or variable wedge angles.
- Common application is in weld examination.





Transducers (cont.)

- Immersion transducers are designed to transmit sound whereby the transducer and test specimen are immersed in a liquid coupling medium (usually water).
- Immersion transducers are manufactured with planar, cylindrical or spherical acoustic lenses (focusing lens).



Instrumentation

- Ultrasonic equipment is usually purchased to satisfy specific inspection needs, some users may purchase general purpose equipment to fulfill a number of inspection applications.
- Test equipment can be classified in a number of different ways, this may include portable or stationary, contact or immersion, manual or automated.
- Further classification of instruments commonly divides them into four general categories: D-meters, Flaw detectors, Industrial and special application.

Instrumentation (cont.)

- D-meters or digital thickness gauge instruments provide the user with a digital (numeric) readout.
- They are designed primarily for corrosion/erosion inspection applications.
- Some instruments provide the user with both a digital readout and a display of the signal. A distinct advantage of these units is that they allow the user to evaluate the signal to ensure that the digital measurements are of the desired features.

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Instrumentation (cont.)

- Flaw detectors are instruments designed primarily for the inspection of components for defects.
- However, the signal can be evaluated to obtain other information such as material thickness values.
- Both analog and digital display.
- Offer the user options of gating horizontal sweep and amplitude threshold.

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Instrumentation (cont.)

- Industrial flaw detection instruments, provide users with more options than standard flaw detectors.
- May be modulated units allowing users to tailor the instrument for their specific needs.
- Generally not as portable as standard flaw detectors.

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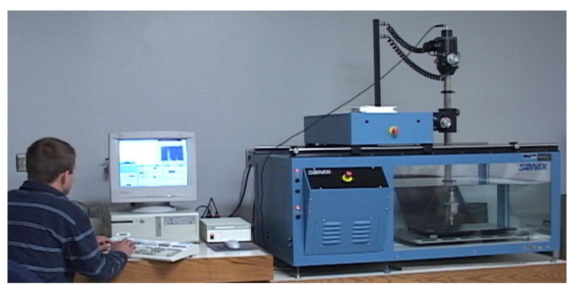
Instrumentation (cont.)

- Immersion ultrasonic scanning systems are used for automated data acquisition and imaging.
- They integrate an immersion tank, ultrasonic instrumentation, a scanning bridge, and computer controls.
- The signal strength and/or the time-of-flight of the signal is measured for every point in the scan plan.
- The value of the data is plotted using colors or shades of gray to produce detailed images of the surface or internal features of a component.



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Images of a Quarter Produced With an Ultrasonic Immersion Scanning System

Gray scale image produced using the sound reflected from the front surface of the coin

Gray scale image produced using the sound reflected from the back surface of the coin (inspected from "heads" side)

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Calibration Standards

Calibration is a operation of configuring the ultrasonic test equipment to known values. This provides the inspector with a means of comparing test signals to known measurements.

Calibration standards come in a wide variety of material types, and configurations due to the diversity of inspection applications.

Calibration standards are typically manufactured from materials of the same acoustic properties as those of the test articles.

The following slides provide examples of specific types of standards.

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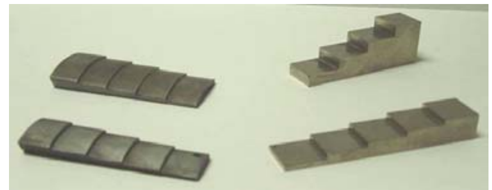
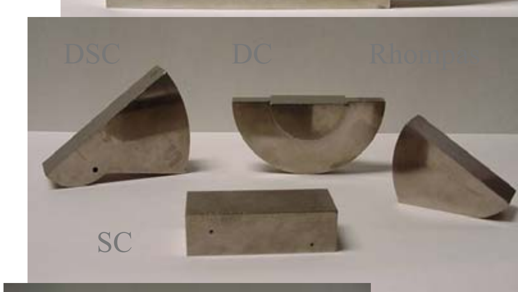
Calibration Standards (cont.)

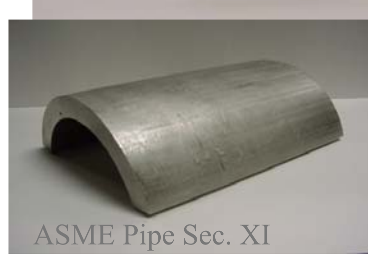
Thickness calibration standards may be flat or curved for pipe and tubing applications, consisting of simple variations in material thickness.



Distance/Area Amplitude standards utilize flat bottom holes or side drilled holes to establish known reflector size with changes in sound path form the entry surface.

Calibration Standards (cont.)



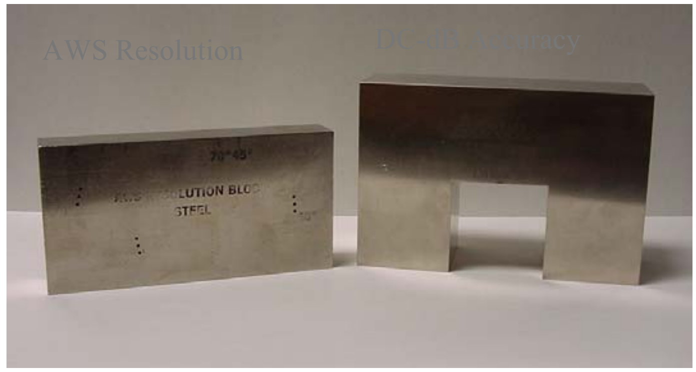


There are also calibration standards for use in angle beam inspections when flaws are not parallel to entry surface.

These standards utilized side drilled holes, notches, and geometric configuration to establish time distance and amplitude relationships.

Qualification Standards

Qualification standards differ from calibration standards in that their use is for purposes of varying proper equipment operation and qualification of equipment use for specific codes and standards.



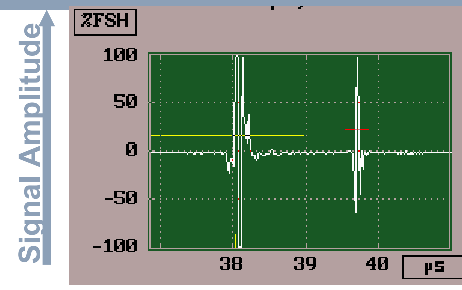
Data Presentation

- Information from ultrasonic testing can be presented in a number of differing formats.
- Three of the more common formats include:
  - A-scan
  - B-scan
  - C-scan

These three formats will be discussed in the next few slides.

Data Presentation - A-scan

- A-scan presentation displays the amount of received ultrasonic energy as a function of time.
- Relative discontinuity size can be estimated by comparing the signal amplitude to that from a known reflector.
- Reflector depth can be determined by the position of the signal on the horizontal sweep.



Time

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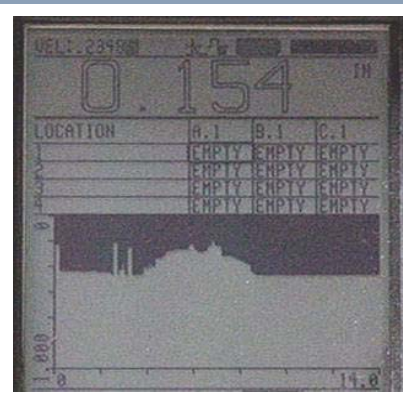
Data Presentation - B-scan

- B-scan presentations display a profile view (cross-sectional) of a test specimen.
- Only the reflector depth in the cross-section and the linear dimensions can be determined.
- A limitation to this display technique is that reflectors may be masked by larger reflectors near the surface.



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Data Presentation - C-scan

- The C-scan presentation displays a plan type view of the test specimen and discontinuities.
- C-scan presentations are produced with an automated data acquisition system, such as in immersion scanning.
- Use of A-scan in conjunction with C-scan is necessary when depth determination is desired.

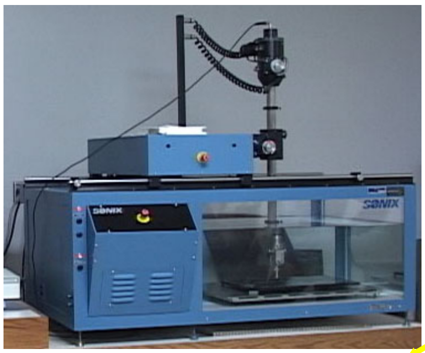
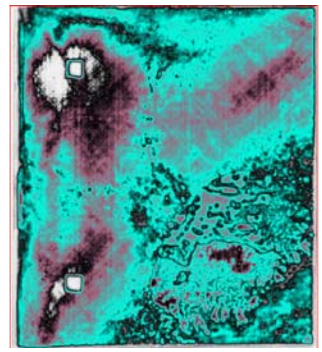


Photo of a Composite Component



C-Scan Image of Internal Features

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Advantage of Ultrasonic Testing

- Sensitive to both surface and subsurface discontinuities.
- Depth of penetration for flaw detection or measurement is superior to other methods.
- Only single-sided access is needed when pulse-echo technique is used.
- High accuracy in determining reflector position and estimating size and shape.
- Minimal part preparation required.
- Electronic equipment provides instantaneous results.
- Detailed images can be produced with automated systems.
- Has other uses such as thickness measurements, in addition to flaw detection.

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Limitations of Ultrasonic Testing

- Surface must be accessible to transmit ultrasound.
- Skill and training is more extensive than with some other methods.
- Normally requires a coupling medium to promote transfer of sound energy into test specimen.
- Materials that are rough, irregular in shape, very small, exceptionally thin or not homogeneous are difficult to inspect.
- Cast iron and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise.
- Linear defects oriented parallel to the sound beam may go undetected.
- Reference standards are required for both equipment calibration, and characterization of flaws.

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Glossary of Terms

- **Acoustical properties**: ultrasonic material characteristics such as velocity, impedance, and attenuation.
- A**STM**: acronym for American Society for Testing and Materials. This society is extensively involved in establishing standards for materials and the testing of materials.
- **Back reflection**: a display signal that corresponds to the far surface of a test specimen, side opposite to transducer when testing with longitudinal waves.
- **Band width**: a range of frequencies either transmitted or received, may be narrow or broad range.
- **B-scan**: presentation technique displaying data in a cross-sectional view.

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Glossary of Terms

- **Calibration**: a sequence of instrument control adjustments/instrument responses using known values to verify instrument operating characteristics. Allows determination of unknown quantities from test materials.
- **CRT**: acronym for Cathode Ray Tube. Vacuum tube that utilizes one or more electron guns for generating an image.
- **C-scan**: presentation technique that displays specimen data in a plan type view.
- **DAC (Distance Amplitude Correction-curves):** a graphical method of allowing for material attenuation. Percentage of DAC is often used as a means of acceptance criteria.
- **Discontinuity**: an interruption in the physical structure of a material, examples include fissures, cracks, and porosity.

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Glossary of Terms

- **IIW**: calibration standard meeting the specification of the International Institute of Welding.
- **Longitudinal (Compression) waves**: ultrasonic mode of propagation in which the particle vibration is parallel to the direction of propagation.
- **Near Surface Resolution**: the ability of an ultrasonic system to display reflectors located close to the entry surface.
- **Pulse-echo**: ultrasonic test method that utilizes reflected sound as a means of collecting test data.
- **Rayleigh (Surface) waves**: ultrasonic mode of propagation where the sound travels along the surface, particle vibration is elliptical.

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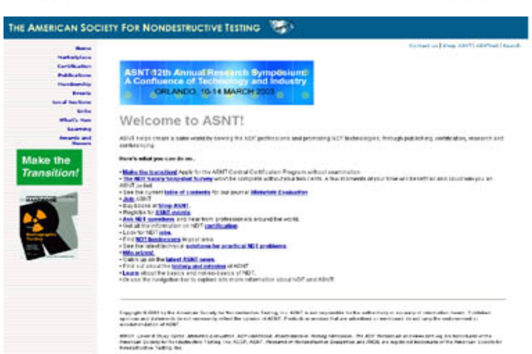
Glossary of Terms

- **Reflection:** the changing in direction of sound waves as they strike a surface.
- **Snell's Law**: an equation of ratios used to determine incident or refracted angle of sound, denotes angle/velocity relationship.
- **Sweep display**: horizontal line on the lower portion of the display, often called the time base line.
- **Through transmission**: test technique in which ultrasound is transmitted from one transducer and received by a separate transducer on the opposite side of the test specimen.
- **Wavelength**: the distance that a sound wave travels as it completes one cycle, normally measured in inches or millimeters.

For More Information

The Collaboration for NDT Education

www.ndt-ed.org



The American Society for Nondestructive Testing

www.asnt.org

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Automatic Ultrasonic Pipeline Girth Weld Inspection

What a Pipeline Engineer/Inspector Needs to Know

Presenter Dr. Mark Lozev Edison Welding Institute

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Thanks
Edison Welding Institute
Transportation Safety Institute
PHMSA Research and Development Division

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192.243 & 195.234 Nondestructive testing

- Nondestructive testing of welds must be performed by any process that will clearly indicate defects that may affect the integrity of the weld.
- Nondestructive testing of welds must be performed in accordance with written procedures; and by persons who have been trained and qualified in the established procedures and with the equipment employed in testing.
- Procedures for the proper interpretation of each weld must be established to ensure the acceptability of the welds under 195.228 or 192.241.

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192.241 & 195.228 Inspection Standard

- The acceptability of a weld that is nondestructively tested or visually inspected is determined according to the standards in Section 9 of API Standard 1104. However, if a girth weld is unacceptable under those standards for a reason other than a crack, and if Appendix A to API 1104 applies to the weld, the acceptability of the weld may be further determined under that appendix.

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API 1104 Appendix A

Appendix A allows Fitness for Service or Engineering Critical Assessment.

Steps for use:

Stress analysis – Axial, Cyclic

Develop specialized welding procedures which includes a special process for procedure qualification

Determination of maximum acceptable imperfection size. Length and Height.

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API 1104 Appendix A (cont.)

The length and height of an imperfection, and its depth below the surface, must be established. The use of ultrasonic techniques…is acceptable, provided the technique's accuracy has been established and any potential inaccuracy is included in the measurement; i.e., the determination of imperfection height shall be conservative.

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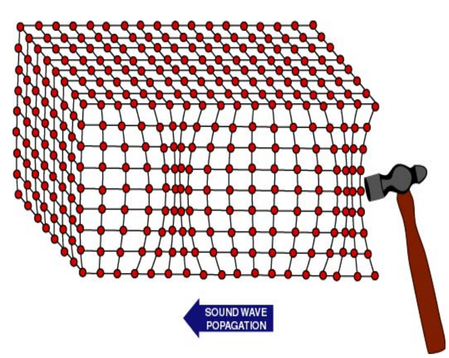
11.4.4 Qualification of the Testing Procedure

- Prior to final written approval, the company shall require the contractor to demonstrate the application of the procedure and ultrasonic systems. A procedure qualification report shall be generated and the results documented prior to use on actual field welds. The qualification process shall be as follows:
  - a. Welds (minimum of 2 per welding procedure) containing defects and acceptable imperfections shall be prepared from actual production pipe material samples utilizing the approved welding procedure specification. Welder qualification welds may be used.
  - b. Radiographs shall be made of the welds and the results documented.
  - c. The UT procedure shall be applied, within the detailed temperature ranges, and the results documented and compared with the radiographs.
  - d. Differences in detection results shall be documented. (Differences in detectability and resolution between ultrasonics and radiography may be noted.) If required by the company, destructive testing of the weld sample shall be made to discover or confirm the results.
  - e. Use of the UT procedure on production welding shall be based on the capability of the implemented UT method/technique/systems to: 1) circumferentially locate, 2) size for length, 3) determine depth from O.D. surface, and 4) axially (weld cross section) locate required imperfections/defects in the test samples. In addition, the procedure must accurately determine the acceptability of welds in accordance with the criteria listed in 9.6 and 11.4.7.

Basic Principles of Sound

- Sound is produced by a vibrating body and travels in the form of a wave.
- Sound waves travel through materials by vibrating the particles that make up the material.
- The pitch of the sound is determined by the frequency of the wave (vibrations or cycles completed in a certain period of time).
- Ultrasound is sound with a pitch too high to be detected by the human ear.



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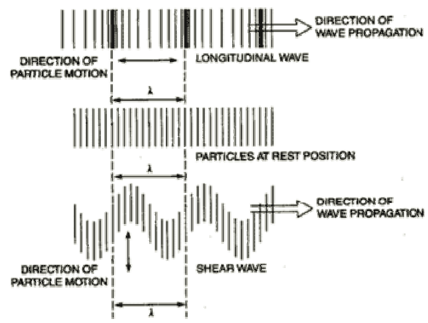
Basic Principles of Sound (cont.)

- The measurement of sound waves from crest to crest determines its wavelength (λ).
- The time is takes a sound wave to travel a distance of one complete wavelength is the same amount of time it takes the source to execute one complete vibration.
- The sound wavelength is inversely proportional to its frequency. ($\lambda = 1/f$)
- Several wave modes of vibration are used in ultrasonic inspection. The most common are longitudinal, shear, and Rayleigh (surface) waves.



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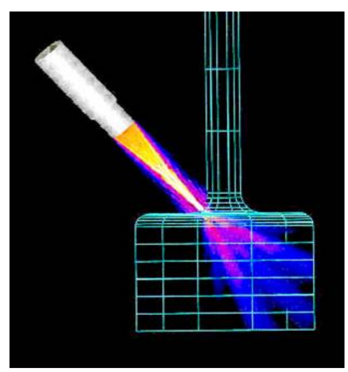
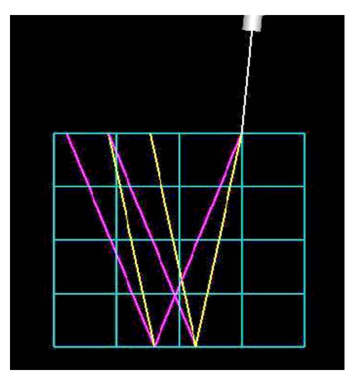
Basic Principles of Sound (cont.)

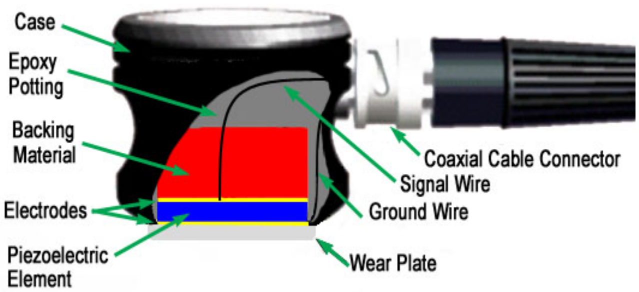
- Ultrasonic waves are very similar to light waves in that they can be reflected, refracted, and focused.
- Reflection and refraction occurs when sound waves interact with interfaces of differing acoustic properties.
- In solid materials, the vibrational energy can be split into different wave modes when the wave encounters an interface at an angle other than 90 degrees.
- Ultrasonic reflections from the presence of discontinuities or geometric features enables detection and location.
- The velocity of sound in a given material is constant and can only be altered by a change in the mode of energy.





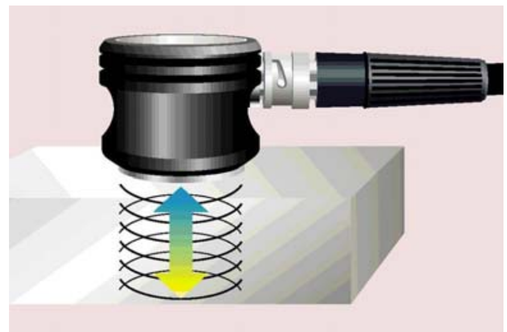
Ultrasound Generation

Ultrasound is generated with a transducer.



The transducer is capable of both transmitting and receiving sound energy.

A piezoelectric element in the transducer converts electrical energy into mechanical vibrations (sound), and vice versa.



Principles of Ultrasonic Inspection

- Ultrasonic waves are introduced into a material where they travel in a straight line and at a constant speed until they encounter a surface.
- At surface interfaces some of the wave energy is reflected and some is transmitted.
- The amount of reflected or transmitted energy can be detected and provides information about the size of the reflector.
- The travel time of the sound can be measured and this provides information on the distance that the sound has traveled.

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Test Techniques

- Ultrasonic testing is a very versatile inspection method, and inspections can be accomplished in a number of different ways.
- Ultrasonic inspection techniques are commonly divided into three primary classifications.
  - **Pulse-echo and Through Transmission**
    (Relates to whether reflected or transmitted energy is used)
  - **Normal Beam and Angle Beam**
    (Relates to the angle that the sound energy enters the test article)
  - **Contact and Immersion**
    (Relates to the method of coupling the transducer to the test article)

Each of these techniques will be discussed briefly in the following slides.

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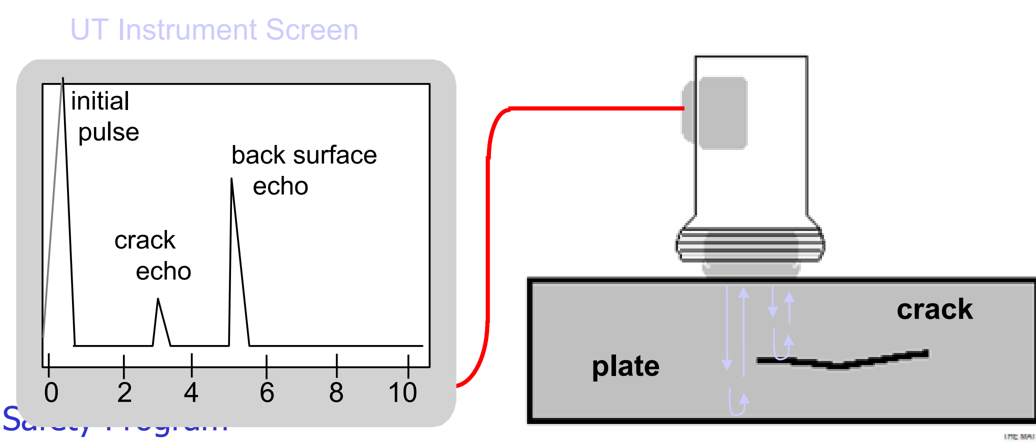
Test Techniques - Pulse-Echo

- **In pulse-echo testing, a transducer sends out a pulse of energy and the same or a second transducer listens for reflected energy (an echo).**
- **Reflections occur due to the presence of discontinuities and the surfaces of the test article.**
- **The amount of reflected sound energy is displayed versus time, which provides the inspector information about the size and the location of features that reflect the sound.**



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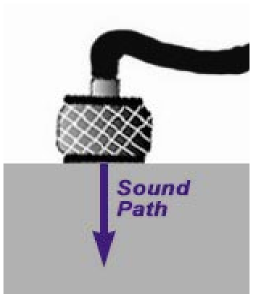
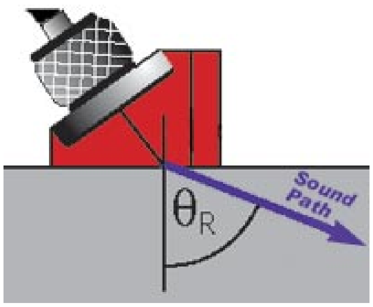
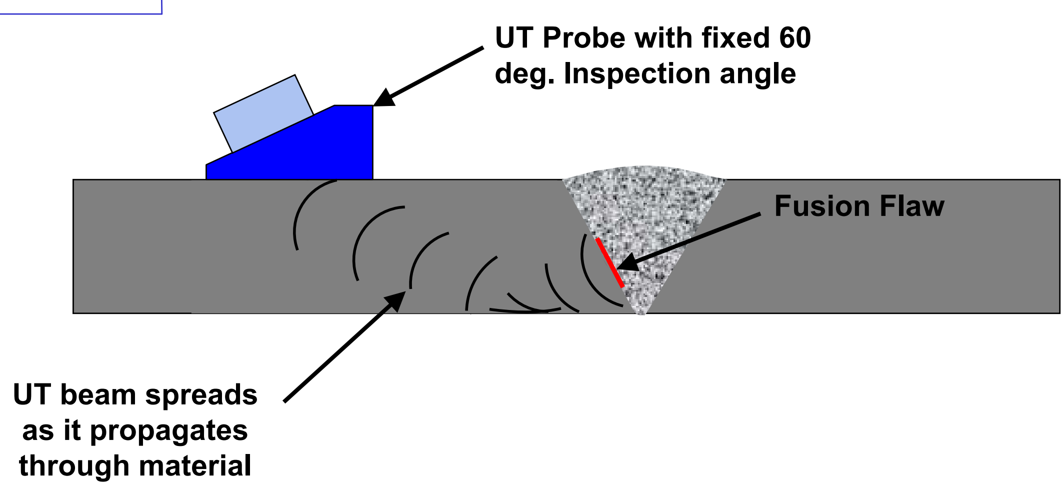
Test Techniques – Normal and Angle Beam





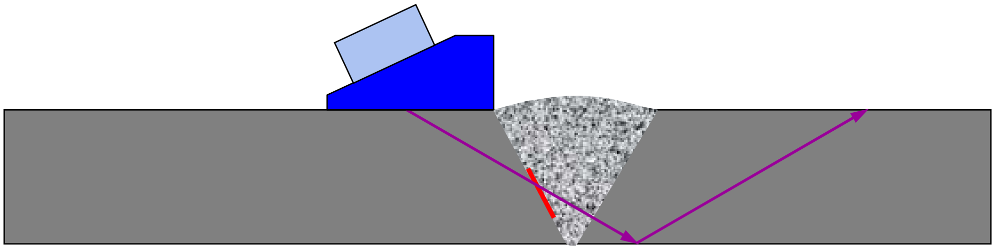
- In normal beam testing, the sound beam is introduced into the test article at 90 degree to the surface.
- In angle beam testing, the sound beam is introduced into the test article at some angle other than 90.
- The choice between normal and angle beam inspection usually depends on two considerations:
  - The orientation of the feature of interest – the sound should be directed to produce the largest reflection from the feature.
  - Obstructions on the surface of the part that must be worked around.

Conventional Manual UT Weld Inspection



The transducer is moved by hand to provide a coverage of the weld.

Automated UT Weld Inspection Scan



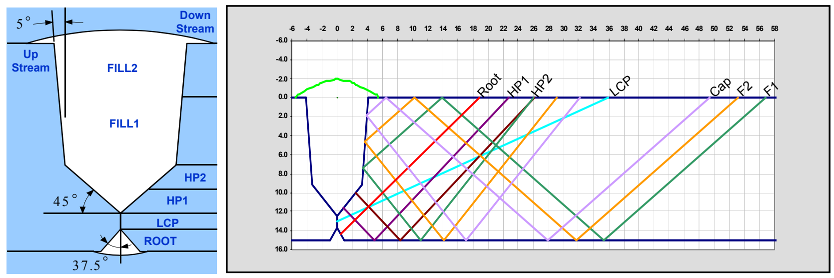
The transducer carrier is moved by a motor-controlled drive unit in one or two directions. The automated mechanical movement of the probe provides good and reliable coverage of the weld.
Anything that mechanically or electronically assists or replaces the operator conducting manual UT can be considered as some form of automated UT.

AUT Instrumentation



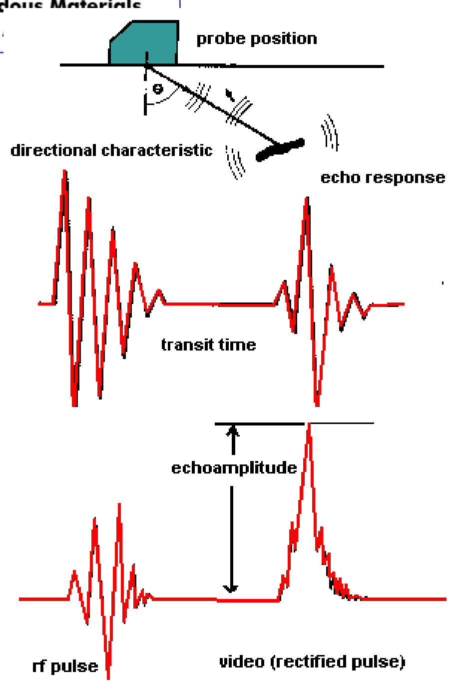


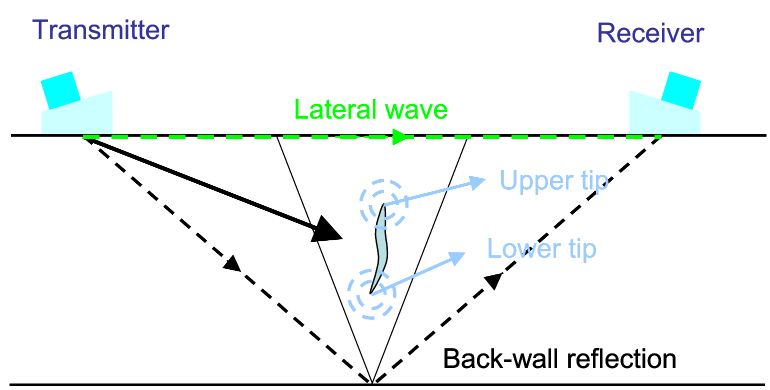

Zonal Discrimination Technique with Focused, Fixed Angle Beam and Multi-probe or Linear PA Search Units



- The weld volume is divided into vertical "zones" and in two halves – up and downstream.
- Each zone has an individual ultrasonic inspection channel with focused beam at fixed angle.
- The number of zones is dependant on the material type, material thickness, bevel type and welding procedure. Assumed defect orientation at the bevel angle and larger size than the beam.
- Optimization of beam profile through variation of radius of curvature (lenses or curved single element probe, or electronically focusing at fixed angle with PA probe), element size, frequency and sizing algorithms.
- Same technique for both multi-probe and PA systems; amplitude-based sizing.

Pulse-Echo and TOFD Basics





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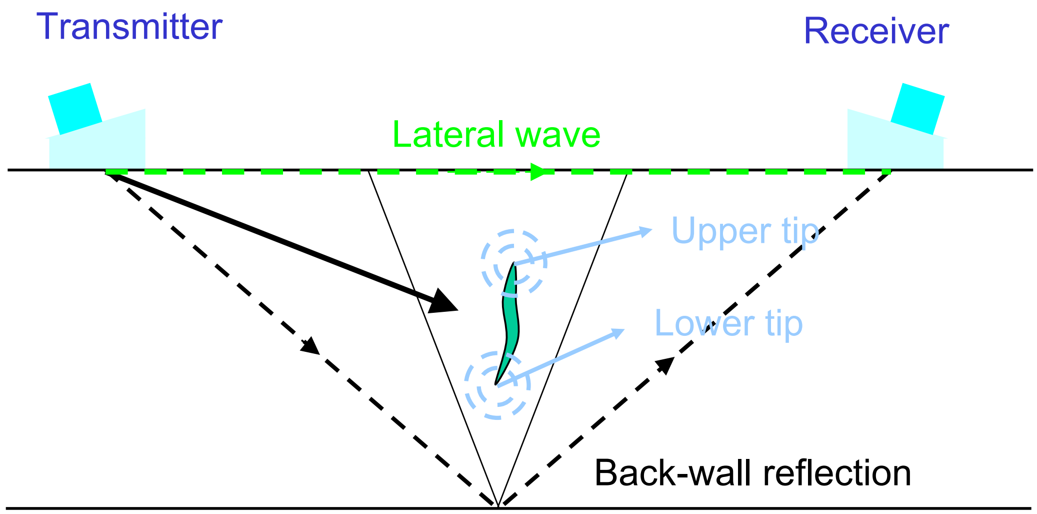
TOFD



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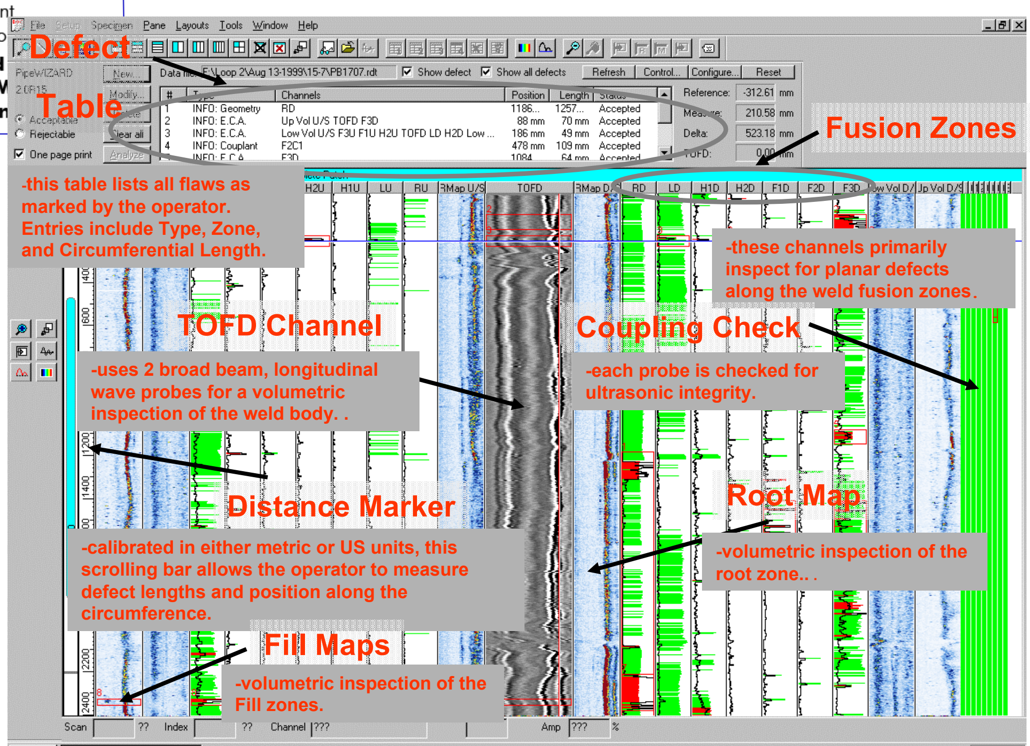
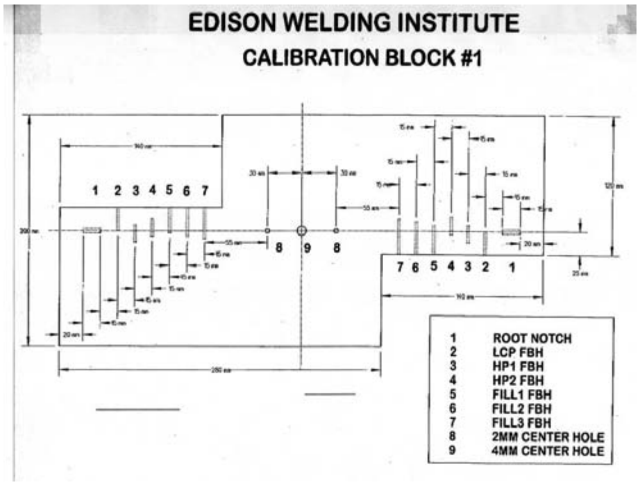
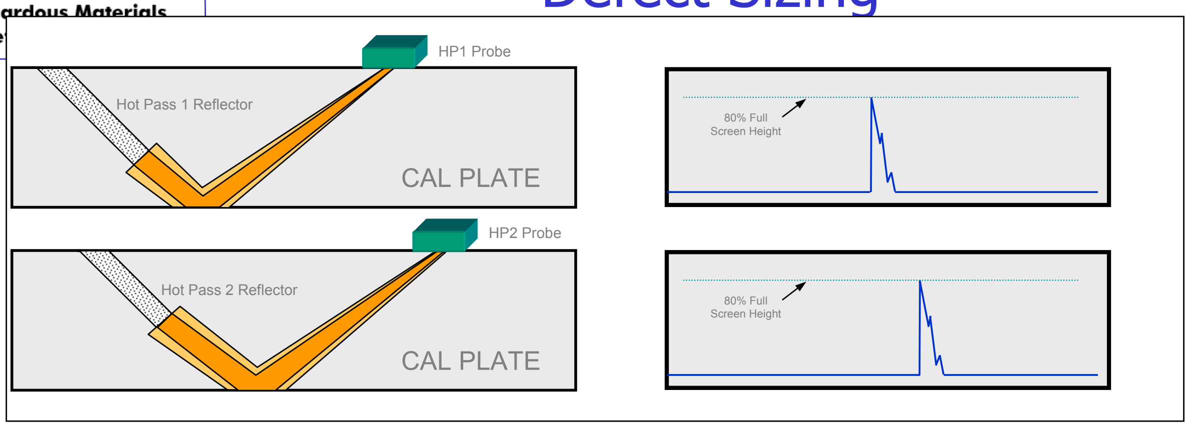
Zonal Discrimination Technique with Focused, Fixed Beam Angle Search Units – Imaging, Strip Chart Layout



Calibration Blocks – ASTM 1961-98

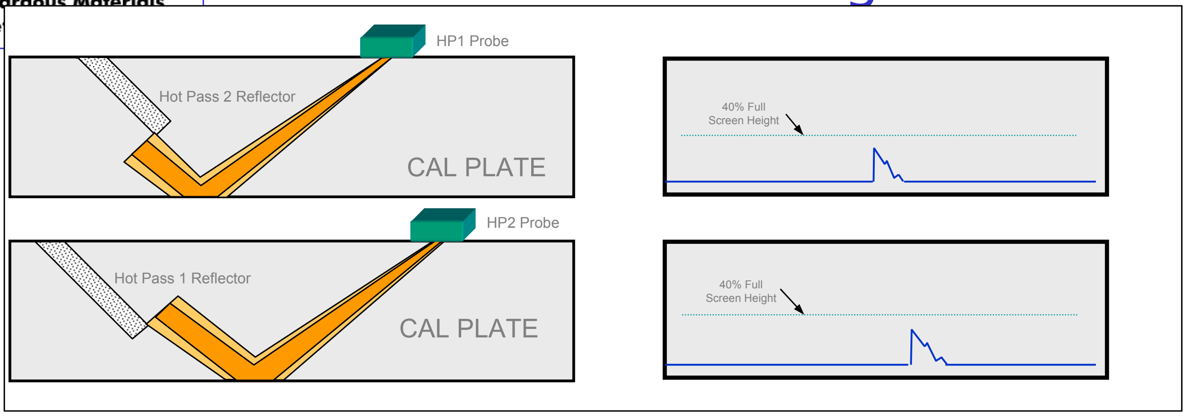


Mechanized Weld Inspection – Defect Sizing



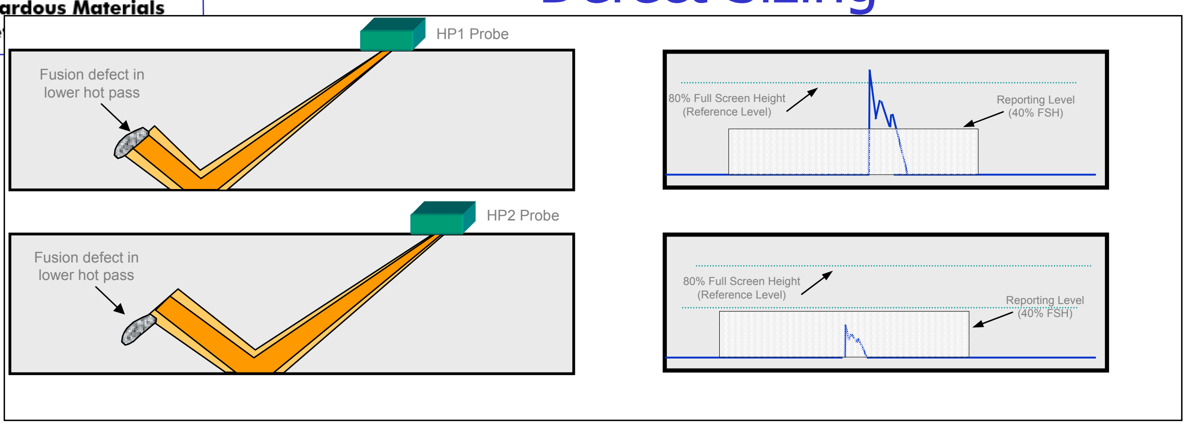
- **Each probe is calibrated on a 2-mm flat-bottomed hole located at the center of the inspection zone.**
- **The channel sensitivity is set to achieve a reflected signal of 80% full screen height (FSH).**

Mechanized Weld Inspection – Defect Sizing



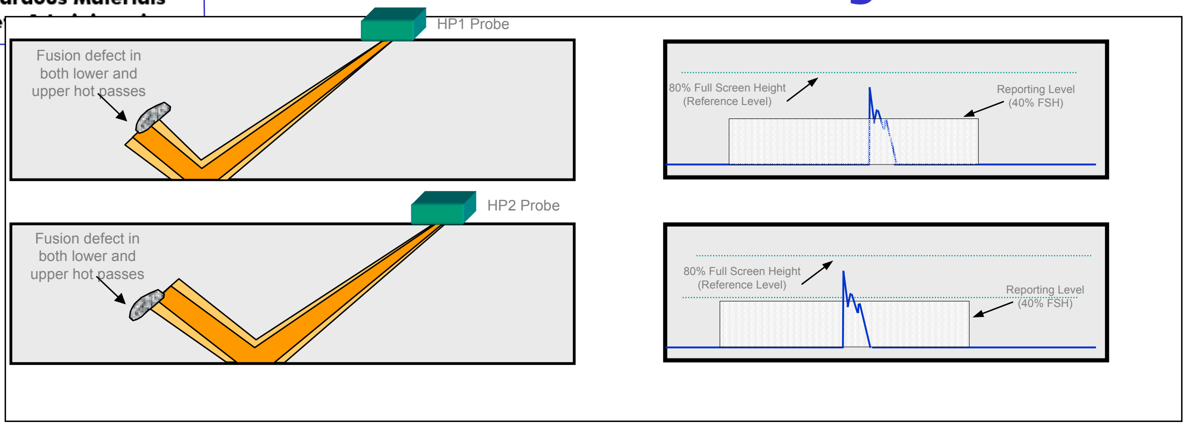
- Each probe is then moved to the adjacent reflector to ensure proper resolution can be achieved.
- The signal from the adjacent reflectors shall be less than the reporting reference level (40% FSH).

Mechanized Weld Inspection – Defect Sizing



- If the defect is contained in only one zone, that channel will register a reflector over the 40% FSH reporting level.
- The adjacent channels will not show a reportable reflector since only a small portion of the defect is within the ultrasonic beam.
- Therefore, the defect is sized to a single zone (2 mm).

Mechanized Weld Inspection – Defect Sizing

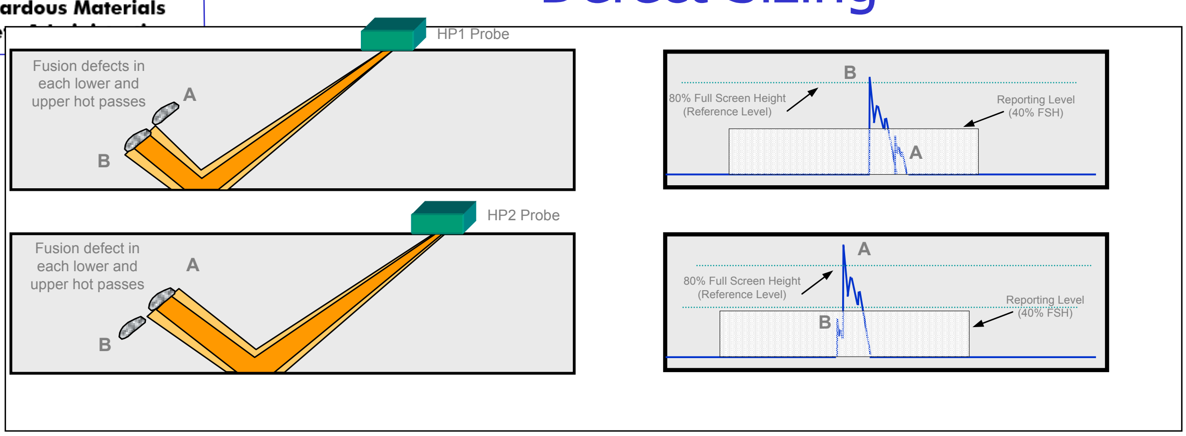


◆ When a defect is equally in two adjacent zones and is at least one zone in height, both zones will register reportable reflectors.

◆ The amplitude of both will be less than the 80% FSH reference level since only a portion of the defect is in each ultrasonic beam.

◆ The defect is sized to the two zones (4 mm).

Mechanized Weld Inspection – Defect Sizing



◆ When two defects are located in separate zones, each channel registers its proper reflector.

◆ The two reflectors are considered to be combined since they are in adjacent zones.

◆ The defect is sized to the two zones (4 mm).

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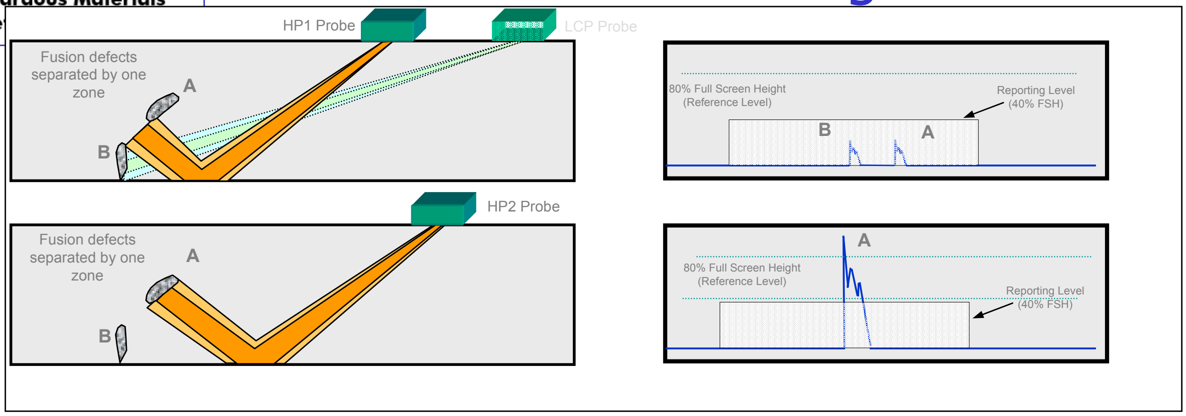
Mechanized Weld Inspection – Defect Sizing



- ◆ When two defects are separated by at least one zone, only the zones with defects register a reportable defect.
- ◆ The "middle" zone may see both reflectors but they will be below the reportable level.
- ◆ The defects are characterized as separate, each with a height of 2 mm.

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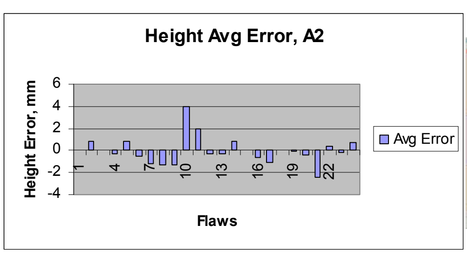
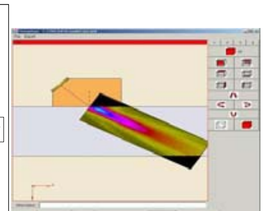
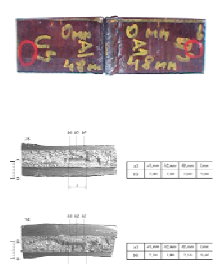
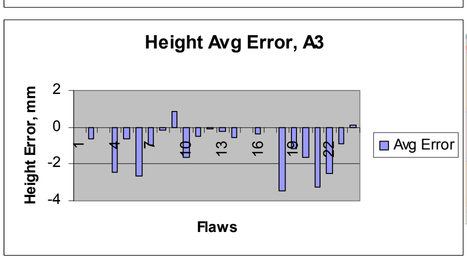
AUT Sizing Capabilities

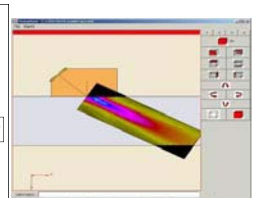
Typical focal spot size 2.6 mm - Focused



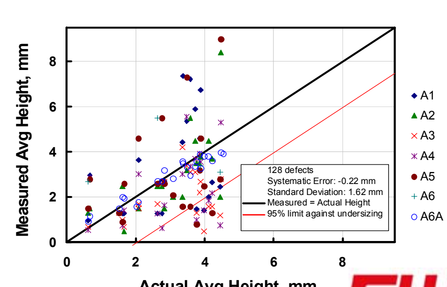








Measured vs. Actual Avg Height, A1-A6A



Typical focal spot size 3.2 mm – Non-focused

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Achieved Sizing Accuracy – Height

Acronym	Approach Description	Height Sizing Accuracy, Avg. Error "a" in mm and % of Detected Flaws		
		a< +/-0.5	+/-0.5>a<+/-2	+/-2>a<+/-4
A1	Focused MultiProbe, amplitude linearization	30 %	35%	30%
A2	Focused MultiProbe, proprietary sizing algorithm	45%	45%	10%
A3	Non-Focused MultiProbe, zone and amplitude interaction rules	30%	45%	25%
A4	Focused Phased Array, 48 el., amplitude linearization	40%	20%	40%
A5	Focused Phased Array, 64 el., amplitude linearization	15%	35%	50%
A6	Focused Phased Array, 64 el., sectorial scanning	25%	25%	50%
A6-open	Focused Phased Array, 32 el., raster and sectorial scanning	75%	25%	N/a

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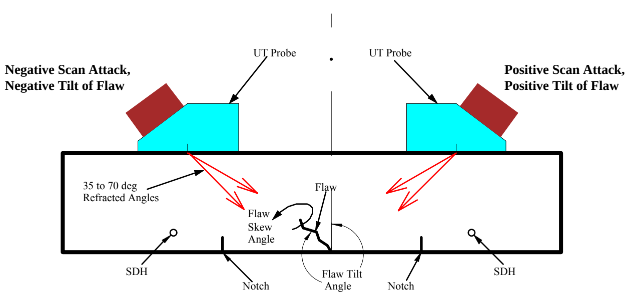
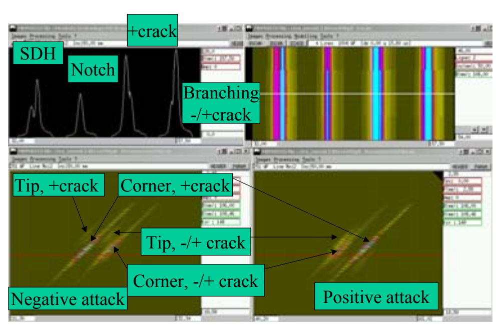
UT Simulations – Set-up and Imaging





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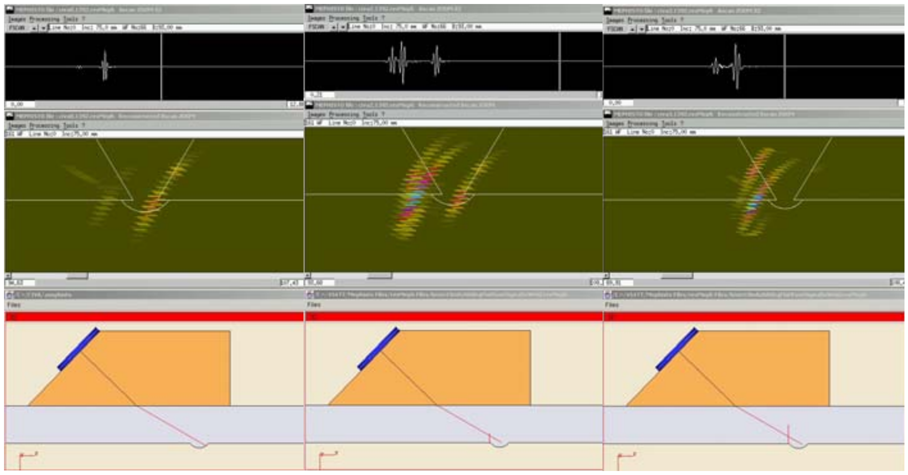
UT Simulations – Example Results



Reflection from Weld Root (left), 1-mm-Deep ID Notch and Nearby Root Geometry (middle) and Signal from 2-mm-Deep ID Notch (right)

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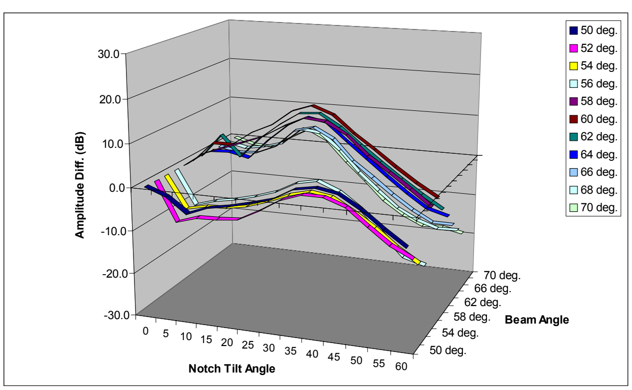
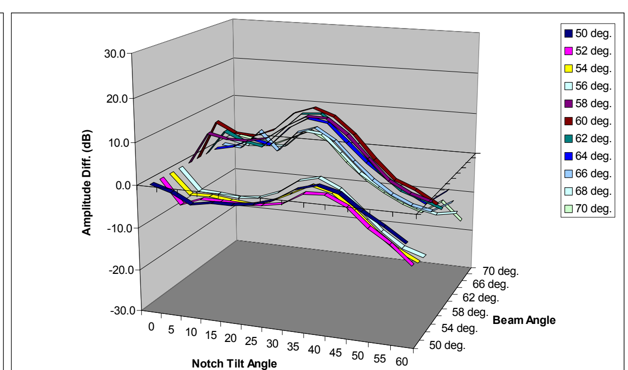
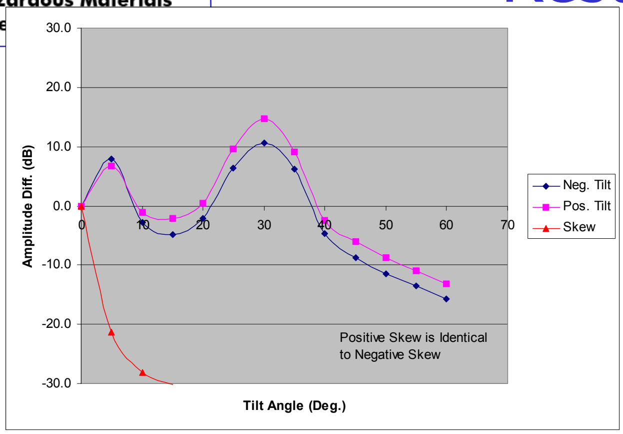
UT simulations – Example Results (cont.)

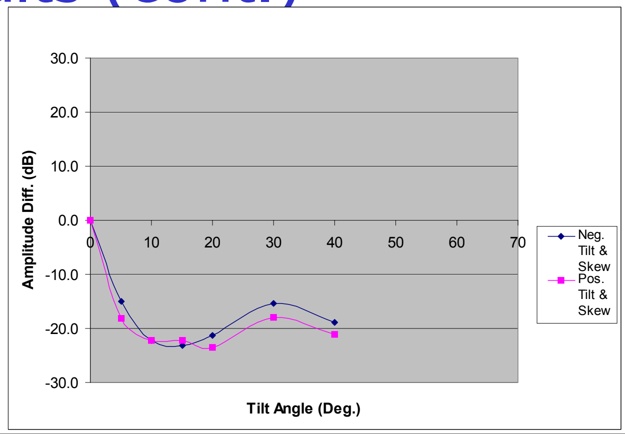




Effect of Positive (left) and Negative (right) Notch Tilt Angle on 10-MHz Signal Amplitude at Various Incident Beam Angles

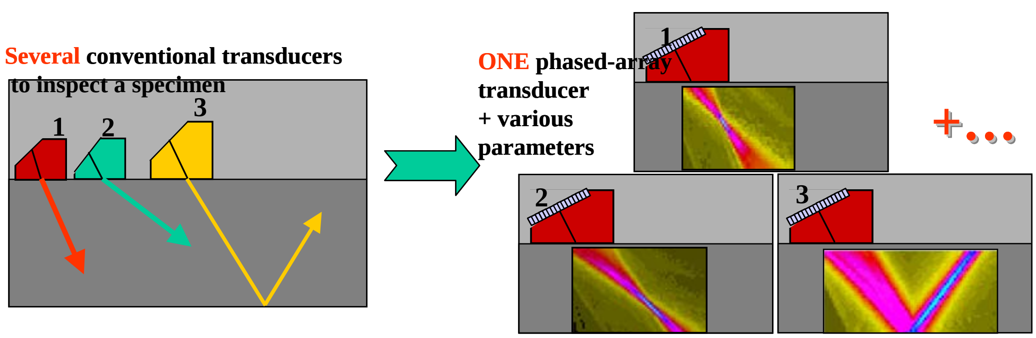
UT simulations – Example Results (cont.)



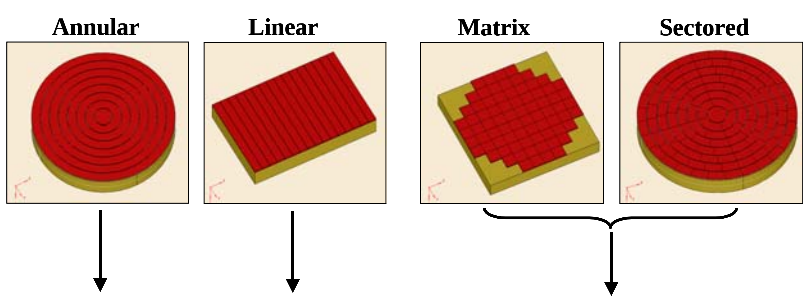


(Left) Amplitude difference between perpendicular ID notch and tilted/skewed notch using 10-MHz, 60-degree shear wave, 32-element PA probe (notch dimensions 1 mm in height x 10 mm in length.); (Right) Amplitude difference between perpendicular ID notch and complex tilted flaw using 10-MHz, 60-degree shear wave, 32-element PA probe (complex flaw dimensions 1 mm in height x 10 mm in length with 0.5- x 2-mm facets.)

Conventional AUT vs. PA AUT



PA Probes



- Axial focusing

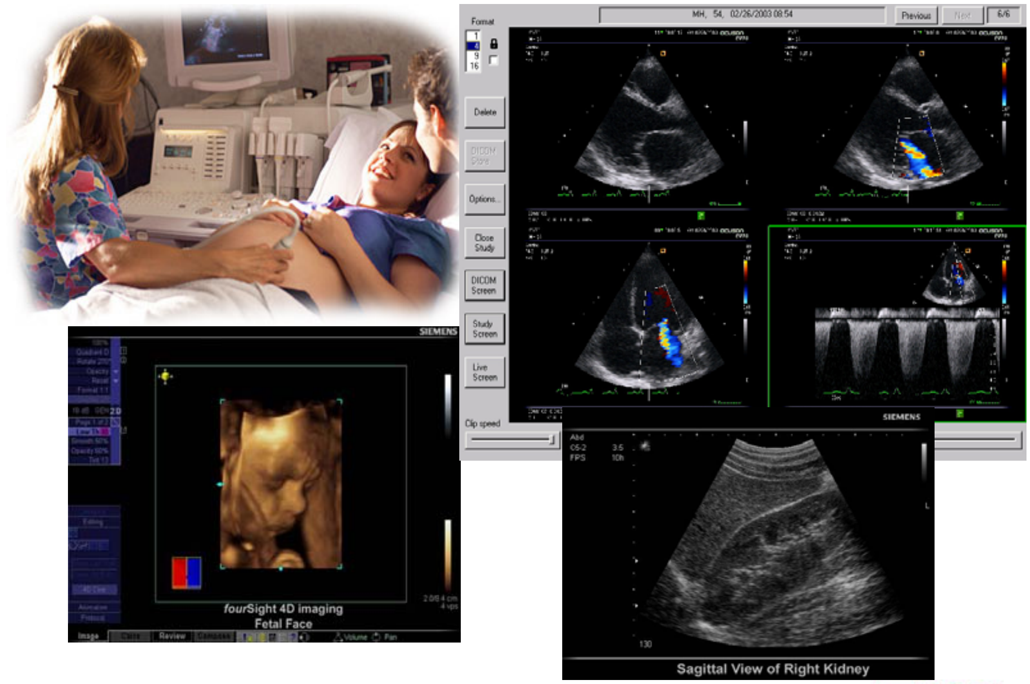
- Axial focusing
- beam-steering

In the array axis plane

- Axial focusing
- Beam-steering

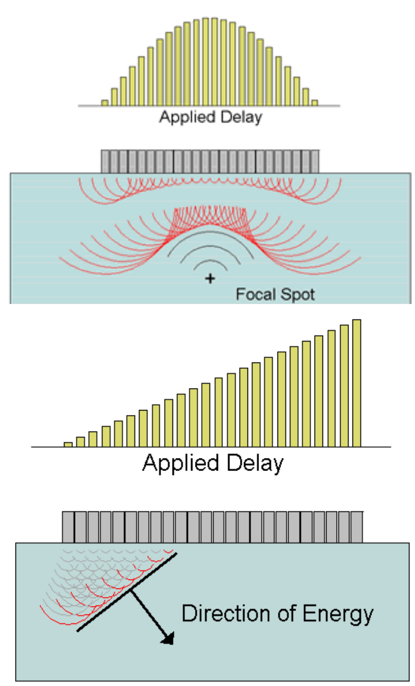
for all directions

PA UT = Medical Ultrasound and Imaging



PA UT – What is it?

- Multiple piezocomposite elements are arranged in one probe.
- Electronics control the excitation timing of each individual element to create an applied delay (focal) law.
- By changing the law, the angle and focal depth of the constructed acoustic beam can be controlled.



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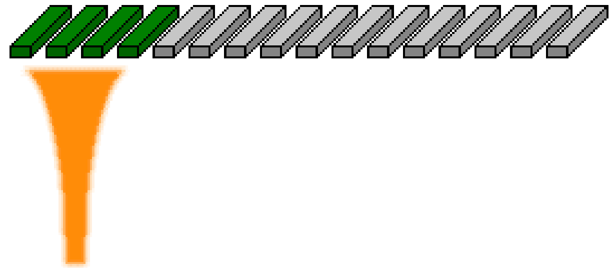
PA UT – Electronic Scanning

- The beam can be electronically scanned across the PA.
- An alternative to mechanical scanning of a conventional probe.
- Faster scanning.
- Reduction in dimensionality of scanning system.



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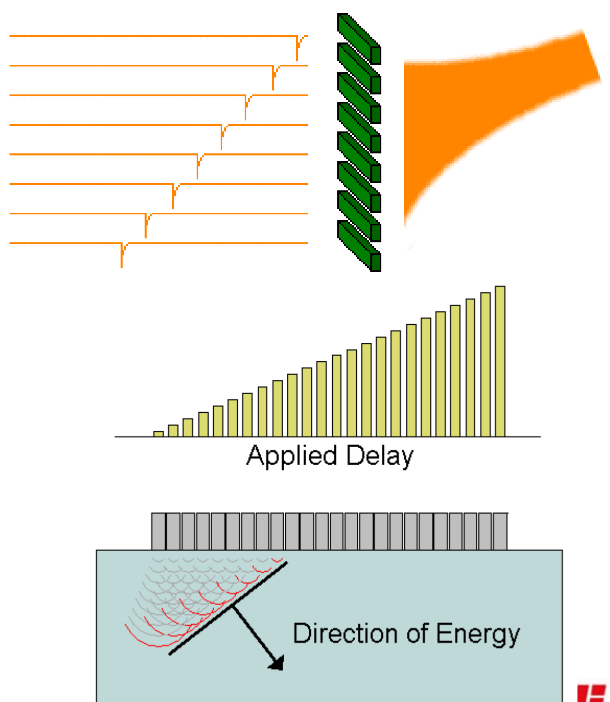
PA UT – Electronic Steering

- A linear delay law can be used to steer the beam in a desired inspection direction.
- Alternative to using multiple probes for a given inspection.
- One transducer can sweep through multiple angles during one scan.
- Volumetric inspections require scanning along only one axis.



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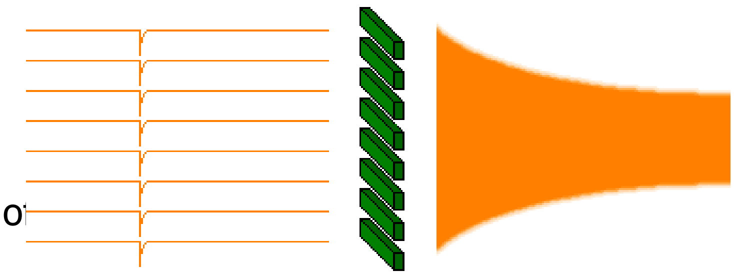
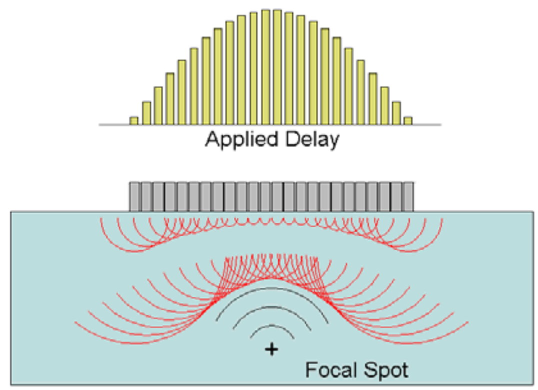
PA UT – Electronic Focusing



- A parabolic delay law results in an acoustic focusing of the beam.
- Dynamic depth focusing (DDF) can be used to create multiple focal depths into the component.
- Alternative to using multiple probes with different focal points.
- Can be used to compensate for focusing aberrations due to surface geometry.



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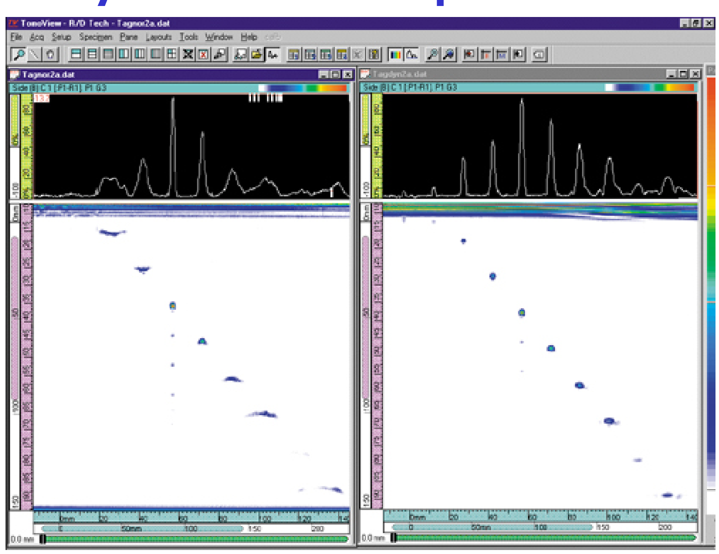
Fixed Focusing vs. Dynamic Depth Focusing



- Dynamic depth focusing (DDF) to extend the focal range of the transducer for thick parts

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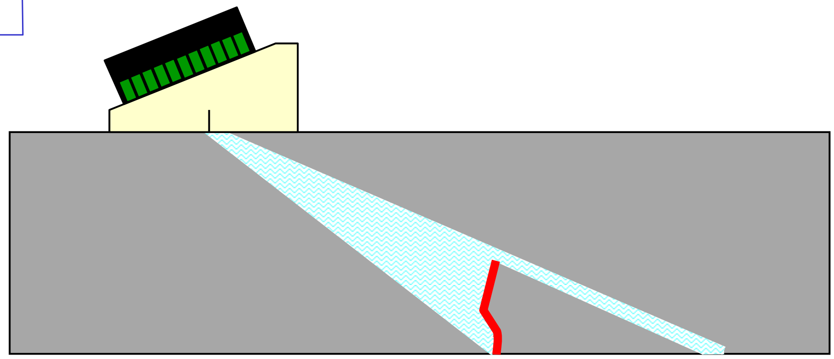
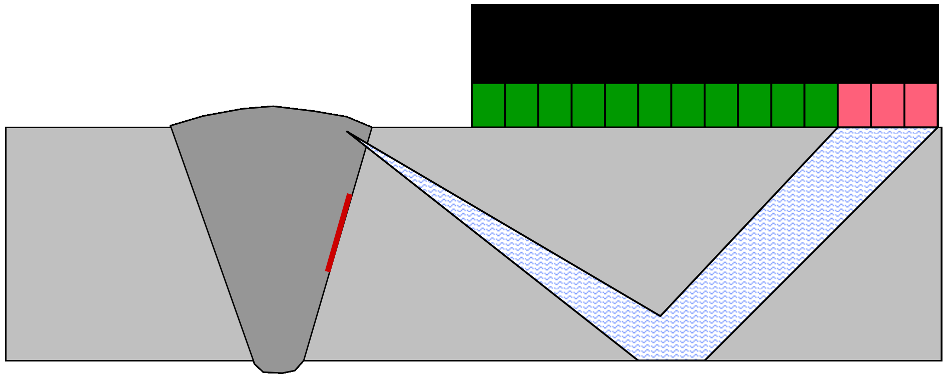
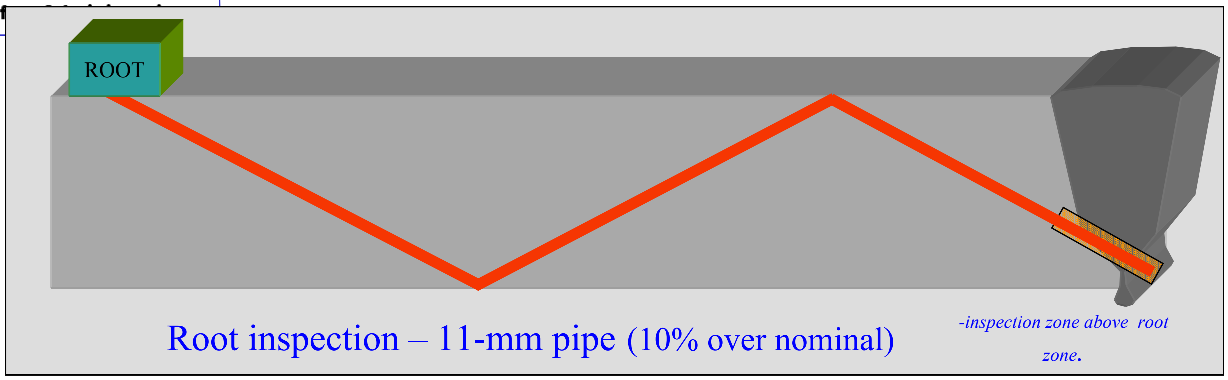
PA Angle Sweep



PA – Butt/Girth Weld Inspection

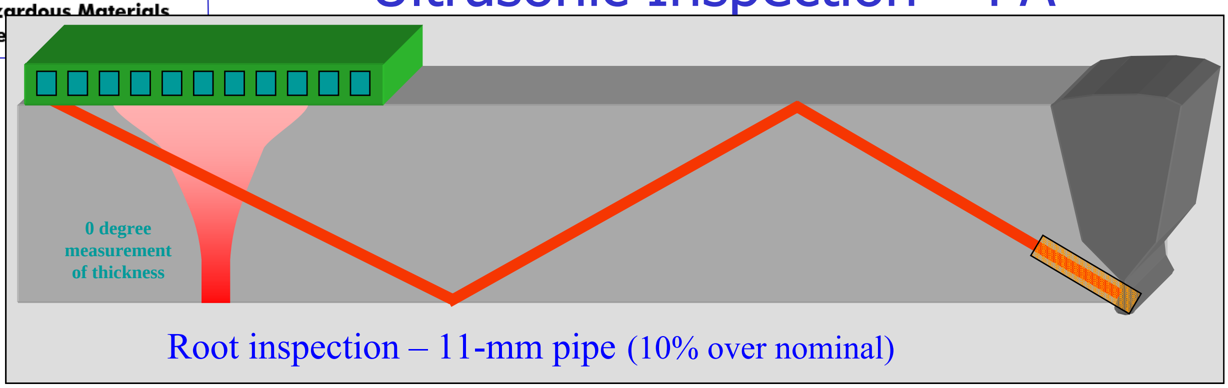


Effect of Pipe Tolerances on Ultrasonic Inspection



- Inspection techniques are based on nominal wall thickness.
- High angled, multi-skip techniques are more prone to errors.
- These errors can be compensated for with PA technology.

Effect of Pipe Tolerances on Ultrasonic Inspection – PA



- A zero-degree examination is performed to measure wall thickness and locate laminar reflectors that may affect weld examination.
- The measured wall thickness is used to re-calculate the proper exit point and sound path for the ultrasonic examination.

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AUT System Detection and Sizing Capabilities - Variables

- Zonal Discrimination Technique with Focused, Fixed Angle Beam and Multi-probe or Linear Phased-array Search Units
  - **material type (very sensitive to “ferritic” or “austenitic” type of base metal and weld material)**
  - **material thickness (very sensitive to small materials thickness change)**
  - **bevel type (very sensitive to bevel configuration and bevel angle)**
  - **welding procedure (very sensitive to welding procedure and weld macrostructure)**
  - **defect orientation (very sensitive to defect missorientation – defect tilt and skew related to the bevel angle)**
- Non-zonal Linear Phased-array Sectorial (S-) Scan Technique
  - **material type (sensitive to “ferritic” or “austenitic” type of base metal and weld material)**
  - **material thickness (not sensitive to wide range of up to 50mm materials thickness change)**
  - **bevel type (not sensitive to bevel configuration and bevel angle)**
  - **welding procedure (sensitive to “ferritic” or “austenitic” weld macrostructure)**
  - **defect orientation (not sensitive to defect tilt, still sensitive to defect skew)**

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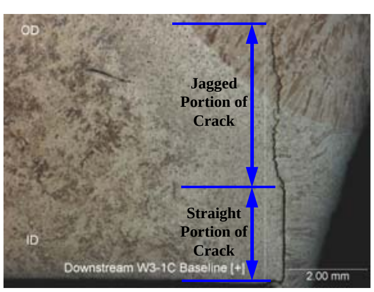
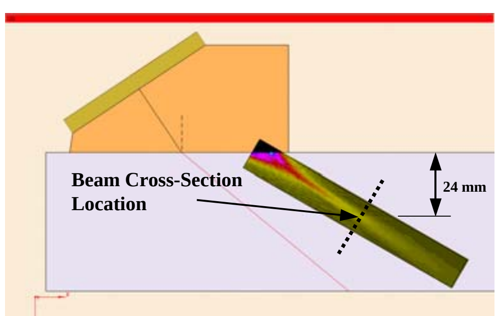
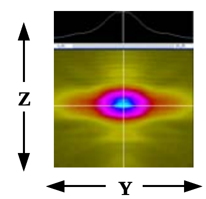
AUT Optimization – Modeling and Simulations

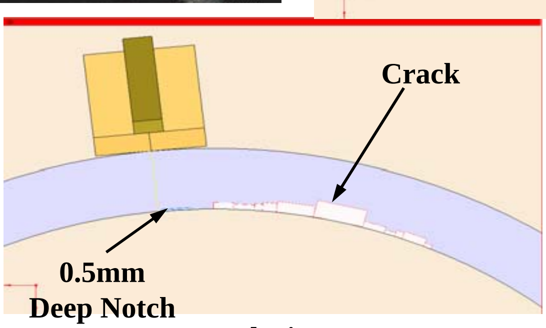




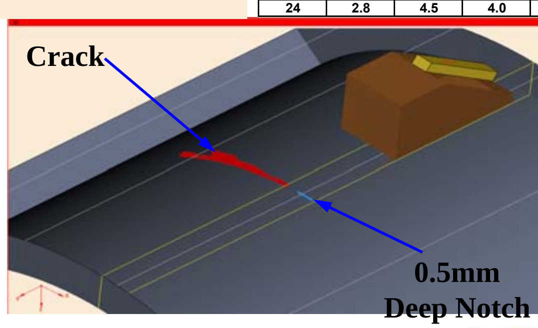
Beam Cross-Section At 24mm Depth



Depth (mm)	6dB		12dB	
	Z (mm)	Y (mm)	Z (mm)	Y (mm)
24	2.8	4.5	4.0	6.8



End View



3D View

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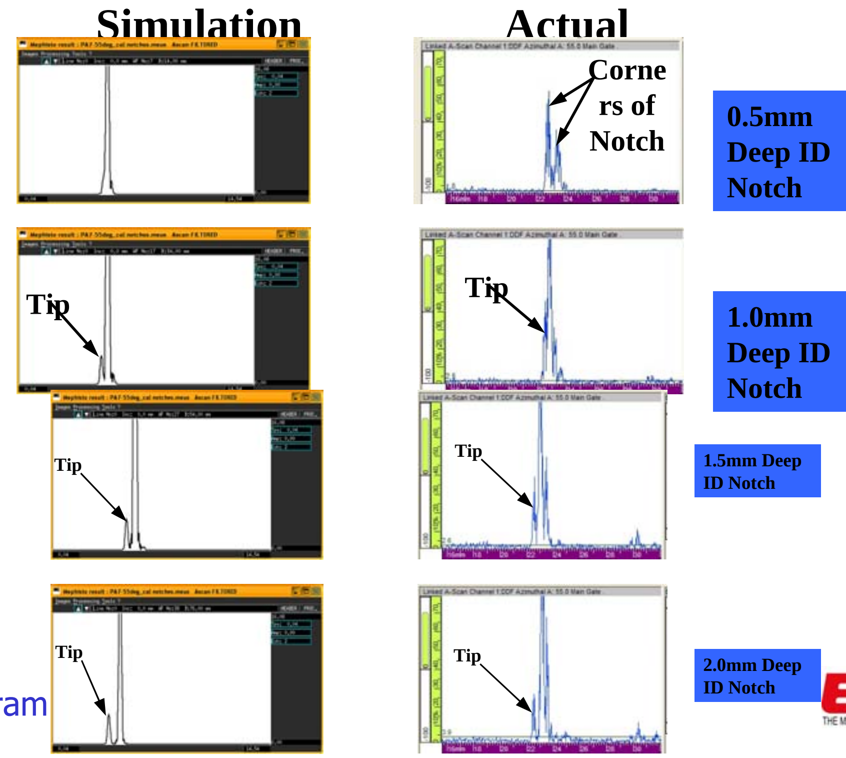
Pipeline and Hazardous Materials Safety Administration

Simulation vs. Actual - PA 7.5 MHz, 60 Element Using 17, 55 Deg., 20 FD



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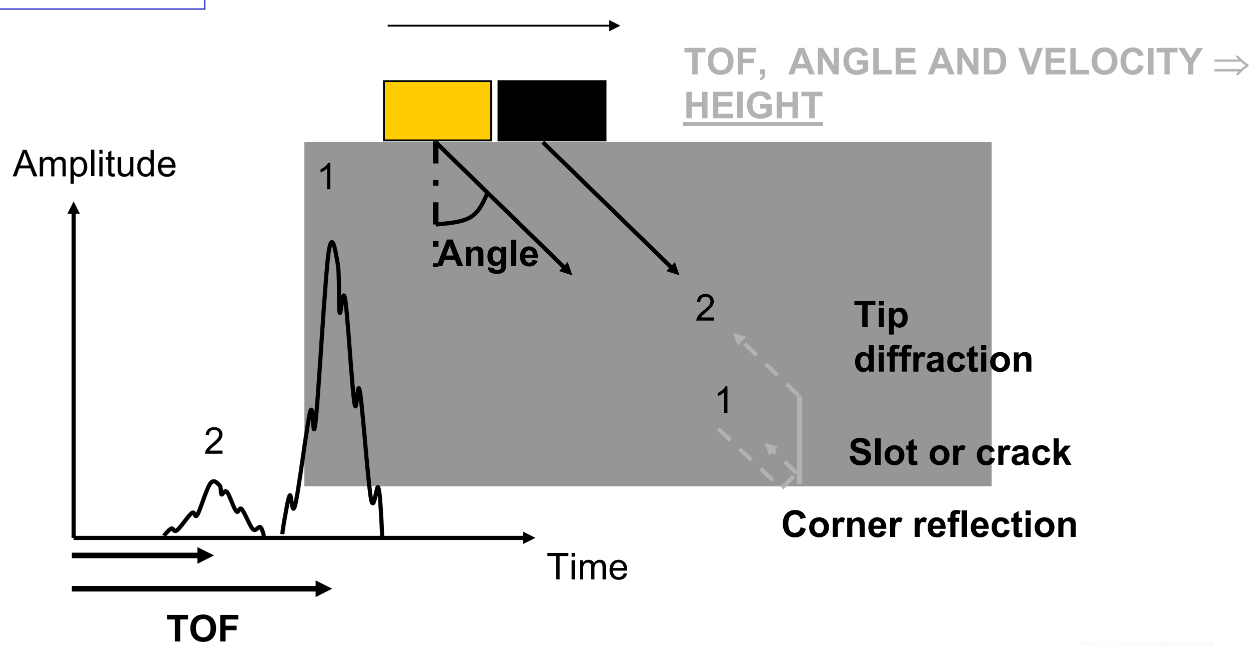
Time-of-Flight (Tip Diffraction)



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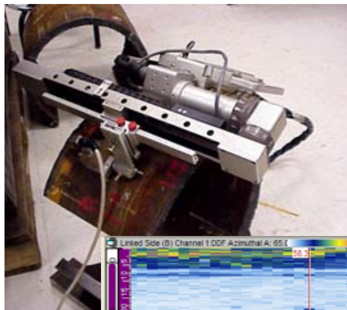
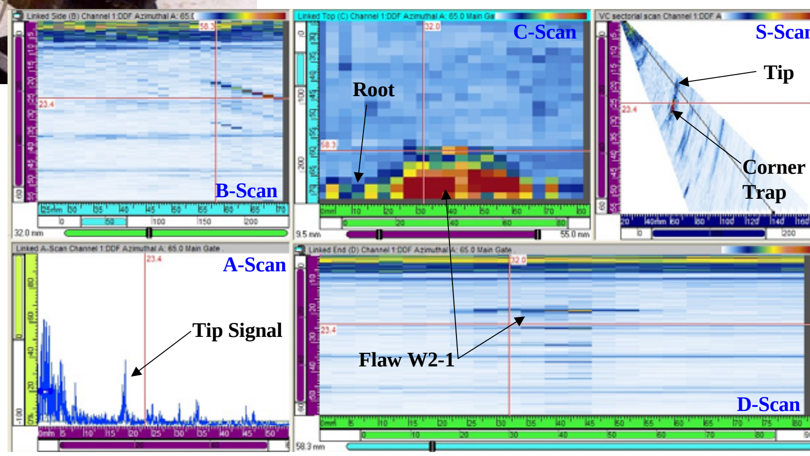
Improved PA Detection, Imaging, and Sizing





Pipeline Safety Program

U.S. Department of Transportation
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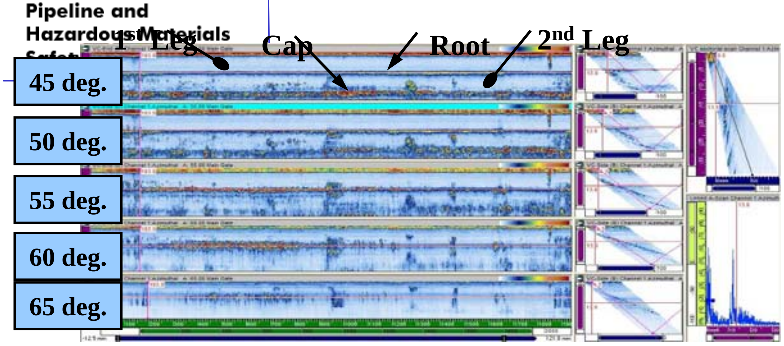
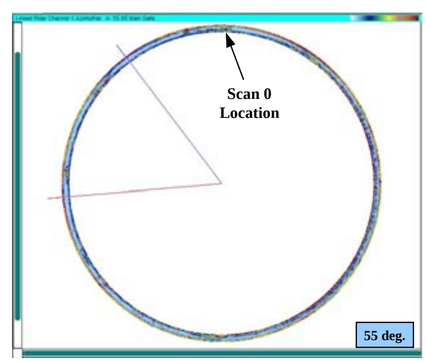
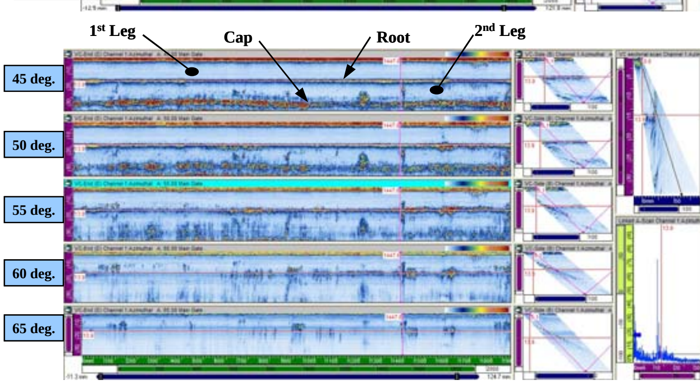
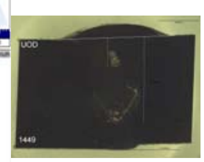
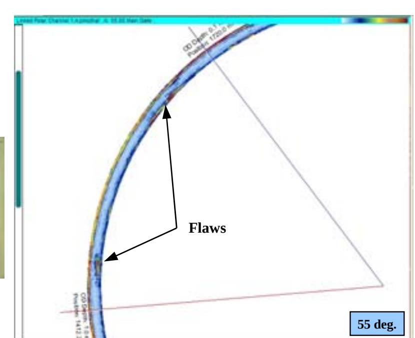
Merged DS vs. US Scans; Polar View - 1412 to 1720 mm











Pipeline Safety Program

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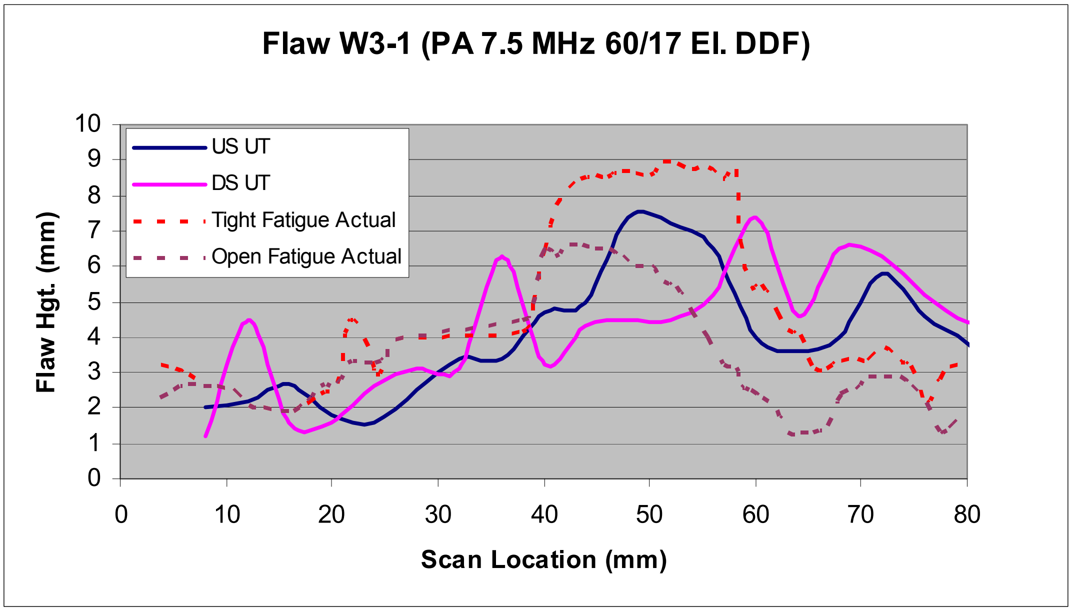
W3-1 Flaw Profile (PA60/17el. DDF)



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Field AUT Verification - General View of DB-30 and Weld #4

Zonal vs. Non-zonal Techniques - Cross Sectioning of Flaws Detected/Missed by AUT

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Location (mm)	Non-zonal PA		Vendor 1		Vendor 2	Vendor 3	Vendor 4	Metallography Location Selected By:
	PA-4 MHz	PA-7 MHz	Zonal, PA	Zonal, Multi-Probe	Zonal, PA	Zonal, Multi-Probe	Zonal, Multi-Probe	
181	US & DS	US & DS	US	missed	US	US	missed	Vendor 1
232	US & DS	US & DS	missed	missed	missed	missed	missed	3rd Party
469	US	US	US	missed	missed	missed	missed	Vendor 1
769	US & DS	US & DS	US	missed	missed	missed	US	Vendor 1
797	US & DS	US & DS	missed	missed	missed	missed	missed	3rd Party
824	US & DS	US & DS	missed	missed	missed	missed	missed	3rd Party
863	US	US	missed	missed	missed	missed	US	3rd Party
953	US & DS	US & DS	US	TOFD	US	US	missed	Vendor 1
1213	DS	DS	US	missed	missed	missed	missed	Vendor 1
1269	US & DS	US & DS	DS	DS	US & DS	US & DS	DS	Vendor 1
1445	US & DS	US & DS	US & DS	TOFD	US	US & DS	missed	3rd Party
1555	No Flaw	No Flaw	No Flaw	No Flaw	No Flaw	No Flaw	No Flaw	Vendor 1
1901	US & DS	US & DS	US & DS	DS	US & DS	US & DS	US & DS	Vendor 1

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Optimized PA Technology has Better Detection Capabilities and Sizing Accuracy even in Austenitic and Dissimilar Welds Involving Steel and Nickel-Based Alloys

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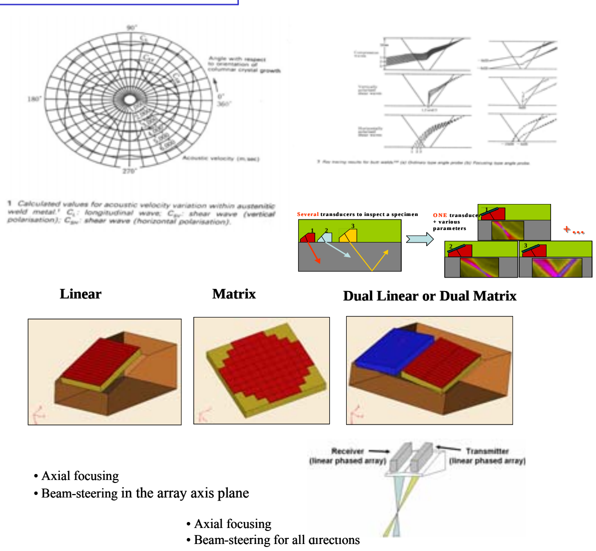

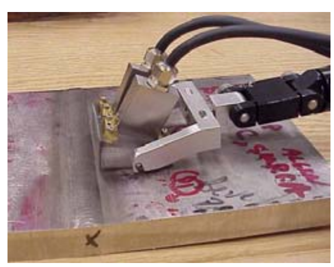

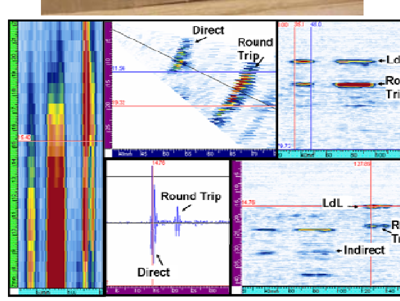

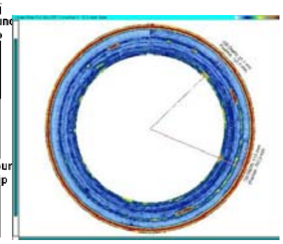

- Dual-PA technology will be of relevance to some of the goals of US-DOE program including Gen-IV constructions and hydrogen pipelines providing better inspections of large grain, highly anisotropic materials

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AUT QUALIFICATION

Mark Lozev, Chief Engineer / NDE Technology Leader

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Mark_Lozev@ewi.org

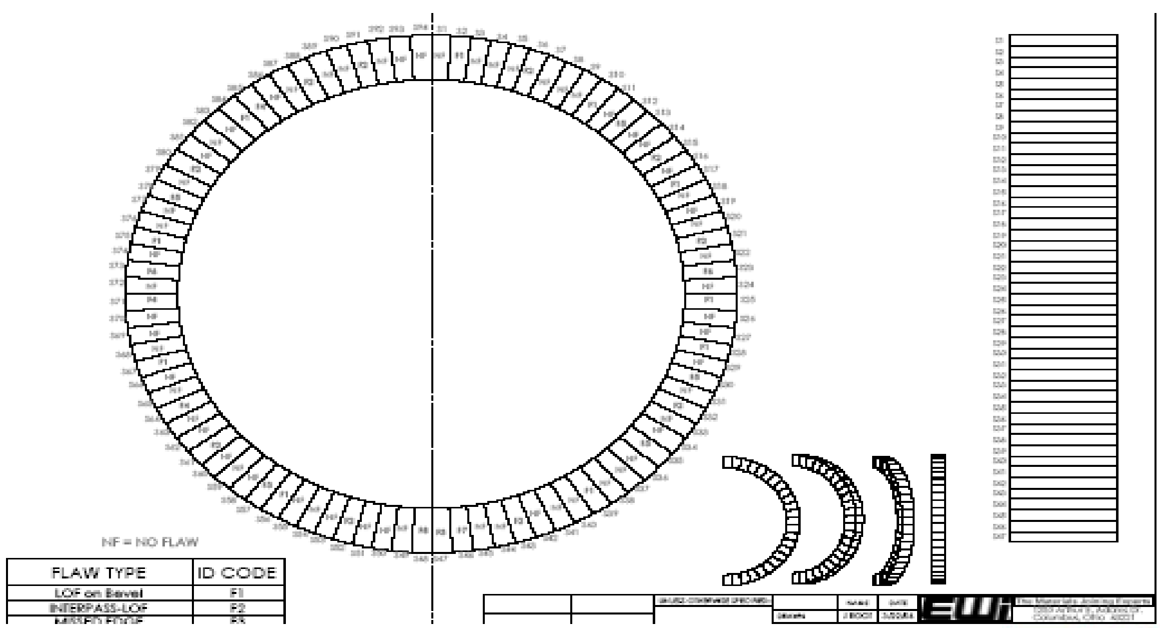
OBJECTIVES

- Critical nature of pipelines and the consequences of structural failure demands designers to adopt reliability and fitness-for-purpose design methods to ensure that structural integrity can be guaranteed throughout the entire design life.
- The use of reliability and fitness-for-purpose based design methods requires the use of inspection techniques that can reliably detect and size fabrication flaws produced during construction and repair.
- Even with advanced AUT methods, there are still uncertainties in defect detection and sizing.
- In order to reliably apply fitness-for-purpose based design and construction methods there is still a need for each specific project to conduct an AUT qualification program.
- The objective of the program is to define the performance and limitations of the AUT systems and define system/operator capabilities to detect, locate, and size flaws for the construction project.
- Approaches – API 1104, DNV OS F101, Company Specification.

TYPICAL TASK LIST FOR AUT QUALIFICATION

- Develop and Issue Plan for AUT Qualification and Bid Package
- Review AUT Contractor Bids with Company and Select AUT Contractor
- Design and Fabricate Test Welds and Calibration Blocks
- Independent NDE (Nondestructive Evaluation)
- AUT Contractor Limited Qualification Trials
- Section of Girth Welds and Measure Flaws
- Compare and Analyze AUT Predictions with Actual Flaws
- Qualify AUT Vendor

PLAN FOR FLAW IMPLANTATION WELD



WELD FLAW IMPLANTATION DESIGN

WELD NO. 1 **423.1 MM OD X 15.08 MM WT** **Rev. 0**

Sector No.	Fabrication Flaw Type	Fabrication Flaw circumferential location			Fabrication Flaw Depth (mm)	Fabrication Flaw Height (mm)	Location (US/DS)	Comments
		Start Location	Stop Location	Total Length (mm)				
S1	NF	0	0	0	0	0	NA	
S2	NF	0	0	0	0	0	NA	
S3	NF	0	0	0	0	0	NA	
S4	F2	130	140	20	7.5	2	NA	On bevel
S5	NF	0	0	0	0	0	NA	
S6	NF	0	0	0	0	0	NA	
S7	NF	0	0	0	0	0	NA	
S8	F6	300	315	15	8	1	NA	
S9	NF	0	0	0	0	0	NA	
S10	NF	0	0	0	0	0	NA	
S11	NF	0	0	0	0	0	NA	
S12	NF	0	0	0	0	0	NA	
S13	F8	490	510	20	12	2	NA	
S14	F9	530	540	10	13	1	DS	
S15	NF	0	0	0	0	0	NA	
S16	F4	610	620	10	ID	0.75	NA	
S17	NF	0	0	0	0	0	NA	
S18	NF	0	0	0	0	0	NA	
S19	F1	735	740	5	13	0.5	US	On bevel
S19	F1	740	755	15	5	1	DS	between 2 - 6 degree
S20	NF	0	0	0	0	0	NA	
S21	NF	0	0	0	0	0	NA	

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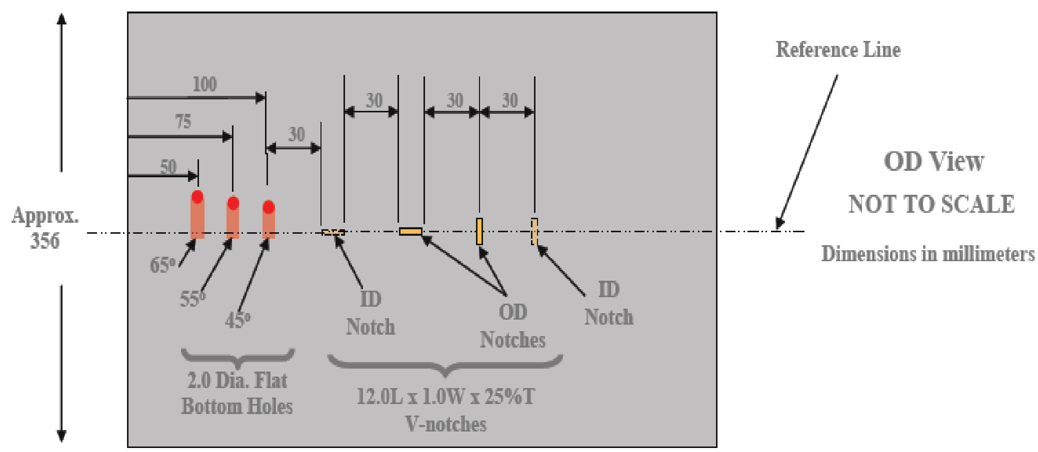
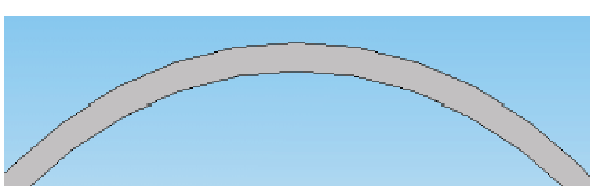
EWI-FINGERPRINTING CALIBRATION BLOCK DRAWING





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FINGERPRINTING CALIBRATION BLOCK CERTIFICATION

Customer:	EDISON WELDING INSTITUTE
End User:	SAME
Cert Standard:	STATIC
Date:	4/7/2006
Accepted By:	

Well Charge:	
AFE Number:	
P.O. Number:	06-0392
Other Ref #:	

14424 Interdrive West
Houston, Texas 77032
281-219-9480
281-219-2317 (Fax)

Pipe Description								Special Instructions
Size	Weight	Thickness	Grade/Alloy	New/Used	Mfg	Length	Serial Number	PER CUSTOMER SUPPLIED DRAWINGS
10"	UNK	15MM	UNK	NEW	UNK	14"	20773-01	

Cust Service Order #
20773-01

Notch Specifications									
Dimensions			Tolerances				References		
Length	Width	Depth	Db Variance	Length	Width	Depth	PIN/BOX	US/DS	P/E
10MM	V	3.8MM	+/-1db	+/-.062"	+/-.005"	+/-.002"			X

Shearwave/UT Prove-up				Thick Gauge/Flaw Removal		Flaw Certification	
Type	Serial #	Angle	Freq.	Serial #	Freq.	Gauge #	Comparator
						95-608	
						PIT GAGE	
Cal. Date:				Cal Date:		12/05/06	

	Surface	Orientation	Length	Width	Depth	RBW	Distance	O'clock		Variance	Db Gain	Checked By		RBW	Checked By	Pit Gauge	Replicate
1	OD	FBH		2MM	9.60		50MM					45DEG			T. BUCK	9.51	
2	OD	FBH		2MM	11.60		75MM					55DEG			T. BUCK	11.64	
3	OD	FBH		2MM	15.60		100MM					65DEG			T. BUCK	15.64	
4	ID	TRANS	10MM	V	3.80		130MM								T. BUCK	3.84	
5	OD	TRANS	10MM	V	3.80		170MM								T. BUCK	3.85	
6	OD	LONG	10MM	V	3.80		210MM								T. BUCK	3.85	
7	ID	LONG	10MM	V	3.80		240MM								T. BUCK	3.86	
8																	
9																	
10																	
11																	
12																	
13																	
14																	
15																	

Authorized By:	
Scan Technician:	T. BUCK
Location	SHOP

Job Acceptance (Signature)	
3rd Party	NONE

UT Tech	
UT Printout	

Traceable to NIST

Removed By		Technician	T. BUCK
UT Tech:		Date:	4/7/06
Replicated - Yes or No		YES	
On file or to Customer		CUST	

Abbreviations / Symbols — ID- Inside Diameter; OD-Outside Diameter; T-Transverse; L-Longitudinal; WR-Wall Reduction; RBW-Remaining Body Wall; FBH-Flat Bottom Hole; DTH-Drill Through Hole; RH-Right Hand; LH-Left Hand

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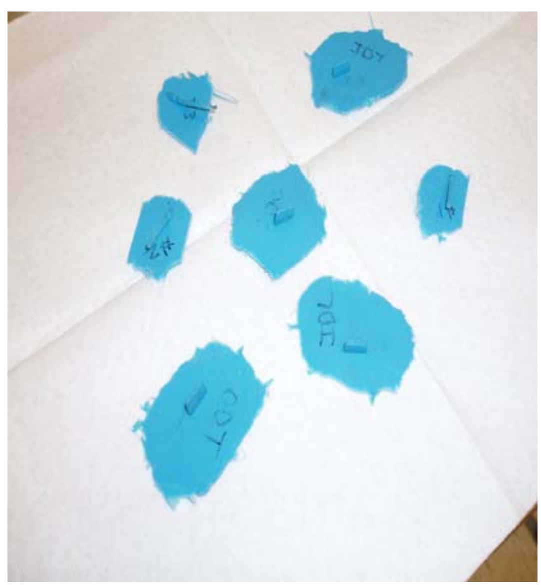
EWI FINGERPRINTING CALIBRATION BLOCK



- EWI CALIBRATION BLOCK
- EWI CALIBRATION BLOCK REFLECTOR REPLICATES

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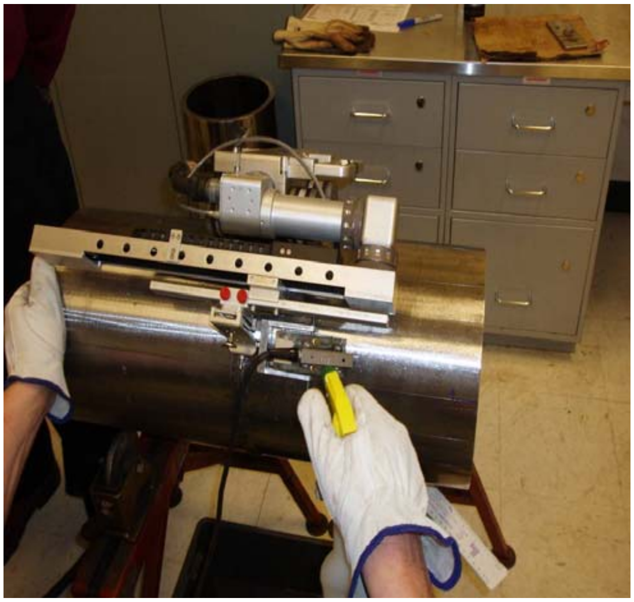
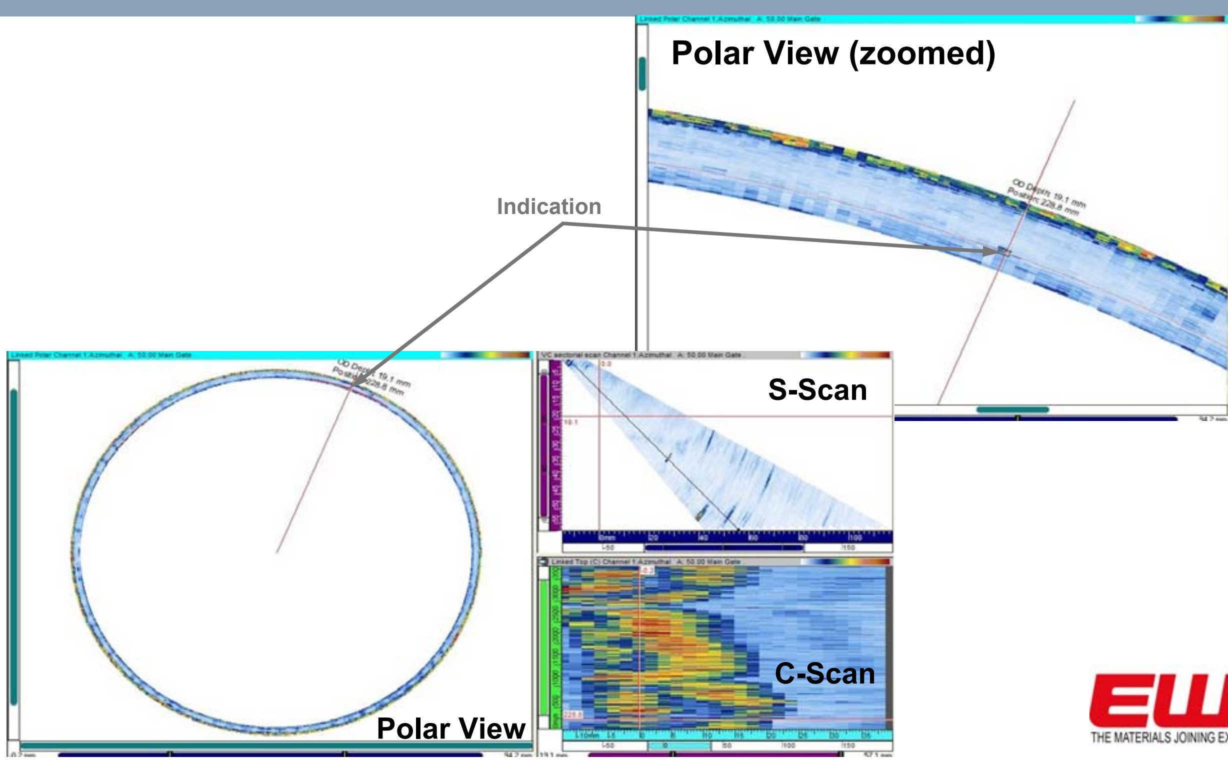
EWI FINGERPRINTING



THE MATERIALS JOINING EXPERTS

FINGERPRINTING POLAR VIEW RESULTS



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AUT CONTRACTOR QUALIFICATION-ROUND ROBIN COMPANY 1

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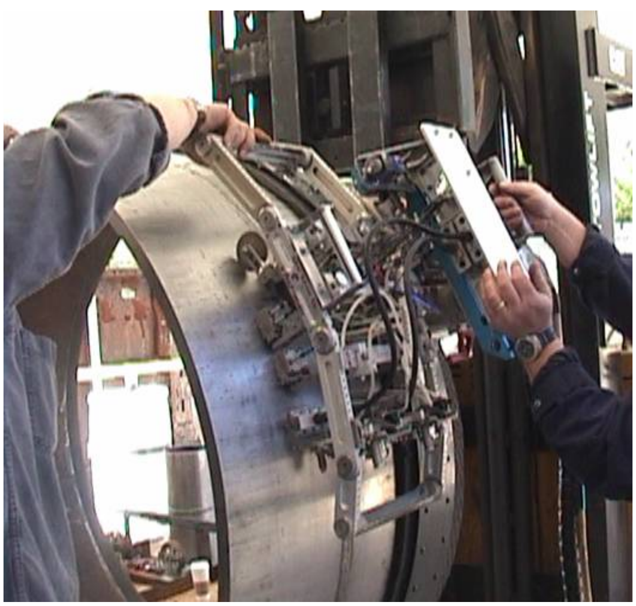
AUT CONTRACTOR QUALIFICATION-ROUND ROBIN COMPANY 2



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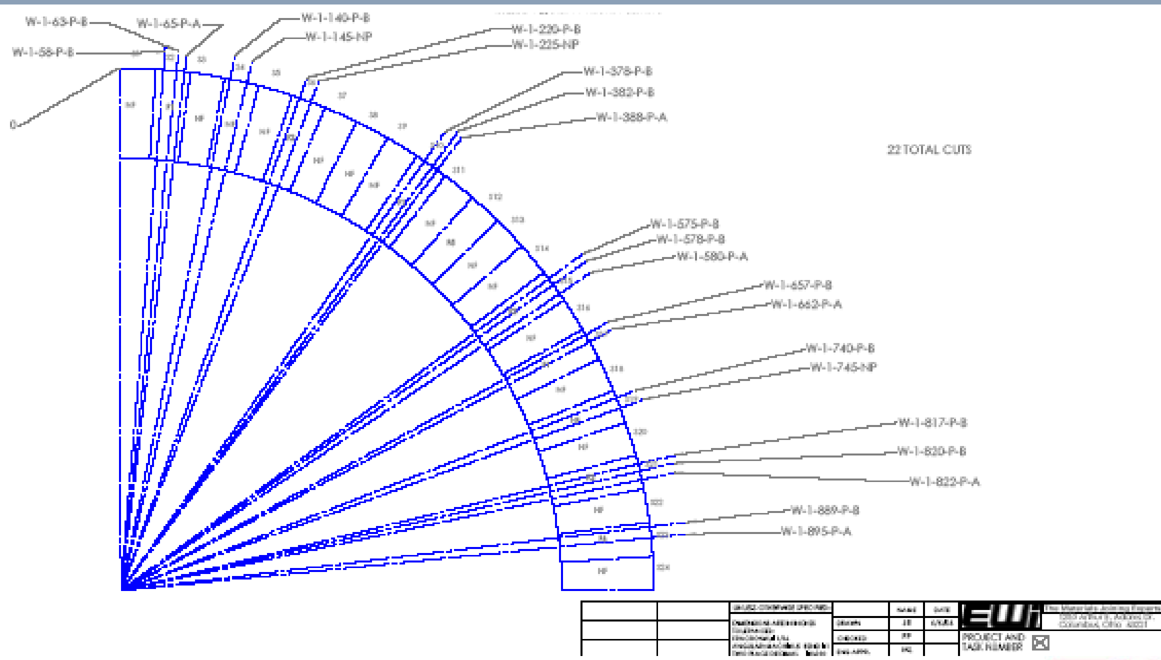
WELD SECTIONING PLAN



THE MATERIALS JOINING EXPERTS

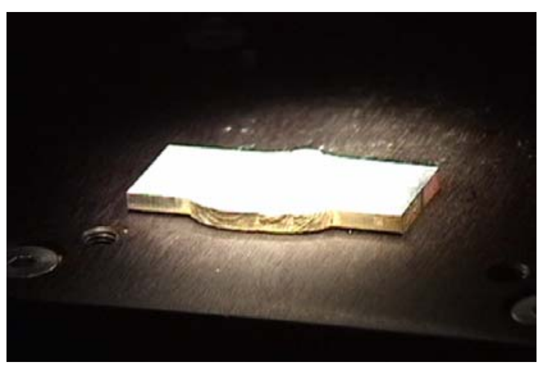
SECTIONING

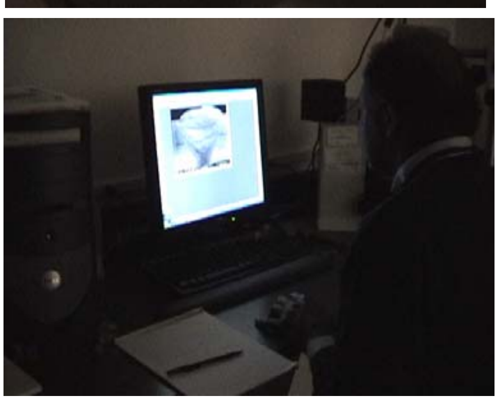
THE MATERIALS JOINING EXPERTS

POLISHING

EWI
THE MATERIALS JOINING EXPERTS

IMAGE ANALYSIS





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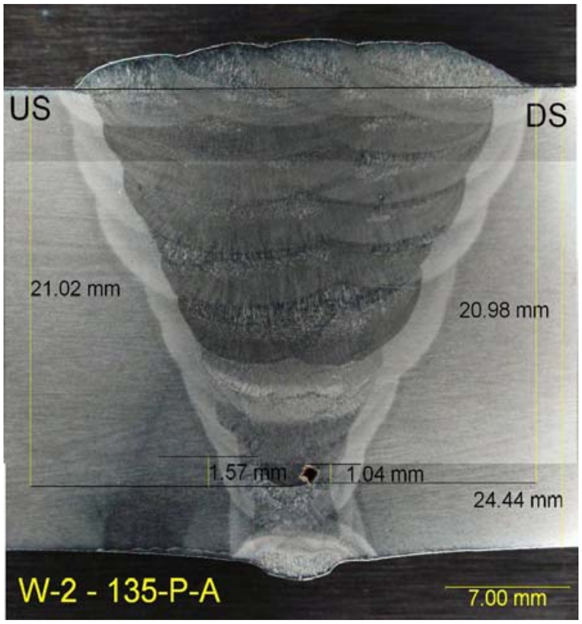
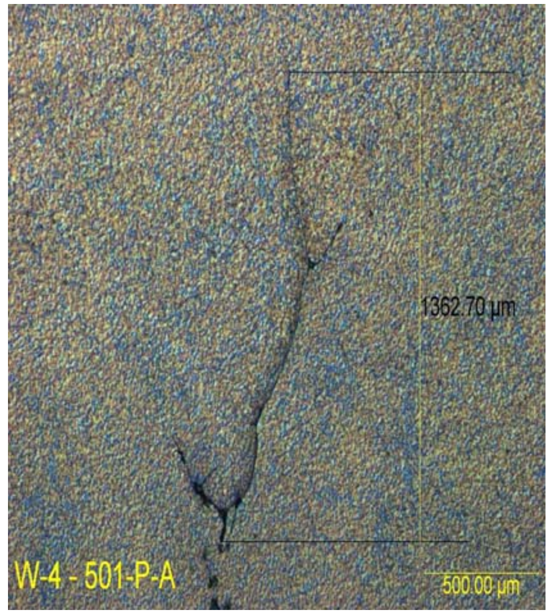
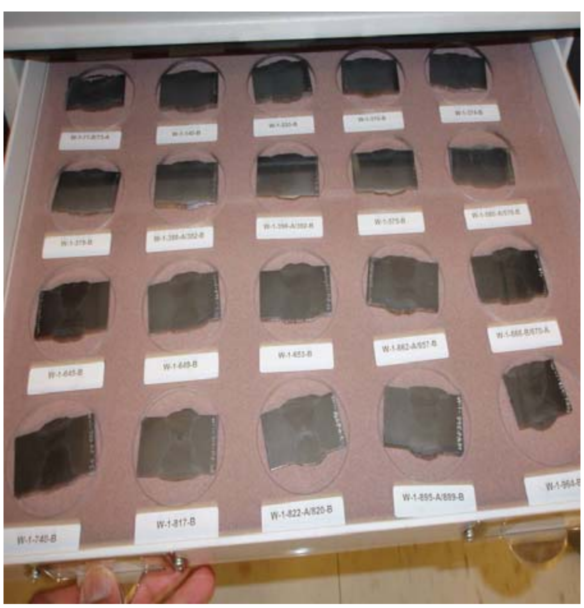
WELD SECTIONING MACROGRAPHS





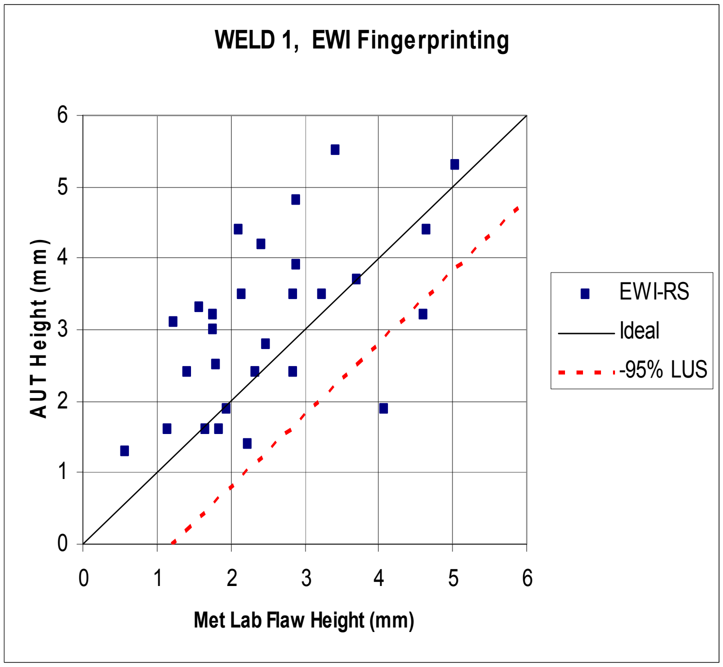
EWI THE MATERIALS JOINING EXPERTS

WELD SECTION COLLECTION



EWI THE MATERIALS JOINING EXPERTS

SIZING PLOTS AND TABLES

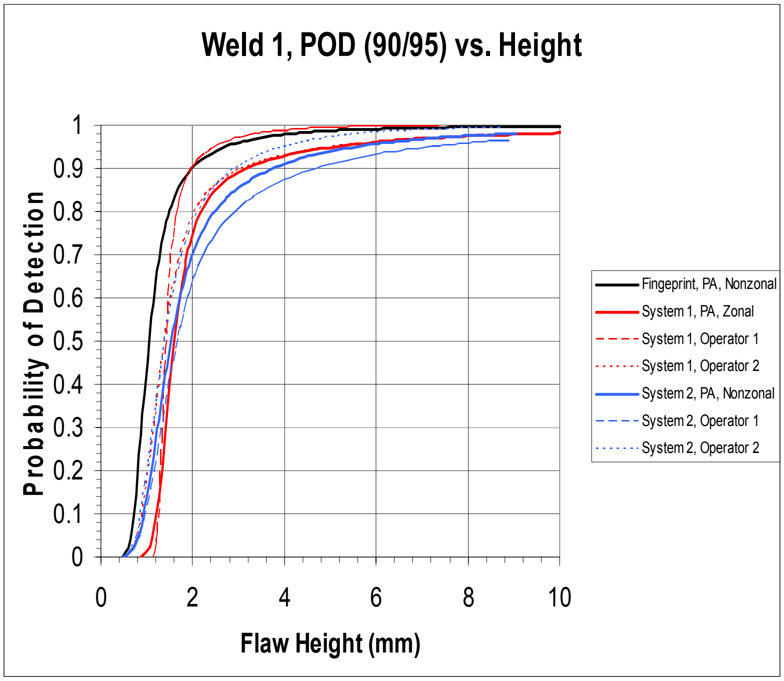


Sizing (Height mm) EWI Fingerprinting Weld No. 1 (CW)		
Standard Deviation (mm)	Systematic (Average) Error (mm)	95% LUS (mm)
1.07	0.60	1.20

SIZING RESULTS SUMMARY

System/Operator	95% LUS (mm), ID, OD & Embedded Flaws					
	Weld 1		Weld 2		Welds 2, 3, and 4	
	Height	Length	Height	Length	Height	Length
EWI Fingerprinting	1.20	4.90	1.10	7.20	0.90	7.20
System 1 Operator 1	1.70	8.20	2.00	12.60	2.15	14.37
System 1 Operator 2	1.30	4.50	1.90	10.70	1.84	10.29
System 1 (All Operators)	1.60	8.40	2.10	12.70	2.07	12.90
System 2 Operator 1	3.30	8.00	2.00	7.80	2.35	7.17
System 2 Operator 1	3.40	8.60	2.00	8.00	1.97	7.08
System 2 (All Operators)	3.30	8.60	2.00	7.90	2.16	7.10

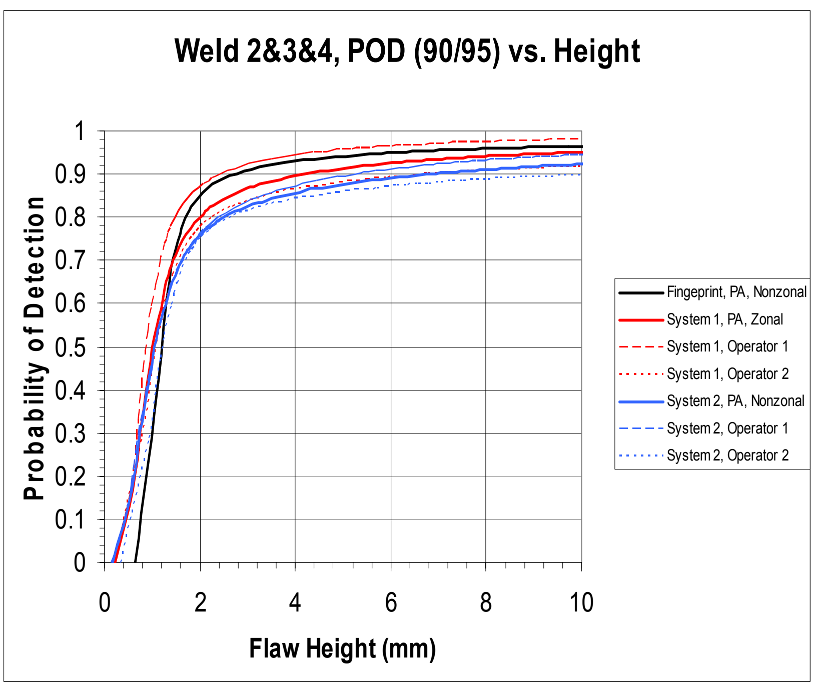
POD PLOTS



Percentile Estimates (Height -mm) EWI Fingerprinting Weld No. 1 (CW)		
a50	a90	a90/95
0.426521	1.14716	1.98512

Percentile Estimates (Height-mm) System 2 Operator 1 Weld No. 1 (CW & CCW)		
a50	a90	a90/95
1.1312	3.26164	4.72854

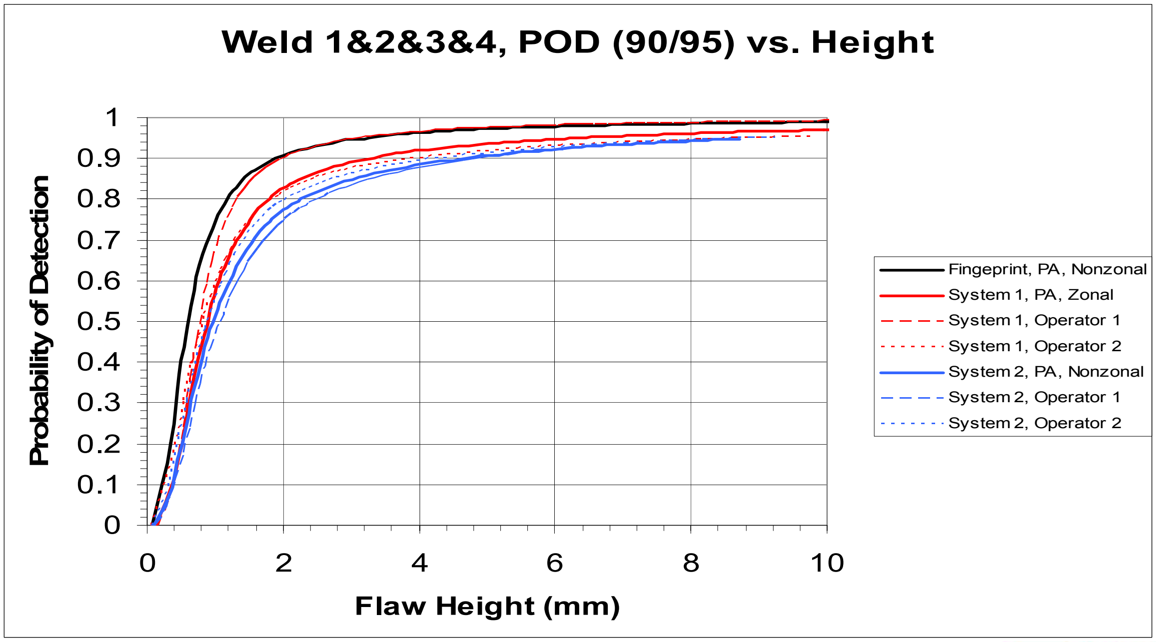
POD PLOTS



Percentile Estimates (Height -mm) EWI Fingerprinting Weld No. 2,3 & 4 (CW)		
a50	a90	a90/95
0.0956	1.12425	2.7271

Percentile Estimates (Height-mm) System 2 Operator 1 Weld No. 2, 3 & 4 (CW & CCW)		
a50	a90	a90/95
0.520182	3.163149	5.33067

POD PLOTS



POD RESULTS SUMMARY

System/Operator	a90/95 (mm), ID and OD and Embedded Flaws					
	Weld 1		Weld 2		Welds 2, 3, and 4	
	Height	Length	Height	Length	Height	Length
EWI Fingerprinting	1.98	13.93	2.15	7.00	2.72	6.64
Company 1, Operator 1	1.99	12.85	3.39	15.72	2.46	12.34
Company 1, Operator 2	3.08	17.53	8.75	22.08	6.91	17.72
Company 1 (All Operators)	3.18	16.96	5.25	22.88	4.23	16.98
Company 2, Operator 1	4.73	38.53	12.73	23.87	5.33	26.42
Company 2, Operator 2	2.92	16.99	12.73	23.87	10.30	28.28
Company 2 (All Operators)	3.75	24.74	12.73	23.87	6.88	27.29

SUMMARY

- Advantageous to use multiple AUT contractors so that the contractor meeting or close to the specified project requirements can be selected.
- EWI's In-house capabilities of fingerprinting, machining, polishing, linear image analysis and statistical analysis carries offers an added advantage to finish the project in time along with meeting the requirements.
- EWI Fingerprinting before blind trial ensures that all defects as planned are implanted and in size range.
- No need for rings cutting using EWI fingerprinting methodology.

THE MATERIALS JOINING EXPERTS

THE MATERIALS JOINING EXPERTS

Acoustic Emission Testing

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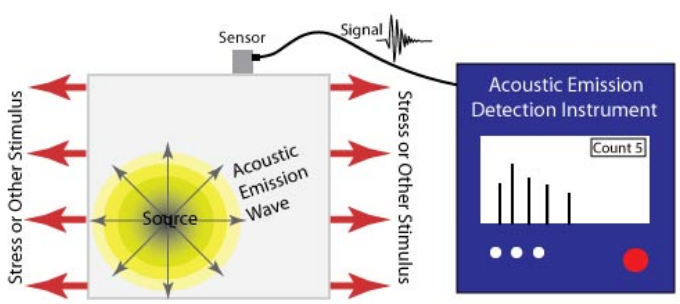
Outline

- Introduction to Acoustic Emission (AE) Testing
- AE Theory - Sources and Waves
- AE Equipment and Sensors
- AE Signal Features
- AE Data Display
- AE Source Location Techniques
- AE Barkhausen Techniques
- AE Applications

Basic Principles of AE

- Acoustic Emission (AE) refers to the generation of transient elastic waves produced by a sudden redistribution of stress in a material.



Basic Principles of AE (cont.)

- When a structure is subjected to an external stimulus (change in pressure, load, or temperature), localized sources trigger the release of energy, in the form of stress waves, which propagate to the surface and are recorded by sensors.
- With the right equipment and setup, motions on the order of picometers (10 -12 m) can be identified.
- Detection and analysis of AE signals can supply valuable information regarding the origin and importance of a discontinuity in a material.
- Because of the versatility of Acoustic Emission Testing (AET), it has many industrial applications (e.g. assessing structural integrity, detecting flaws, testing for leaks, or monitoring weld quality) and is used extensively as a research tool.

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Basic Principles of AE – Passive vs. Active NDE (cont.)

- The first AE difference pertains to the origin of the signal.
- Instead of supplying energy to the object under examination, AET simply listens for the energy released by the object.
- AE tests are often performed on structures while in operation, as this provides adequate loading for propagating defects and triggering acoustic emissions.

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Basic Principles of AE – Passive vs. Active NDE (cont.)

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

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Basic Principles of AE – Passive vs. Active NDE (cont.)

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

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AE Sources - General

- Sources of AE vary from natural events like earthquakes and rockbursts to the initiation and growth of cracks, slip and dislocation movements, melting, twinning, and phase transformations in metals.
- In composites, matrix cracking and fiber breakage and debonding contribute to acoustic emissions. AE’s have also been measured and recorded in polymers, wood, and concrete, among other materials.

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AE Sources - General (cont.)

- When a stress is exerted on a material, a strain in induced in the material as well.
- Depending on the magnitude of the stress and the properties of the material, an object may return to its original dimensions or be permanently deformed after the stress is removed.
- These two conditions are well known as elastic and plastic deformation, respectively.

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AE Sources - General (cont.)

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

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AE Sources – Fatigue Cracks (cont.)

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

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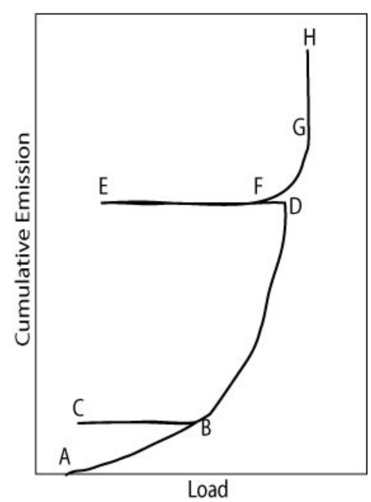
AE Sources – Energy (cont.)

- The amount of energy released by an acoustic emission and the amplitude of the waveform are related to the magnitude and velocity of the source event. The amplitude of the emission is proportional to the velocity of crack propagation and the amount of surface area created. Large, discrete crack jumps will produce larger AE signals than cracks that propagate slowly over the same distance.
- Detection and conversion of these elastic waves to electrical signals is the basis of AE testing. Analysis of these signals yield valuable information regarding the origin and importance of a discontinuity in a material. As discussed in the following section, specialized equipment is necessary to detect the wave energy and decipher which signals are meaningful.

AE Sources – Activity in Structural Loading (cont.)

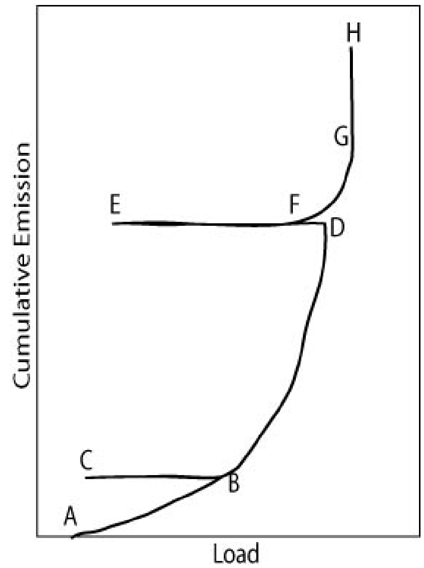
- AE signals generated under different loading patterns can provide valuable information concerning the structural integrity of a material.
- Load levels that have been previously exerted on a material do not produce AE activity.
- In other words, discontinuities created in a material do not expand or move until that former stress is exceeded.
- This phenomenon, known as the Kaiser Effect, can be seen in the load versus AE plot to the right - segment BCB .



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

AE Sources – Activity in Structural Loading (cont.)

- As the object is loaded, acoustic emission events accumulate (segment AB).
- When the load is removed and reapplied (segment BCB - Kaiser Effect), AE events do not occur again until the load at point B is exceeded.
- As the load exerted on the material is increased again (BD), AE's are generated and stop when the load is removed.



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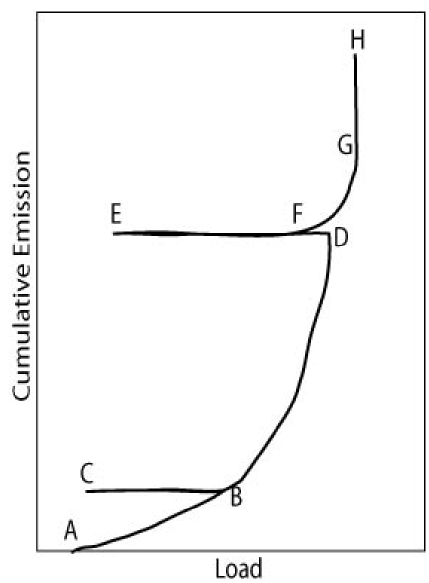
AE Sources – Activity in Structural Loading (cont.)

- However, at point F, the applied load is high enough to cause significant emissions even though the previous maximum load (D) was not reached.
- This phenomenon is known as the Felicity Effect – segment DEF This effect can be quantified using the Felicity Ratio, which is the load where considerable AE resumes, divided by the maximum applied load (F/D).
- As the object load is put on hold, AE events accumulate during the hold also (segment GH).



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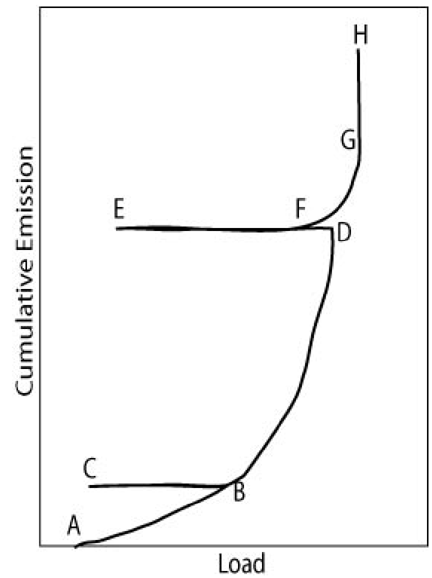
AE Sources – Activity in Structural Loading (cont.)

- Knowledge of the Kaiser Effect and Felicity Effect can be used to determine if major structural defects are present.
- This can be achieved by applying constant loads (relative to the design loads exerted on the material) and "listening" to see if emissions continue to occur while the load is held.
- As shown in the figure, if AE signals continue to be detected during the holding of these loads (GH), it is likely that substantial structural defects are present.
- In addition, a material may contain critical defects if an identical load is reapplied and AE signals continue to be detected.



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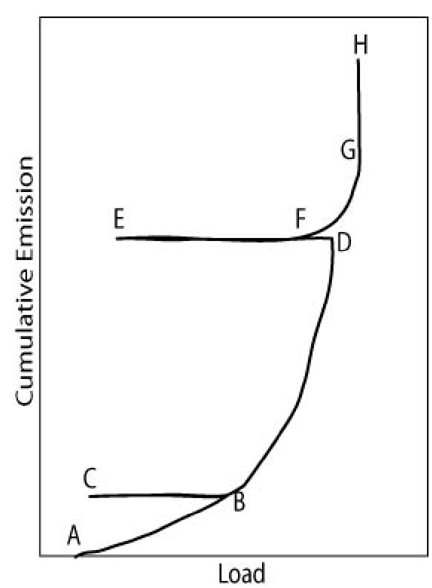
AE Sources – Activity in Structural Loading (cont.)

- Another guideline governing AE's activity during structural loading is the Dunegan corollary, which states that if acoustic emissions are observed prior to a previous maximum load, some type of new damage must have occurred.
- Time dependent processes like corrosion, creep and hydrogen embrittlement tend to render the Kaiser Effect useless.



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AE Sources – Noise (cont.)

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

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AE Sources – Noise (cont.)

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

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AE Sources – Pseudo Sources (cont.)

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

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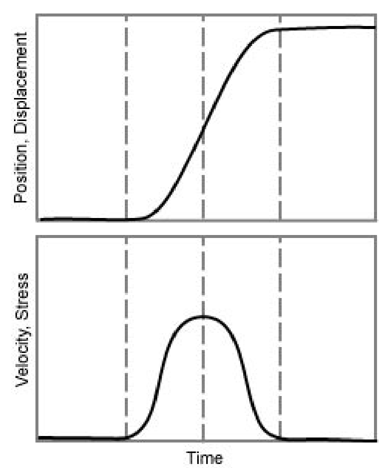
AE Waves Propagation

- A primitive wave released at the AE source is illustrated in the figure right.
- The displacement waveform is a step-like function corresponding to the permanent change associated with the source process.
- The analogous velocity and stress waveforms are essentially pulse-like.



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

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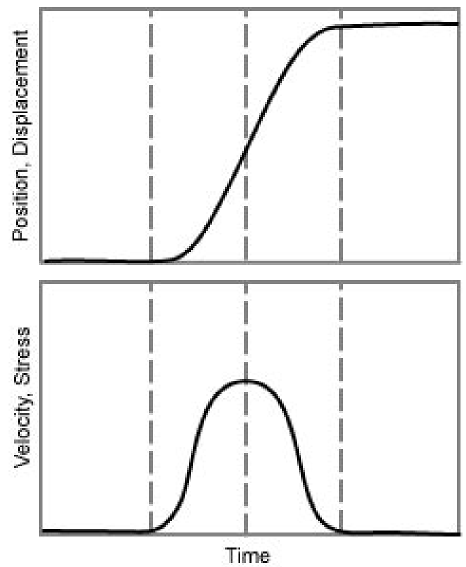
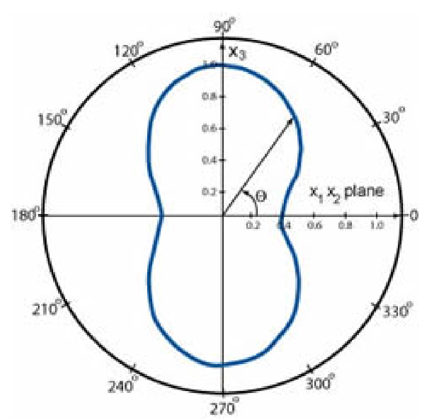
AE Waves Propagation (cont.)

- The width and height of the primitive pulse depend on the dynamics of the source process.
- Source processes such as microscopic crack jumps and precipitate fractures are usually completed in a fraction of a microsecond or a few microseconds, which explains why the pulse is short in duration.
- The amplitude and energy of the primitive pulse vary over an enormous range from submicroscopic dislocation movements to gross crack jumps.



AE Waves Propagation (cont.)

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



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

AE Waves Propagation (cont.)

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

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AE Waves Propagation (cont.)

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

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AE Waves Propagation (cont.)

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

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AE Waves Attenuation

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

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AE Waves Attenuation (cont.)

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

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AE Waves Modes and Velocity

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

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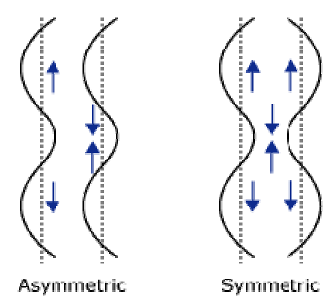
AE Waves Modes and Velocity – Plate and Lamb Waves (cont.)

- Plate waves can be propagated only in very thin metals. Lamb waves are the most commonly used plate waves in NDT.
- Lamb waves are complex vibrational waves that travels through the entire thickness of a material.
- Propagation of Lamb waves depends on the density and the elastic material properties of a component.
- They are also influenced a great deal by the test frequency and material thickness.

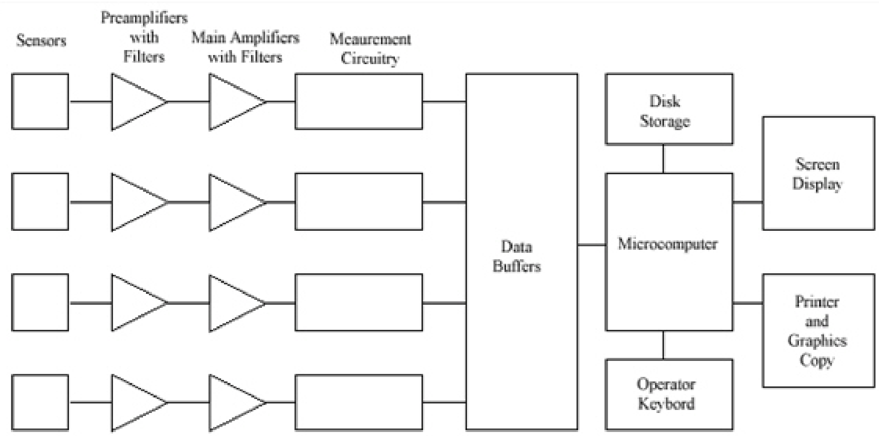
AE Waves Modes and Velocity – Lamb Waves (cont.)

- With Lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical.
- The complex motion of the particles is similar to the elliptical orbits for surface waves.
- Symmetrical Lamb waves move in a symmetrical fashion about the median plane of the plate. This is sometimes called the extensional mode because the wave is “stretching and compressing” the plate in the wave motion direction. Wave motion in the symmetrical mode is most efficiently produced when the exciting force is parallel to the plate.
- The asymmetrical Lamb wave mode is often called the “flexural mode” because a large portion of the motion moves in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.



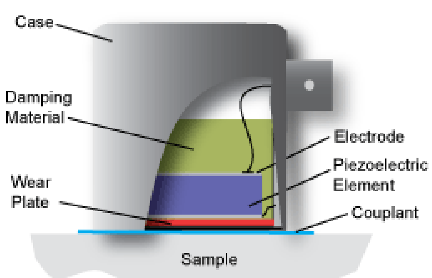
AE Equipment - Schematic Diagram

- Typically, AE systems contain a sensor, preamplifier, filter, and amplifier, along with measurement, display, and storage equipment (e.g. oscilloscopes, voltmeters, and personal computers).



AE Equipment - Sensors

- Acoustic emission sensors respond to dynamic motion that is caused by an AE event.
- This is achieved through transducers which convert mechanical movement into an electrical voltage signal.
- The transducer element in an AE sensor is almost always a piezoelectric crystal, which is commonly made from a ceramic such as lead zirconate titanate (PZT).
- Transducers are selected based on operating frequency, sensitivity and environmental characteristics, and are grouped into two classes: resonant and broadband.
- The majority of AE equipment is responsive to movement in its typical operating frequency range of 30 kHz to 1 MHz.
- For materials with high attenuation (e.g. plastic composites), lower frequencies may be used to better distinguish AE signals. The opposite holds true as well.



AE Equipment - Processing

- Ideally, the AE signal that reaches the mainframe will be free of background noise and electromagnetic interference. Unfortunately, this is not realistic.
- However, sensors and preamplifiers are designed to help eliminate unwanted signals. First, the preamplifier boosts the voltage to provide gain and cable drive capability. To minimize interference, a preamplifier is placed close to the transducer; in fact, many transducers today are equipped with integrated preamplifiers.
- Next, the signal is relayed to a bandpass filter for elimination of low frequencies (common to background noise) and high frequencies.
- Following completion of this process, the signal travels to the acoustic system mainframe and eventually to a computer or similar device for analysis and storage.
- Depending on noise conditions, further filtering or amplification at the mainframe may still be necessary.

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AE Equipment - Processing (cont.)

- After passing the AE system mainframe, the signal comes to a detection/measurement circuit as shown in the figure directly above.
- Note that multiple-measurement circuits can be used in multiple sensor/channel systems for source location purposes (to be described later).
- At the measurement circuitry, the shape of the conditioned signal is compared with a threshold voltage value that has been programmed by the operator.
- Signals are either continuous (analogous to Gaussian, random noise with amplitudes varying according to the magnitude of the AE events) or burst-type.

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AE Equipment - Processing (cont.)

- Each time the threshold voltage is exceeded, the measurement circuit releases a digital pulse.
- The first pulse is used to signify the beginning of a hit. (A hit is used to describe the AE event that is detected by a particular sensor.
- One AE event can cause a system with numerous channels to record multiple hits.) Pulses will continue to be generated while the signal exceeds the threshold voltage.
- Once this process has stopped for a predetermined amount of time, the hit is finished (as far as the circuitry is concerned).
- The data from the hit is then read into a microcomputer and the measurement circuit is reset.

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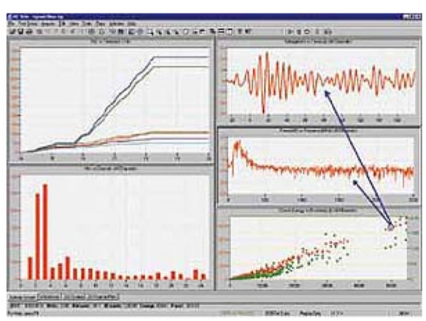
AE Equipment – Hit Driven Systems and Measurement of Signal Features

- Although several AE system designs are available (combining various options, sensitivity, and cost), most AE systems use a hit-driven architecture.
- The hit-driven design is able to efficiently measure all detected signals and record digital descriptions for each individual feature (detailed later in this section).
- During periods of inactivity, the system lies dormant.
- Once a new signal is detected, the system records the hit or hits, and the data is logged for present and/or future display.
- Also common to most AE systems is the ability to perform routine tasks that are valuable for AE inspection. These tasks include quantitative signal measurements with corresponding time and/or load readings, discrimination between real and false signals (noise), and the collection of statistical information about the parameters of each signal.



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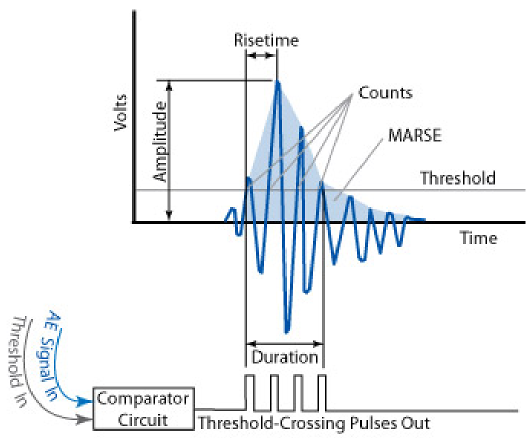
AE Signal Features

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



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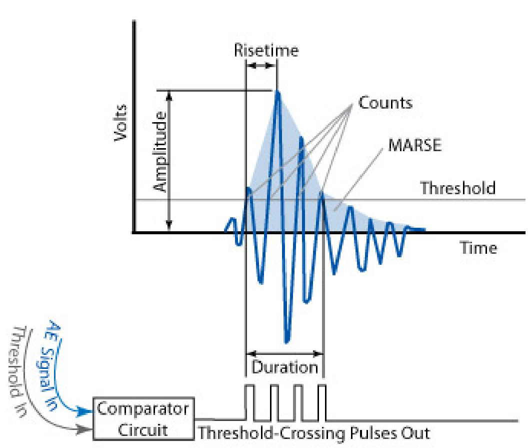
AE Signal Features (cont.)

- **Rise time, R,** is the time interval between the first threshold crossing and the signal peak. This parameter is related to the propagation of the wave between the source of the acoustic emission event and the sensor. Therefore, rise time is used for qualification of signals and as a criterion for noise filter.
- **Duration, D**, is the time difference between the first and last threshold crossings. Duration can be used to identify different types of sources and to filter out noise. Like counts (N), this parameter relies upon the magnitude of the signal and the acoustics of the material.



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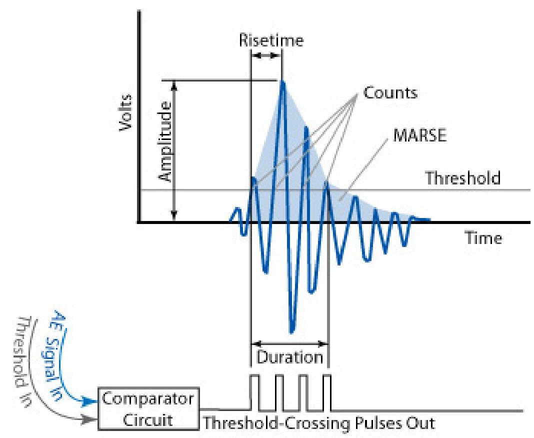
AE Signal Features (cont.)

- **MARSE, E**, sometimes referred to as energy counts, is the measure of the area under the envelope of the rectified linear voltage time signal from the transducer. This can be thought of as the relative signal amplitude and is useful because the energy of the emission can be determined. MARSE is also sensitive to the duration and amplitude of the signal, but does not use counts or user defined thresholds and operating frequencies. MARSE is regularly used in the measurements of acoustic emissions.
- **Counts, N**, refers to the number of pulses emitted by the measurement circuitry if the signal amplitude is greater than the threshold. Depending on the magnitude of the AE event and the characteristics of the material, one hit may produce one or many counts. While this is a relatively simple parameter to collect, it usually needs to be combined with amplitude and/or duration measurements to provide quality information about the shape of a signal.



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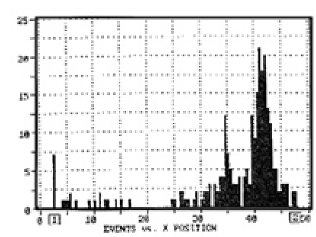
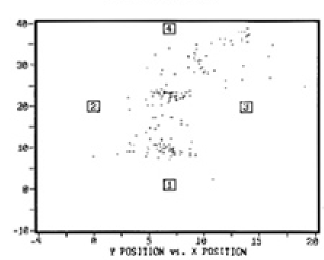
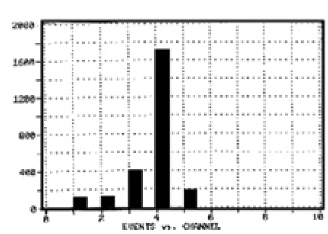
AE Data Display - Location

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







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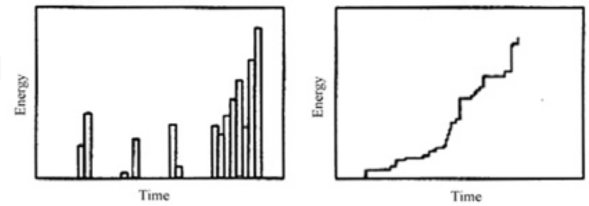
AE Data Display - Activity

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



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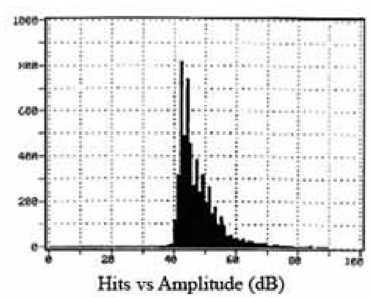
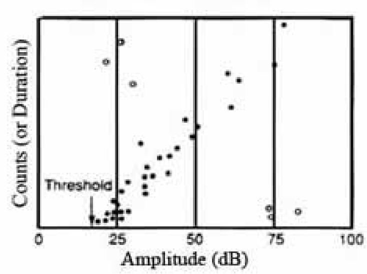
AE Data Display - Intensity

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





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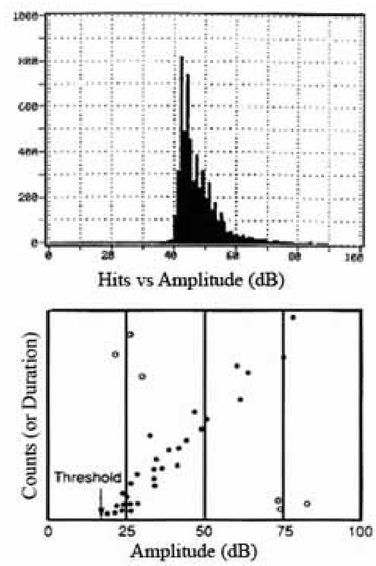
AE Data Display - Crossplots

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

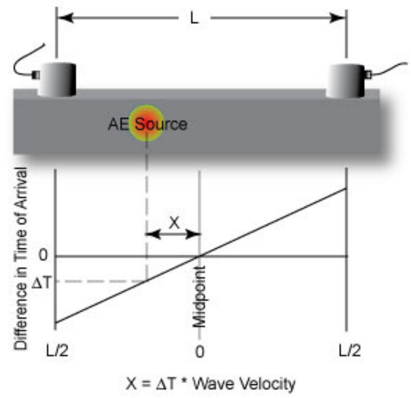


AE Source Location – Multi-Channel Techniques

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

AE Source Location – Linear Location Technique

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



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AE Source Location – Zonal and Point Location Techniques

- When using AE to identify a source location in a planar material, three or more sensors are used, and the optimal position of the source is between the sensors.
- Two categories of source location analysis are used for this situation: zonal location and point location.

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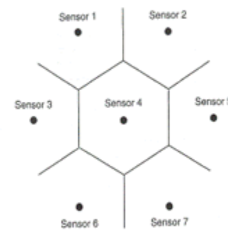
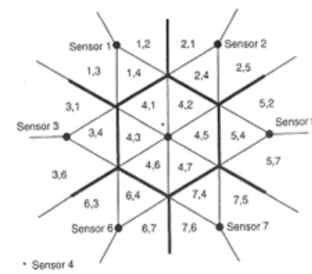
AE Source Location – Zonal Location Technique

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





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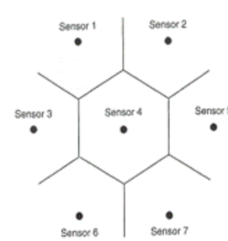
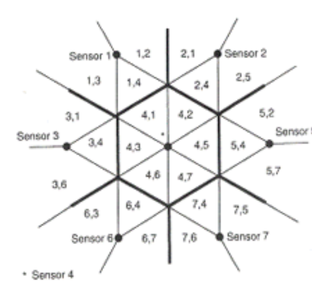
AE Source Location – Zonal Location Technique (cont.)

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





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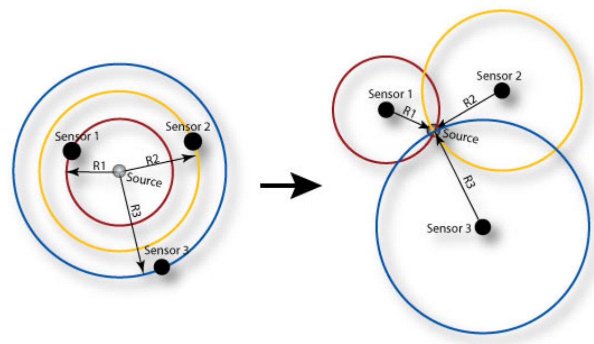
AE Source Location – Point Location Technique

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



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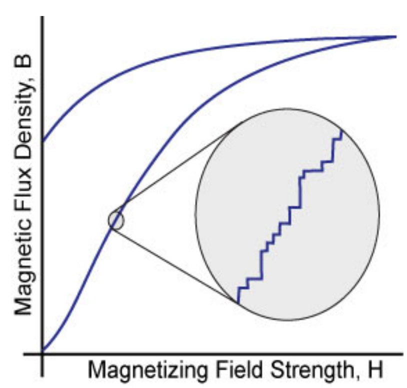
AE Barkhausen Techniques - Barkhausen Effect

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



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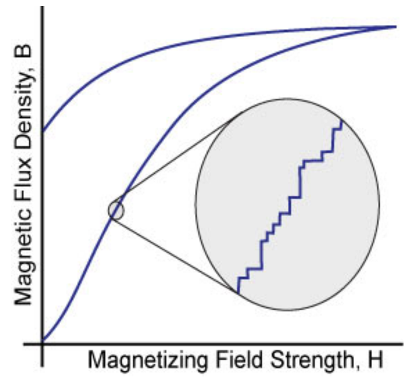
AE Barkhausen Techniques - Barkhausen Noise

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



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AE Applications - Weld Monitoring

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

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AE Applications - Gas Trailer Tubes

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

EWI THE MATERIALS JOINING EXPERTS

AE Applications - Bridges

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

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AE Applications - Bucket Truck (Cherry Pickers) Integrity Evaluation

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

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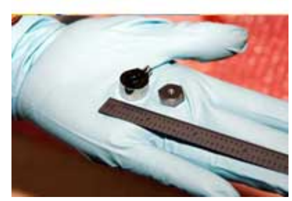
AE Applications - Aerospace Structures

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



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AE Applications - Others

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

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AE Applications – Standards and Guidelines

- There are a number of standards and guidelines that describe AE testing and application procedures as supplied by the American Society for Testing and Materials (ASTM). Examples:

  - ASTM E 749-96 is a standard practice of AE monitoring of continuous welding.

  - ASTM E 1932 for the AE examination of small parts.

  - ASTM E1419-00 for the method of examining seamless, gas-filled, pressure vessels.

  - ASTM F914 governs the procedures for examining insulated aerial personnel devices.

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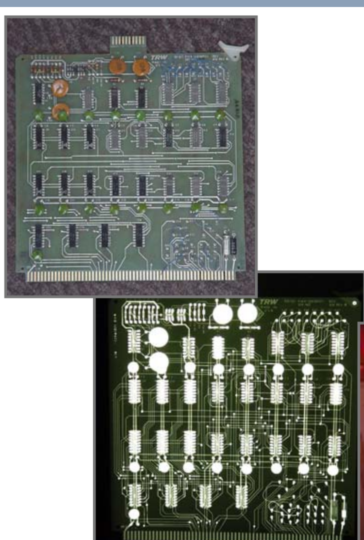
Radiography Testing

Radiography Testing



Prepared by the Collaboration for NDT Education.
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THE MATERIALS JOINING EXPERTS

Introduction

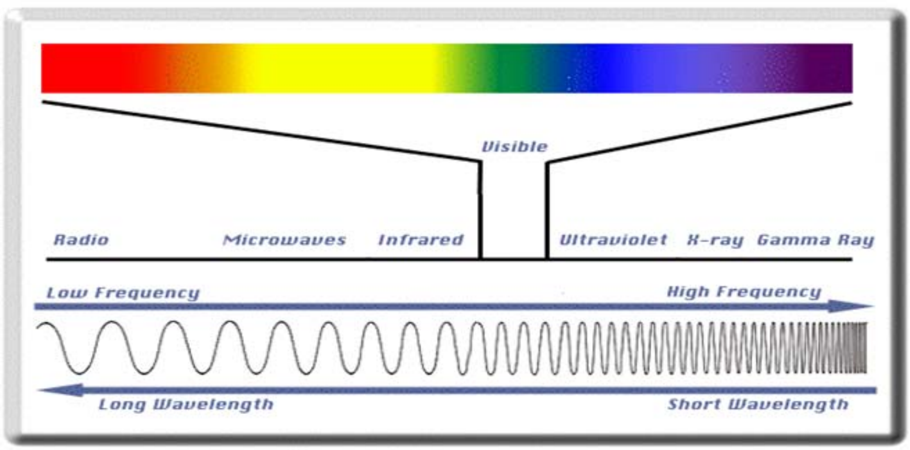
- This module presents information on the NDT method of radiographic inspection or radiography.
- Radiography uses penetrating radiation that is directed towards a component.
- The component stops some of the radiation. The amount that is stopped or absorbed is affected by material density and thickness differences.
- These differences in "absorption" can be recorded on film, or electronically.

Outline

- Electromagnetic Radiation
- General Principles of Radiography
- Sources of Radiation
  - Gamma Radiography
  - X-ray Radiography
- Imaging Modalities
  - Film Radiography
  - Computed Radiography
  - Real-Time Radiography
  - Direct Digital Radiography
  - Computed Radiography
- Radiation Safety
- Advantages and Limitations
- Glossary of Terms

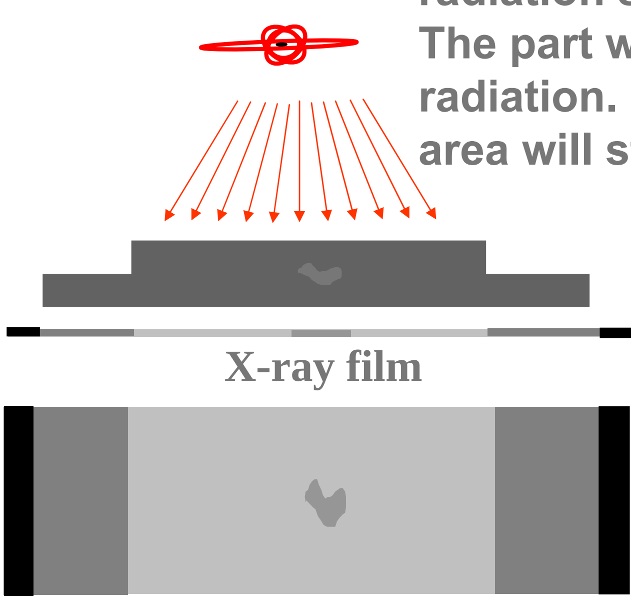
Electromagnetic Radiation

The radiation used in Radiography testing is a higher energy (shorter wavelength) version of the electromagnetic waves that we see every day. Visible light is in the same family as x-rays and gamma rays.



General Principles of Radiography

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



Top view of developed film

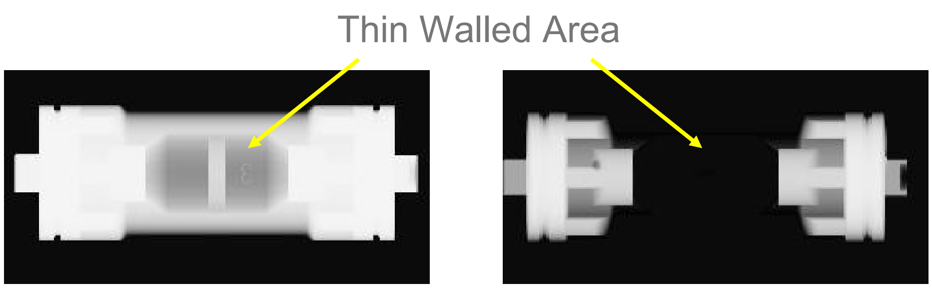
The film darkness (density) will vary with the amount of radiation reaching the film through the test object.

= less exposure

= more exposure

General Principles of Radiography

- The energy of the radiation affects its penetrating power. Higher energy radiation can penetrate thicker and more dense materials.
- The radiation energy and/or exposure time must be controlled to properly image the region of interest.



Low Energy Radiation

High Energy Radiation

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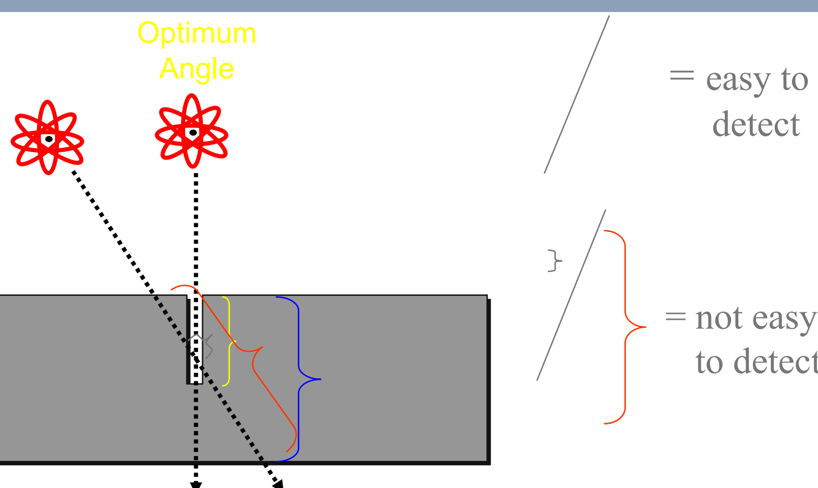
IDL 2001

Flaw Orientation

Radiography has sensitivity limitations when detecting cracks.



X-rays "see" a crack as a thickness variation and the larger the variation, the easier the crack is to detect.

When the path of the x-rays is not parallel to a crack, the thickness variation is less and the crack may not be visible.

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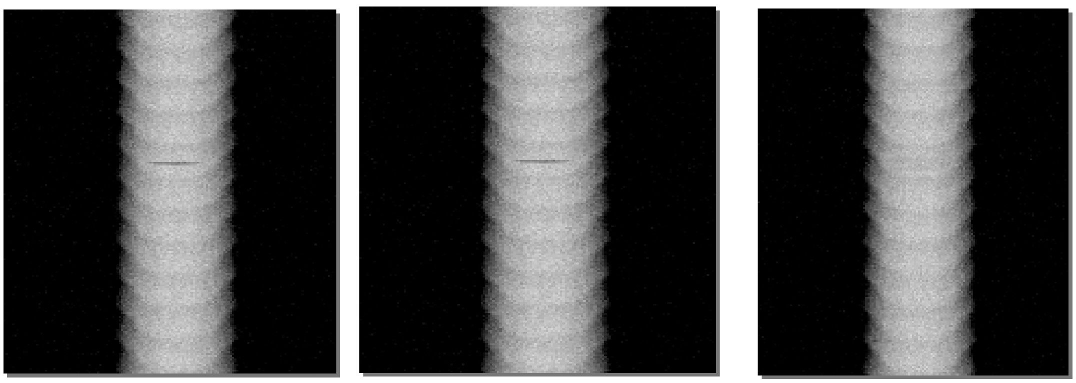
Flaw Orientation (cont.)

Since the angle between the radiation beam and a crack or other linear defect is so critical, the orientation of defect must be well known if radiography is going to be used to perform the inspection.



0° 10° 20°

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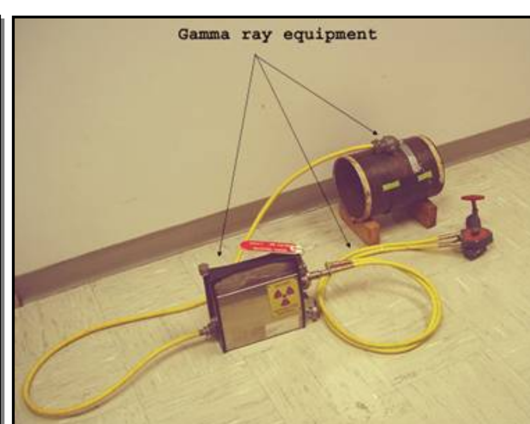
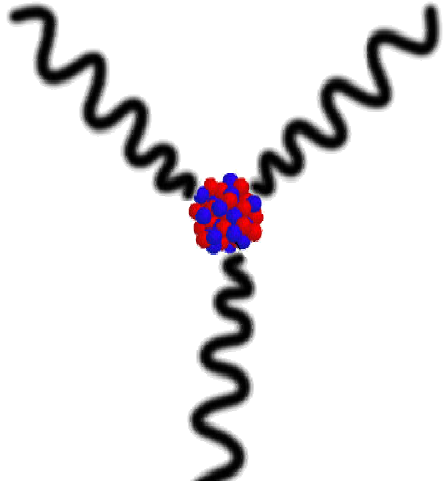
Radiation Sources

Two of the most commonly used sources of radiation in industrial radiography are x-ray generators and gamma ray sources. Industrial radiography is often subdivided into "X-ray Radiography" or "Gamma Radiography", depending on the source of radiation used.



Gamma Radiography

- Gamma rays are produced by a radioisotope.
- A radioisotope has an unstable nuclei that does not have enough binding energy to hold the nucleus together.
- The spontaneous breakdown of an atomic nucleus resulting in the release of energy and matter is known as radioactive decay.



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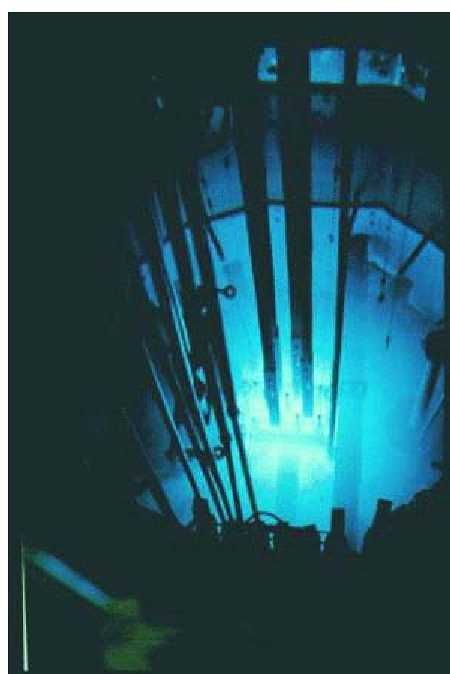
Gamma Radiography (cont.)

- Most of the radioactive material used in industrial radiography is artificially produced.
- This is done by subjecting stable material to a source of neutrons in a special nuclear reactor.
- This process is called activation.



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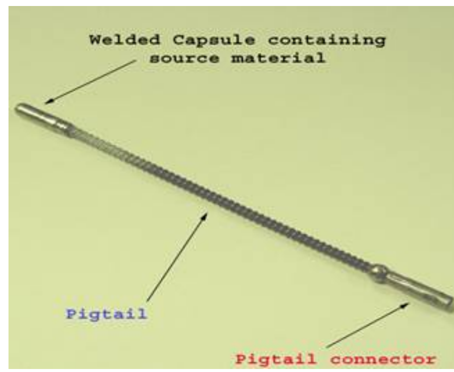
Gamma Radiography (cont.)

Unlike X-rays, which are produced by a machine, gamma rays cannot be turned off. Radioisotopes used for gamma radiography are encapsulated to prevent leakage of the material.

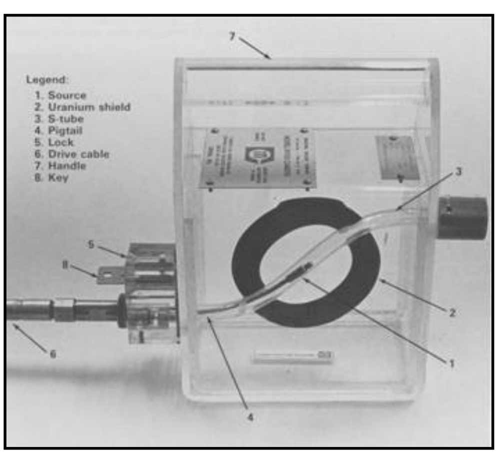
The radioactive "capsule" is attached to a cable to form what is often called a "pigtail."

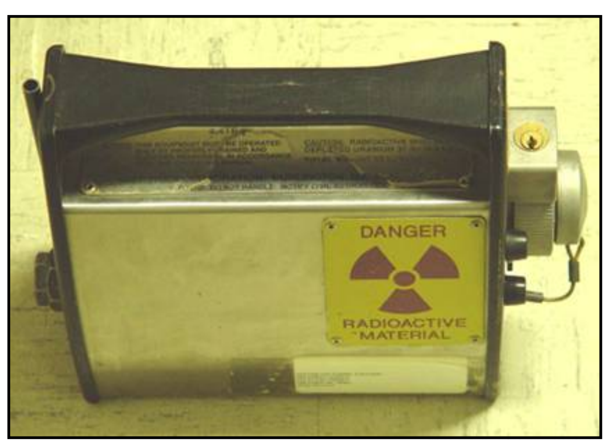
The pigtail has a special connector at the other end that attaches to a drive cable.



Gamma Radiography (cont.)

A device called a "camera" is used to store, transport and expose the pigtail containing the radioactive material. The camera contains shielding material which reduces the radiographer's exposure to radiation during use.

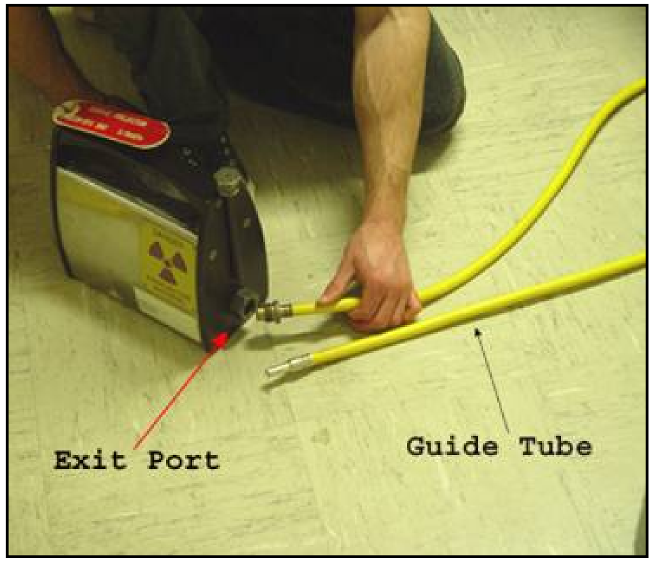




Gamma Radiography (cont.)

A hose-like device called a guide tube is connected to a threaded hole called an "exit port" in the camera.

The radioactive material will leave and return to the camera through this opening when performing an exposure!



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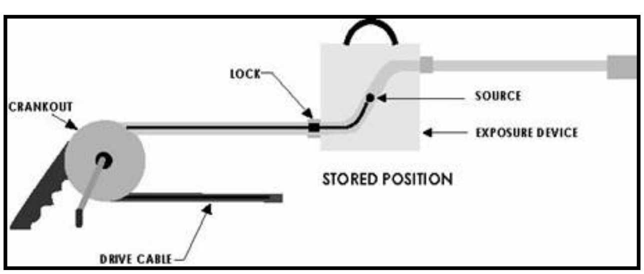
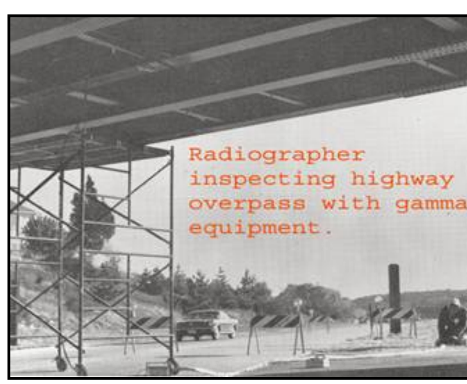
Gamma Radiography (cont.)

A "drive cable" is connected to the other end of the camera. This cable, controlled by the radiographer, is used to force the radioactive material out into the guide tube where the gamma rays will pass through the specimen and expose the recording device.



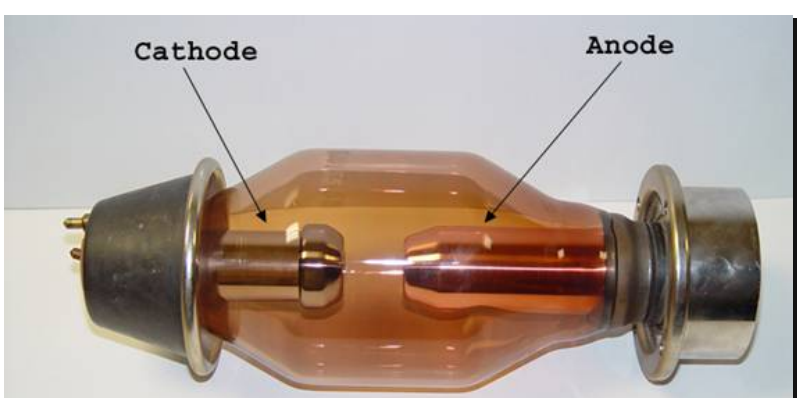


X-ray Radiography

Unlike gamma rays, x-rays are produced by an X-ray generator system. These systems typically include an X-ray tube head, a high voltage generator, and a control console.

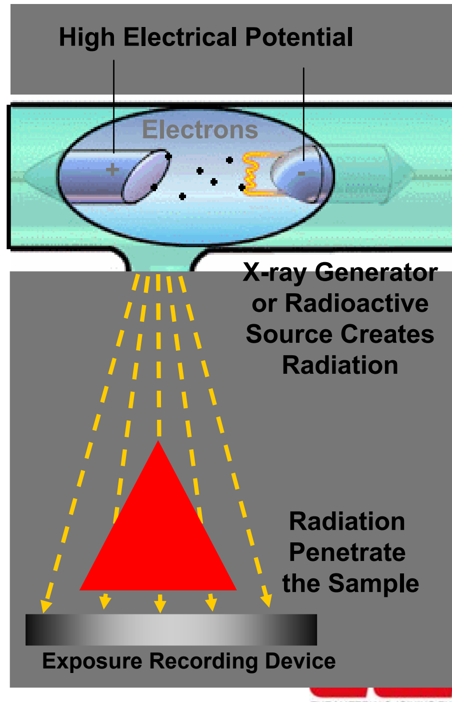
X-ray Radiography (cont.)

- X-rays are produced by establishing a very high voltage between two electrodes, called the anode and cathode.
- To prevent arcing, the anode and cathode are located inside a vacuum tube, which is protected by a metal housing.



X-ray Radiography (cont.)

- The cathode contains a small filament much the same as in a light bulb.
- Current is passed through the filament which heats it. The heat causes electrons to be stripped off.
- The high voltage causes these "free" electrons to be pulled toward a target material (usually made of tungsten) located in the anode.
- The electrons impact against the target. This impact causes an energy exchange which causes x-rays to be created.



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Imaging Modalities

Several different imaging methods are available to display the final image in industrial radiography:

- Film Radiography
- Real Time Radiography
- Computed Tomography (CT)
- Digital Radiography (DR)
- Computed Radiography (CR)

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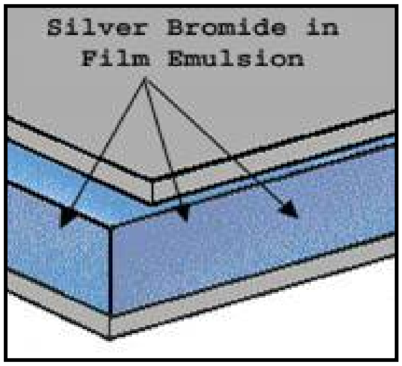
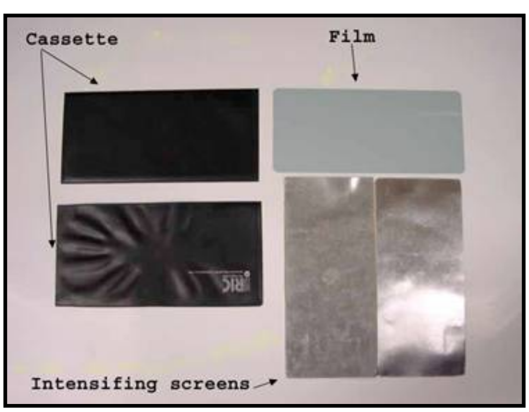
Film Radiography

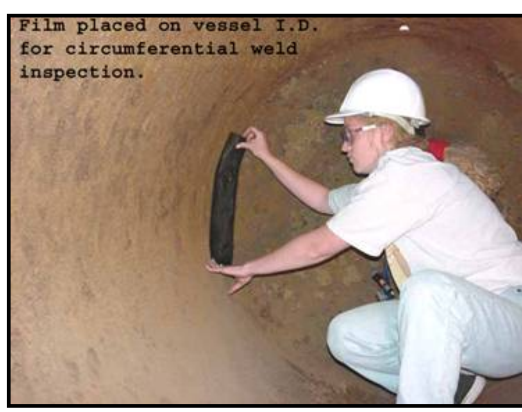


- One of the most widely used and oldest imaging mediums in industrial radiography is radiographic film.
  - Film contains microscopic material called silver bromide.
  - Once exposed to radiation and developed in a darkroom, silver bromide turns to black metallic silver which forms the image.

Film Radiography (cont.)

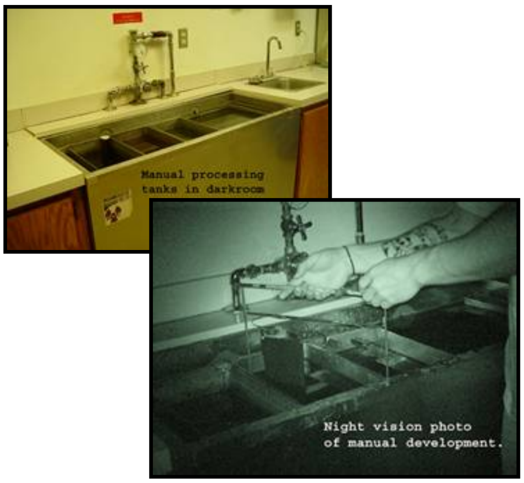
- Film must be protected from visible light. Light, just like x-rays and gamma rays, can expose film. Film is loaded in a “light proof” cassette in a darkroom.
- This cassette is then placed on the specimen opposite the source of radiation. Film is often placed between lead screens to intensify the effects of the radiation.

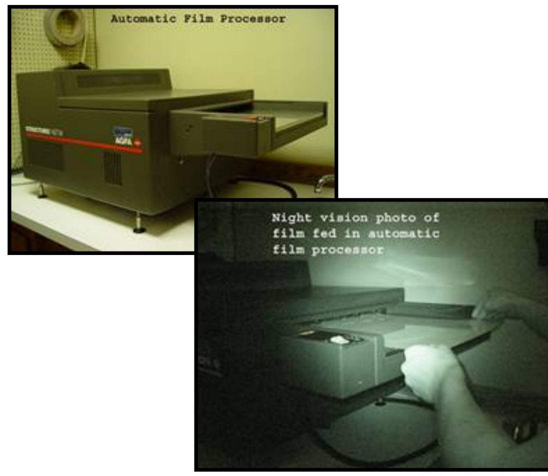




Film Radiography (cont.)

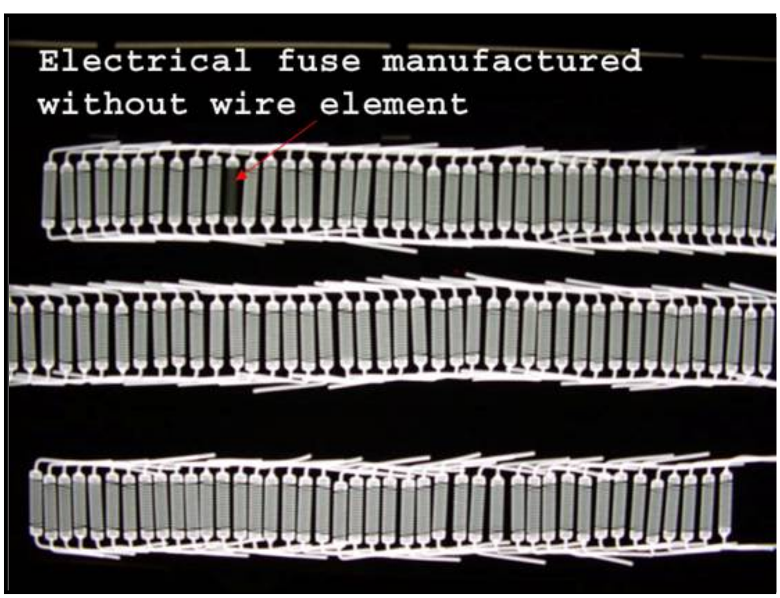
- In order for the image to be viewed, the film must be "developed" in a darkroom. The process is very similar to photographic film development.
- Film processing can either be performed manually in open tanks or in an automatic processor.





Film Radiography (cont.)

Once developed, the film is typically referred to as a "radiograph."



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Digital Radiography

- One of the newest forms of radiographic imaging is "Digital Radiography".
- Requiring no film, digital radiographic images are captured using either special phosphor screens or flat panels containing micro-electronic sensors.
- No darkrooms are needed to process film, and captured images can be digitally enhanced for increased detail.
- Images are also easily archived (stored) when in digital form.

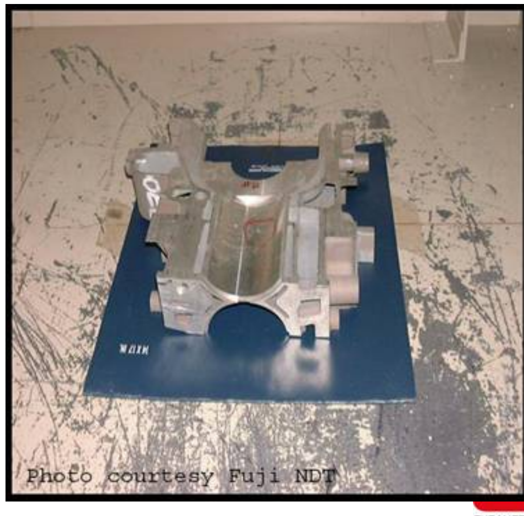
Digital Radiography (cont.)

There are a number of forms of digital radiographic imaging including:

- Computed Radiography (CR)
- Real-time Radiography (RTR)
- Direct Radiographic Imaging (DR)
- Computed Tomography

Computed Radiography

Computed Radiography (CR) is a digital imaging process that uses a special imaging plate which employs storage phosphors.



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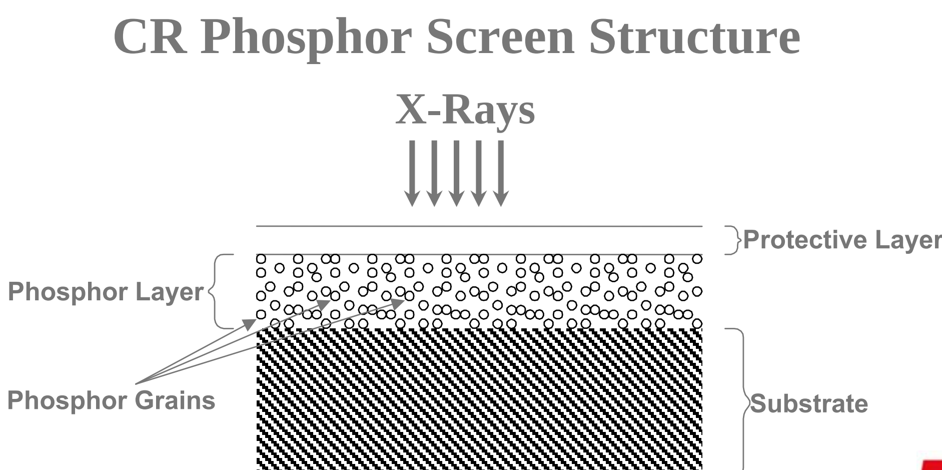
Computed Radiography (cont.)

X-rays penetrating the specimen stimulate the phosphors. The stimulated phosphors remain in an excited state.



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Computed Radiography (cont.)

After exposure:

The imaging plate is read electronically and erased for re-use in a special scanner system.

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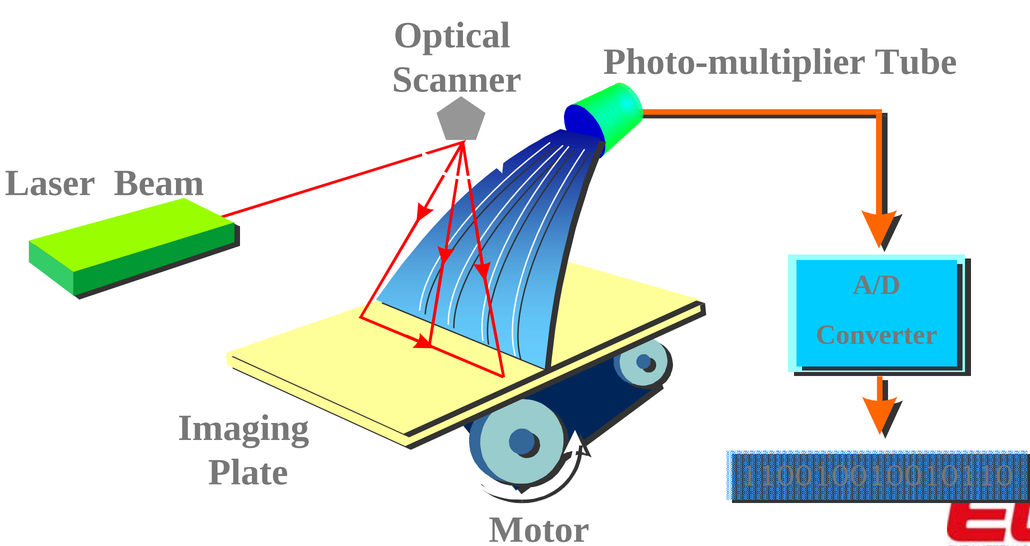
Computed Radiography (cont.)

As a laser scans the imaging plate, light is emitted where X-rays stimulated the phosphor during exposure. The light is then converted to a digital value.



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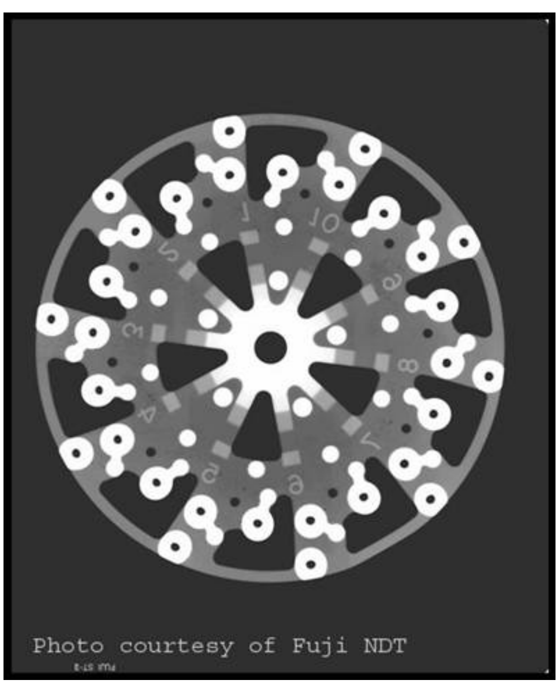
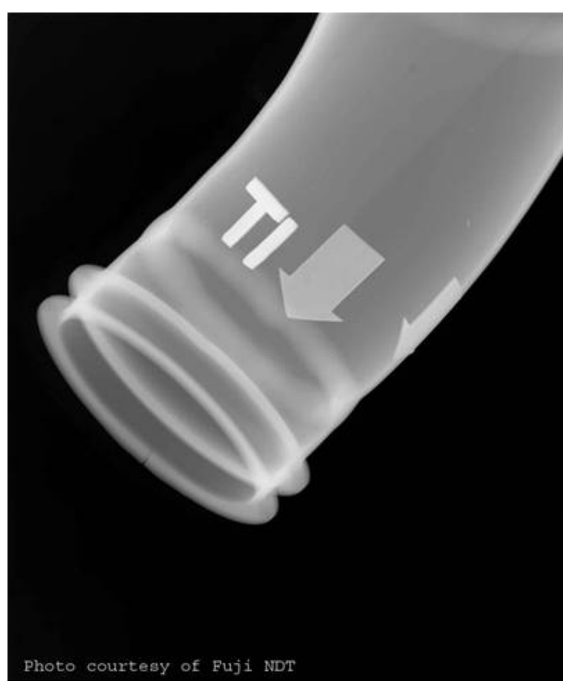
Computed Radiography (cont.)

Digital images are typically sent to a computer workstation where specialized software allows manipulation and enhancement.

Computed Radiography (cont.)

Examples of computed radiographs:





Real-Time Radiography

- Real-Time Radiography (RTR) is a term used to describe a form of radiography that allows electronic images to be captured and viewed in real time.
- Because image acquisition is almost instantaneous, X-ray images can be viewed as the part is moved and rotated.
- Manipulating the part can be advantageous for several reasons:
  - It may be possible to image the entire component with one exposure.
  - Viewing the internal structure of the part from different angular prospectives can provide additional data for analysis.
  - Time of inspection can often be reduced.

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Real-Time Radiography (cont.)

- The equipment needed for an RTR includes:
  - X-ray tube
  - Image intensifier or other real-time detector
  - Camera
  - Computer with frame grabber board and software
  - Monitor
  - Sample positioning system (optional)

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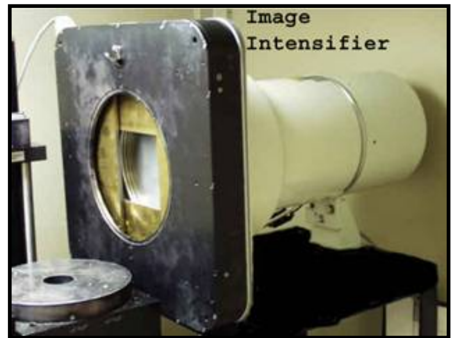
Real-Time Radiography (cont.)

- The image intensifier is a device that converts the radiation that passes through the specimen into light.
- It uses materials that fluoresce when struck by radiation.
- The more radiation that reaches the input screen, the more light that is given off.
- The image is very faint on the input screen so it is intensified onto a small screen inside the intensifier where the image is viewed with a camera.

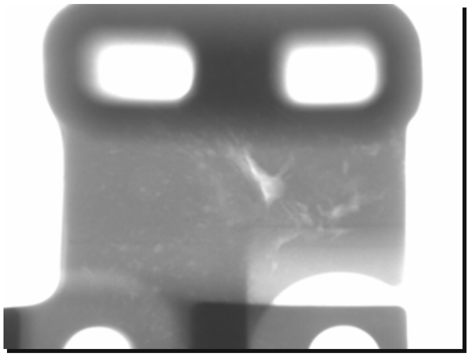


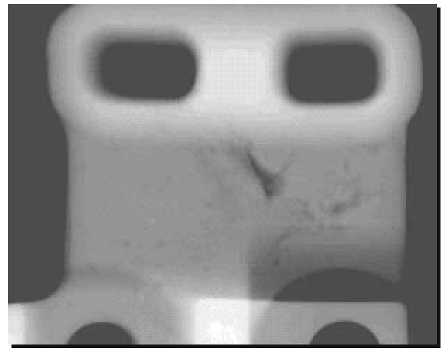
Real-Time Radiography (cont.)

- A special camera which captures the light output of the screen is located near the image intensifying screen.
- The camera is very sensitive to a variety of different light intensities.
- A monitor is then connected to the camera to provide a viewable image.
- If a sample positioning system is employed, the part can be moved around and rotated to image different internal features of the part.

Real-Time Radiography (cont.)

Comparing Film and Real-Time Radiography





Real-time images are lighter in areas where more X-ray photons reach and excite the fluorescent screen.

Film images are darker in areas where more X-ray photons reach and ionize the silver molecules in the film.

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Direct Radiography

- **Direct radiography (DR) is a form of real-time radiography that uses a special flat panel detector.**
- **The panel works by converting penetrating radiation passing through the test specimen into minute electrical charges.**
- **The panel contains many micro-electronic capacitors. The capacitors form an electrical charge pattern image of the specimen.**
- **Each capacitor's charge is converted into a pixel which forms the digital image.**

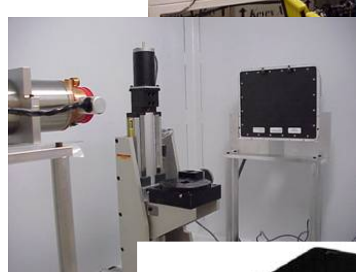
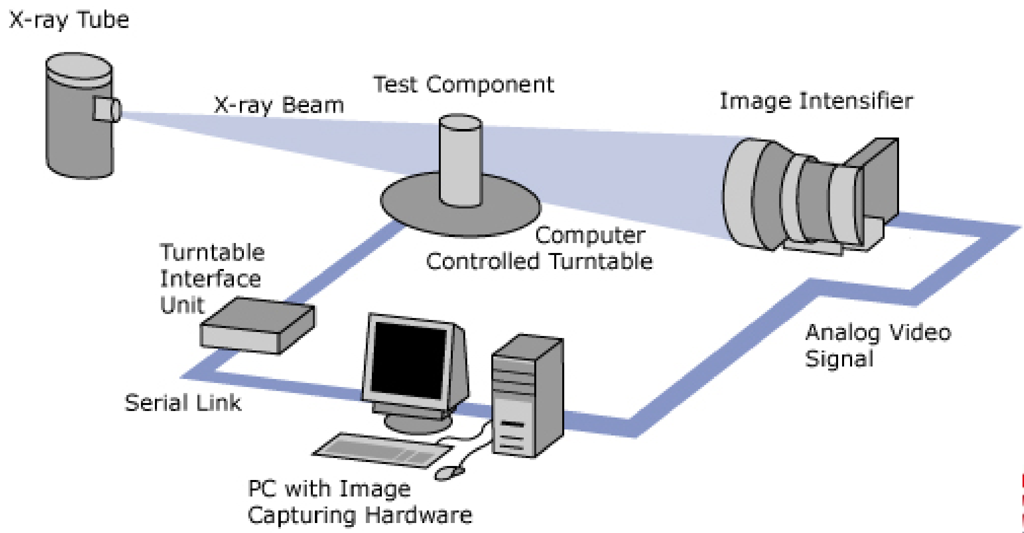


Image courtesy AFGA NDT

RTS

Computed Tomography

Computed Tomography (CT) uses a real-time inspection system employing a sample positioning system and special software.



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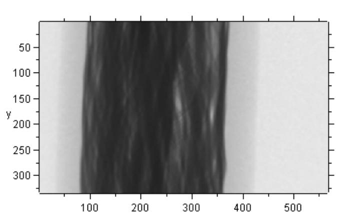
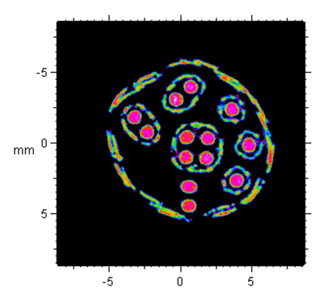
Computed Tomography (cont.)

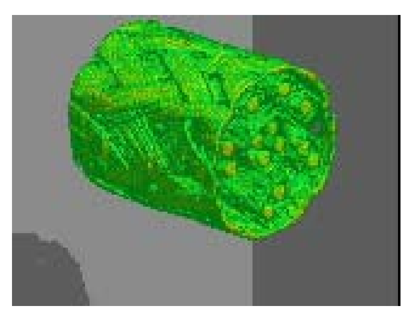
- **Many separate images are saved (grabbed) and complied into 2-dimensional sections as the sample is rotated.**
- **2-D images are them combined into 3-dimensional images.**



Real-Time Captures



Compiled 2-D Images



Compiled 3-D Structure

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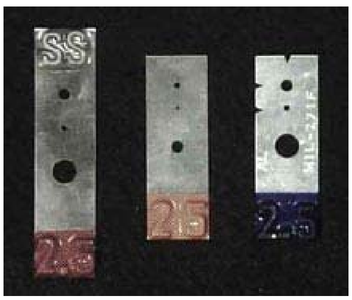
Image Quality

- Image quality is critical for accurate assessment of a test specimen's integrity.
- Various tools called Image Quality Indicators (IQIs) are used for this purpose.
- There are many different designs of IQIs. Some contain artificial holes of varying size drilled in metal plaques while others are manufactured from wires of differing diameters mounted next to one another.



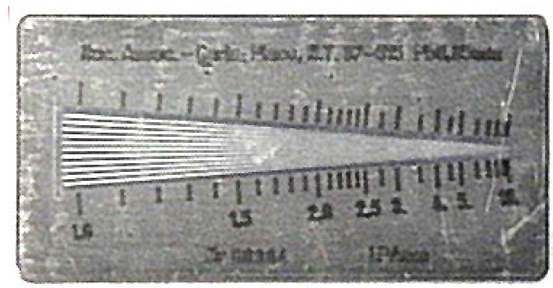
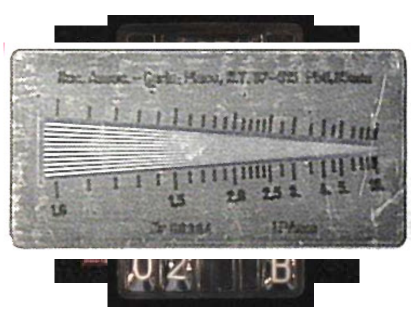
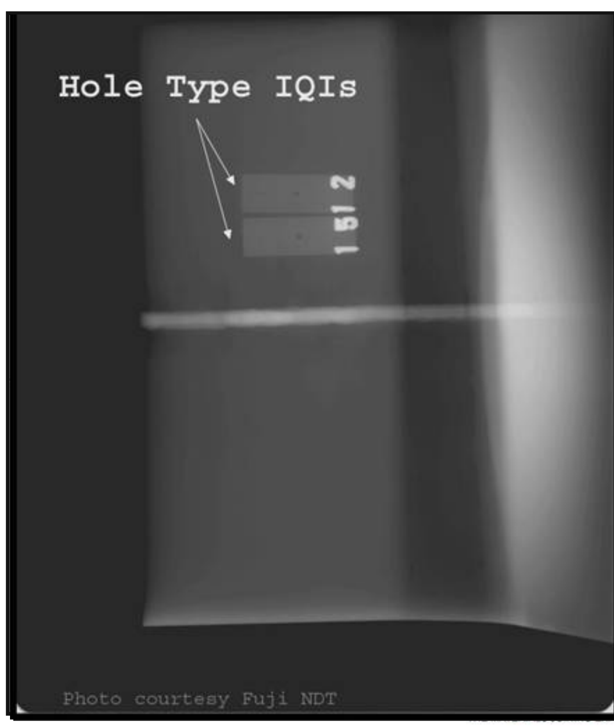


Image Quality (cont.)

- IQIs are typically placed on or next to a test specimen.
- Quality typically being determined based on the smallest hole or wire diameter that is reproduced on the image.





Radiation Safety

Use of radiation sources in industrial radiography is heavily regulated by state and federal organizations due to potential public and personal risks.

Radiation Safety (cont.)

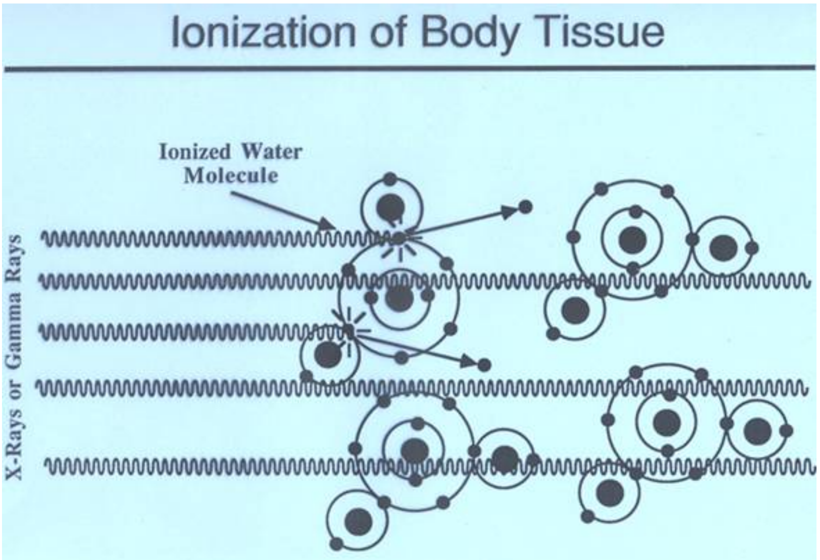
There are many sources of radiation. In general, a person receives roughly 100 mrem/year from natural sources and roughly 100 mrem/year from manmade sources.

Natural Sources	Annual Dose (mrem/year)
Cosmic rays (radiation from the sun and outer space)	28
Building materials	4
The human body	25
The earth	26

Manmade Sources	Annual Dose (mrem/year)
Medical (primarily from diagnostic X-rays)	90
Fallout from atomic bombs	5
Nuclear power production	.3
Consumer products (mostly from color TV sets)	1

Radiation Safety (cont.)

X-rays and gamma rays are forms of ionizing radiation, which means that they have the ability to form ions in the material that is penetrated. All living organisms are sensitive to the effects of ionizing radiation (radiation burns, x-ray food pasteurization, etc.)



X-rays and gamma rays have enough energy to liberate electrons from atoms and damage the molecular structure of cells.

This can cause radiation burns or cancer.

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Radiation Safety (cont.)

Technicians who work with radiation must wear monitoring devices that keep track of their total absorption, and alert them when they are in a high radiation area.

Survey Meter

Pocket Dosimeter

Radiation Alarm

Radiation Badge

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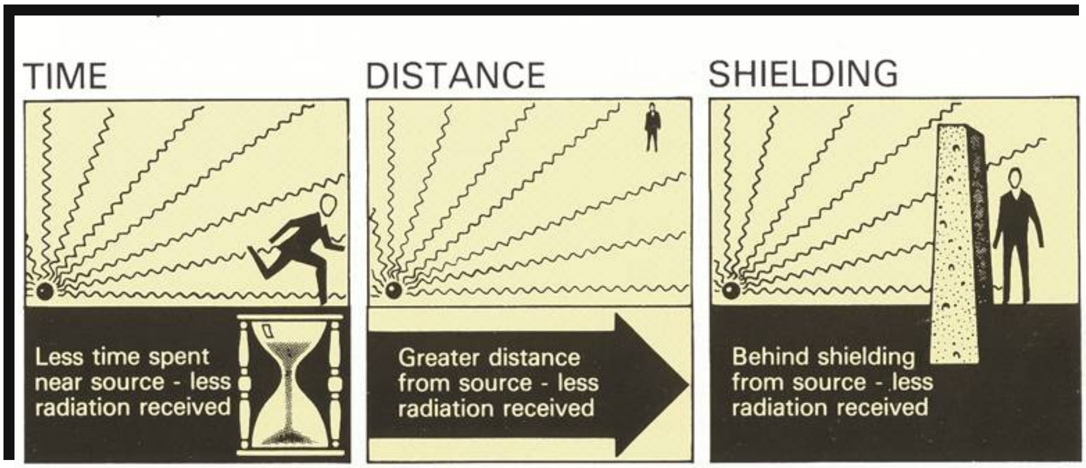
Radiation Safety (cont.)

There are three means of protection to help reduce exposure to radiation:



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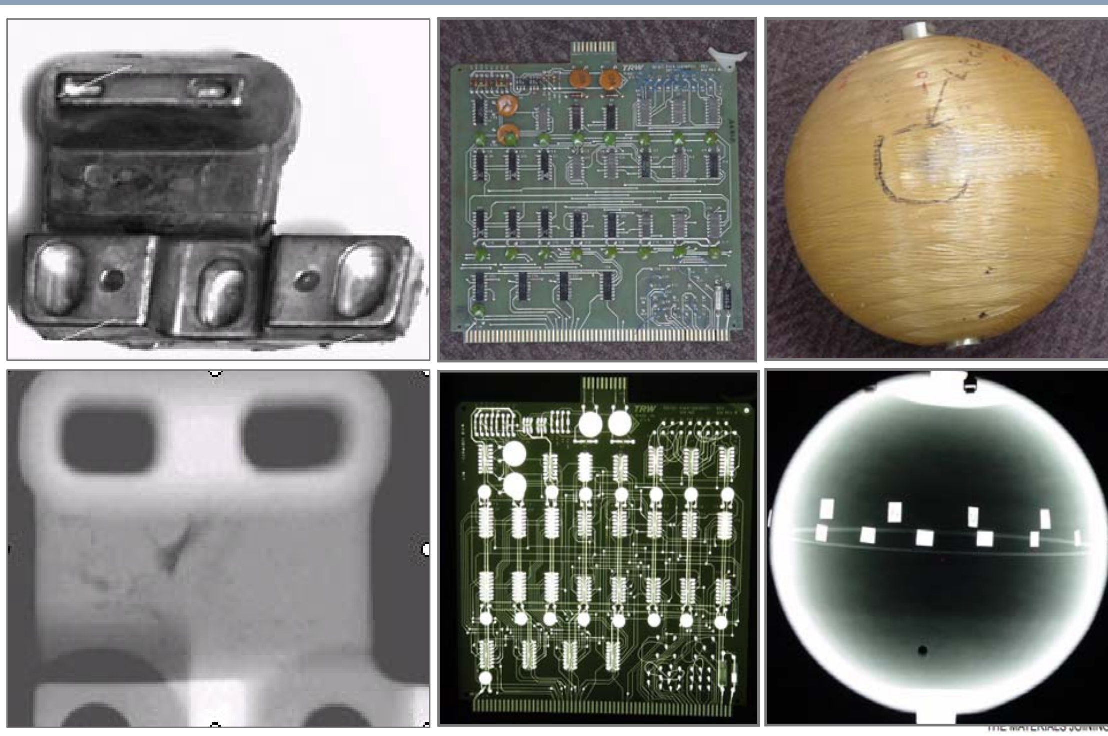
Radiographic Images



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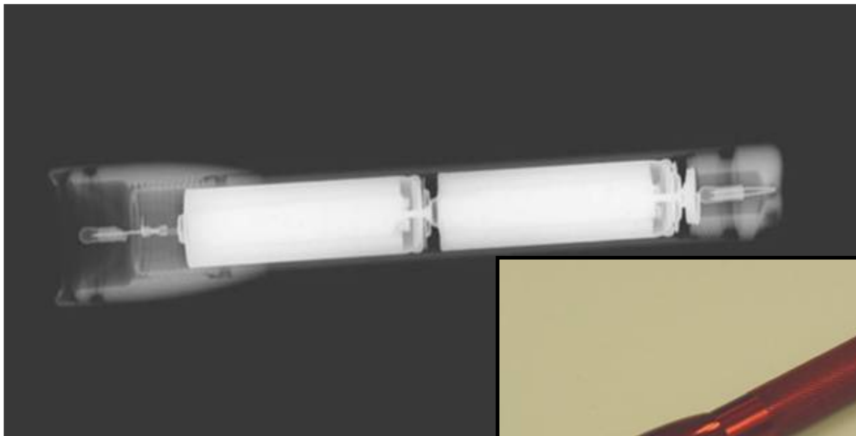
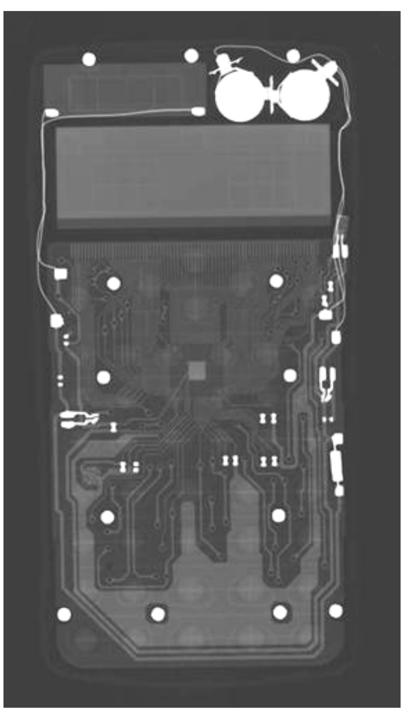
Radiographic Images

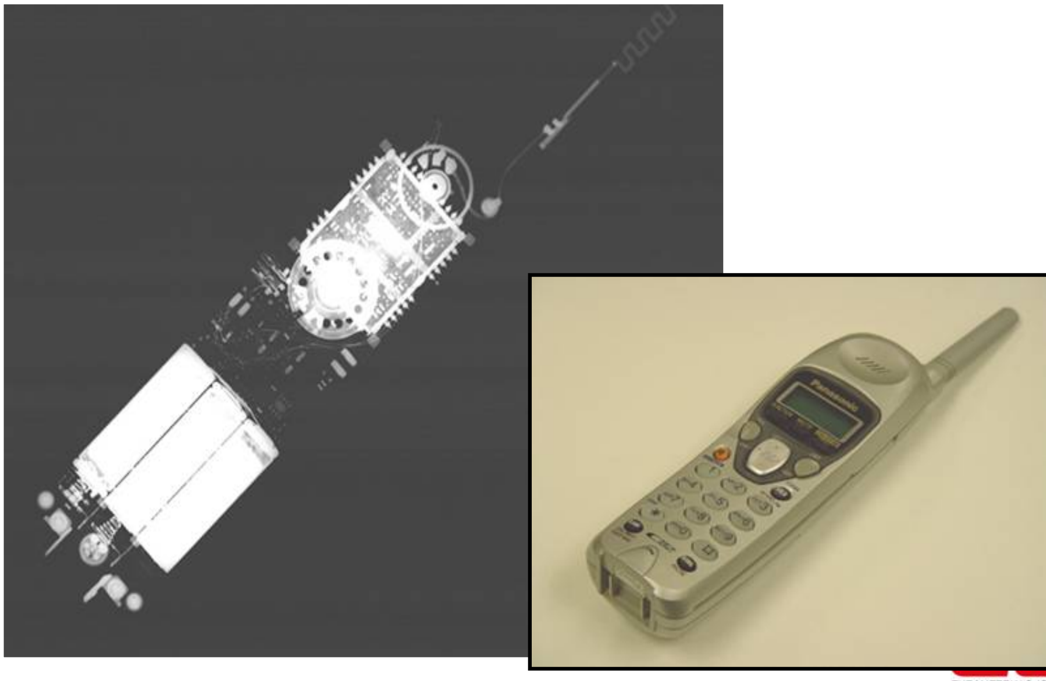
Can you determine what object was radiographed in this and the next three slides?



Radiographic Images



Radiographic Images



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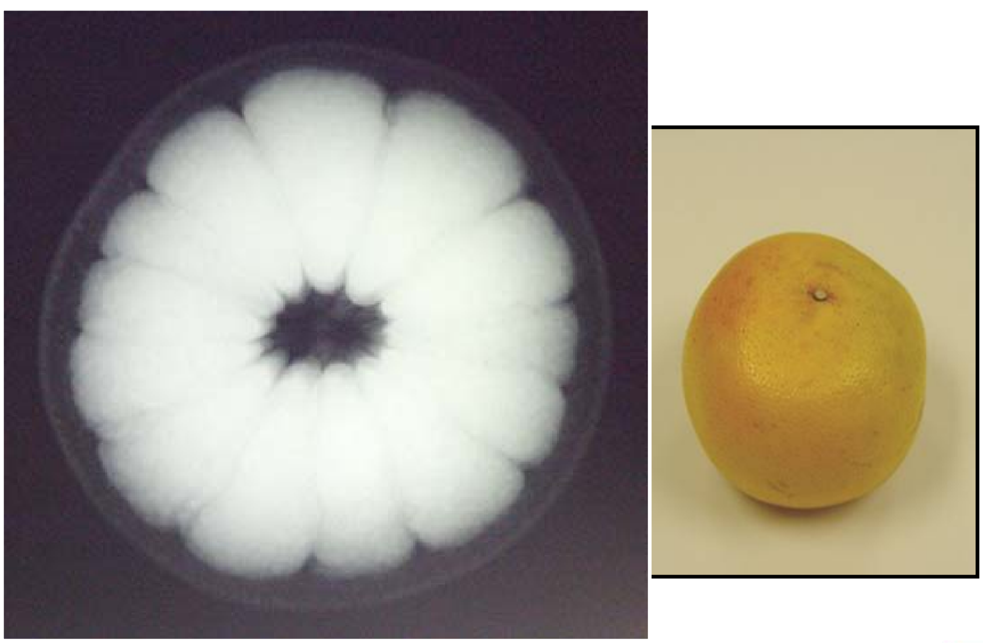
Radiographic Images



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Advantages of Radiography

- Technique is not limited by material type or density.
- Can inspect assembled components.
- Minimum surface preparation required.
- Sensitive to changes in thickness, corrosion, voids, cracks, and material density changes.
- Detects both surface and subsurface defects.
- Provides a permanent record of the inspection.

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Disadvantages of Radiography

- Many safety precautions for the use of high intensity radiation.
- Many hours of technician training prior to use.
- Access to both sides of sample required.
- Orientation of equipment and flaw can be critical.
- Determining flaw depth is impossible without additional angled exposures.
- Expensive initial equipment cost.

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Glossary of Terms

- **Activation:** the process of creating radioactive material from stable material usually by bombarding a stable material with a large number of free neutrons. This process typically takes place in a special nuclear reactor.
- **Anode:** a positively charged electrode.
- **Automatic Film Processor:** a machine designed to develop film with very little human intervention. Automatic processors are very fast compared to manual development.

Glossary of Terms

- **Capacitor:** an electrical device that stores an electrical charge which can be released on demand.
- **Cathode:** a negatively charged electrode.
- **Darkroom:** a darkened room for the purpose of film development. Film is very sensitive to exposure by visible light and may be ruined.
- **Exposure:** the process of radiation penetrating and object.
- **Gamma Rays**: electromagnetic radiation emitted from the nucleus of a some radioactive materials.

Glossary of Terms

- **Phosphor:** a chemical substance that emits light when excited by radiation.
- **Pixel:** Short for ***Pic****ture* ***El****ement,* a pixel is a single point in a graphic image. Graphics monitors display pictures by dividing the display screen into thousands (or millions) of pixels, arranged in rows and columns. The pixels are so close together that they appear connected.
- **Photo-multiplier tube:** an amplifier used to convert light into electrical signals.

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Glossary of Terms

- **Radioactive:** to give off radiation spontaneously.
- **Radiograph:** an image of the internal structure of and object produced using a source of radiation and a recording device.
- **Silver Bromide:** silver and bromine compound used in film emulsion to form the image seen on a radiograph.

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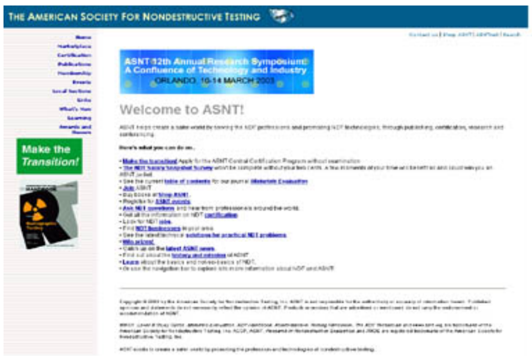
For More Information

The Collaboration for NDT Education

www.ndt-ed.org



The American Society for Nondestructive Testing

www.asnt.org

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Liquid Penetrant Testing

PENETRANT TESTING

Prepared by the Collaboration for NDT Education.
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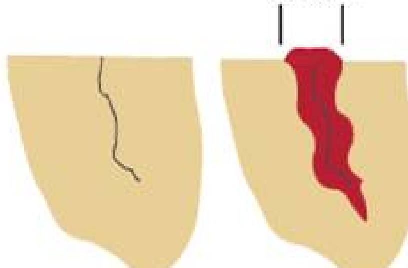
THE MATERIALS JOINING EXPERTS

Introduction

- This module is intended to provide an introduction to the NDT method of penetrant testing.
- Penetrant Testing, or PT, is a nondestructive testing method that builds on the principle of Visual Inspection.
- PT increases the “seeability” of small discontinuities that the human eye might not be able to detect alone.



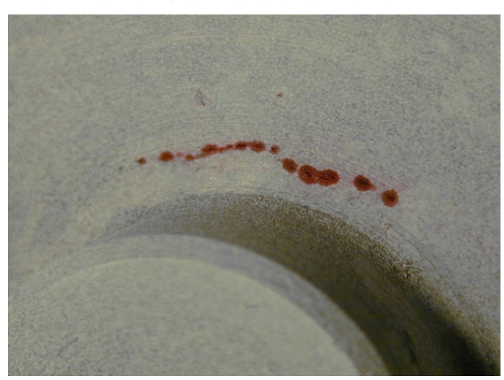
THE MATERIALS JOINING EXPERTS

Outline

- General Introduction
- Penetrant Materials and Considerations
- Basic Steps in Penetrant Testing
- Common Equipment
- Advantages and Limitations
- Summary
- Glossary of Terms

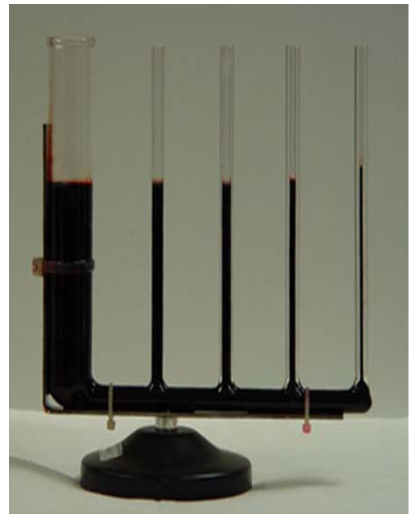
How Does PT Work?

- In penetrant testing, a liquid with high surface wetting characteristics is applied to the surface of a component under test.
- The penetrant "penetrates" into surface breaking discontinuities via capillary action and other mechanisms.
- Excess penetrant is removed from the surface and a developer is applied to pull trapped penetrant back the surface.
- With good inspection technique, visual indications of any discontinuities present become apparent.



What Makes PT Work?

- Every step of the penetrant process is done to promote capillary action.
- This is the phenomenon of a liquid rising or climbing when confined to small openings due to surface wetting properties of the liquid.
- Some examples:
  - Plants and trees draw water up from the ground to their branches and leaves to supply their nourishment.
  - The human body has miles of capillaries that carry life sustaining blood to our entire body.



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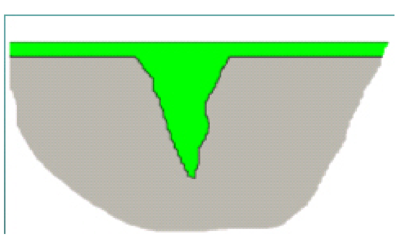
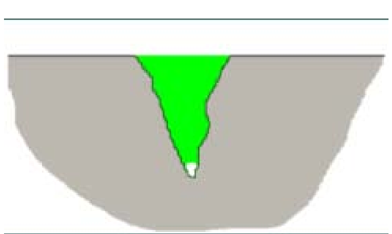
Basic Process of PT

1) Clean & Dry Component

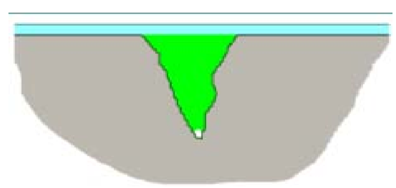
2) Apply Penetrant



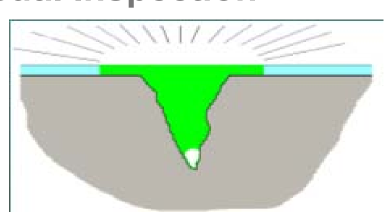
3) Remove Excess



4) Apply Developer



5) Visual Inspection



6) Post Clean Component

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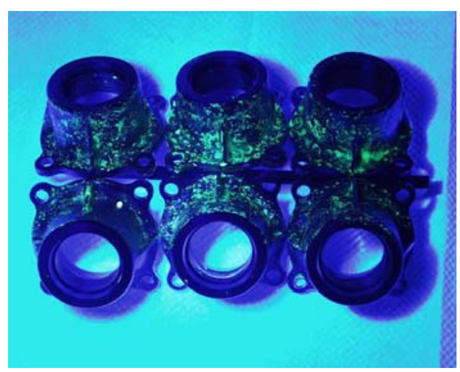
What Can Be Inspected Via PT?

Almost any material that has a relatively smooth, non-porous surface on which discontinuities or defects are suspected.

What Can *NOT* be Inspected Via PT?

- Components with rough surfaces, such as sand castings, that trap and hold penetrant.
- Porous ceramics
- Wood and other fibrous materials.
- Plastic parts that absorb or react with the penetrant materials.
- Components with coatings that prevent penetrants from entering defects.

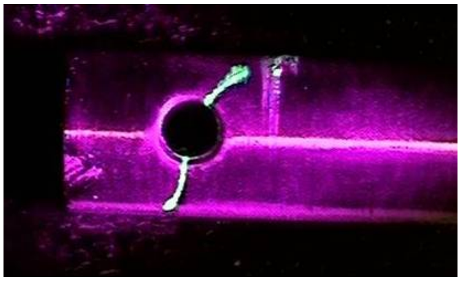


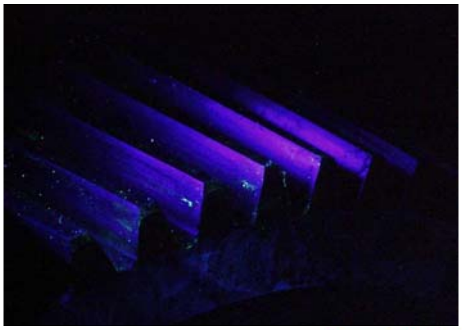
Defect indications become less distinguishable as the background "noise" level increases.

What Types of Discontinuities Can Be Detected Via PT?

All defects that are open to the surface.

- Rolled products-- cracks, seams, laminations.
- Castings--cold shuts, hot tears, porosity, blow holes, shrinkage.
- Forgings– cracks, laps, external bursts.
- Welds– cracks, porosity, undercut, overlap, lack of fusion, lack of penetration.





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Choices of Penetrant Materials

Penetrant

Type

I Fluorescent
II Visible

Method

A Water Washable
B Postemulsifiable - Lipophilic
C Solvent Removable
D Postemulsifiable - Hydrophilic

Developer

Form

Dry Powder
Wet, Water Soluble
Wet, Water Suspendable
Wet, Non-Aqueous

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Penetrant Materials

Penetrants are formulated to possess a number of important characteristics. To perform well, a penetrant must:

- Spread easily over the surface being inspected.
- Be drawn into surface breaking defects by capillary action or other mechanisms.
- Remain in the defect but remove easily from the surface of the part.
- Remain fluid through the drying and developing steps so it can be drawn back to the surface.
- Be highly visible or fluoresce brightly to produce easy to see indications.
- Not be harmful to the inspector or to the material being tested.

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Sensitivity Levels

- Penetrants are also formulated to produce a variety of sensitivity levels. The higher the sensitivity level, the smaller the defect that the penetrant system is capable of detecting.
- The four sensitivity levels are:
  - Level 4 - Ultra-High Sensitivity
  - Level 3 - High Sensitivity
  - Level 2 - Medium Sensitivity
  - Level 1 - Low Sensitivity
- As the sensitivity level increases, so does the number of nonrelevent indications. Therefore, a penetrant needs to be selected that will find the defects of interest but not produce too many nonrelevent indications.

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Visible Vs Fluorescent PT

- Inspection can be performed using visible (or red dye) or fluorescent penetrant materials.
- Visible Pt is performed under white light while fluorescent PT must be performed using an ultraviolet light in a darkened area. All are all in the level 1 sensitivity range.
- Fluorescent PT is more sensitive than visible PT because the eye is more sensitive to a bright indication on a dark background. Sensitivity ranges from 1 to 4.

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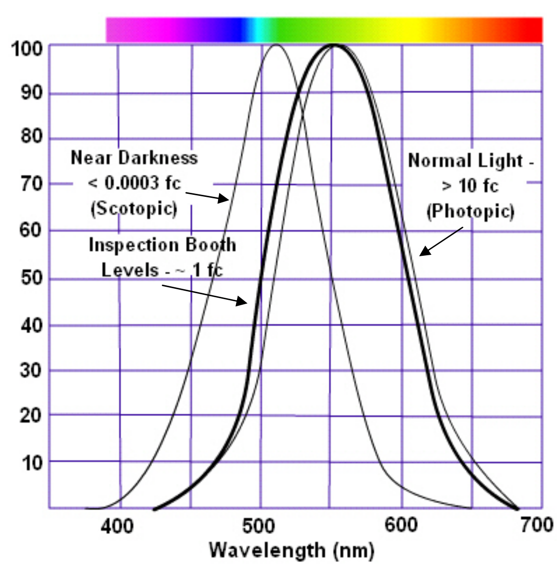
Why is Visible Penetrant Red and Fluorescent Penetrant Green?

- Visible penetrant is usually red because red stands out and provides a high level of contrast against a light background
- Fluorescent penetrant is green because the eye is most sensitive to the color green due to the number and arrangement of the cones (the color receptors) in the eye.



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Penetrant Removal Method

Penetrants are also classified by the method of removing the excess penetrant.

- **Solvent Removable** penetrants are removed by wiping with a cloth dampened with solvent. They are supplied in aerosol cans for portability and are primarily used for spot checks.
- **Water Washable** penetrants are removed with a course spray of water. They are the easiest to employ and most cost effective when inspecting large areas.
- **Post-Emulsifiable** penetrants are water-washable only after they have reacted with an emulsifier solution. A post-emulsifiable system is used when washing the penetrant out of the defect is a concern. The emulsifier is given time to reacts with the penetrant on the surface but not the penetrant trapped in the flaw.

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Developers

- **The role of the developer is to pull trapped penetrant out of defects and to spread it out on the surface so that it can be seen. Also provides a light background to increase contrast when visible penetrant is used.**
- **Developer materials are available in several different forms**
  - **Dry Powder** is a mix of light fluffy powder that clumps together where penetrant bleeds back to the surface to produces very defined indications.
  - **Wet, Water Suspendable** is a powder that is suspended in a water that covers the surface with a relatively uniform layer of developer when the water is evaporated. The solution is somewhat difficult to maintain as the powder settles out over time.
  - **Wet, Water Soluble** is a crystalline powder that forms a clear solution when mixed with water. The solution recrystallizes on the surface when the water is driven off. Indications sometimes lack definition and look milky. Not recommended for use with water-washable penetrants.
  - **Wet, Non-Aqueous** - is supplied in a spray can and is the most sensitive developer for inspecting small areas. It is too costly and difficult to apply to large areas.

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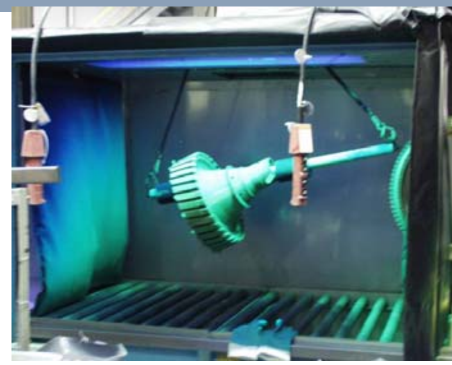
6 Steps of Penetrant Testing

1. Pre-Clean
2. Penetrant Application
3. Excess Penetrant Removal
4. Developer Application
5. Inspect/Evaluate
6. Post-clean



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Pre-cleaning – Step 1

- Parts must be free of dirt, rust, scale, oil, grease, etc. to perform a reliable inspection.
- The cleaning process must remove contaminants from the surfaces of the part and defects, and must not plug any of the defects.

Pre-cleaning is the most important step in the PT process!!!

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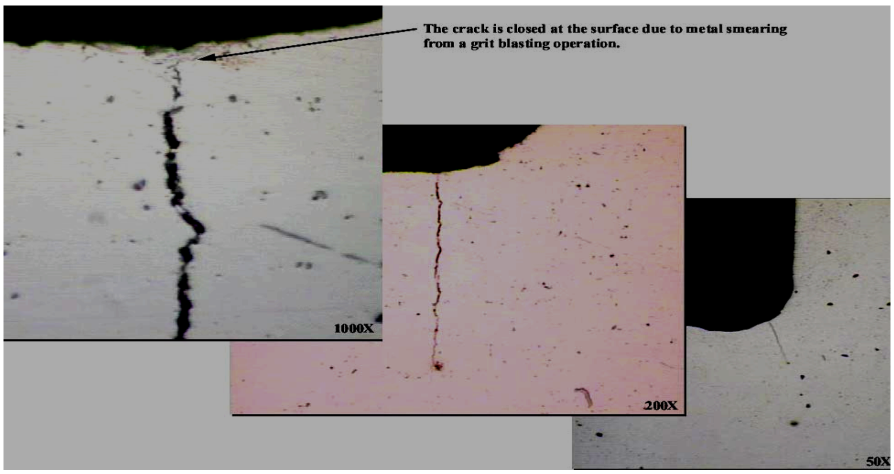
Caution About Metal Smearing

Some machining, surface finishing and cleaning operations can cause a thin layer of metal to smear on the surface and prevent penetrant from entering any flaws that may be present. Etching of the surface prior to inspection is sometimes required.



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Penetrant Application – Step 2

Many methods of application are possible such as:

- Brushing
- Spraying
- Dipping/ Immersing
- Flow-on
- And more

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Dwell Time

- The penetrant solution must be allowed to "dwell" on the surface of the part to allow the penetrant time to fill any defects present.
- The dwell time vary according to penetrant type, temperature, material type and surface finish.

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Excess Penetrant Removal – Step 3

The removal technique depends upon the type of penetrant used, as stated earlier…

- Solvent Removable
- Water Washable
- Post Emulsifiable

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Excess Penetrant Removal – Step 3 (cont.)

Water Washable

- A coarse water spray is used to remove the excess penetrant.
- The procedure used as a guideline for the inspection will specify water temperature (typically 50-100°F) and pressure (typically not more than 40 psi), etc.

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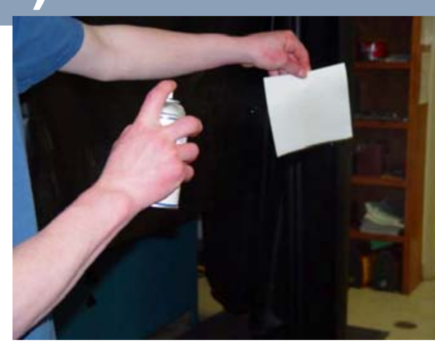
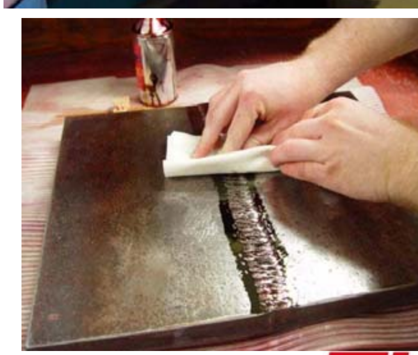
Excess Penetrant Removal – Step 3 (cont.)

Solvent Removable

- The part is wiped with a clean dry cloth to remove the bulk of the excess penetrant.
- Then, a cloth lightly dampened with solvent is used to remove any remaining penetrant on the surface.





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Excess Penetrant Removal – Step 3 (cont.)

Solvent Removable (cont.)

Any time a solvent is used in the penetrant inspection process, a suitable flash time is required to allow excess solvent to evaporate.

Excess Penetrant Removal – Step 3 (cont.)

Post Emulsifiable

- When there is concern about removing much of the penetrant from the defect, a post emulsifiable system is used.
- This involves an additional step in which an emulsifier is applied to the surface of the part after the penetrant dwell time.
- The emulsifier is given just enough time to react with the penetrant on the surface to render it water washable but not enough time to diffuse into the penetrant trapped in the defects.

Developer Application – Step 4

The method of developer application is is dependent on the type of developer used. The primary methods for the following main developer types will be covered in the following slides.

– Dry
– Wet
– Nonaqueous Wet

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Developer Application – Step 4 (cont.)

Dry Powder Developer

- Prior to applying a dry powder developer, the component must be thoroughly dried. Drying is usually accomplished in a hot air circulating oven.
- The developer is then applied by immersing the part in the powder or by dusting of the part with the powder.
- The part can also be placed in a developer dust cloud chamber.

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Developer Application – Step 4 (cont.)

Wet Developer

(water- suspended and water- soluble)

- Wet developers are applied by immersing or spraying the part while it is still wet from the penetrant removal process.
- The part is completely coated and the excess liquid allowed to drain to prevent pooling
- The part is then dried in a hot air circulating oven.

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Developer Application – Step 4 (cont.)

Nonaqueous Developer (AKA Solvent-Suspended)

- Nonaqueous developer is applied by a aerosol spray to a thoroughly dried and cooled part.
- A thin even coating should be applied. The coating should be white but still slightly transparent when performing a visible dye penetrant inspection, and even thinner when performing a fluorescent penetrant inspection.

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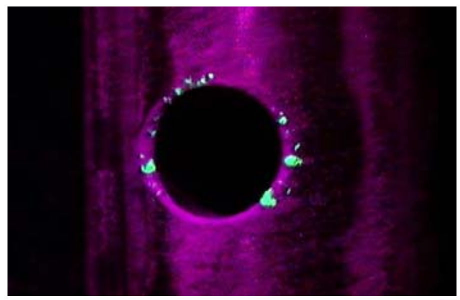
Inspection/Evaluation – Step 5

In this step the inspector evaluates the penetrant indications against specified accept/reject criteria and attempts to determine the origin of the indication.

The indications are judged to be either relevant, non-relevant or false.

Non-relevant weld geometry indications



Relevant crack indications from an abusive drilling process

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Inspection/Evaluation – Step 5

A very important step of evaluation is to document findings on an inspection report form or other record keeping form.

This may be supported with drawings or photos of indications, etc.

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Post Clean – Step 6

The final step in the penetrant inspection process is to thoroughly clean the part that has been tested to remove all penetrant processing materials.

The residual materials could possibly affect the performance of the part or affect its visual appeal.

Penetrant Inspection Systems

Penetrant systems can be highly portable or stationary.

Portable Penetrant System

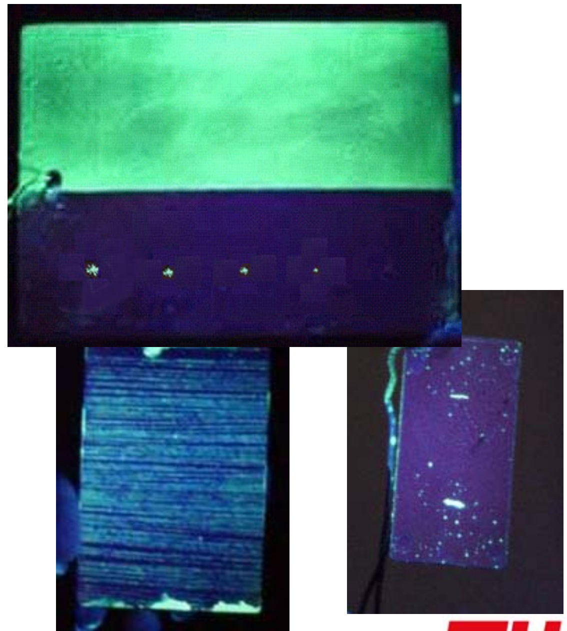
Image courtesy of Nebraska Army National Guard

Stationary Penetrant System

Verification of Penetrant System Performance

Since penetrant testing involves multiple processing steps, the performance of the materials and the processes should be routinely checked using performance verification tools, which include:

- TAM Panels
- Crack Sensitivity Panels
- Run Check Panels



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Advantages of Penetrant Testing

- Relative ease of use.
- Can be used on a wide range of material types.
- Large areas or large volumes of parts/materials can be inspected rapidly and at low cost.
- Parts with complex geometries are routinely inspected.
- Indications are produced directly on surface of the part providing a visual image of the discontinuity.
- Initial equipment investment is low.
- Aerosol spray cans can make equipment very portable.

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Limitations of Penetrant Testing

- Only detects surface breaking defects.
- Requires relatively smooth nonporous material.
- Precleaning is critical. Contaminants can mask defects.
- Requires multiple operations under controlled conditions.
- Chemical handling precautions necessary (toxicity, fire, waste).
- Metal smearing from machining, grinding and other operations inhibits detection. Materials may need to be etched prior to inspection.
- Post cleaning is necessary to remove chemicals.

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Summary

- Penetrant testing (PT) is one of the most widely used nondestructive testing methods.
- Its popularity can be attributed to two main factors, which are its relative ease of use and its flexibility.
- However, PT involves a number of processing steps that must be closely control to achieve optimal sensitivity.

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Glossary of Terms

- **Capillary Action** - the tendency of certain liquids to travel or climb when exposed to small openings.
- **Contrast** - the relative amount of light emitted or reflected between and indication and its background.
- **Defect** - a discontinuity that effects the usefulness of a part or specimen.
- **Developer** - a finely divided material applied over the surface of a part to help promote reverse capillary action and thus bring out a penetrant indication.

Glossary of Terms

- **Discontinuity** - any interruption in the normal physical structure of a part or weld. It may or may not affect the usefulness of a part.
- **Dwell Time** - the period of time that a penetrant or developer must remain in contact with the surface of a part under test.
- **Emulsification Time** - the time allowed for the emulsifier to render the penetrant water washable and thus allow the part to be washed.
- **Emulsifier** - a material applied over a film of penetrant that renders it water washable.

Glossary of Terms

- **Evaluation** - the process of deciding as to the severity of the condition after an indication has been interpreted.
- **False Indication** - an indication caused by improper processing; not caused by a relevant or non-relevant condition.
- **Flash Time** - the time required for the solvent to evaporate from the surface of a part when used to preclean or remove excess penetrant.
- **Fluorescent Dye** - a dye which becomes fluorescent (gives off light) when exposed to short wave radiation such as ultraviolet light.

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Glossary of Terms

- **Indication** - the visible evidence or penetrant bleed-out on the surface of the specimen
- **Interpretation** - the process of evaluating an indication in an attempt to determine the cause and nature of the discontinuity.
- **Non-Aqueous Developer** - a developer in which developing powder is applied as a suspension in a quick drying solvent
- **Penetrant** - a liquid used in fluorescent or visible dye penetrant inspection to penetrate into the surface openings of parts inspected via these methods

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Glossary of Terms

- **Relevant Indication** - an indication that has been determined not to be false or non-relevant - and actual discontinuity
- **Seeability** - the characteristic of an indication that enables it to be seen against the adverse conditions of background, outside light, etc.
- **Sensitivity** - the ability of a penetrant to detect surface openings. Higher sensitivity indicates smaller discontinuities can be detected
- **Ultraviolet Light** (or Black Light) - light energy just below the visible range of violet light (356 nanometers).

Glossary of Terms

- **Viscosity** - the resistance of a fluid to the motion of its particles
- **Washability** - the property of a penetrant which permits it to be cleaned from the surface of a part by washing with water

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For More Information

The Collaboration for NDT Education

www.ndt-ed.org

The American Society for Nondestructive Testing

www.asnt.org

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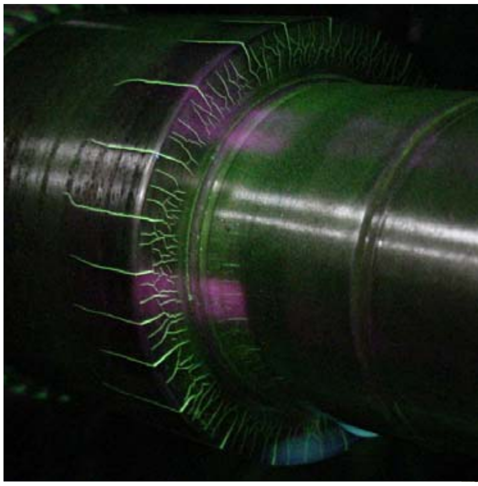
Magnetic Particle Testing

MAGNETIC PARTICLE TESTING



Prepared by the Collaboration for NDT Education.
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THE MATERIALS JOINING EXPERTS

Introduction

- This module is intended to present information on the widely used method of magnetic particle inspection.
- Magnetic particle inspection can detect both production discontinuities (seams, laps, grinding cracks and quenching cracks) and in-service damage (fatigue and overload cracks).

THE MATERIALS JOINING EXPERTS

Outline

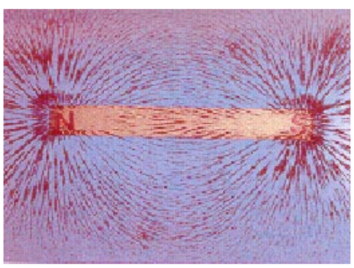
- Magnetism and Ferromagnetic Materials
- Introduction of Magnetic Particle Inspection
- Basic Procedure and Important Considerations
  - Component pre-cleaning
  - Introduction of magnetic field
  - Application of magnetic media
  - Interpretation of magnetic particle indications
- Examples of MPI Indications

THE MATERIALS JOINING EXPERTS

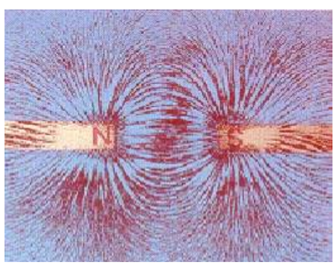
Introduction to Magnetism

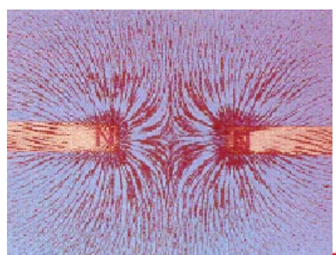
Magnetism is the ability of matter to attract other matter to itself. Objects that possess the property of magnetism are said to be magnetic or magnetized and magnetic lines of force can be found in and around the objects. A magnetic pole is a point where the a magnetic line of force exits or enters a material.

Magnetic field lines:
- Form complete loops.
- Do not cross.
- Follow the path of least resistance.
- All have the same strength.
- Have a direction such that they cause poles to attract or repel.



Magnetic lines of force around a bar magnet


Opposite poles attracting


Similar poles repelling

THE MATERIALS JOINING EXPERTS

Ferromagnetic Materials

- A material is considered ferromagnetic if it can be magnetized. Materials with a significant Iron, nickel or cobalt content are generally ferromagnetic.
- Ferromagnetic materials are made up of many regions in which the magnetic fields of atoms are aligned. These regions are call magnetic domains.
- Magnetic domains point randomly in demagnetized material, but can be aligned using electrical current or an external magnetic field to magnetize the material.

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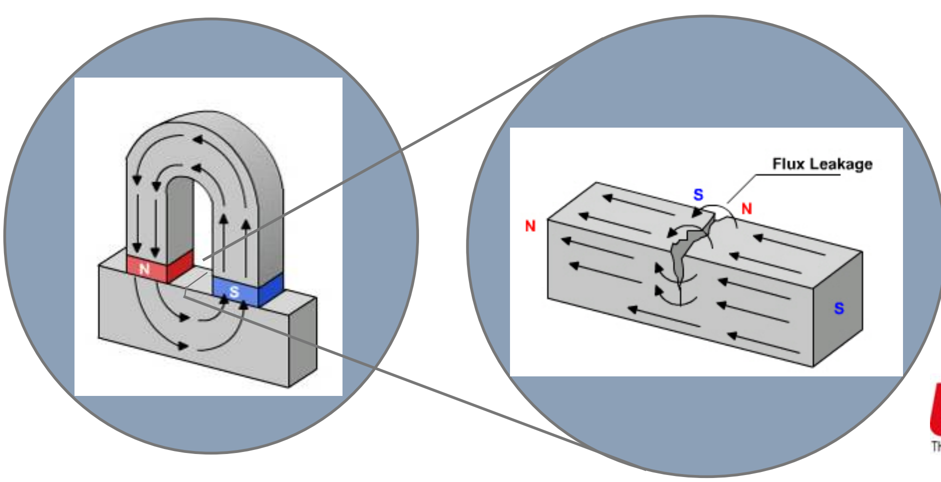
How Does Magnetic Particle Inspection Work?

A ferromagnetic test specimen is magnetized with a strong magnetic field created by a magnet or special equipment. If the specimen has a discontinuity, the discontinuity will interrupt the magnetic field flowing through the specimen and a leakage field will occur.



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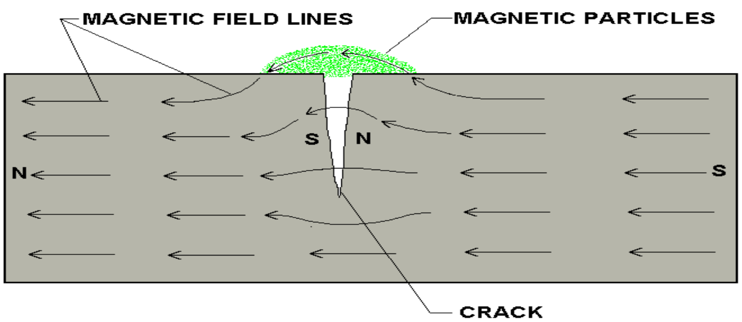
How Does Magnetic Particle Inspection Work? (Cont.)

Finely milled iron particles coated with a dye pigment are applied to the test specimen. These particles are attracted to leakage fields and will cluster to form an indication directly over the discontinuity. This indication can be visually detected under proper lighting conditions.



Basic Procedure

Basic steps involved:

1. Component pre-cleaning
2. Introduction of magnetic field
3. Application of magnetic media
4. Interpretation of magnetic particle indications

Pre-cleaning

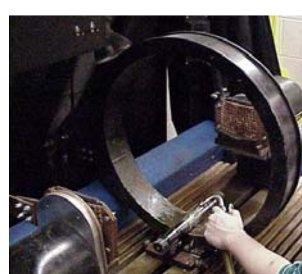
When inspecting a test part with the magnetic particle method it is essential for the particles to have an unimpeded path for migration to both strong and weak leakage fields alike. The part's surface should be clean and dry before inspection.

Contaminants such as oil, grease, or scale may not only prevent particles from being attracted to leakage fields, they may also interfere with interpretation of indications.

Introduction of the Magnetic Field

The required magnetic field can be introduced into a component in a number of different ways.

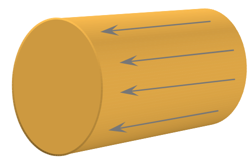
1. Using a permanent magnet or an electromagnet that contacts the test piece
2. Flowing an electrical current through the specimen
3. Flowing an electrical current through a coil of wire around the part or through a central conductor running near the part.

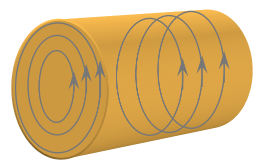


Direction of the Magnetic Field

Two general types of magnetic fields (longitudinal and circular) may be established within the specimen. The type of magnetic field established is determined by the method used to magnetize the specimen.

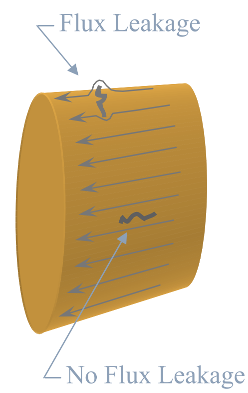
- **A longitudinal magnetic field has magnetic lines of force that run parallel to the long axis of the part.**
- **A circular magnetic field has magnetic lines of force that run circumferentially around the perimeter of a part.**



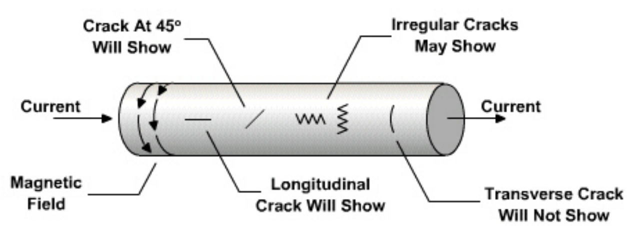


Importance of Magnetic Field Direction

Being able to magnetize the part in two directions is important because the best detection of defects occurs when the lines of magnetic force are established at right angles to the longest dimension of the defect. This orientation creates the largest disruption of the magnetic field within the part and the greatest flux leakage at the surface of the part. An orientation of 45 to 90 degrees between the magnetic field and the defect **is necessary** to form an indication.

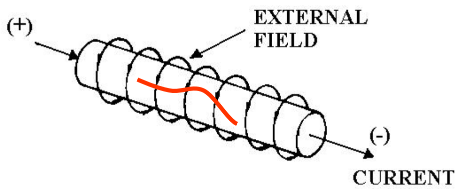


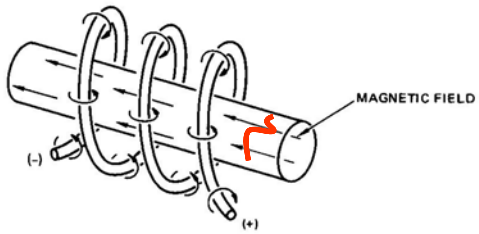
Since defects may occur in various and unknown directions, each part is normally magnetized in two directions at right angles to each other.



Question

? From the previous slide regarding the optimum test sensitivity, which kinds of defect are easily found in the images below?





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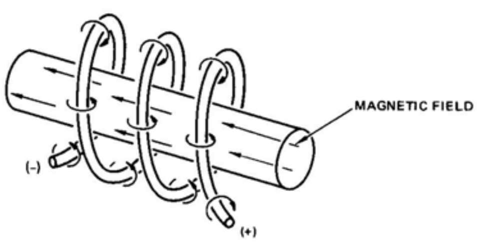
Producing a Longitudinal Magnetic Field Using a Coil



A longitudinal magnetic field is usually established by placing the part near the inside or a coil's annulus. This produces magnetic lines of force that are parallel to the long axis of the test part.

Coil on Wet Horizontal Inspection Unit

Portable Coil

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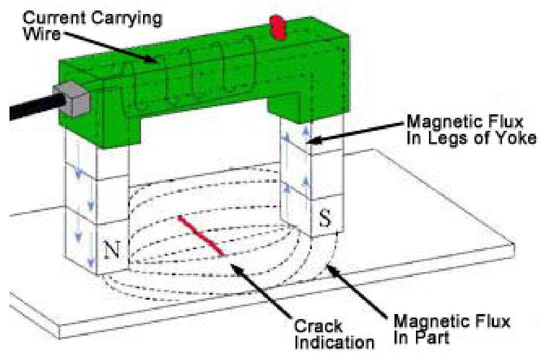
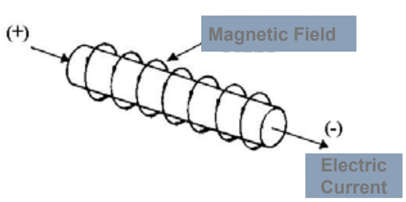
Producing a Longitudinal Field Using Permanent or Electromagnetic Magnets

Permanent magnets and electromagnetic yokes are also often used to produce a longitudinal magnetic field. The magnetic lines of force run from one pole to the other, and the poles are positioned such that any flaws present run normal to these lines of force.

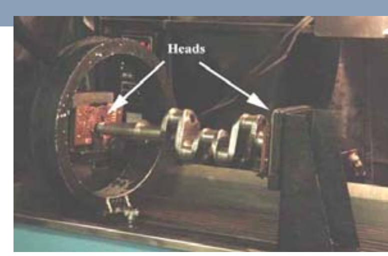


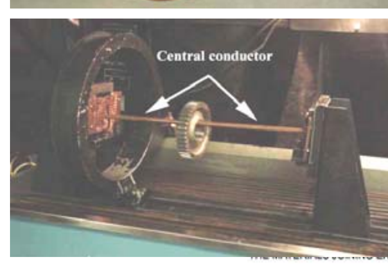
Circular Magnetic Fields



Circular magnetic fields are produced by passing current through the part or by placing the part in a strong circular magnet field.

A headshot on a wet horizontal test unit and the use of prods are several common methods of injecting current in a part to produce a circular magnetic field. Placing parts on a central conductors carrying high current is another way to produce the field.





Application of Magnetic Media (Wet Versus Dry)

MPI can be performed using either dry particles, or particles suspended in a liquid. With the dry method, the particles are lightly dusted on to the surface. With the wet method, the part is flooded with a solution carrying the particles.

The dry method is more portable. The wet method is generally more sensitive since the liquid carrier gives the magnetic particles additional mobility.

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Dry Magnetic Particles

Magnetic particles come in a variety of colors. A color that produces a high level of contrast against the background should be used.

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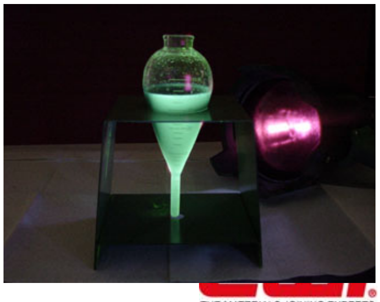
Wet Magnetic Particles

Wet particles are typically supplied as visible or fluorescent. Visible particles are viewed under normal white light and fluorescent particles are viewed under black light.



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Interpretation of Indications

After applying the magnetic field, indications that form must interpreted. This process requires that the inspector distinguish between relevant and non-relevant indications.

The following series of images depict relevant indications produced from a variety of components inspected with the magnetic particle method.

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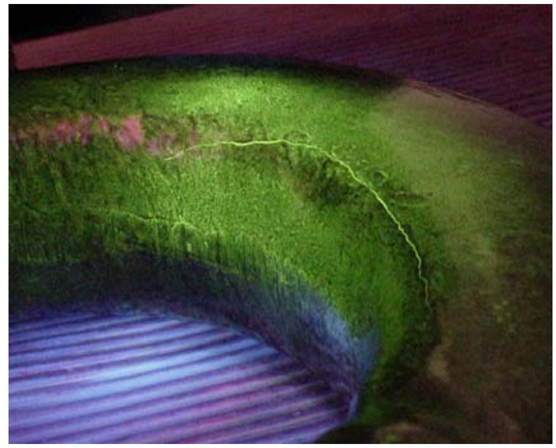
Crane Hook with Service Induced Crack



Fluorescent, Wet Particle Method

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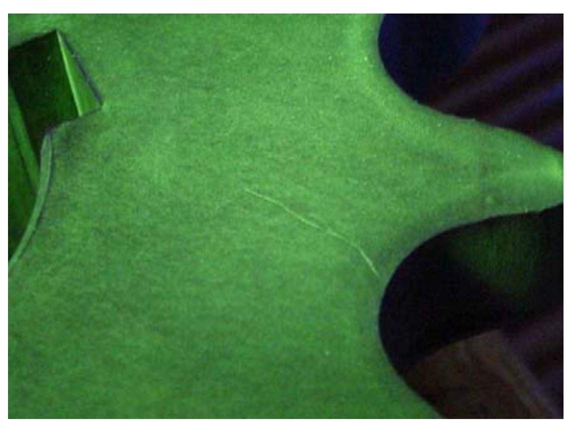
Gear with Service Induced Crack



Fluorescent, Wet Particle Method

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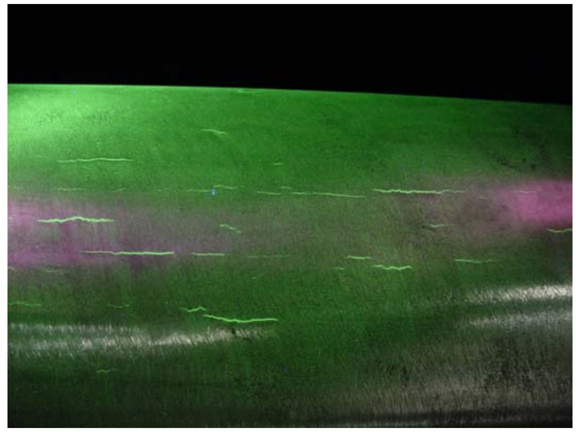
Drive Shaft with Heat Treatment Induced Cracks



Fluorescent, Wet Particle Method

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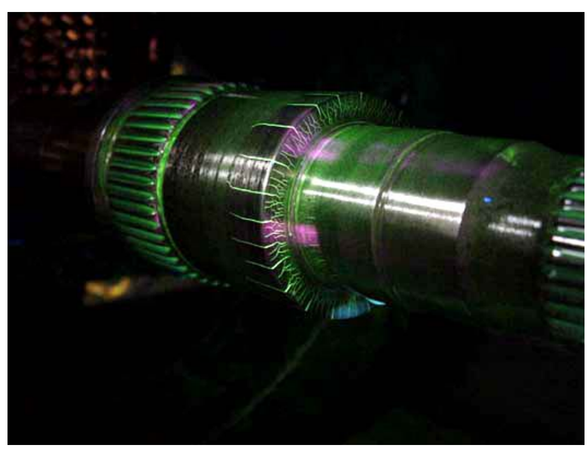
Splined Shaft with Service Induced Cracks



Fluorescent, Wet Particle Method

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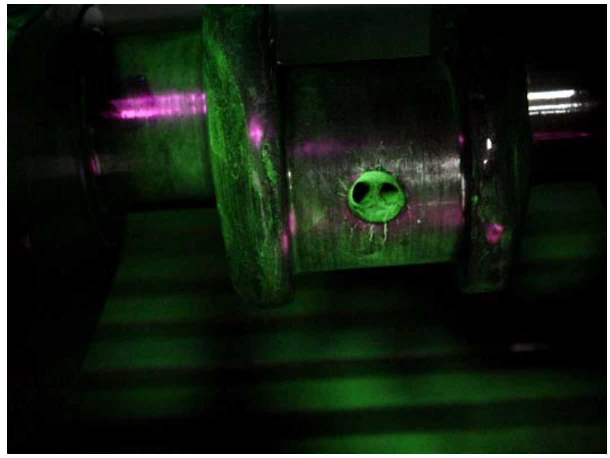
Threaded Shaft with Service Induced Crack

Fluorescent, Wet Particle Method

Large Bolt with Service Induced Crack

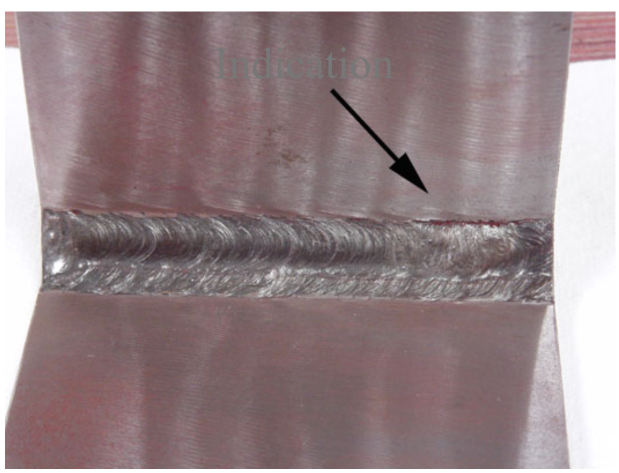
Fluorescent, Wet Particle Method

Crank Shaft with Service Induced Crack Near Lube Hole



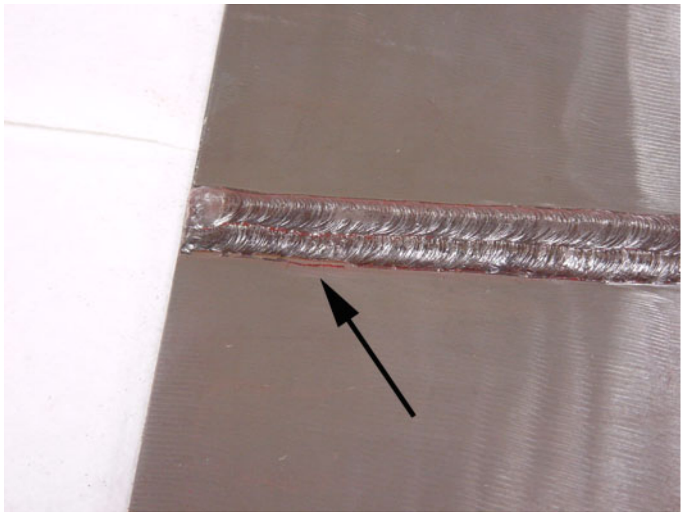
Fluorescent, Wet Particle Method

Lack of Fusion in SMAW Weld



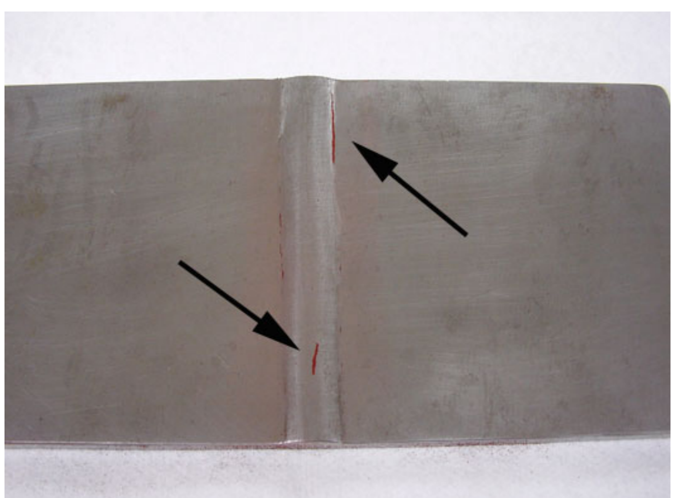
Visible, Dry Powder Method

Toe Crack in SMAW Weld



Visible, Dry Powder Method

Throat and Toe Cracks in Partially Ground Weld



Visible, Dry Powder Method

Demagnetization

- Parts inspected by the magnetic particle method may sometimes have an objectionable residual magnetic field that may interfere with subsequent manufacturing operations or service of the component.
- Possible reasons for demagnetization include:
  - May interfere with welding and/or machining operations
  - Can effect gauges that are sensitive to magnetic fields if placed in close proximity.
  - Abrasive particles may adhere to components surface and cause and increase in wear to engines components, gears, bearings etc.

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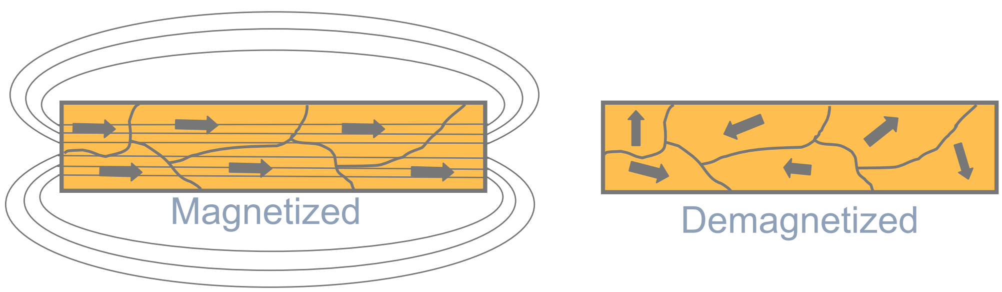
Demagnetization (Cont.)

- Demagnetization requires that the residual magnetic field is reversed and reduced by the inspector.
- This process will scramble the magnetic domains and reduce the strength of the residual field to an acceptable level.



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Advantages of Magnetic Particle Inspection

- Can detect both surface and VERY NEAR sub-surface defects.
- Can inspect parts with irregular shapes easily.
- Precleaning of components is not as critical as it is for some other inspection methods. Most contaminants within a flaw will not hinder flaw detectability.
- Fast method of inspection and indications are visible directly on the specimen surface.
- Considered low cost compared to many other NDT methods.
- Is a very portable inspection method especially when used with battery powered equipment.

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Limitations of Magnetic Particle Inspection

- Cannot inspect non-ferrous materials such as aluminum, magnesium or most stainless steels.
- Inspection of large parts may require use of equipment with special power requirements.
- Some parts may require removal of coating or plating to achieve desired inspection sensitivity.
- Limited subsurface discontinuity detection capabilities. Maximum depth sensitivity is approximately 0.6” (under ideal conditions).
- Post cleaning, and post demagnetization is often necessary.
- Alignment between magnetic flux and defect is important

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Glossary of Terms

- **Black Light:** ultraviolet light which is filtered to produce a wavelength of approximately 365 nanometers. Black light will cause certain materials to fluoresce.
- **Central conductor:** an electrically conductive bar usually made of copper used to introduce a circular magnetic field in to a test specimen.
- **Coil:** an electrical conductor such a copper wire or cable that is wrapped in several or many loops that are brought close to one another to form a strong longitudinal magnetic field.

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Glossary of Terms

- **Discontinuity:** an interruption in the structure of the material such as a crack.
- **Ferromagnetic:** a material such as iron, nickel and cobalt or one of it's alloys that is strongly attracted to a magnetic field.
- **Heads:** electrical contact pads on a wet horizontal magnetic particle inspection machine. The part to be inspected is clamped and held in place between the heads and shot of current is sent through the part from the heads to create a circular magnetic field in the part.
- **Leakage field:** a disruption in the magnetic field. This disruption must extend to the surface of the part for particles to be attracted.

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Glossary of Terms

- **Non-relevant indications:** indications produced due to some intended design feature of a specimen such a keyways, splines or press fits.
- **Prods:** two electrodes usually made of copper or aluminum that are used to introduce current in to a test part. This current in turn creates a circular magnetic field where each prod touches the part. (Similar in principal to a welding electrode and ground clamp).
- **Relevant indications:** indications produced from something other than a design feature of a test specimen. Cracks, stringers, or laps are examples of relevant indications.

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Glossary of Terms

- **Suspension:** a bath created by mixing particles with either oil or water.
- **Yoke:** a horseshoe magnet used to create a longitudinal magnetic field. Yokes may be made from permanent magnets or electromagnets.

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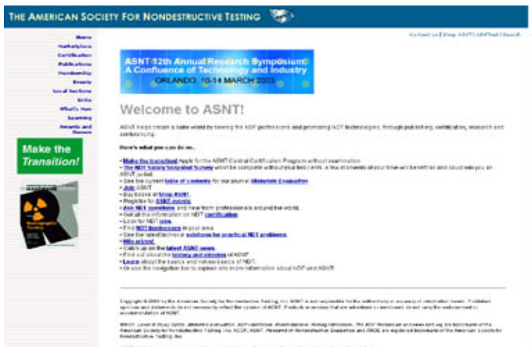
For More Information

The Collaboration for NDT Education

www.ndt-ed.org



The American Society for Nondestructive Testing

www.asnt.org

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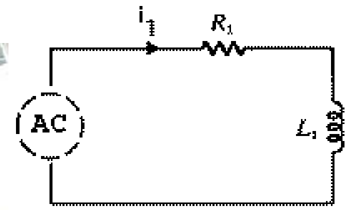
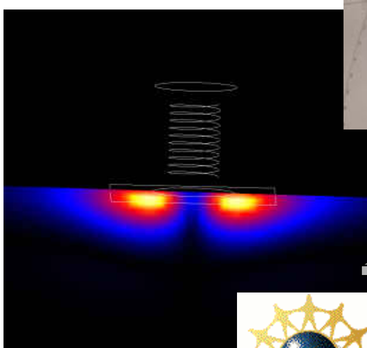
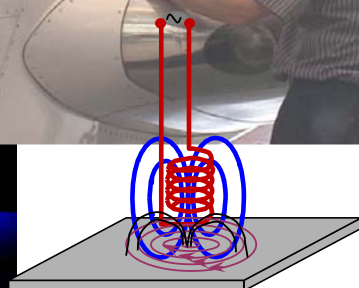
Eddy Current Testing

Eddy Current Testing







Prepared by the Collaboration for NDT Education.
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Introduction

- This module is intended to present information on the NDT method of eddy current inspection.
- Eddy current inspection is one of several methods that use the principal of "electromagnetism" as the basis for conducting examinations. Several other methods such as Remote Field Testing (RFT), Flux Leakage and Barkhausen Noise also use this principle.

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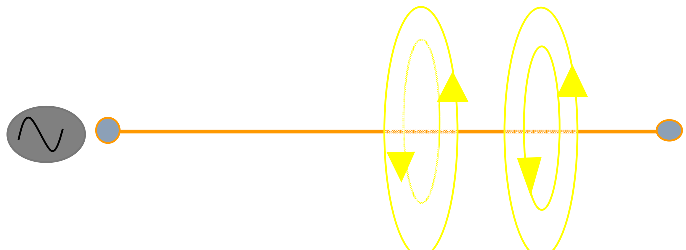
Outline

- Electromagnetic induction
- Generation of eddy currents
- Inspection applications
- Equipment utilized in eddy current inspection
  - Probes/Coils
  - Instrumentation
  - Reference standard
- Advantages and Limitations
- Glossary of Terms

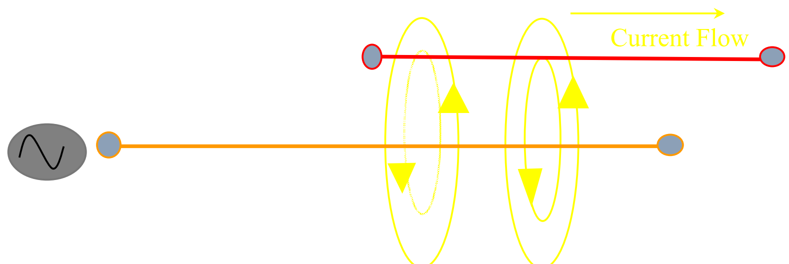
Electromagnetic Induction

- Eddy currents are created through a process called electromagnetic induction.
- When alternating current is applied to the conductor, such as copper wire, a magnetic field develops in and around the conductor.
- This magnetic field expands as the alternating current rises to maximum and collapses as the current is reduced to zero.



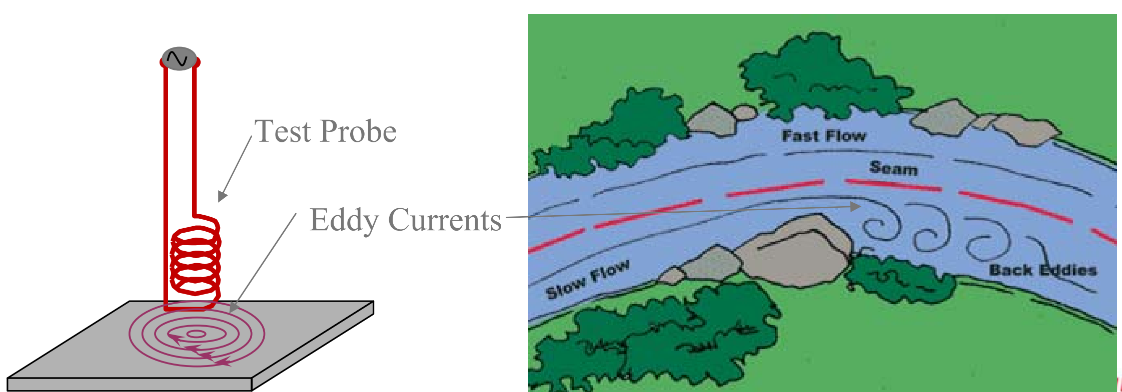
Electromagnetic Induction (cont.)

If another electrical conductor is brought into the proximity of this changing magnetic field, the reverse effect will occur. Magnetic field cutting through the second conductor will cause an "induced" current to flow in this second conductor. Eddy currents are a form of induced currents!



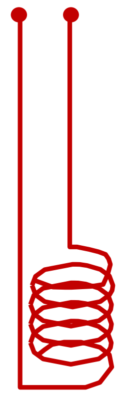
Generation of Eddy Currents

Eddy currents are induced electrical currents that flow in a circular path. They get their name from "eddies" that are formed when a liquid or gas flows in a circular path around obstacles when conditions are right.



Generation of Eddy Currents **(cont.)**

In order to generate eddy currents for an inspection a "probe" is used. Inside the probe is a length of electrical conductor which is formed into a coil.



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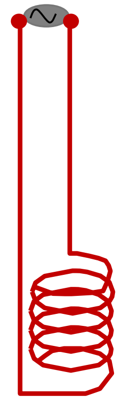
Generation of Eddy Currents **(cont.)**

Alternating current is allowed to flow in the coil at a frequency chosen by the technician for the type of test involved.



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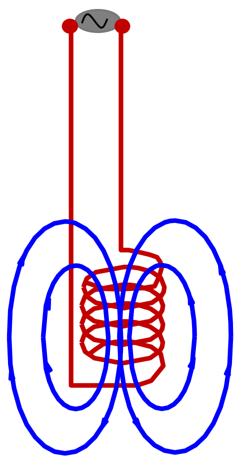
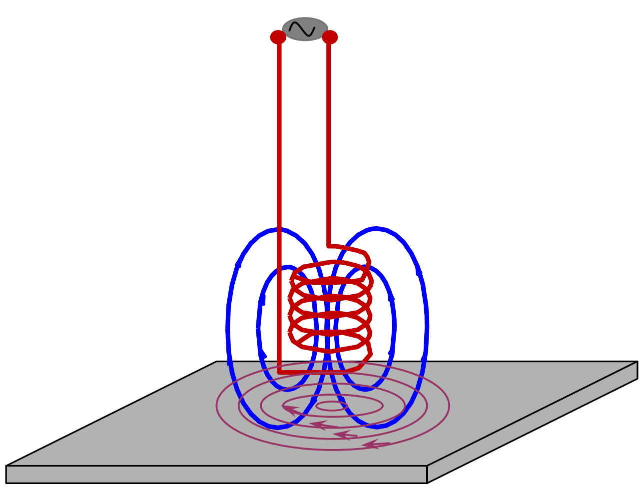
Generation of Eddy Currents **(cont.)**

A dynamic expanding and collapsing magnetic field forms in and around the coil as the alternating current flows through the coil.



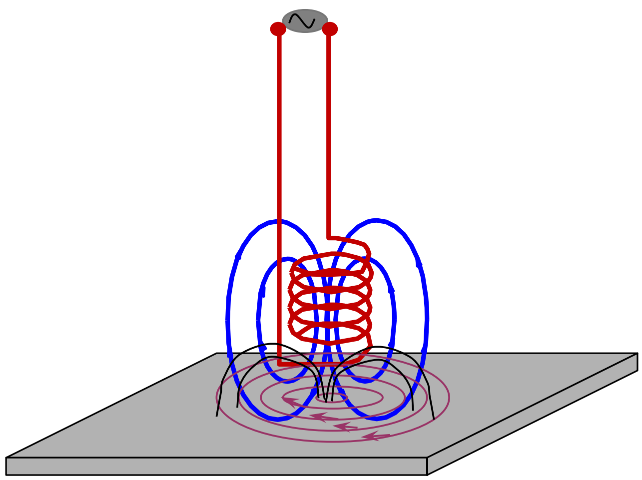
Generation of Eddy Currents **(cont.)**

When an electrically conductive material is placed in the coil's dynamic magnetic field electromagnetic, induction will occur and eddy currents will be induced in the material.



Generation of Eddy Currents **(cont.)**

Eddy currents flowing in the material will generate their own "secondary" magnetic field which will oppose the coil's "primary" magnetic field.



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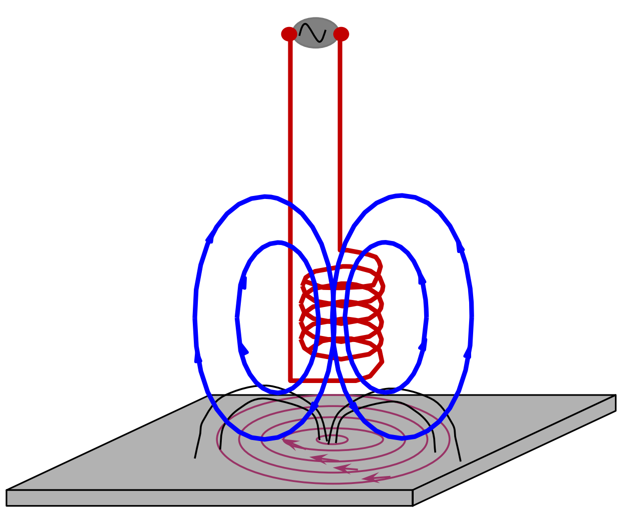
Generation of Eddy Currents **(cont.)**

This entire electromagnetic induction process to produce eddy currents may occur from several hundred to several million times each second depending upon inspection frequency.



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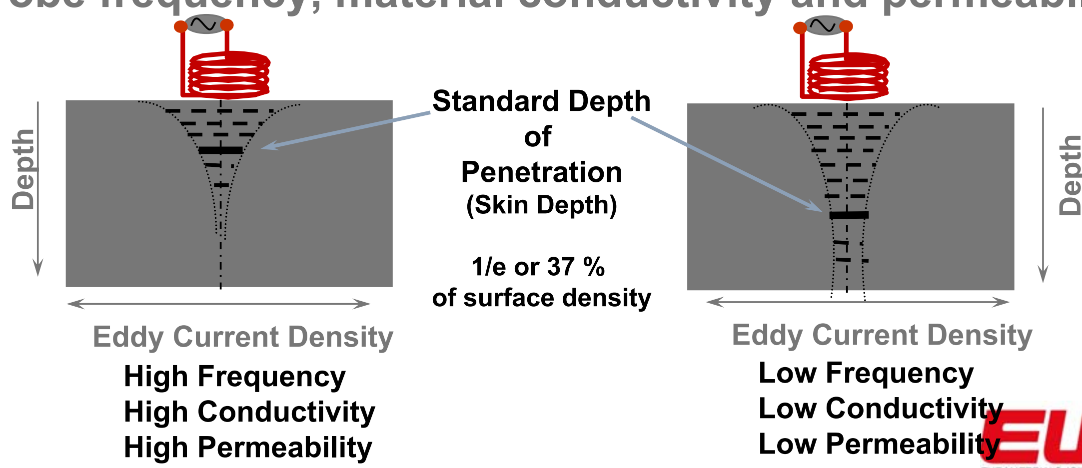
Generation of Eddy Currents (cont.)

Eddy currents are strongest at the surface of the material and decrease in strength below the surface. The depth that the eddy currents are only 37% as strong as they are on the surface is known as the standard depth of penetration or skin depth. This depth changes with probe frequency, material conductivity and permeability.



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Inspection Data

- There are three characteristics of the specimen that affect the strength of the induced eddy currents.
  - The electrical conductivity of the material
  - The magnetic permeability of the material
  - The amount of solid material in the vicinity of the test coil.
- Information about the strength of the eddy currents within the specimen is determined by monitoring changes in voltage and/or current that occur in the coil.
- The strength of the eddy currents changes the electrical impedance (Z) of the coil.

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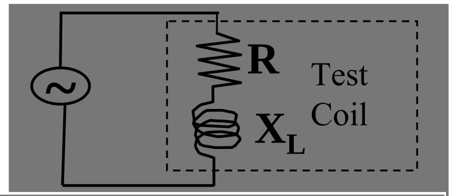
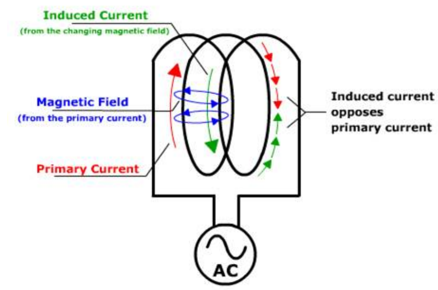
Inspection Data (cont.)

Impedance (Z) in an eddy current coil is the total opposition to current flow. In a coil, Z is made up of resistance (R) and inductive reactance (XL).



Definitions:

- **Resistance - The opposition of current flow, resulting in a change of electrical energy into heat or another form of energy.**
- **Inductive Reactance (X_L) - Resistance to AC current flow resulting from electromagnetic induction in the coil.**
- **Impedance (Z) - The combined opposition to current flow resulting from inductive reactance and resistance.**



In an AC coil, induction from the magnetic field of one loop of the coil causes a secondary current in all other loops. The secondary current opposes the primary current.

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Inspection Applications

One of the major advantages of eddy current as an NDT tool is the variety of inspections that can be performed. The following slides depict some of the these capabilities.

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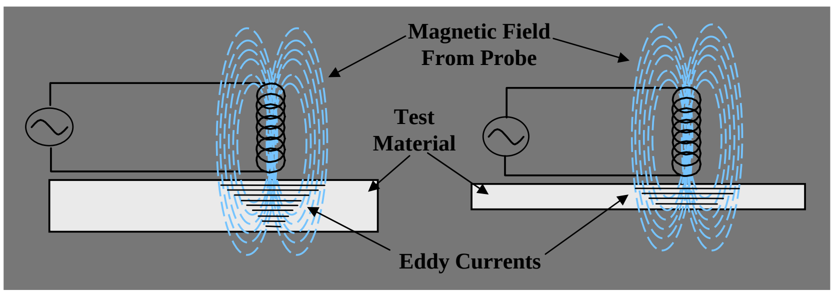
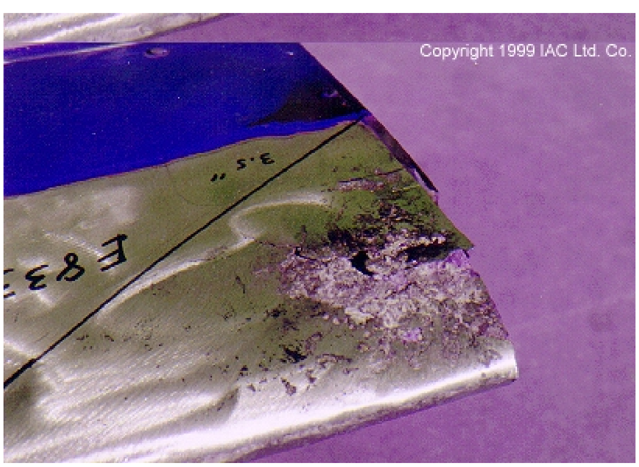
Material Thickness Measurement

- Thickness measurements are possible with eddy current inspection within certain limitations.
- Only a certain amount of eddy currents can form in a given volume of material.
- Therefore, thicker materials will support more eddy currents than thinner materials.
- The strength (amount) of eddy currents can be measured and related to the material thickness.



Material Thickness Measurement (cont.)

Eddy current inspection is often used in the aviation industries to detect material loss due to corrosion and erosion.



Material Thickness Measurement (cont.)

Eddy current inspection is used extensively to inspect tubing at power generation and petrochemical facilities for corrosion and erosion.

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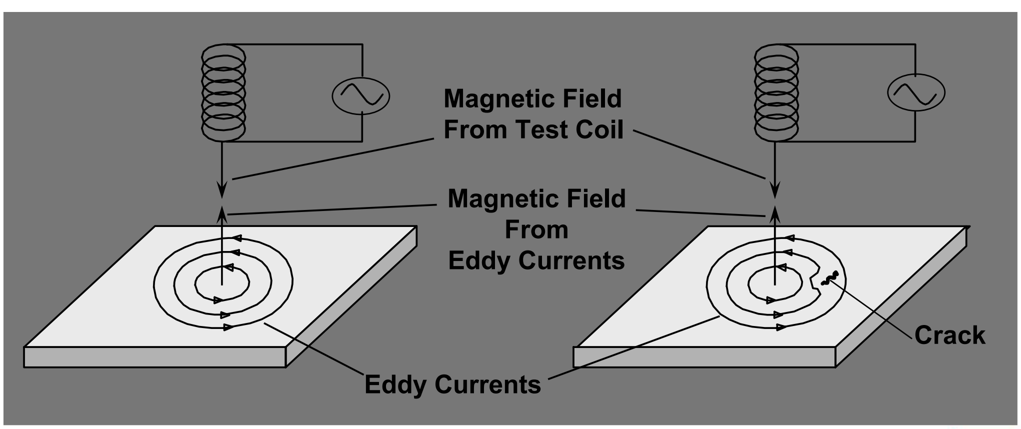
Crack Detection

Crack detection is one of the primary uses of eddy current inspection. Cracks cause a disruption in the circular flow patterns of the eddy currents and weaken their strength. This change in strength at the crack location can be detected.



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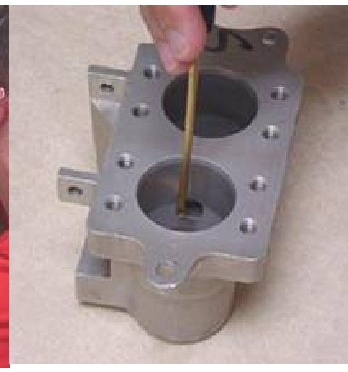
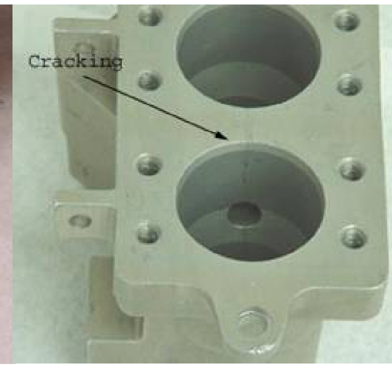
Crack Detection (cont.)

Eddy current inspection is exceptionally well suited for the detection of cracks, with an especially high sensitivity to detection of surface breaking cracks.

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Crack Detection (cont.)

Eddy current inspection of "bead seat" area on aircraft wheel for cracks using special probe that conforms to the shape of the rim.


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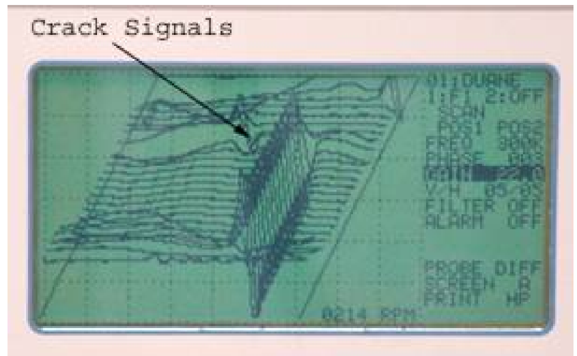
Crack Detection (cont.)

Loading points, such as fastener holes, are high stress areas and often the site of service induced fatigue cracking. Rotating probe guns can be used to inspect a large number of holes in a short period of time. The photo on the right is a waterfall plot of the cross section of a fastener hole. Each horizontal line represents one rotation of the probe gun. A vertical signal indicates a crack.



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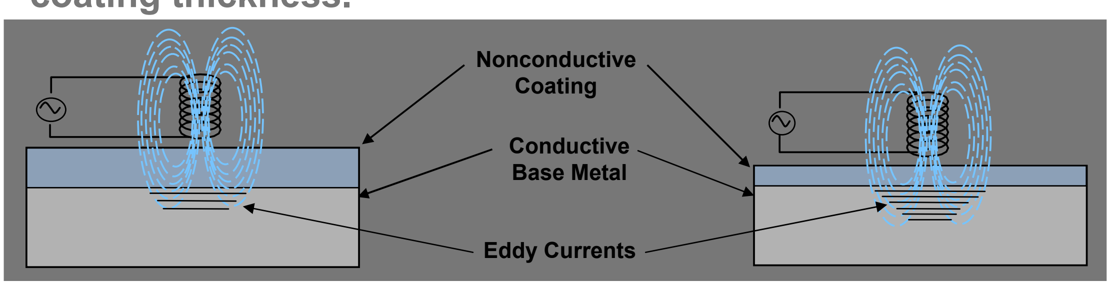
Nonconductive Coating Measurement

Nonconductive coatings on electrically conductive substrates can be measured very accurately with eddy current inspection. (Accuracy of less that one mil is not uncommon.)

- The coating displaces the eddy current probe from the conductive base material and this weaken the strength of the eddy currents.
- This reduction in strength can be measured and related to coating thickness.



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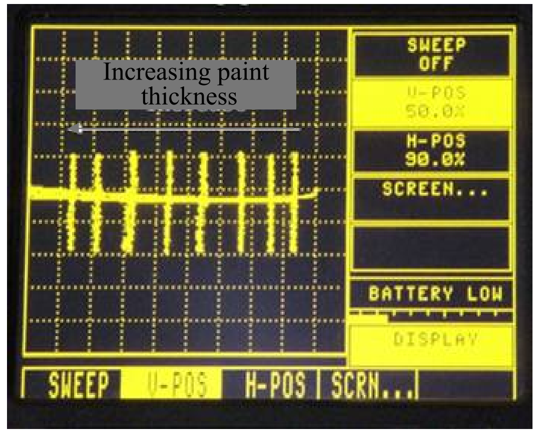
Nonconductive Coating Measurement (cont.)

The photo to the left shows an aircraft panel paint thickness inspection. On the right, the display of a digital eddy current inspection instrument shows the different signals obtained by measuring eight different thicknesses of paint on aluminum.



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Monitoring Conductivity and Permeability Variations

Eddy current inspection is sensitive to changes in a material's electrical conductivity and magnetic permeability. This "sensitivity" allows the inspection method to be used for such inspection procedures as:

- **Material Identification**
- **Material Sorting**
- **Determination of heat damage**
- **Cladding and plating thickness measurement**
- **Case depth determination**
- **Heat treatment monitoring**

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Conductivity Measurements

Boeing employees in Philadelphia were given the privilege of evaluating the Liberty Bell for damage using NDT techniques. Eddy current methods were used to measure the electrical conductivity of the Bell's bronze casing at a various points to evaluate its uniformity.

Equipment

- Equipment for eddy current inspection is very diversified. Proper equipment selection is important if accurate inspection data is desired for a particular application.
- As a minimum, at least three basic pieces of equipment are needed for any eddy current examination:
  - Instrumentation
  - Probes
  - Reference Standards

Instrumentation - Meters

Meters are typically the simplest form of eddy current instrumentation.

The two general categories of meters are digital and analog.

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Digital Meters

Digital meters are typically designed to examine one specific attribute of a test component such as conductivity or nonconductive coating thickness. These meters tend to have slightly higher accuracy than analog devices.

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Analog Meters

Analog meters can be used for many different inspection applications such as crack detection, material thickness measurements, nonconductive coating measurements or conductive coating measurements.

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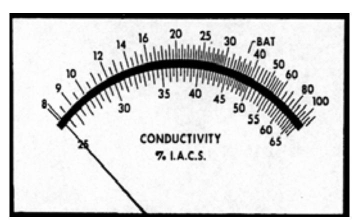
Analog Meters (cont.)

The display read-out found on most analog instruments is typically either a calibrated or uncalibrated display.

- Calibrated displays have an inherent scaling factor which correlates to the property the instrument is designed to measure such as conductivity.



- Uncalibrated displays are typically more flexible in the variety of different tests they can perform. These types of instruments, however, require the use of data extrapolation techniques if quantitative data is desired.

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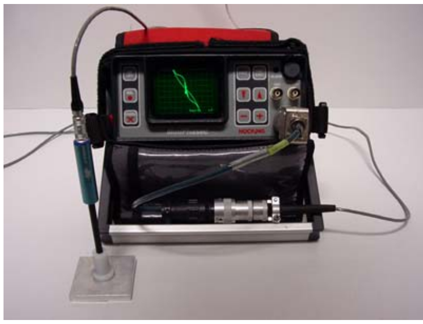
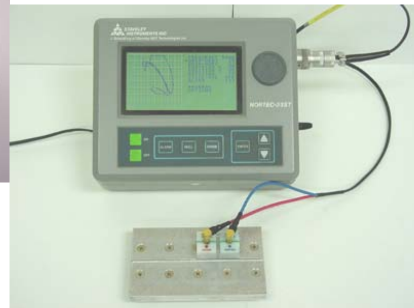
Portable Eddy Scopes

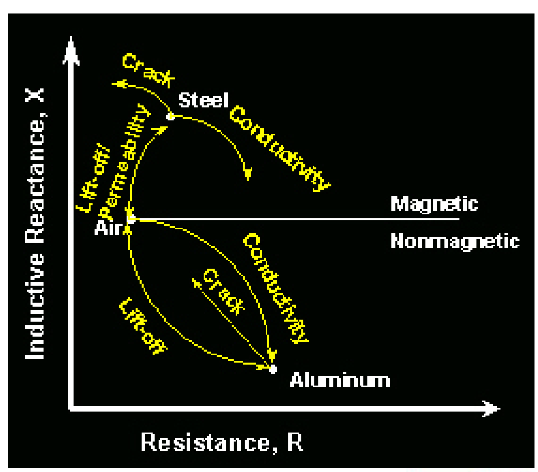




Portable Eddy Scopes (cont.)

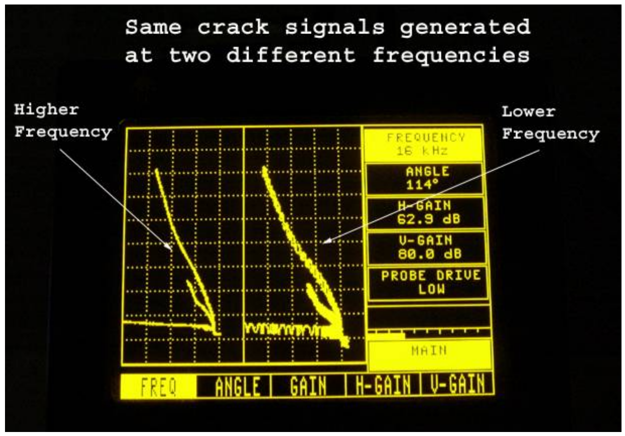
Portable eddy scopes are another category of instrumentation and they present the inspection data in the form of an impedance plane diagram.

- On the impedance diagram, the total impedance is displayed by plotting its resistance component and inductive reactance component at 90 degrees to each other.
- This is beneficial for both separation and identification of test variables that can effect inspection results.



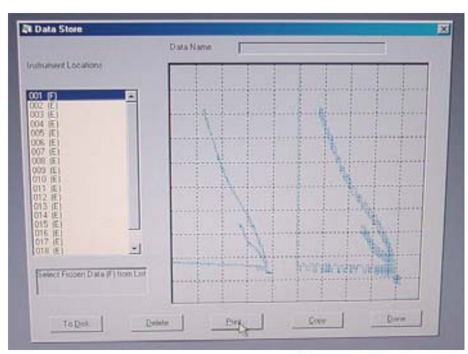
Portable Eddy Scopes (cont.)

Modern eddy scopes are usually digital based instruments which can often be purchased as either a single or dual frequency tester. Dual frequency instruments are capable of sequentially driving a probe at two different inspection frequencies.

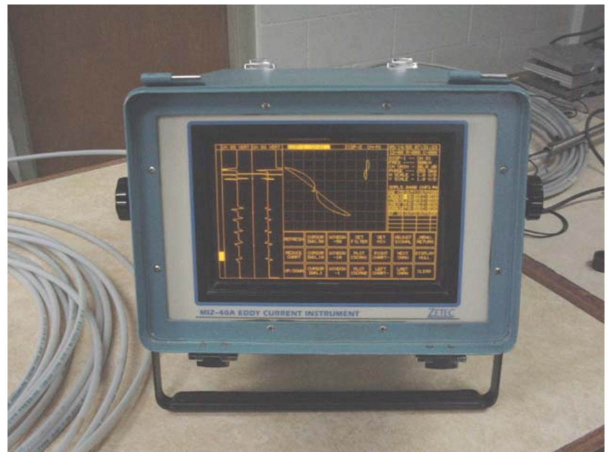


Portable Eddy Scopes (cont.)

Digital scopes often have an RS232 (serial) connection for interfacing with a serial printer or computer as well as provisions for output of signals to recording devices such as a strip-chart recorder. In addition, these instruments contain a small amount of RAM so that equipment settings as well as screen presentations can be stored for later reference.



Multi-Frequency Eddy Current Instruments



Multi-Frequency Eddy Current Instruments (cont.)

- **Multi-Frequency instruments usually refer to equipment that can drive inspection coils at more than two frequencies either sequentially (multiplexing) or simultaneously.**

- **This type of instrumentation is used extensively for tubing inspection in the power generation, chemical and petrochemical industries.**

- **These instruments are often capable of being computer networked and may have as many as four probes attached to them at one time.**

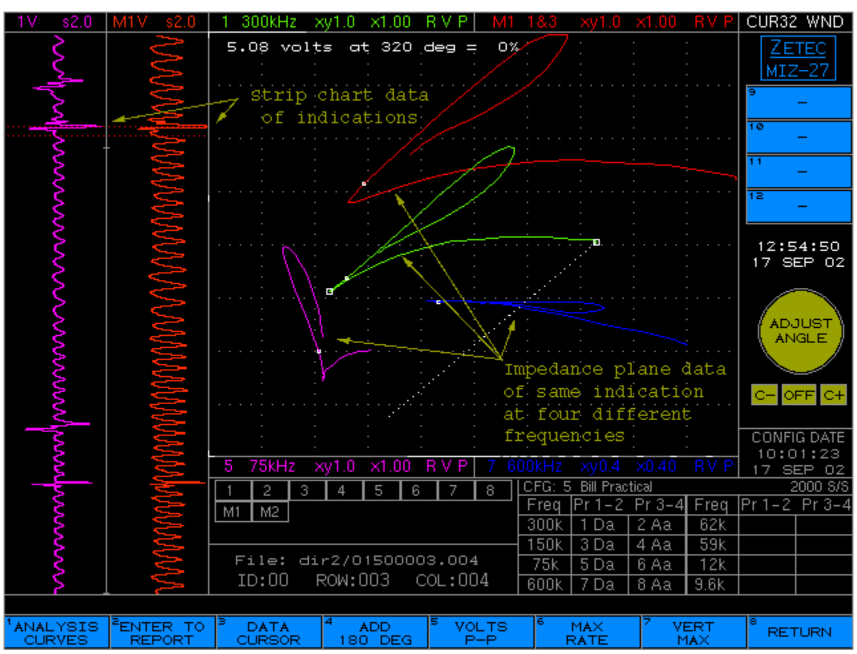
Multi-Frequency Eddy Current Instruments (cont.)

Advantages of Multi-frequency inspections:

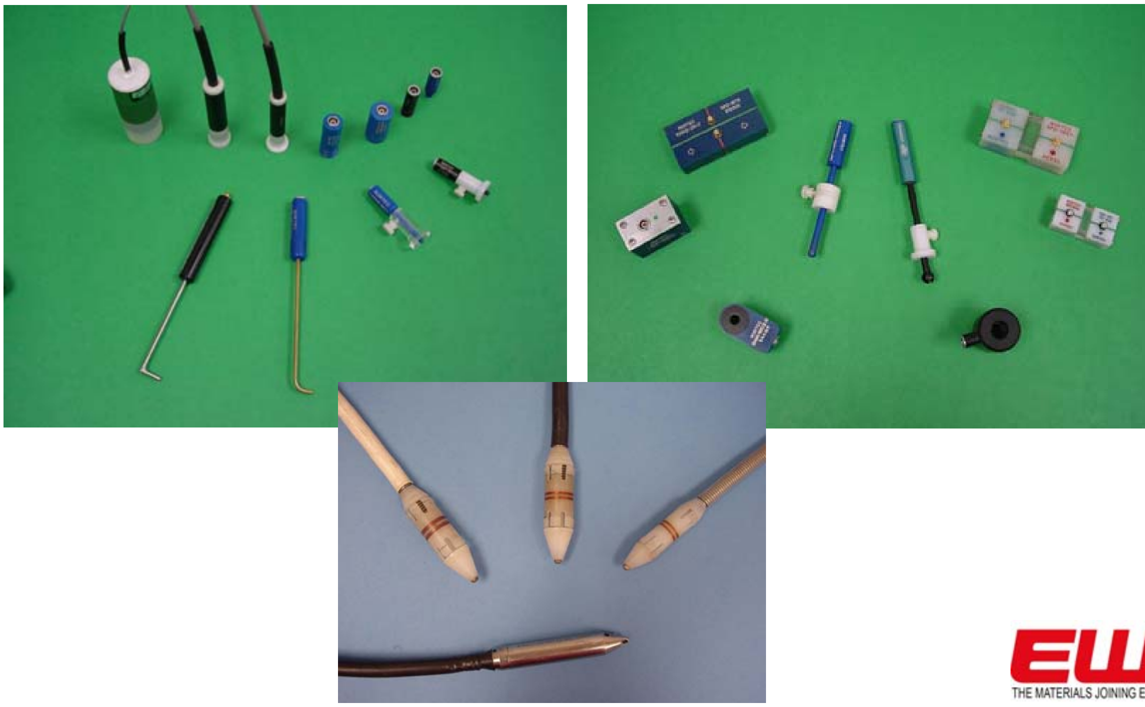
- Allows increased inspection information to be collected from one probe pulling.
- Provides for comparison of same discontinuity signal at different frequencies.
- Allows mixing of frequencies which helps to reduce or eliminate sources of noise.
- Often improves detection, interpretation and sizing capabilities of discontinuities.

Multi-Frequency Eddy Current Instruments (cont.)

Screen of multi-frequency instrument during inspection.



Eddy Current Probes



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Eddy Current Probes (cont.)

- Probes selection is critical to acquiring adequate inspection data.
- Several factors to consider include:
  - Material penetration requirements (surface vs. subsurface)
  - Sensitivity requirements
  - Type of probe connections on eddy current instrument (many variations)
  - Probe and instrument impedance matching (will probe work with instrument)
  - Probe size (smaller probes penetrate less)
  - Probe type (absolute, differential, reflection or hybrid)

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Eddy Current Probes (cont.)

- Due the the large variety of probes in eddy current testing there are many different systems of classification.
- Three of the most common classifications are:
  - Surface probes
  - Inside Diameter (I.D.) or Bobbin Probes
  - Outside Diameter (O.D.) or Encircling probes

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Eddy Current Probes (cont.)

Surface probes are coils that are typically mounted close to one end of a plastic housing. As the name implies, the technician moves the coil end of the probe over the surface of the test component.

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Eddy Current Probes (cont.)

Some surface probes are specifically designed for crack detection of fastener holes. These include sliding probes, ring probes and hole probes.

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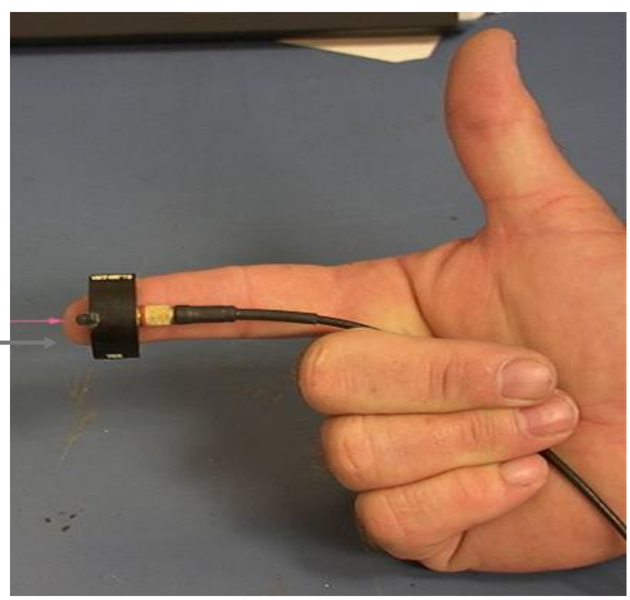
Eddy Current Probes (cont.)

Surface probes can be very small in size to allow accessibility to confined areas.

Finger Probe



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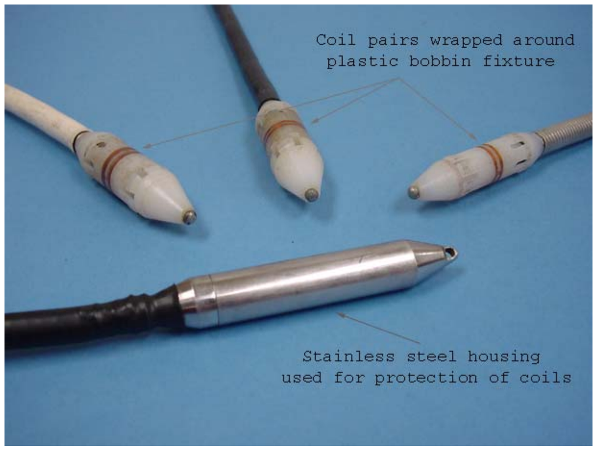
Eddy Current Probes (cont.)

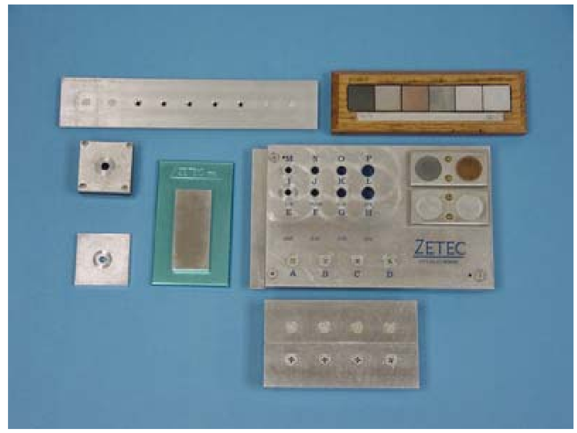
Inside Diameter (I.D.) probes, also known as bobbin probes, are coils that are usually wound circumferentially around a plastic housing. These probes are primarily designed for inspection inside of tubular materials.



Eddy Current Probes (cont.)

Outside Diameter (O.D.) probes are coils that are wound the circumference of a hollow fixture. The coil is designed such that the test part is ran through the middle of the coil. These probes can be used to inspect bars, rods as well as tubes.

Reference Standards



Reference Standards (cont.)

- In order to give the eddy current inspector useful data while conducting an inspection, signals generated from the test specimen must be compared with known values.
- Reference standards are typically manufactured from the same or very similar material as the test specimen.
- Many different types of standards exist for due to the variety of eddy current inspections performed.
- The following slides provide examples of specific types of standards.

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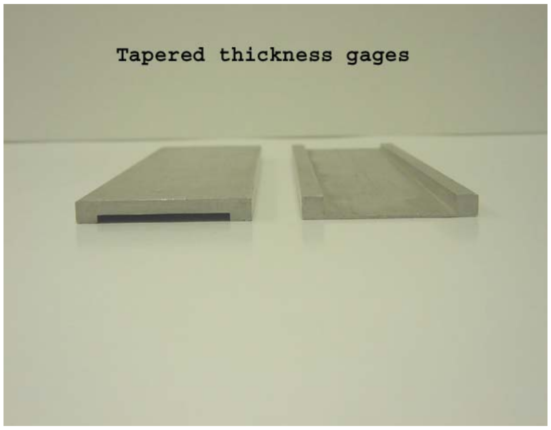
Reference Standards (cont.)

Material thickness standards used to help determine such things as material thinning caused by corrosion or erosion.



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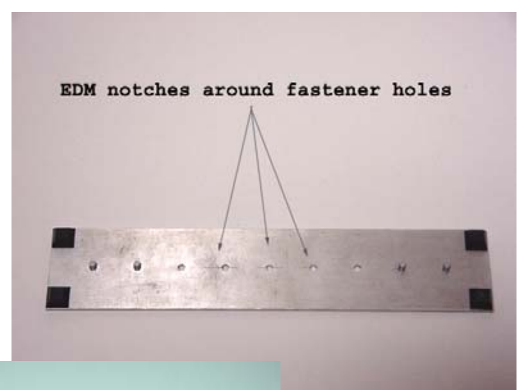
Reference Standards (cont.)

Crack Standards:



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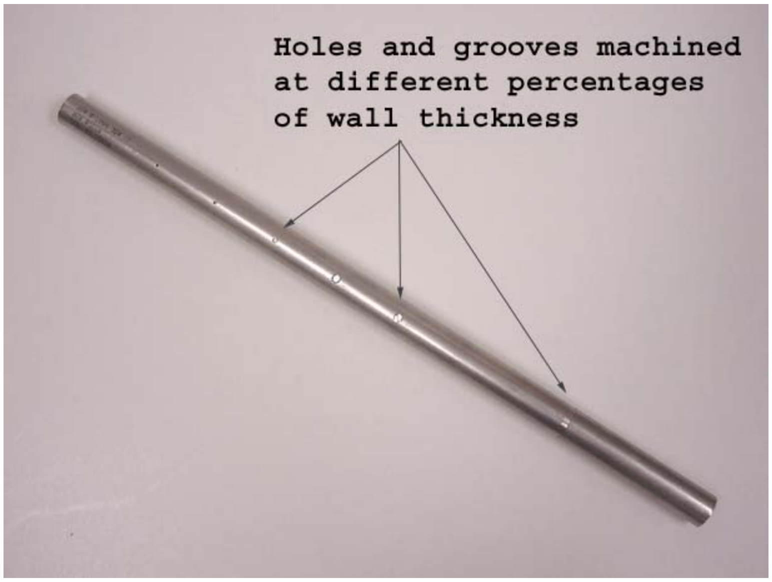
Reference Standards (cont.)

ASME Tubing Pit Standard:



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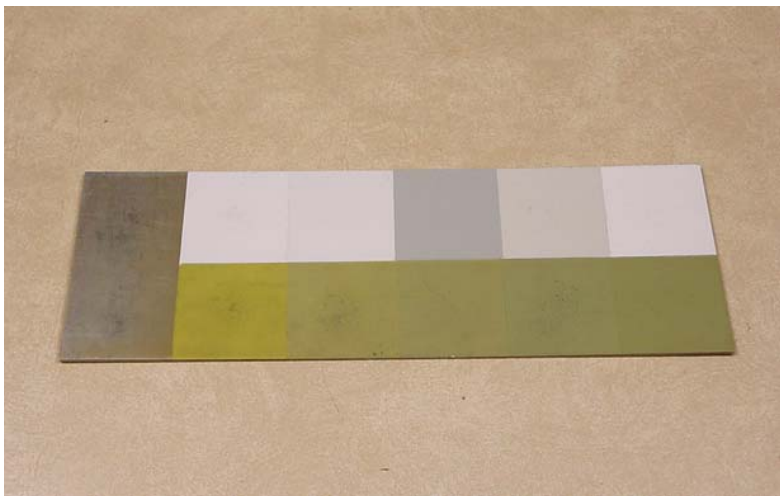
Reference Standards (cont.)

Nonconductive coating (paint) standard with various thickness of paint on aluminum substrate.



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Advantages of Eddy Current Inspection

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

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Limitations of Eddy Current Inspection

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

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Glossary of Terms

- **Alternating Current**: electrical current that regularly reverses direction.
- **Analog**: being or relating to a mechanism in which data is represented by continuously variable physical quantities such as a watch with hour and minute hands.
- **ASME**: acronym for American Society of Mechanical Engineers. This society is highly involved in establishing and maintaining industrial standards.

THE MATERIALS JOINING EXPERTS

Glossary of Terms

- **CRT**: acronym for Cathode Ray Tube. Vacuum tube that uses one or more electron guns for generating an image.
- **Calibration**: adjustment of a test systems response using known values so that unknown quantities may be derived.
- **Conductor**: material capable of allowing electrical current to flow through it.
- **Discontinuity**: an interruption in the physical structure of a part. Cracks are examples of discontinuities.
- **EDM**: acronym for Electrical Discharge Machine.

THE MATERIALS JOINING EXPERTS

Glossary of Terms

- **EDM**: acronym for Electrical Discharge Machine. Machining technique which uses an electrode and electrical current to remove metal. Sometimes used to prepare calibration standards for eddy current testing.
- **Electromagnetic Induction**: process which creates electrical current flow when a dynamic magnetic field is brought into close proximity with an electrical conductor.
- **Extrapolation**: to project or predict unknown values from know quantities.

THE MATERIALS JOINING EXPERTS

Glossary of Terms

- **I.A.C.S.**: acronym for International Annealed Copper Standard. Standard unit of measurement of electrical conductivity in eddy current testing with pure annealed copper as the standard, measuring 100% at 20 degrees Celsius.
- **Impedance Plane Diagram**: A diagram that depicts the changes in electrical impedance that occur in an eddy current coil as test variables change.
- **Multiplexing**: use of a time sharing system in which a coil is stimulated at several different frequencies one after another for a certain amount of time. Results from each stimulation can then be processed and displayed.

THE MATERIALS JOINING EXPERTS

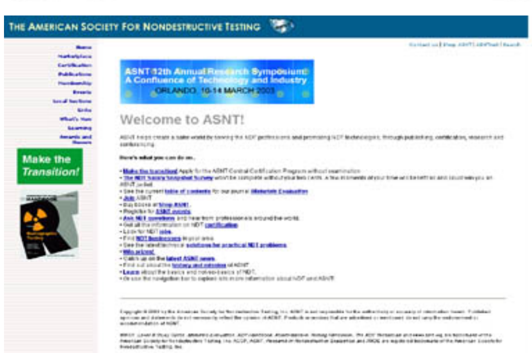
Glossary of Terms

- **Permeability**: the ease with which a material can be magnetized.
- **Probe**: common term used in eddy current inspection that refers to the test coil.
- **RAM**: acronym for Random Access Memory. Most modern eddy current instruments have some form of memory used as a data buffer to store information.

For More Information

The Collaboration for NDT Education

www.ndt-ed.org



The American Society for Nondestructive Testing

www.asnt.org

AUT Data Interpretation

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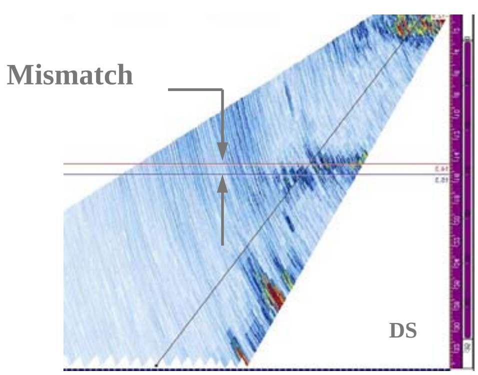
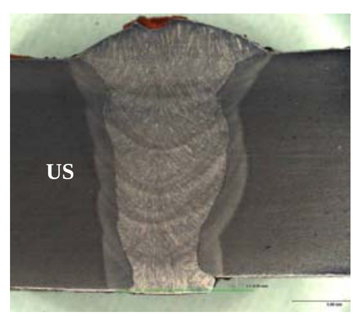
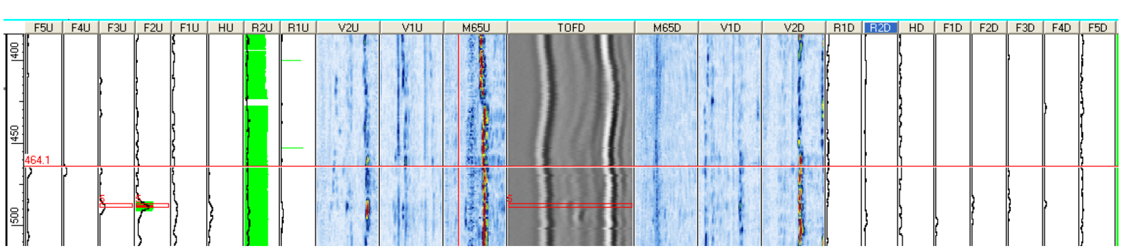
Root Mismatch







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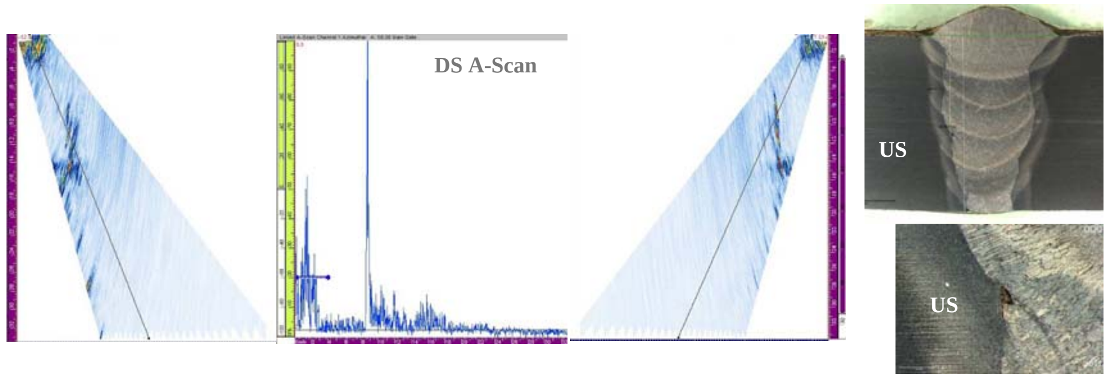

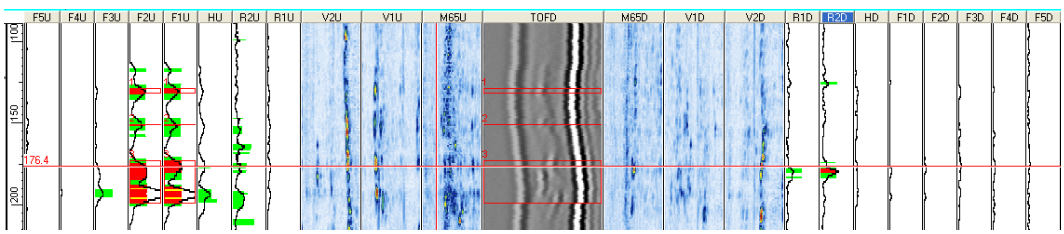

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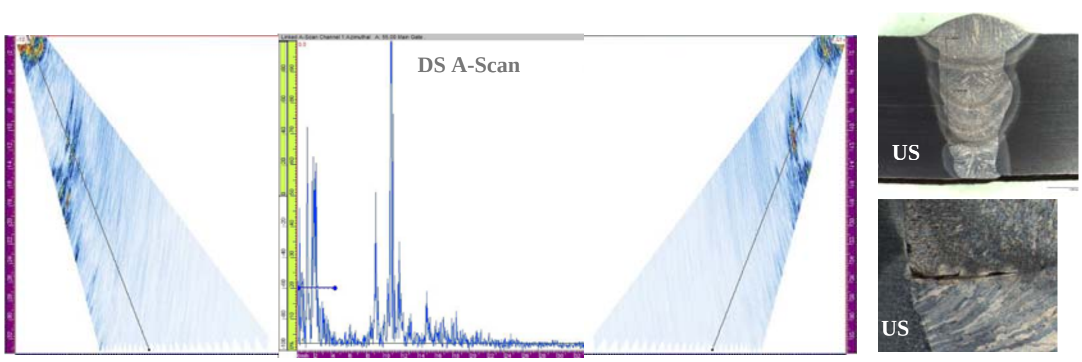

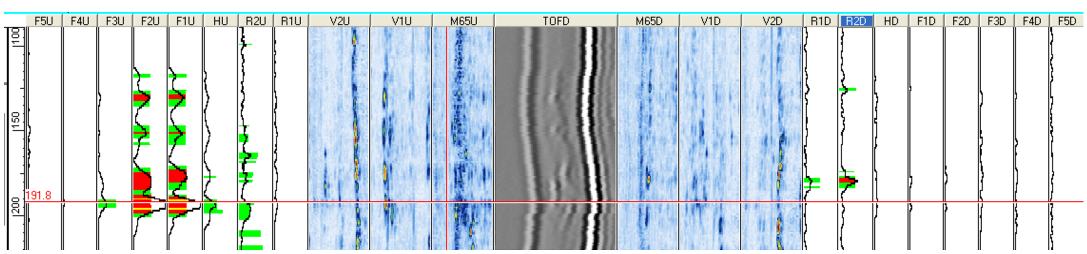

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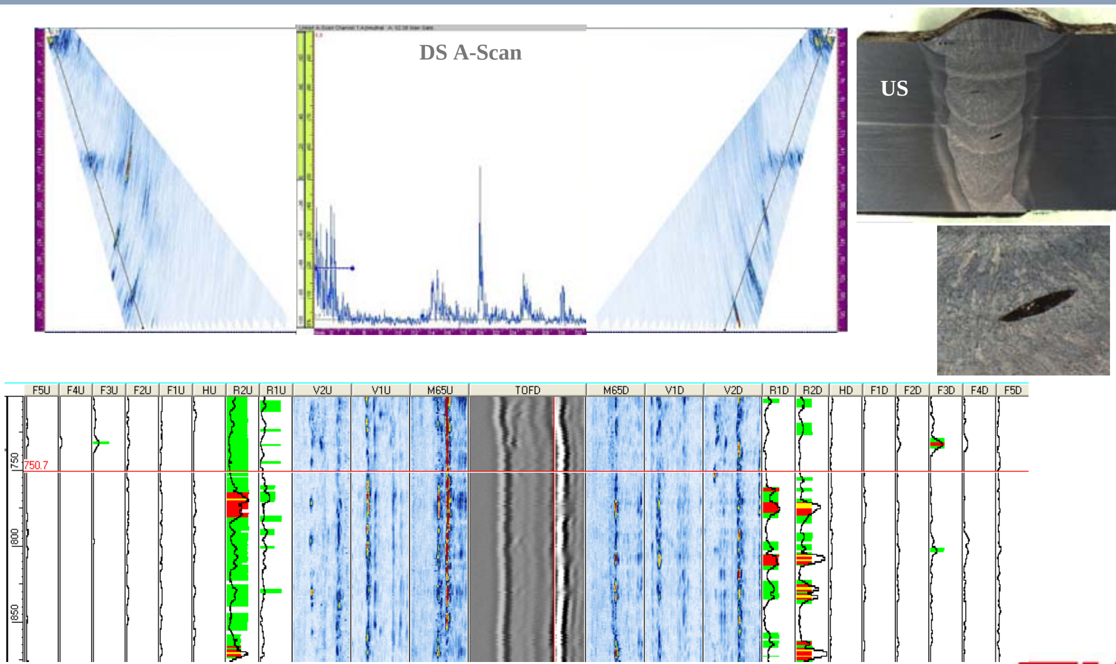

THE MATERIALS JOINING EXPERTS

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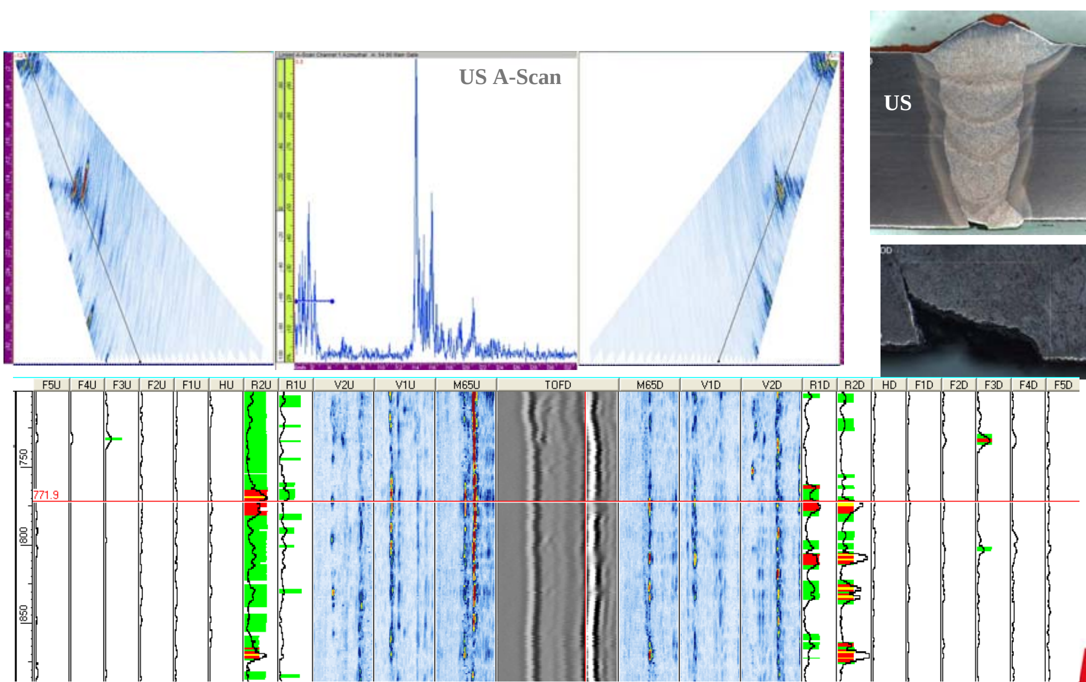

THE MATERIALS JOINING EXPERTS

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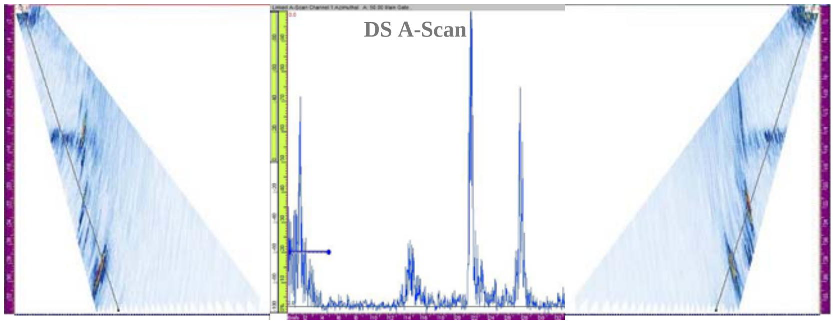

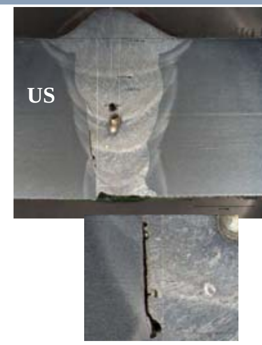

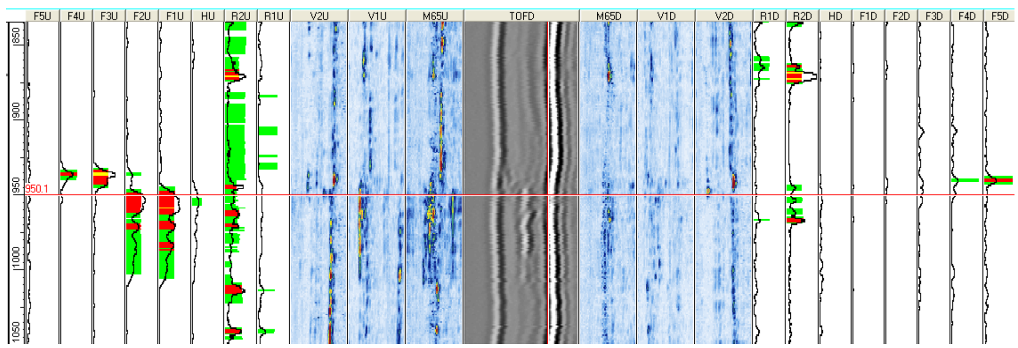

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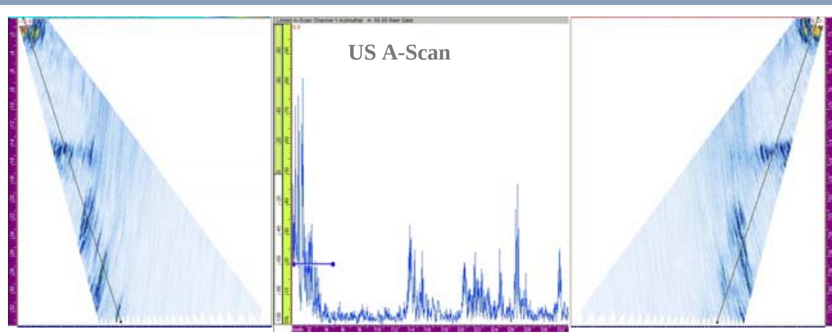

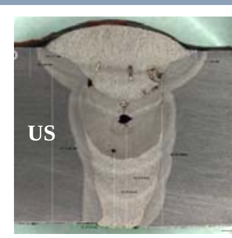

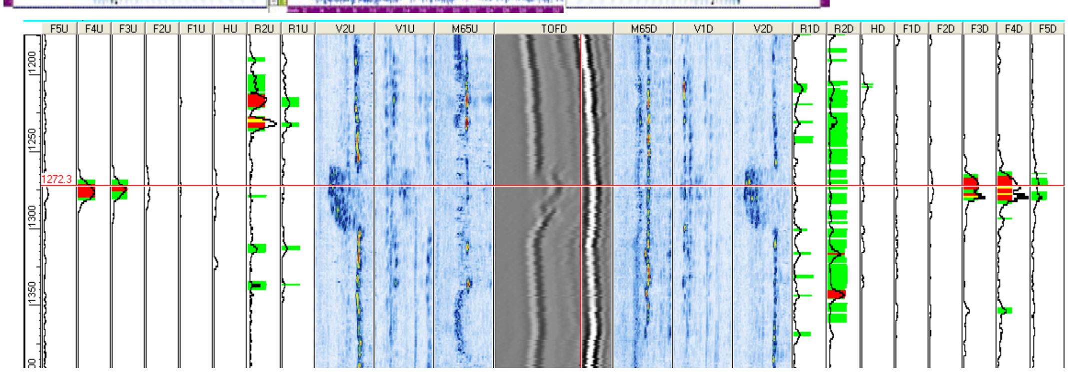

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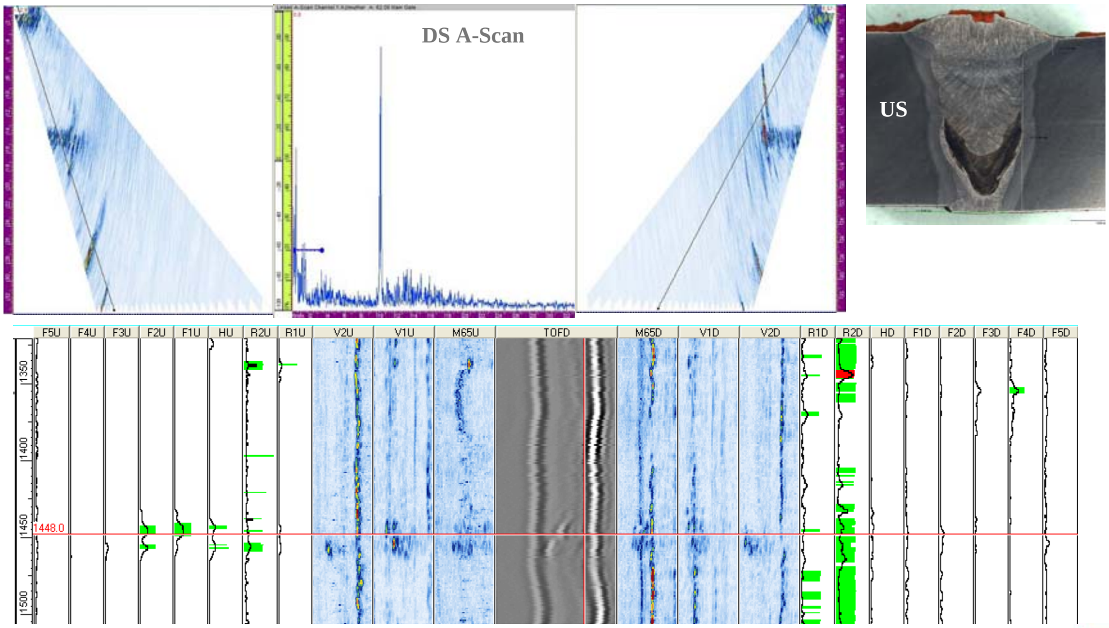

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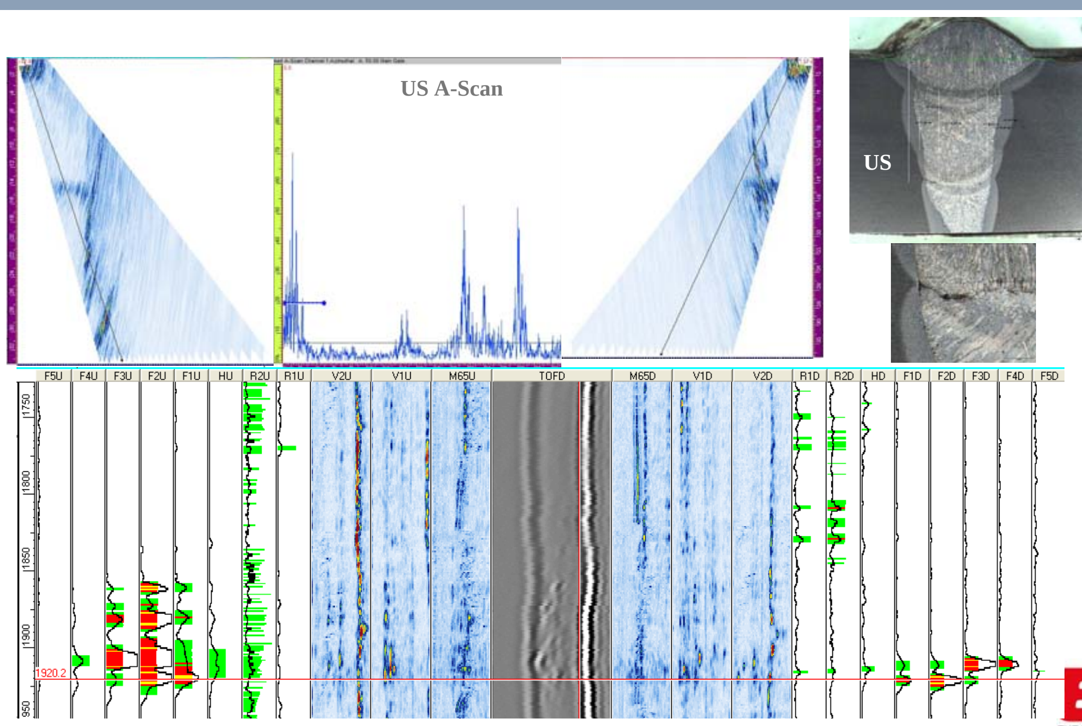
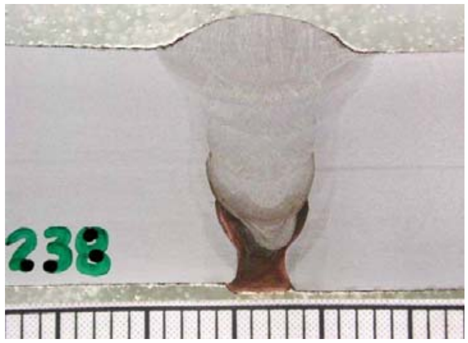
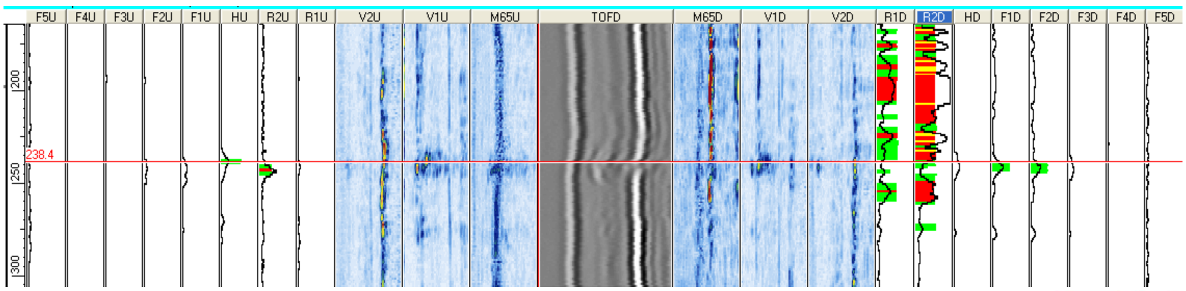


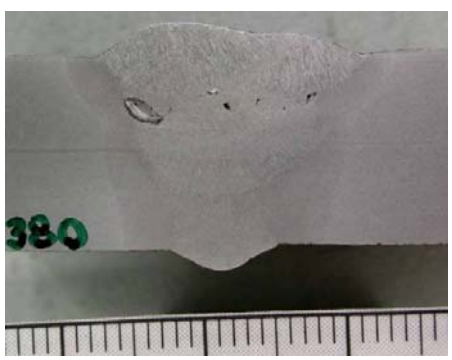
Location W3-238

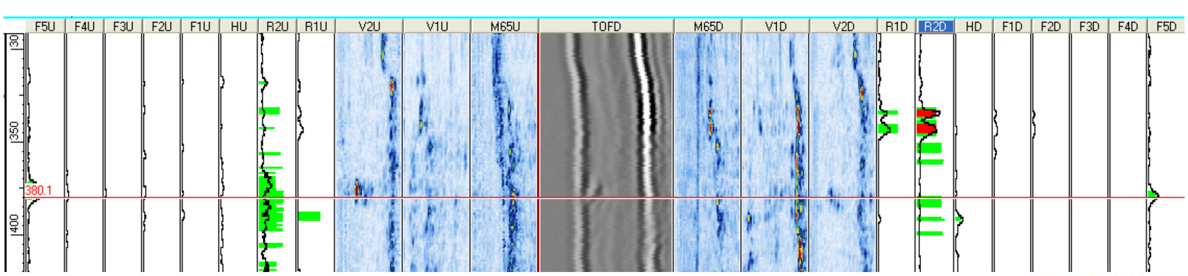




THE MATERIALS JOINING EXPERTS

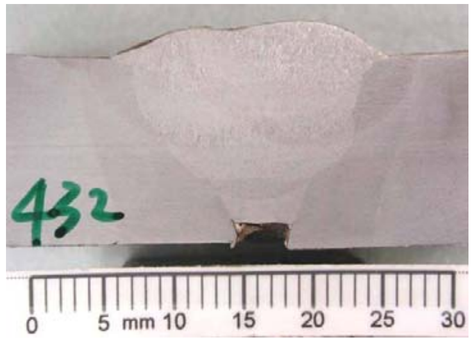
Location W3-380

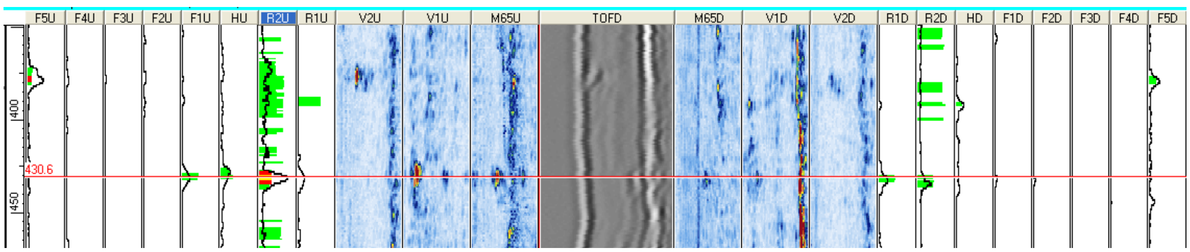




THE MATERIALS JOINING EXPERTS

Location W3-430





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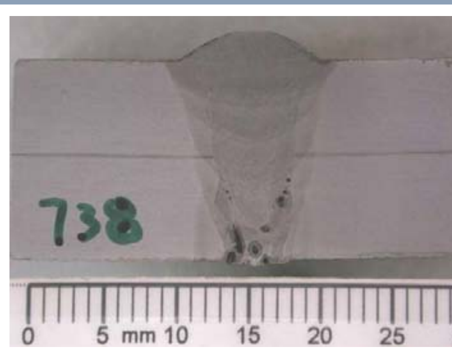

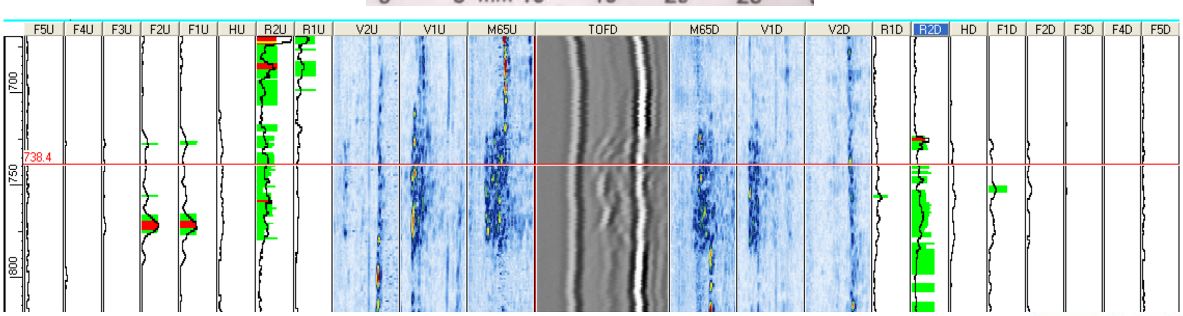

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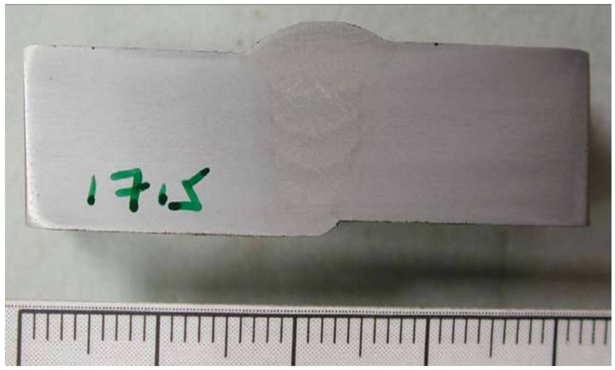
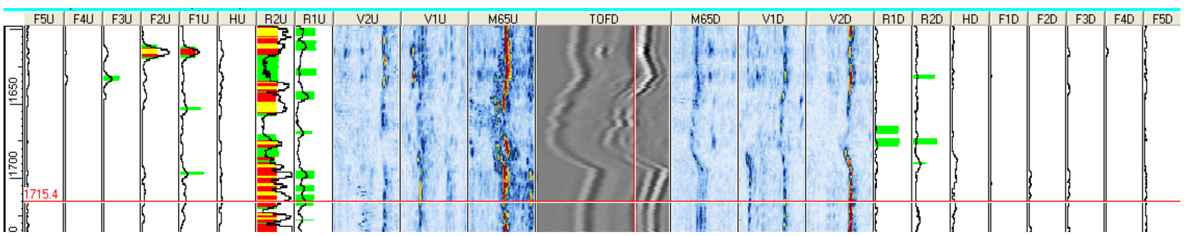
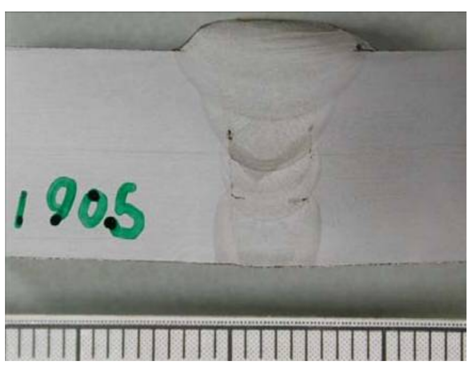
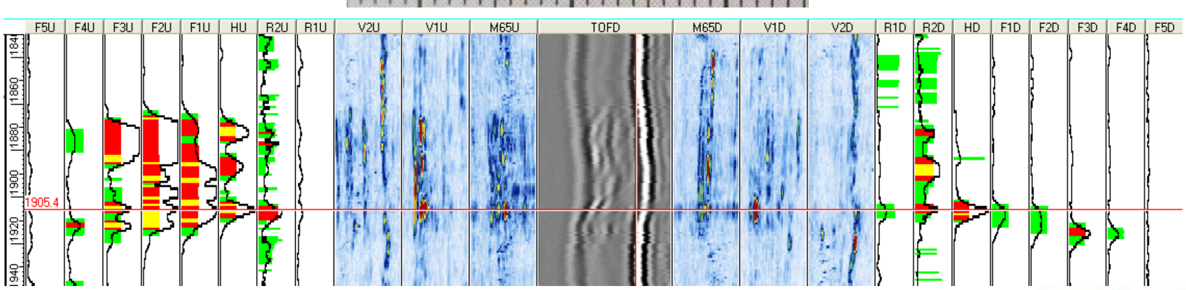




THE MATERIALS JOINING EXPERTS

Location W3-1905





THE MATERIALS JOINING EXPERTS

AUT of Girth Welds

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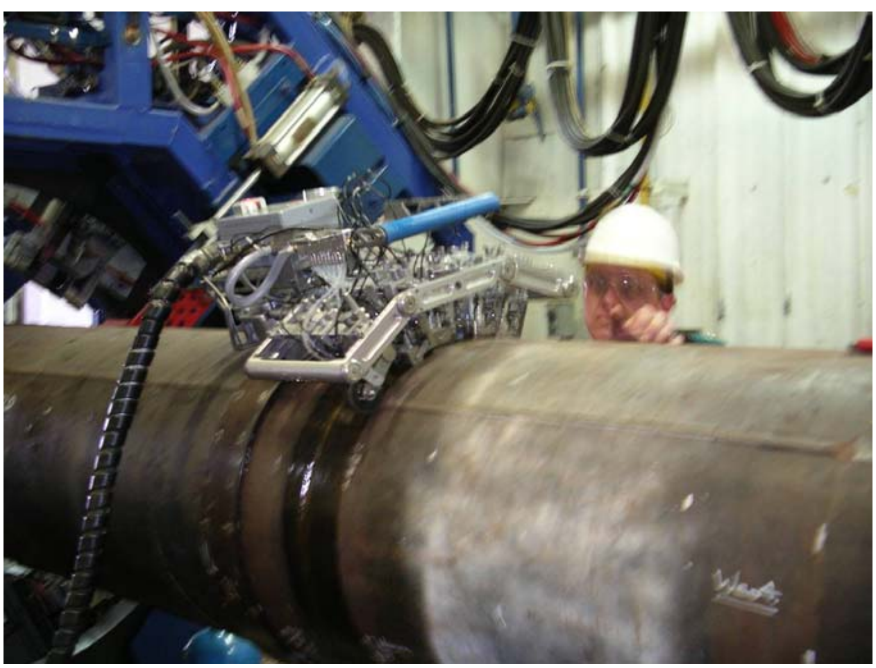
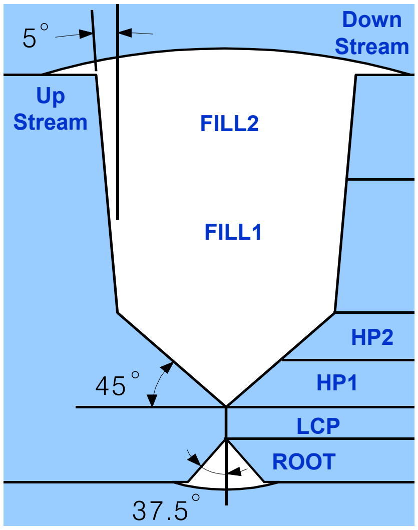
AUT



EWI THE MATERIALS JOINING EXPERTS

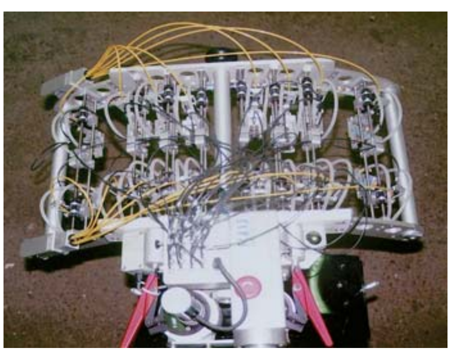
Mechanized Weld Inspection – Zone Discrimination

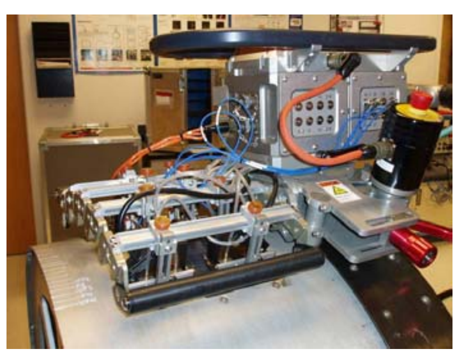


- The weld volume is divided into vertical "zones".
- The Mechanized weld is divided in two halves – up and downstream.
- Each zone has an individual ultrasonic inspection channel.
- The number of zones is dependant on the material thickness, bevel type, and welding procedure.

EWI THE MATERIALS JOINING EXPERTS

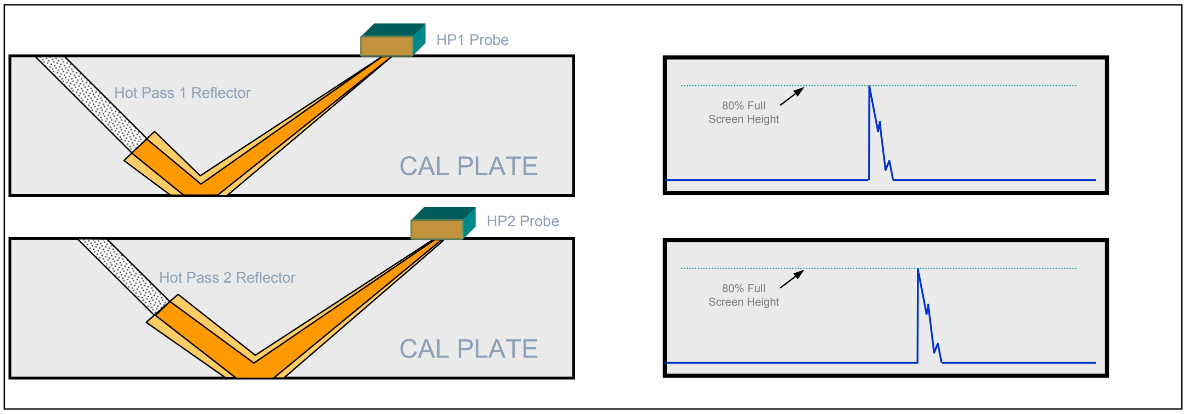
Multi-probe and PA Scanners





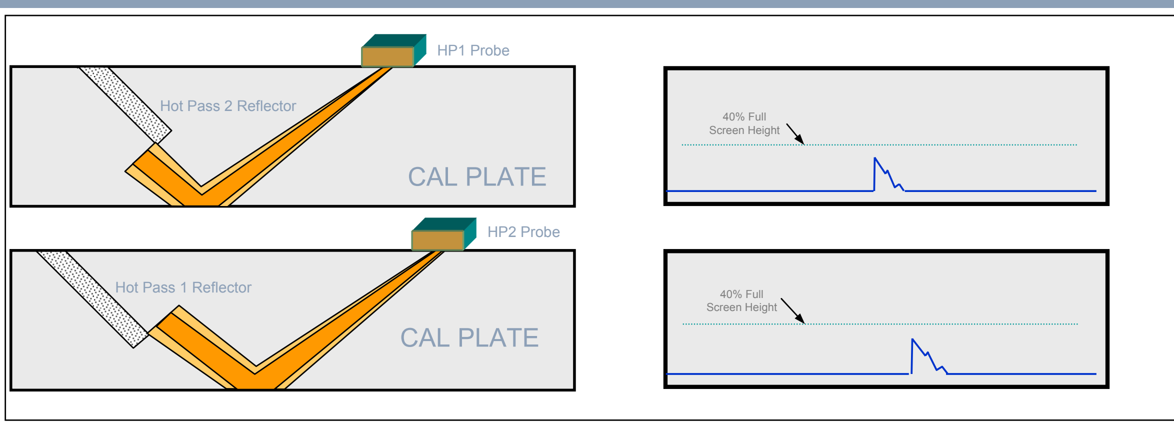
EWI THE MATERIALS JOINING EXPERTS

Mechanized Weld Inspection – Defect Sizing



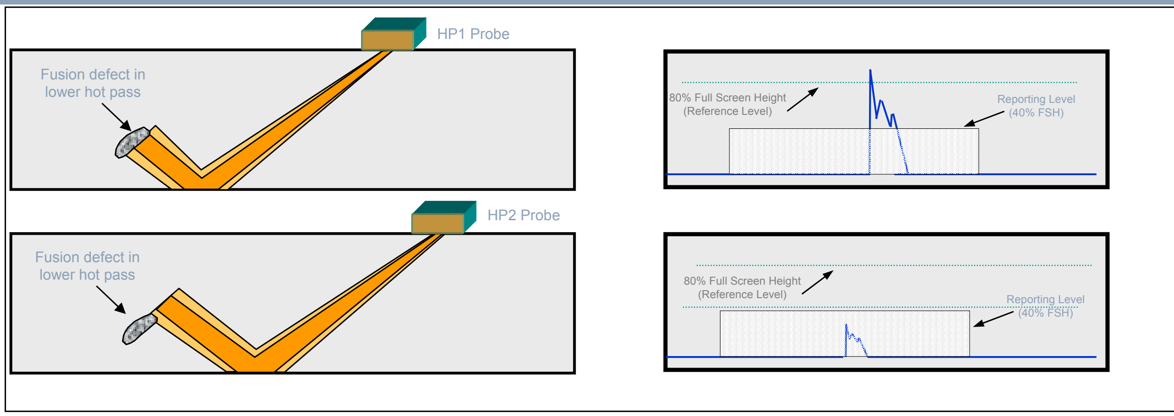
- Each probe is typically calibrated on a 2 or 3mm diameter flat-bottomed hole located at the center of the inspection zone.
- The channel sensitivity is set to achieve a reflected signal of 80% full screen height (FSH).

Mechanized Weld Inspection – Defect Sizing



- Each probe is then moved to the adjacent reflector to ensure proper resolution can be achieved.
- The signal from the adjacent reflectors shall be less than the reporting reference level (40% FSH).

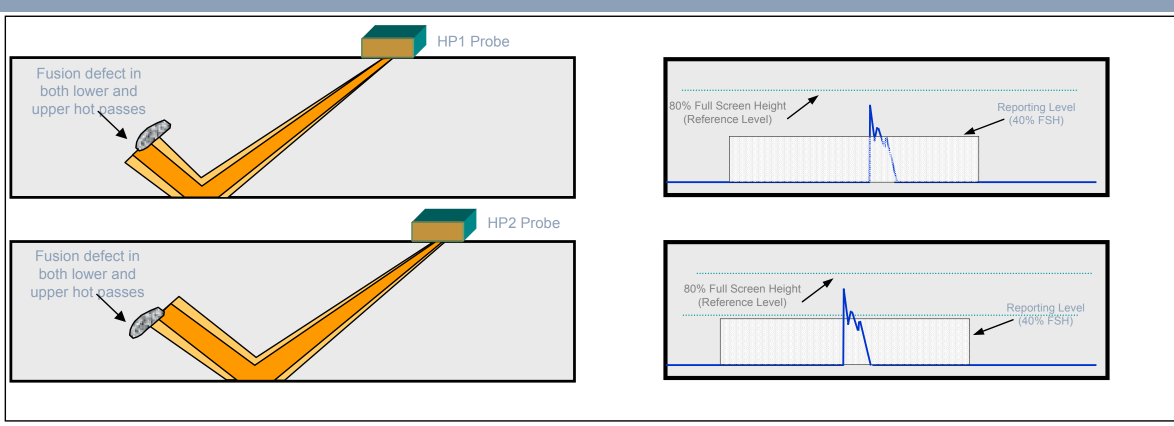
Mechanized Weld Inspection – Defect Sizing



- If the defect is contained in only one zone, that channel will register a reflector over the 40% FSH reporting level.
- The adjacent channels will not show a reportable reflector since only a small portion of the defect is within the ultrasonic beam.
- Therefore, the defect is sized to a single zone.

EWI THE MATERIALS JOINING EXPERTS

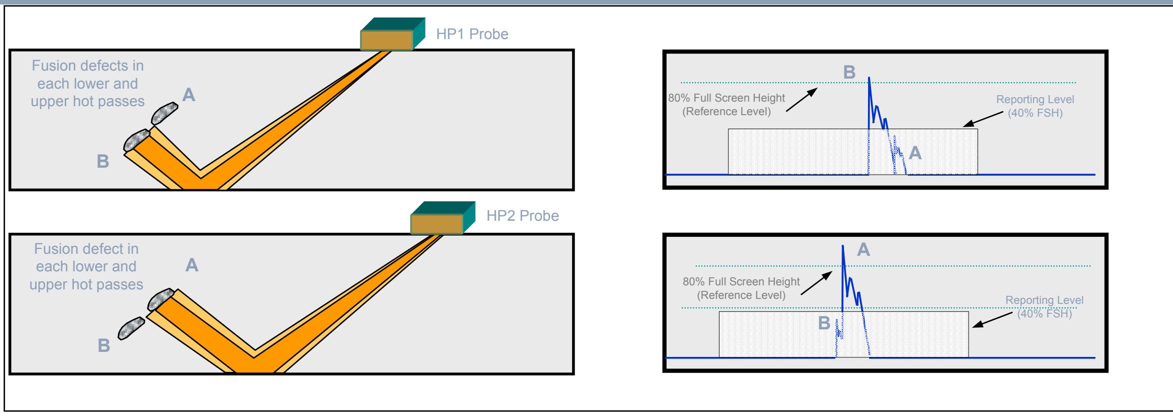
Mechanized Weld Inspection – Defect Sizing



- When a defect is equally in two adjacent zones and is at least one zone in height, both zones will register reportable reflectors.
- The amplitude of both will be less than the 80% FSH reference level since only a portion of the defect is in each ultrasonic beam.
- The defect is sized to the two zones.

EWI THE MATERIALS JOINING EXPERTS

Mechanized Weld Inspection – Defect Sizing



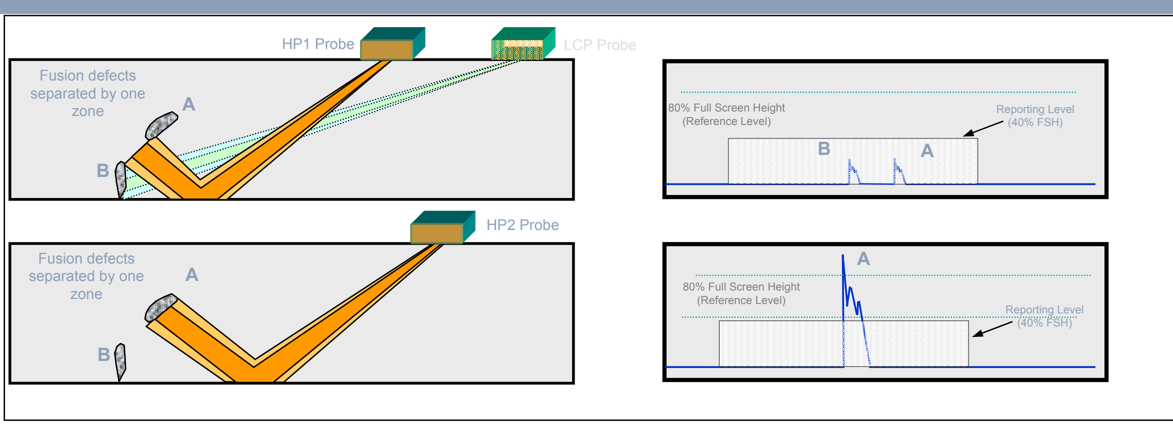
◆ When two defects are located in separate zones, each channel registers its proper reflector.

◆ The two reflectors are considered to be combined since they are in adjacent zones.

◆ The defect is sized to the two zones.

EWI THE MATERIALS JOINING EXPERTS

Mechanized Weld Inspection – Defect Sizing



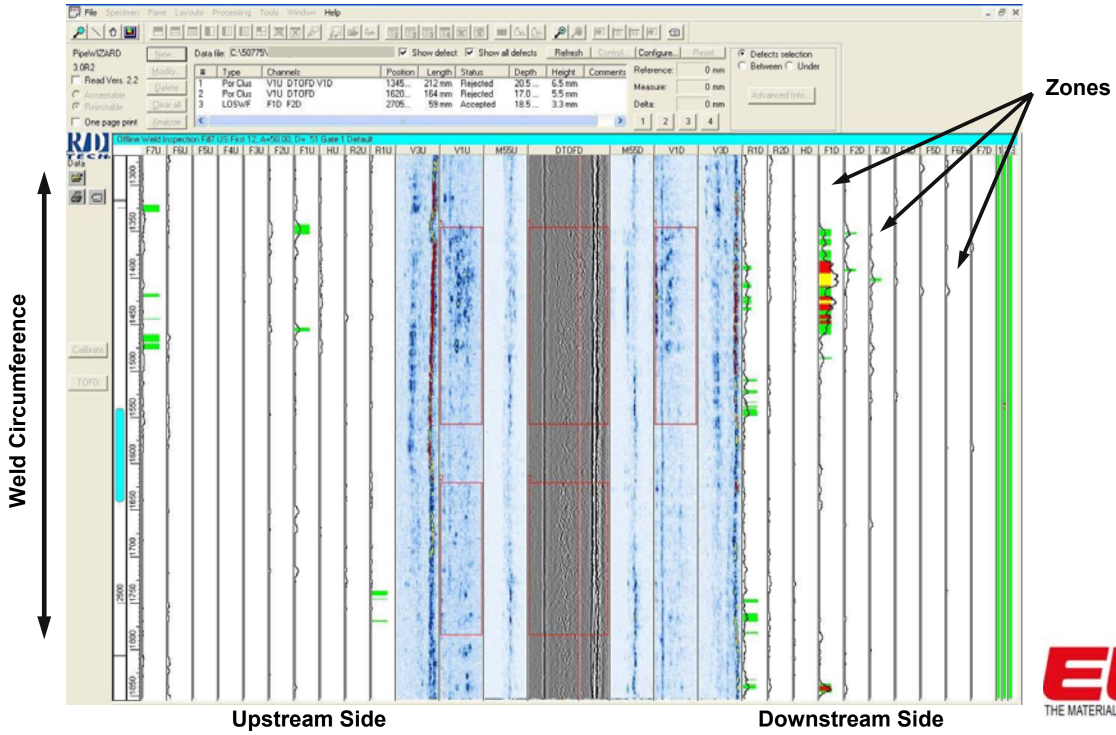
◆ When two defects are separated by at least one zone, only the zones with defects register a reportable defect.

◆ The “middle” zone may see both reflectors but they will be below the reportable level.

◆ The defects are characterized as separate defects

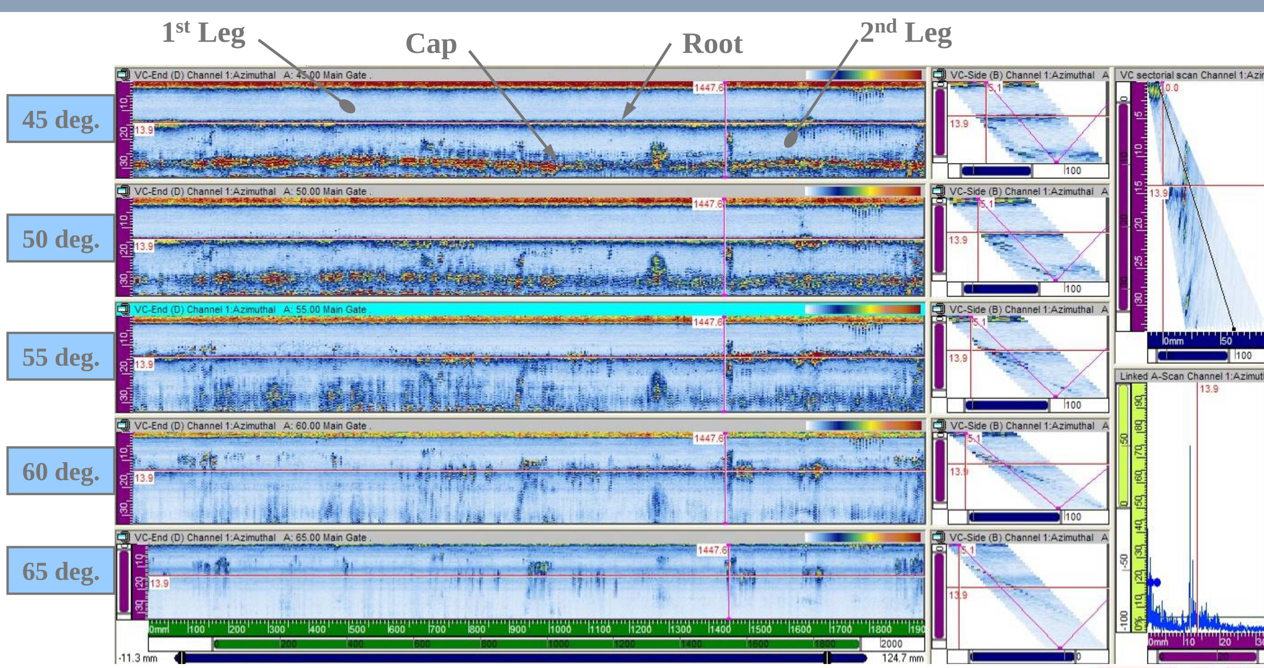
EWI THE MATERIALS JOINING EXPERTS

Typical Strip Chart Display



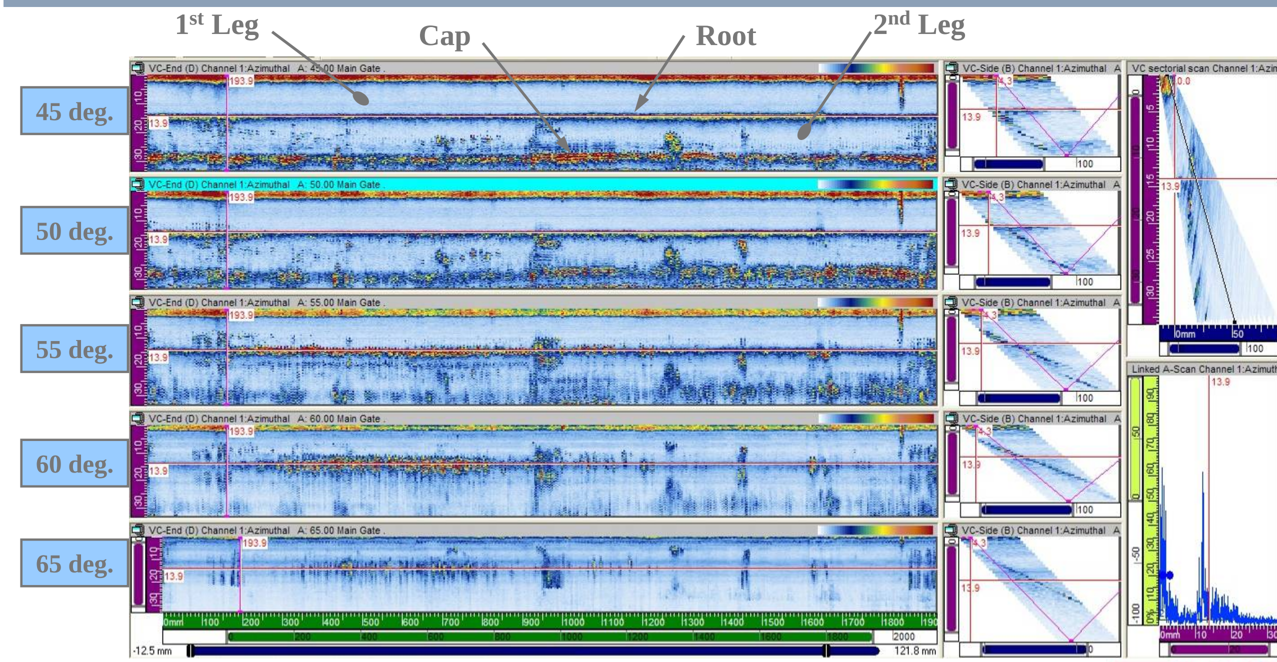
THE MATERIALS JOINING EXPERTS

PA 7 MHz US Scan

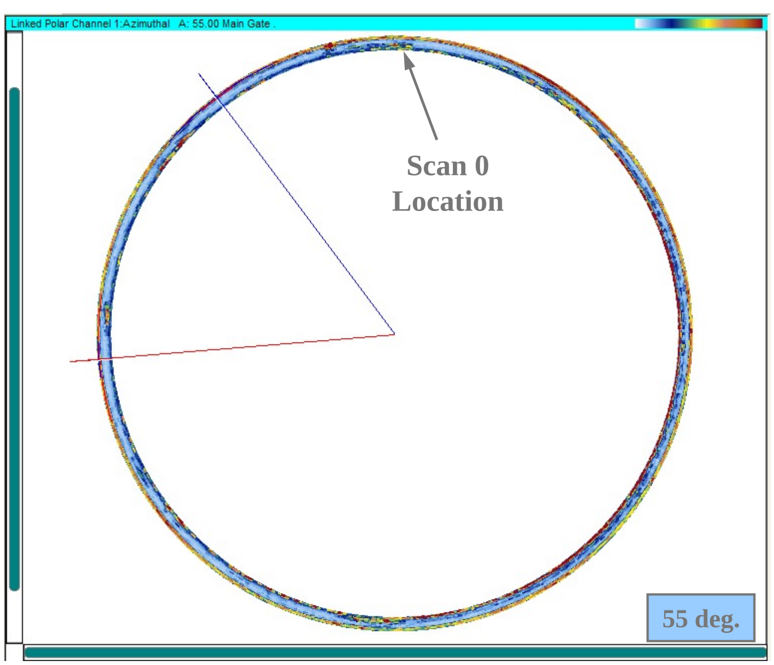


THE MATERIALS JOINING EXPERTS

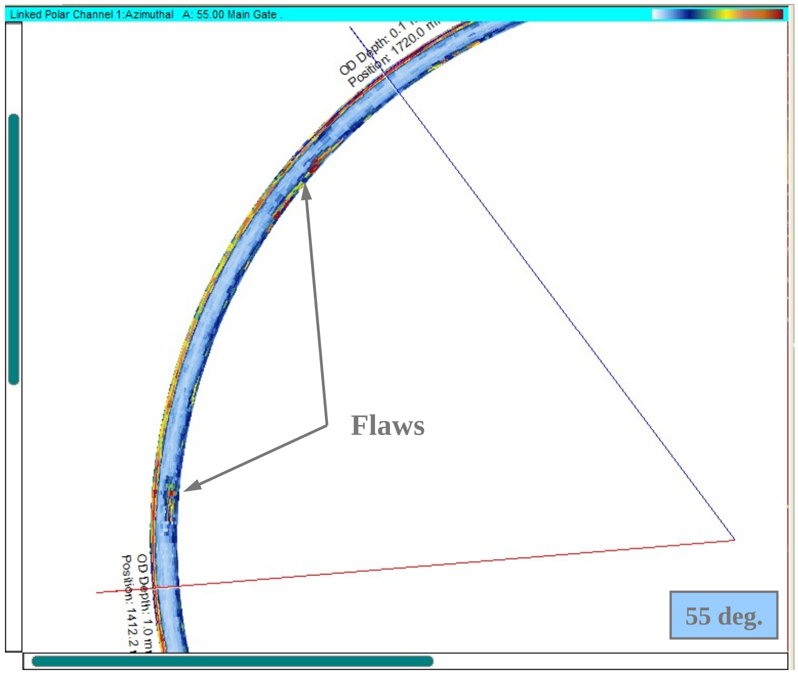
PA 7 MHz DS Scan



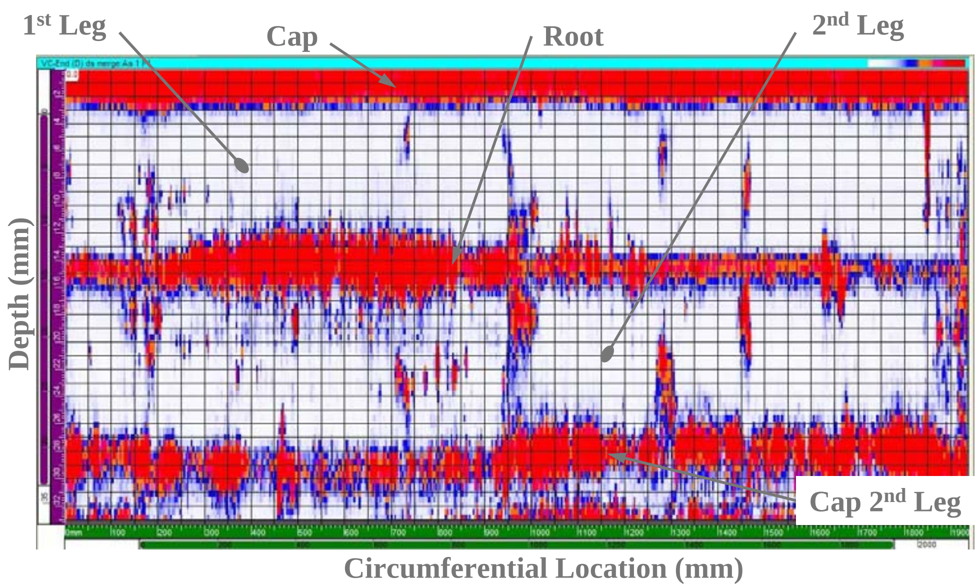
PA 7 MHz DS Scan – Polar View of Girth Weld



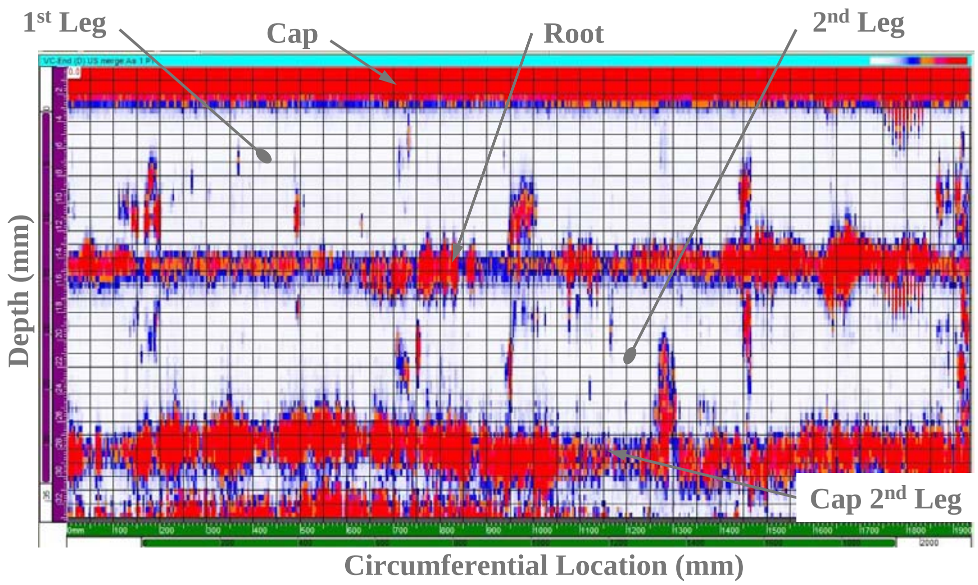
PA 7 MHz DS Scan – Polar View Location 1412 to 1720



DS Merged Scan Data

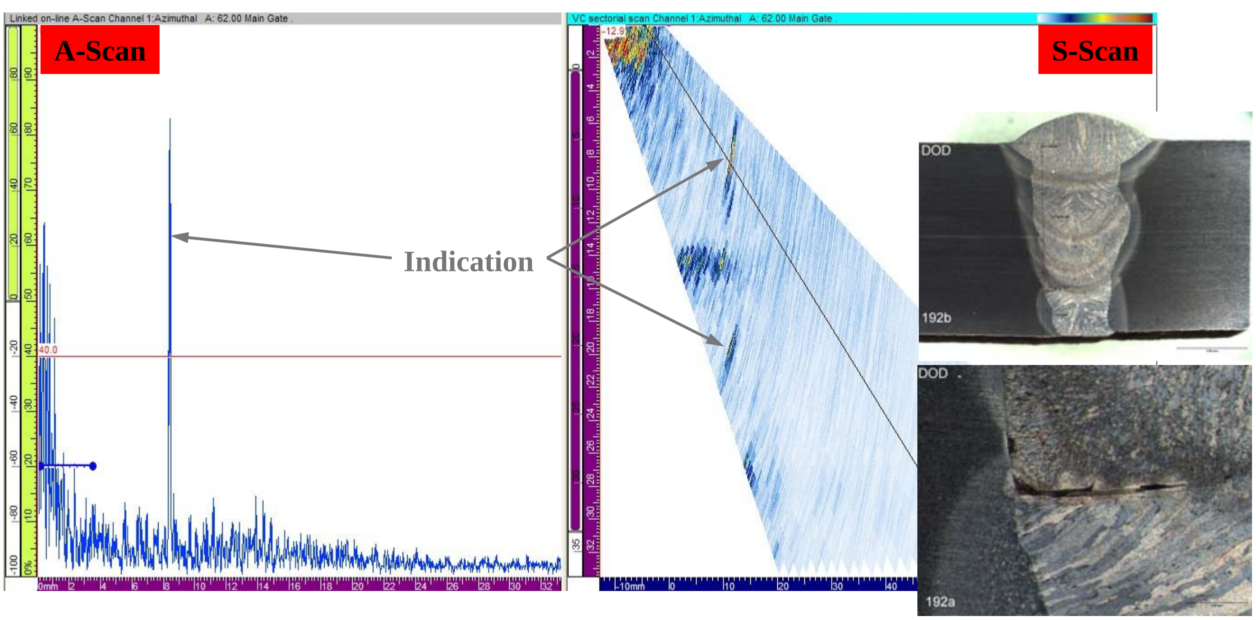


US Merged Scan Data



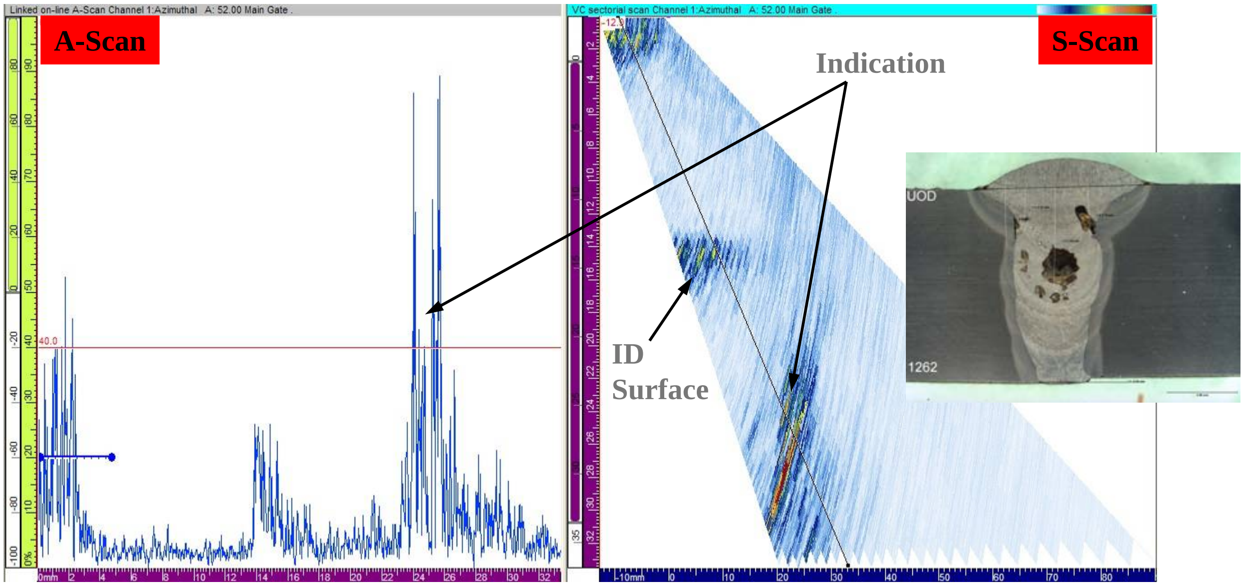
THE MATERIALS JOINING EXPERTS

Electronic Angle Sweep

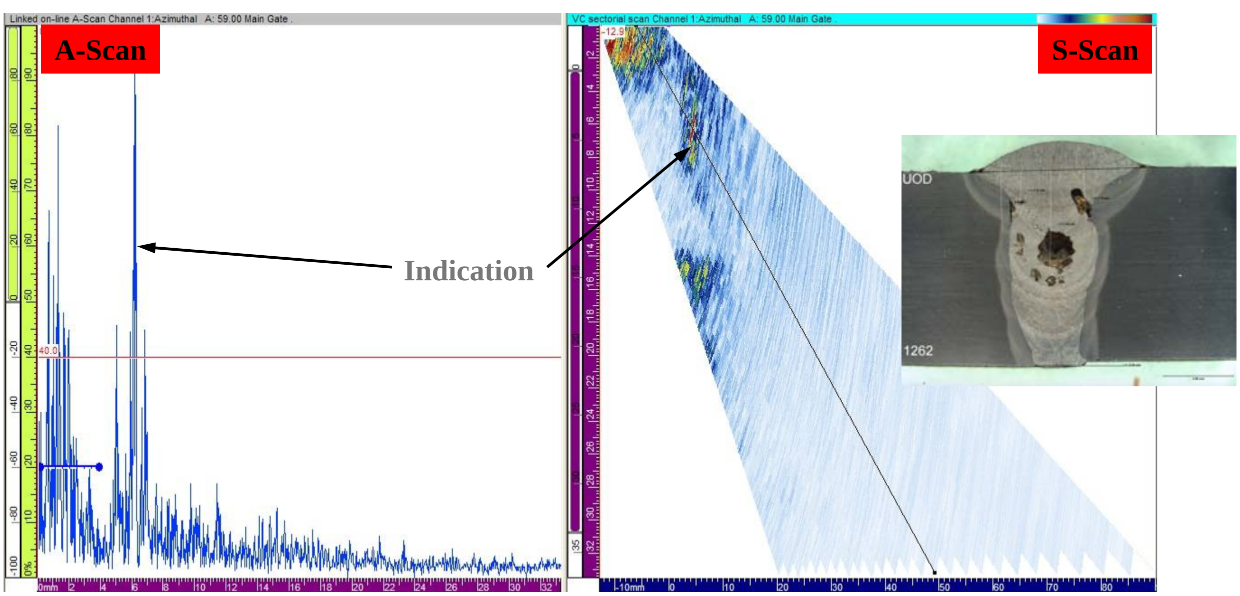


THE MATERIALS JOINING EXPERTS

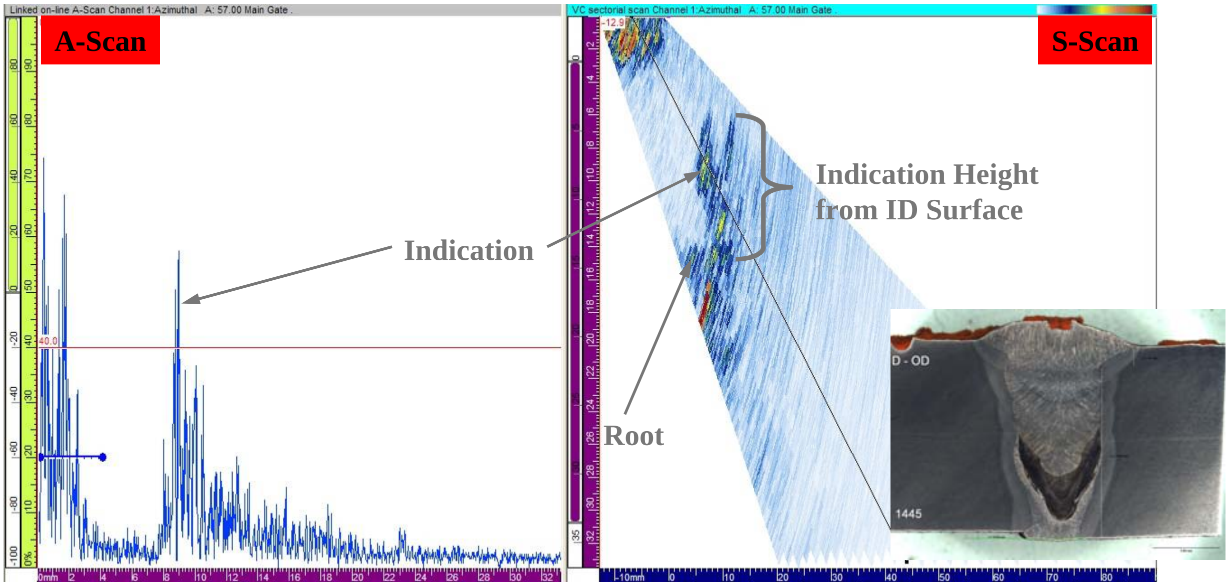
Porosity Indications (2nd Leg)



Porosity Indications (1st Leg)



Flaw Height Measurment Using S-Scan Display



UT Modeling and Inspection Simulation

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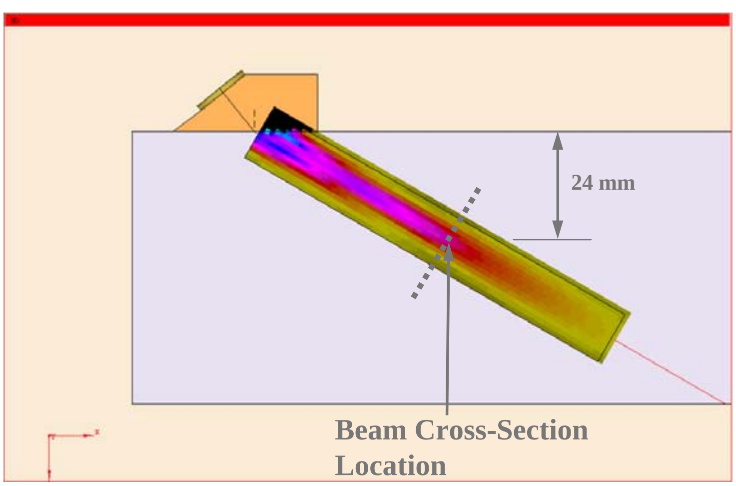
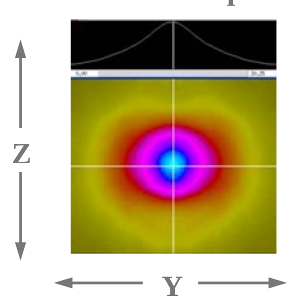
Overview

- Software modeling and simulation tools provide a good means of determining the adequacy or robustness of different UT techniques to detect and size flaws of interest
- Effects from part geometry and material can be evaluated
- Effects of flaw misorientation can be evaluated without the expense of fabricating mockups for each condition
- Non-standard probe configurations can be evaluated before purchasing

SE 12mm Dia. 5 MHz, 60 Degree



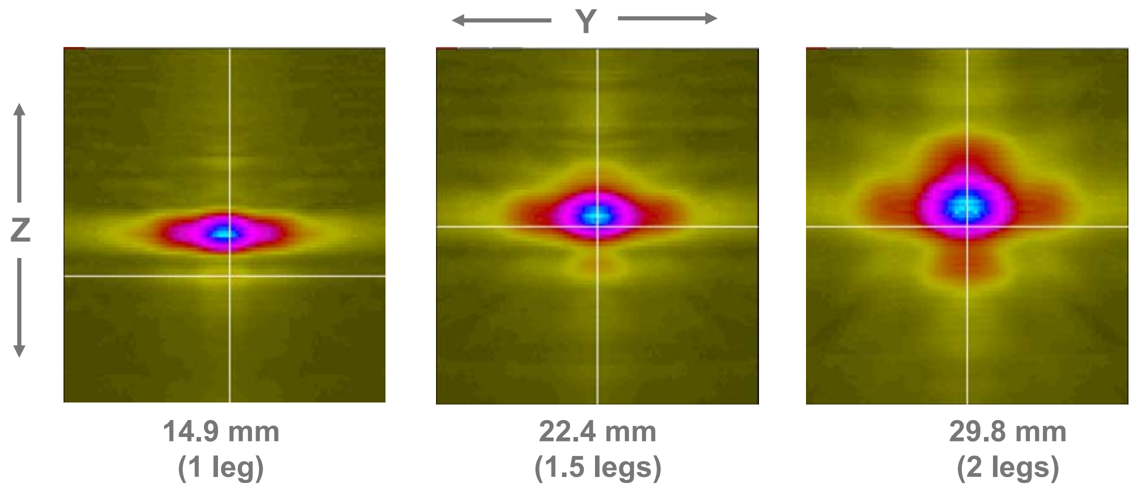
Beam Cross-Section
At 24mm Depth



Depth (mm)	6dB		12dB	
	Z (mm)	Y (mm)	Z (mm)	Y (mm)
24	5.0	4.4	7.0	7.2

Beam Cross-Sections Example

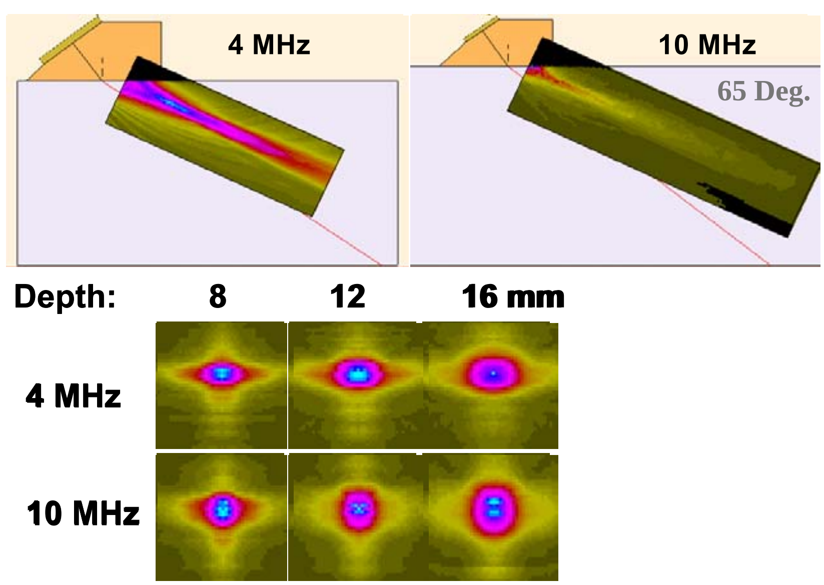
PA 17 Active Elements, 7.5 MHz, 14mm Focal Depth 52 degree shear



Depth (mm)	6dB		12dB	
	Z (mm)	Y (mm)	Z (mm)	Y (mm)
15	1.8	3.5	2.5	7.2
22	2.3	3.9	3.3	6.2
30	3.0	4.5	4.5	6.8

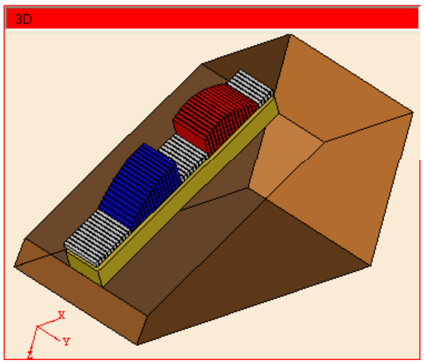
EWI THE MATERIALS JOINING EXPERTS

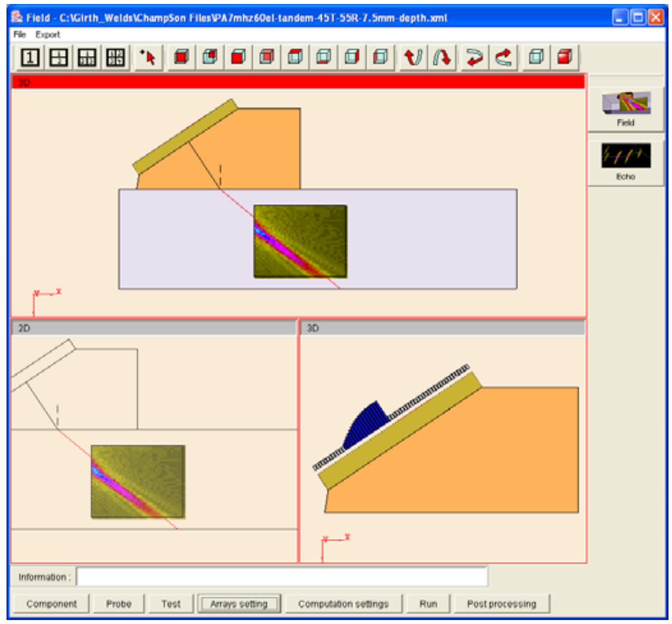
Modeling & Simulation for Optimization



EWI THE MATERIALS JOINING EXPERTS

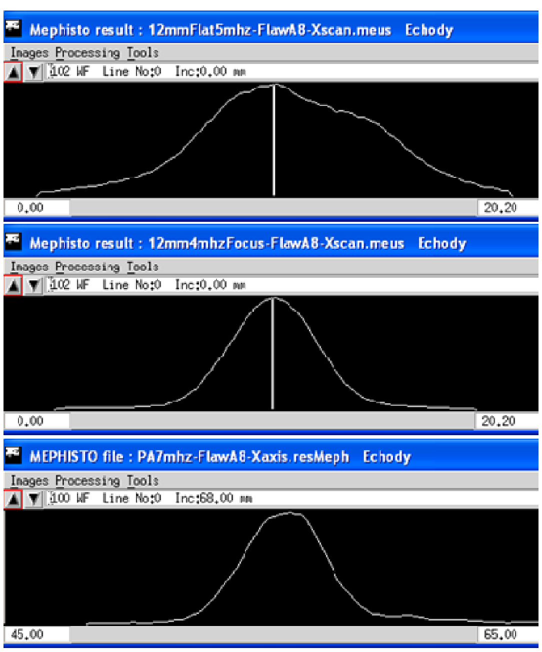
PA Tandem P/C Using Selected Elements

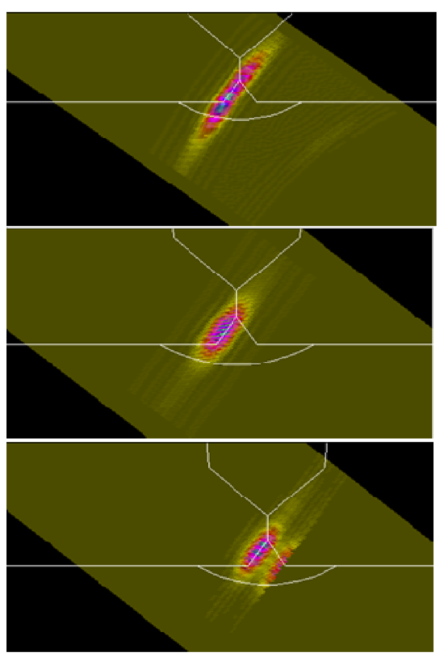




EWI THE MATERIALS JOINING EXPERTS

Visualization of Beam Spread Effects





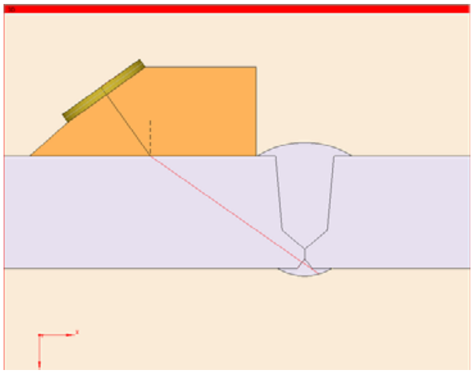
12.7mm Dia. 5 MHz Flat

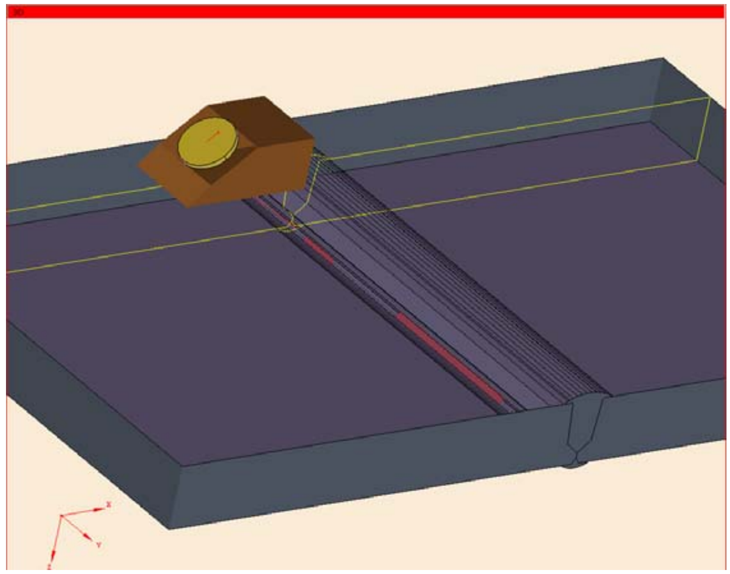
12.7mm Dia. 4 MHz Focus (75mm Rad.)

PA 7.5 MHz 17 active elements

EWI THE MATERIALS JOINING EXPERTS

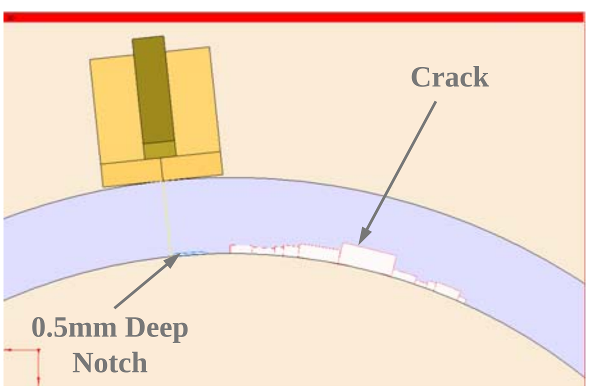
Implanted Flaws & Geometry



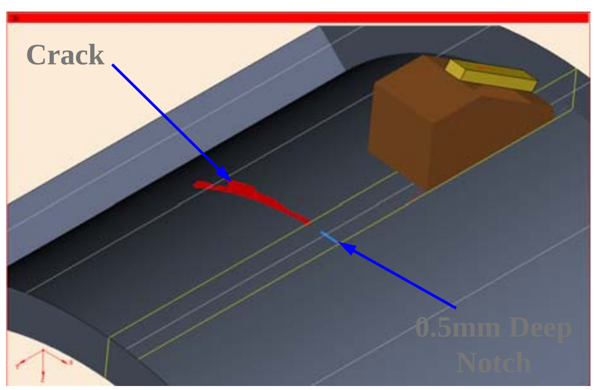


THE MATERIALS JOINING EXPERTS

UT Inspection Simulation of Fatigue Crack



End View



3D View

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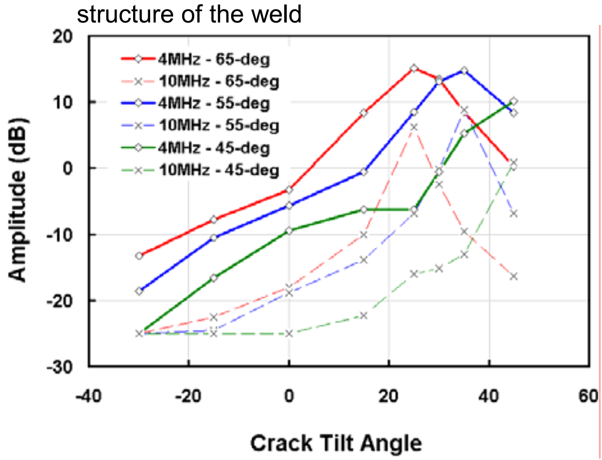
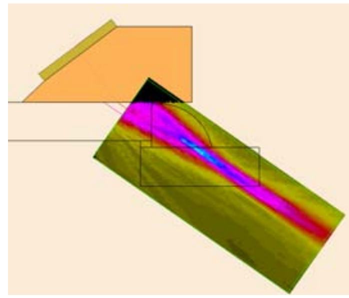
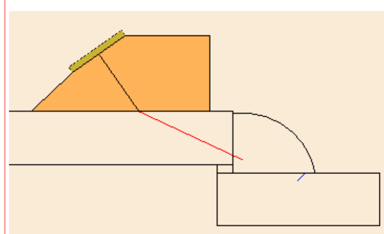
Simulation of Sleeve Inspection

Notes:

- 45 degrees cannot quite reach peak signal before sliding off edge of sleeve
- This measurement may not work, depending on the geometry and structure of the weld







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Phased Array UT - General

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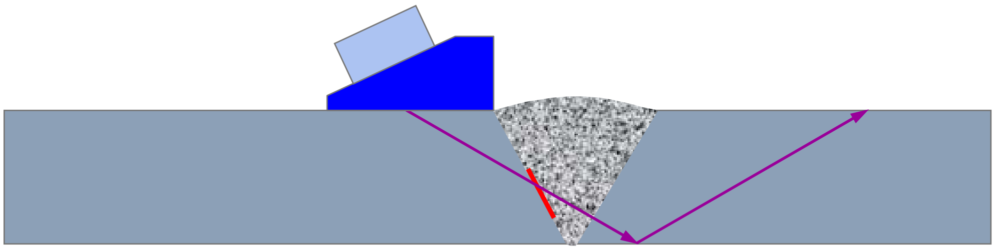
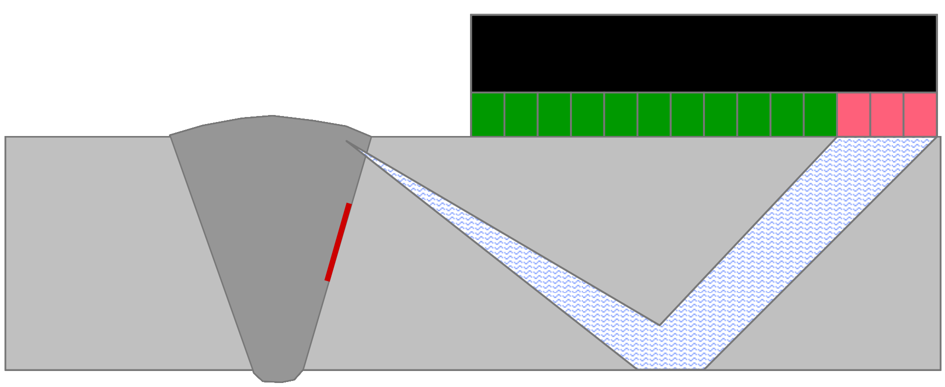
Conventional UT Weld Inspection Scan



Mechanical movement of probe provides good coverage of weld

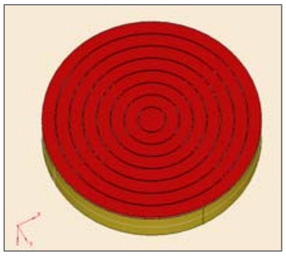
Phased Array – Weld Inspection



Electronic Linear Scan at a Fixed Angle

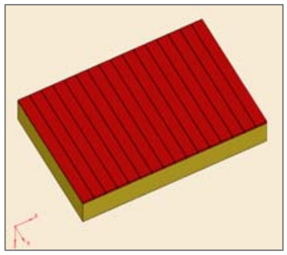
Phased Array Probe Designs

Annular



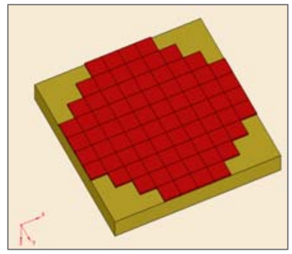
Depth focusing

Linear

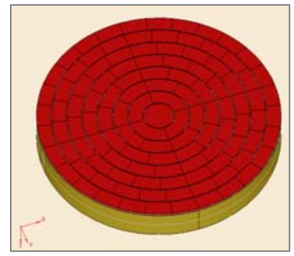


Focusing & beam steering in the primary probe axis

2D Matrix



Sectored



Focusing & beam steering in all directions

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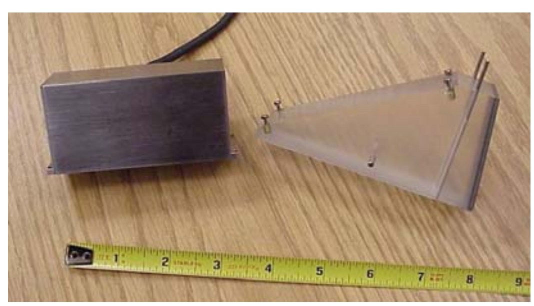
Phased Array Probes

128 Element
7.5 MHz

16 Element
5 MHz



32 Element
2 MHz

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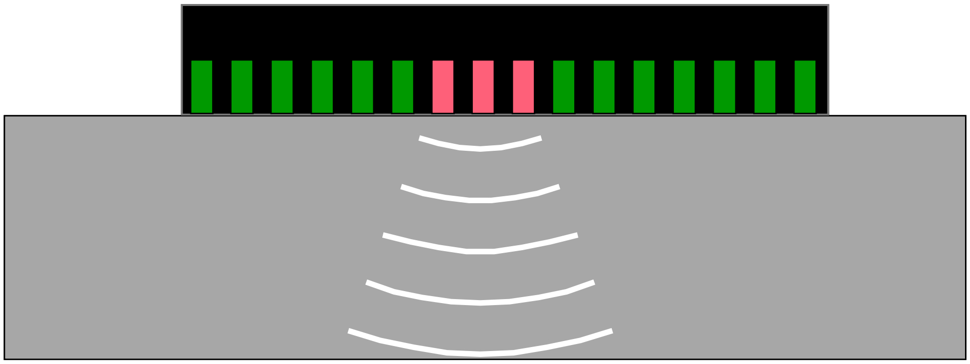
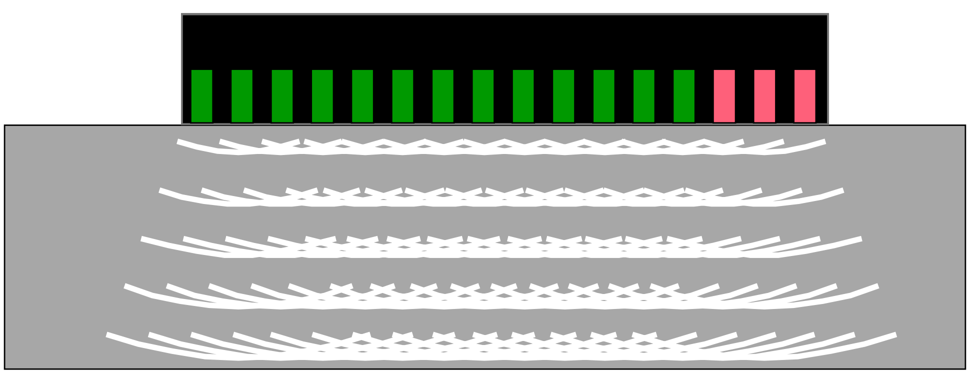
Phased Array – Wave Propagation

Controlling the Active Probe Aperture by Firing Selected Elements

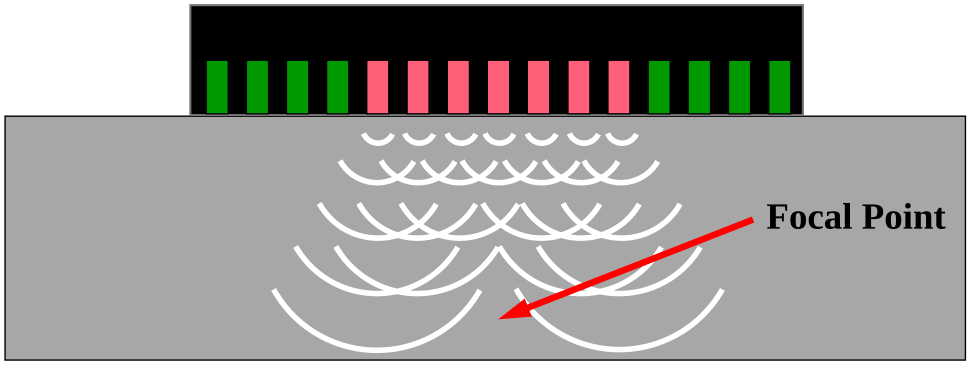


Phased Array – Linear Scan



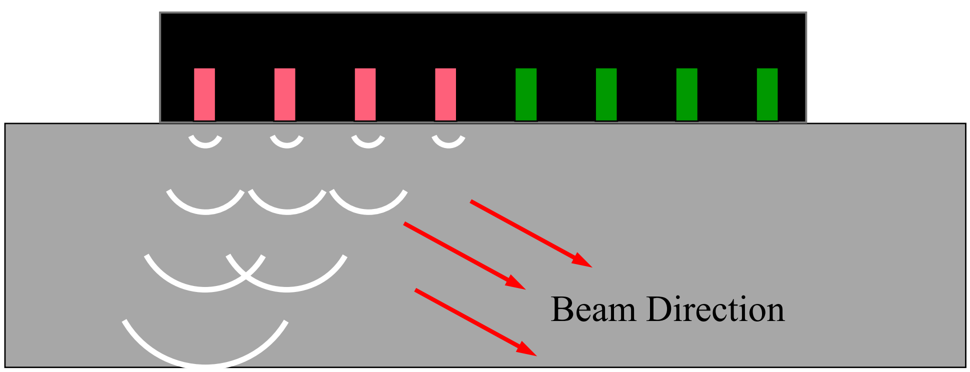
- ***Electronic Linear Scanning*** **can be accomplished by pulsing a selected number of elements sequentially along the length of the array**

Phased Array – Beam Focusing



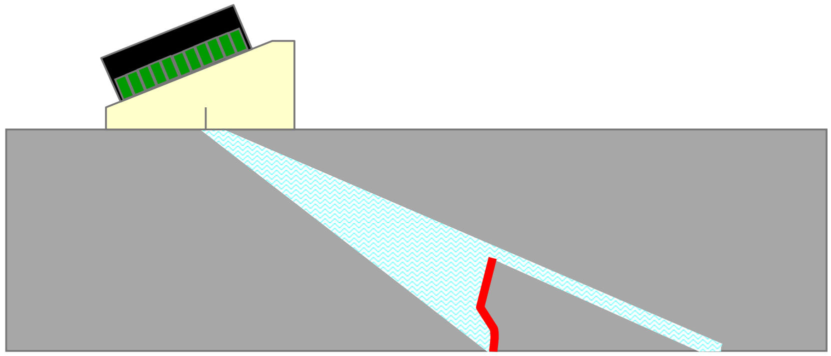
- ***Electronic Beam Focusing*** **can be accomplished by delaying the pulsing of elements in a symmetrical combination**

Phased Array – Beam Steering



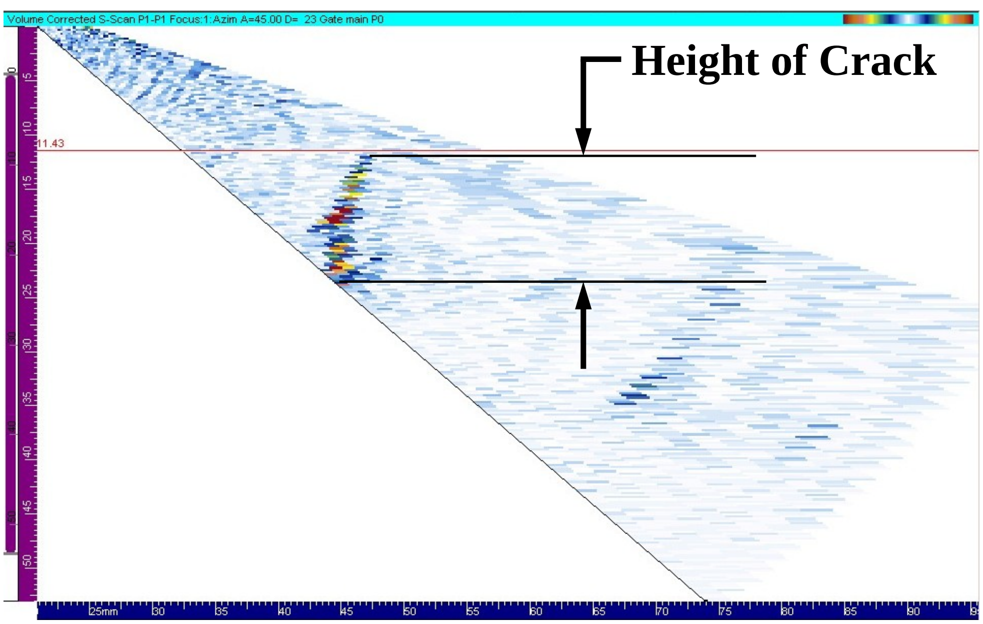
- ***Electronic Beam Steering*** **can be accomplished by delaying the pulsing of each element in a sequentially increasing rate**

Phased Array: Angle Sweep



THE MATERIALS JOINING EXPERTS

Phased Array: Sector Scan of Cracked Weld



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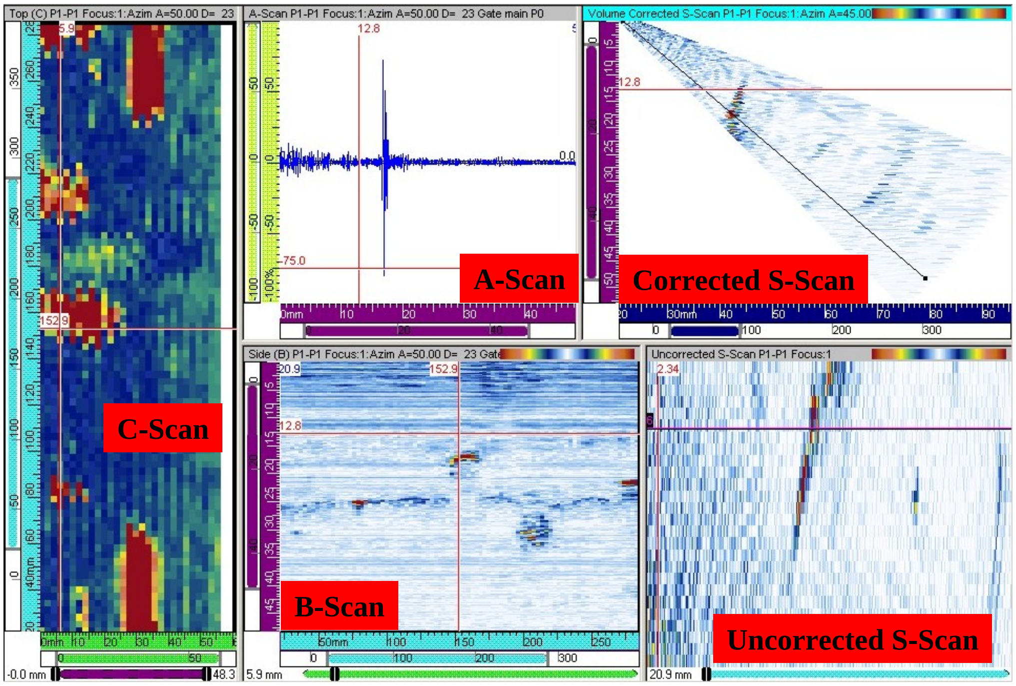
Display of Phased Array Data



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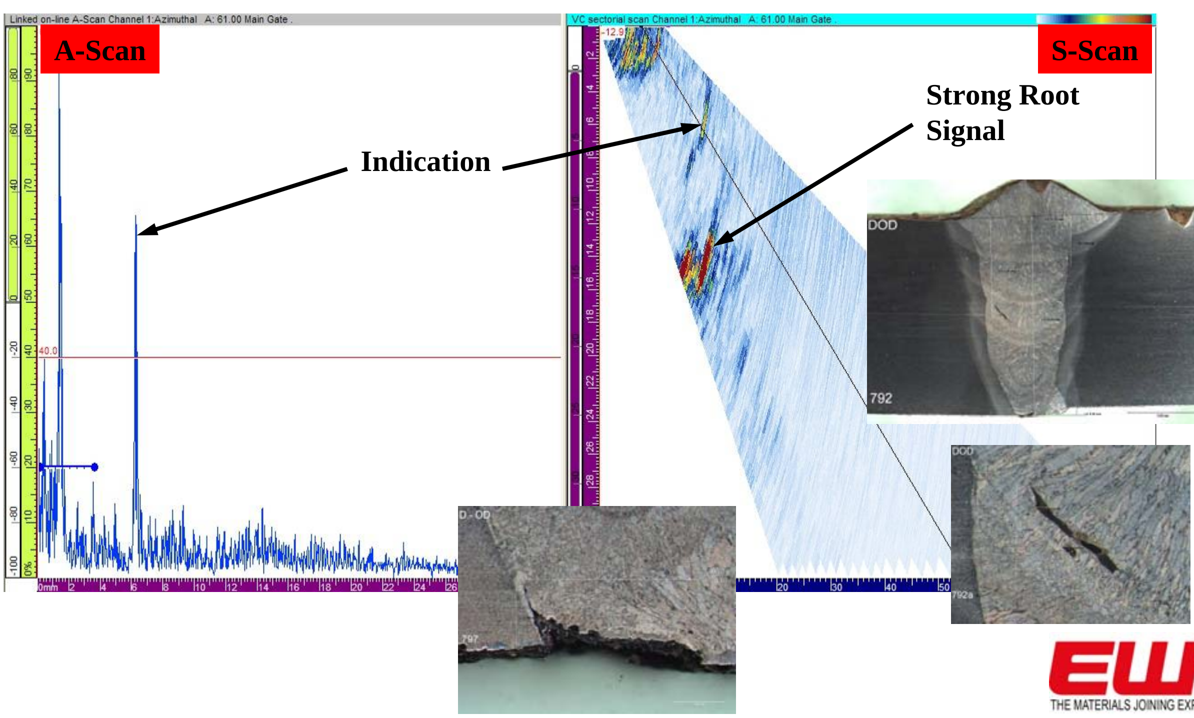
24-in. Diameter Girth Weld; PA7 60/16, FD 20



THE MATERIALS JOINING EXPERTS

UT Weld Inspection Refresher

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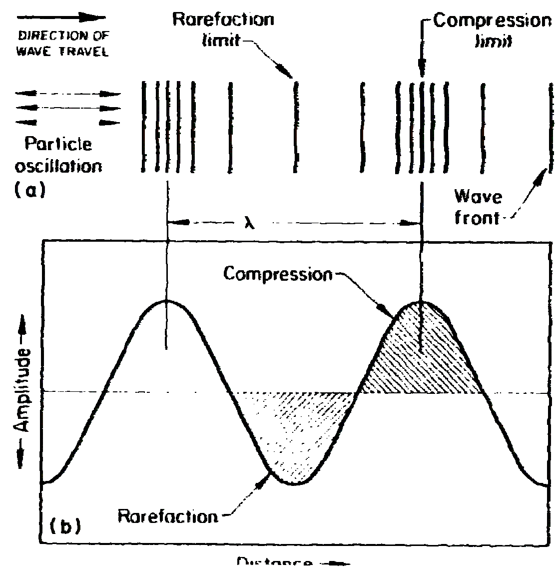
Purpose

Familiarize participant with basic UT weld inspection terminology and principles as a preliminary to advanced UT techniques

Compression (Longitudinal) Waves

- Commonly referred to as Longitudinal waves or "L-Waves"
- Sound that can be heard is in compression mode
- Molecules are excited and move in the same direction as the sound wave propagation
- Compression waves can travel in all materials



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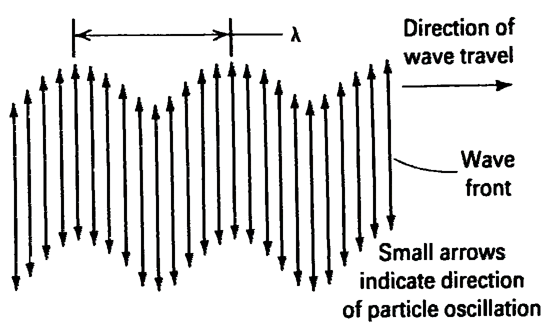
Shear (Transverse) Waves

- Only solid materials are capable of transmitting shear waves
- Shear waves are so named because the direction of molecular excitation is transverse to the direction of wave propagation



- Shear wave velocities are roughly half the compression wave velocities for a given material

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Typical Sound Velocities

Material	LONGITUDINAL			SHEAR		
	Velocity		Wavelength @ 5 MHz	Velocity		Wavelength @ 5 MHz
	M/s	in./μs	(mm)	M/s	in./μs	(mm)
Air	330	0.013	0.07	---	---	---
Aluminum	6300	0.248	1.26	3100	0.122	0.62
Copper	4660	0.183	0.93	2260	0.089	0.45
Plexiglass	2700	0.106	0.54	1100	0.043	0.22
Rexolite	2330	0.092	0.47	1100	0.043	0.22
Carbon Steel	5900	0.232	1.18	3230	0.127	0.65
Titanium	6100	0.240	1.22	3100	0.12205	0.62
Water	1480	0.058	0.30	---	---	---

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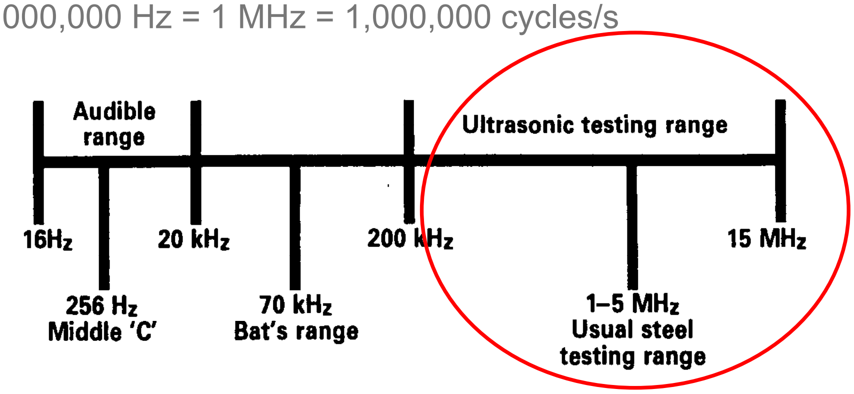
Frequency

- Since sound is a series of vibrations, one way of measuring it is to count the number of vibrations per second, which is frequency
- Unit of measurement is Hertz (Hz)
  - 1 Hz = 1 cycle/s
  - 1,000 Hz = 1 KHz = 1,000 cycles/s
  - 1,000,000 Hz = 1 MHz = 1,000,000 cycles/s



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Wavelength

- Wavelength is the distance from one point to the next identical point along a repetitive waveform
- It is dependent upon the material sound velocity and the transducer frequency
- Wavelength (λ) = Velocity/Frequency or $\lambda = \frac{V}{F}$
- Examples:
  - Wavelength of 200 Hz sound in air = 332/200 = 1.66 m
  - Wavelength of 2 MHz compression wave in steel = 5,920/2,000,000 = 2.96 mm
  - Wavelength of 2 MHz shear wave in steel = 3,250/2,000,000 = 1.63 mm

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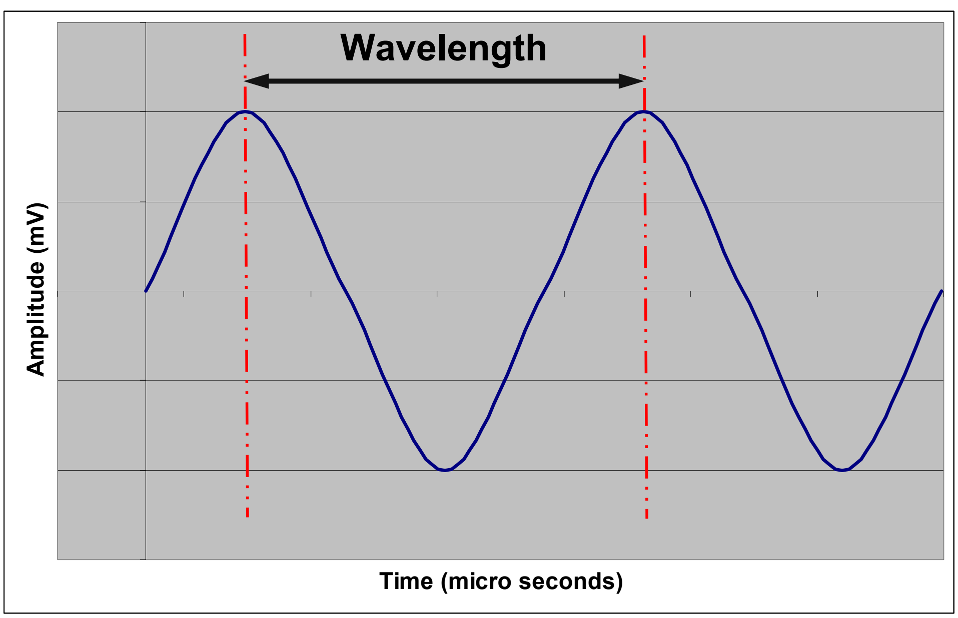
Wavelength

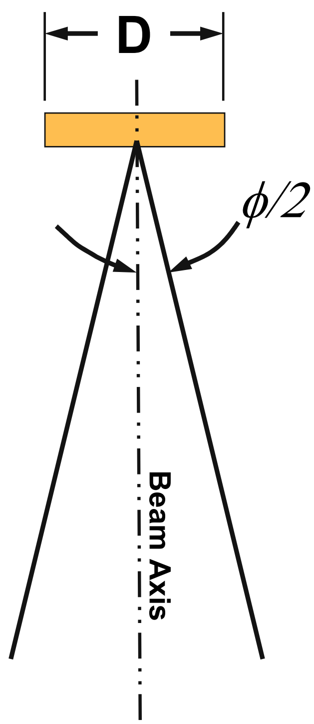


THE MATERIALS JOINING EXPERTS

Effects of Wavelength in UT

- Shorter wavelengths can detect smaller flaws
  - Therefore, shear waves of a given frequency will be capable of detecting smaller flaws in a material than compression waves
- Discontinuities of a size less than $\lambda/2$ may not be detected
- Shorter wavelengths attenuate quicker and therefore do not penetrate thicker material as well as long wavelengths would

Beam Spread



$$Sin\ \phi/2 = 0.514\left(\frac{c}{fD}\right)$$

c = sound velocity in material

f = frequency

D = probe diameter

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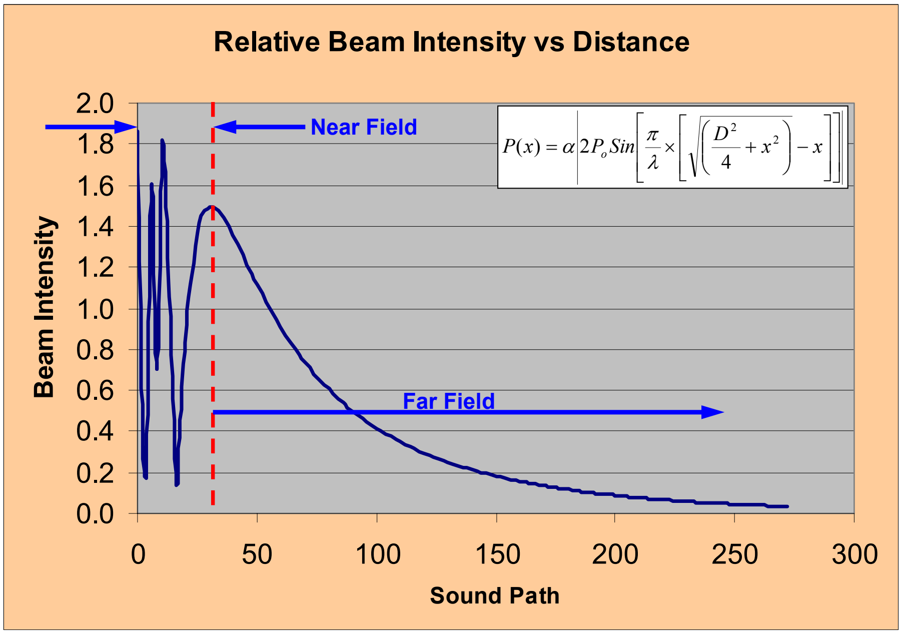
Near Field and Far Field

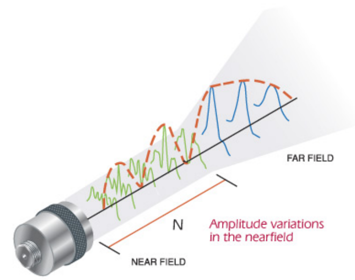


5 MHz, 12.7 mm Diameter L-Wave Probe

$$N = \frac{D^2}{4\lambda}$$

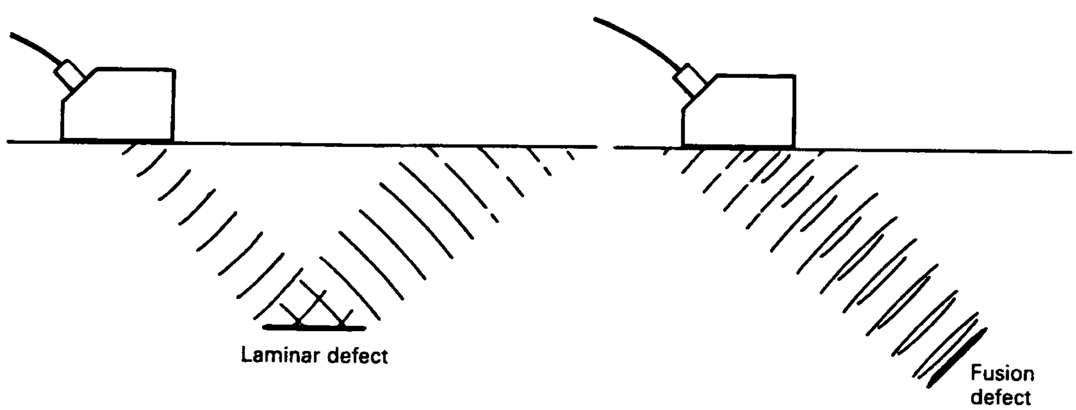
λ = wavelength

D = probe diameter



Courtesy: Olympus NDT

Effect of Flaw Orientation and Beam Angle



Energy reflected away from probe

Energy reflected back to probe

Probe Selection

- Factors to be considered:
  - Test object thickness
  - Test object diameter
  - Surface condition
  - Metallurgical condition, e.g., grain size
  - Type, position, and orientation of likely discontinuities
  - Flaw sizing accuracy

Probe Selection (Frequency Effects)

- Increase in transducer frequency will:
  - Increase near field zone length
  - Increase sensitivity to small flaws
  - Increase resolution
  - Increase sound attenuation
  - Decrease beam spread
  - Decrease sound penetration depth
  - Decrease ability to tolerate rough surfaces

Probe Selection (Element Size Effects)

- Increase in transducer element size will:
  - Increase near field zone length
  - Increase beam size
  - Increase sound intensity
  - Decrease beam spread

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Snell's Law

$$\frac{V_1}{V_2} = \frac{\sin \theta_1}{\sin \theta_2}$$

Where: V_1 = Velocity of sound in material 1
V_2 = Velocity of sound in material 2
θ_1 = Angle of incidence
θ_2 = Angle of refraction

Or this may also be expressed as:

$$\sin\theta_2 = \frac{V_2 \sin\theta_1}{V_1}$$

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Example of Snell's Law

Given: Rexolite Velocity = 2330 M/s

Steel Shear Wave Velocity = 3230 M/s

Rexolite Wedge Angle = 33 degrees

Calculate: Refracted shear wave angle in steel

$$\sin\theta_2 = \frac{3230 \times \sin 33^o}{2330}$$

$$\sin\theta_2 = 0.755$$

$$\theta_2 = \sin^{-1}(0.755)$$

$$\theta_2 = 49^o$$

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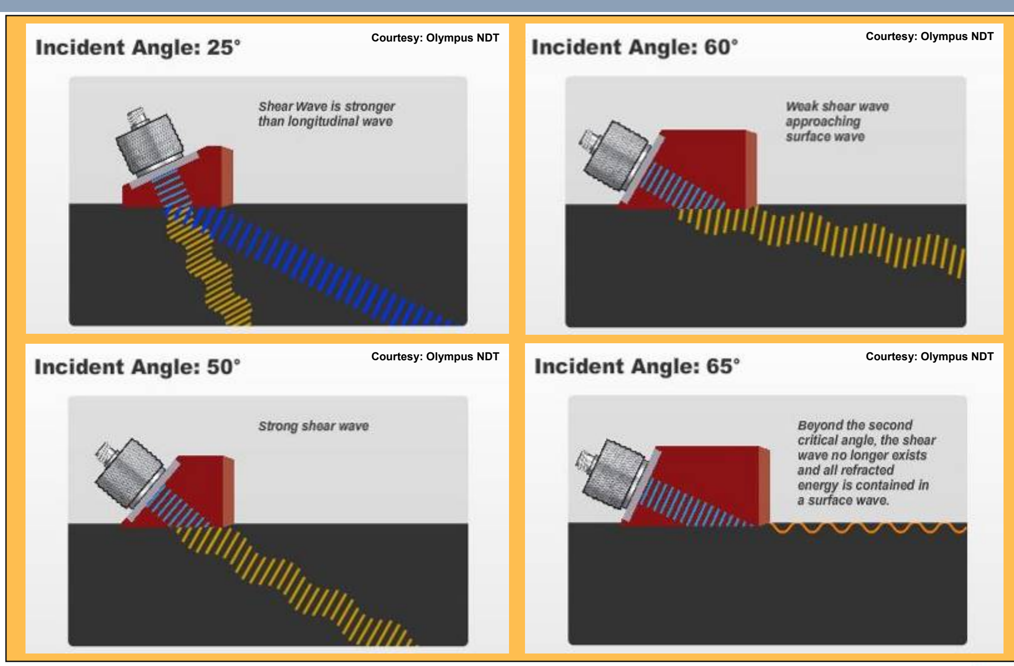
Effect of Wedge Angle



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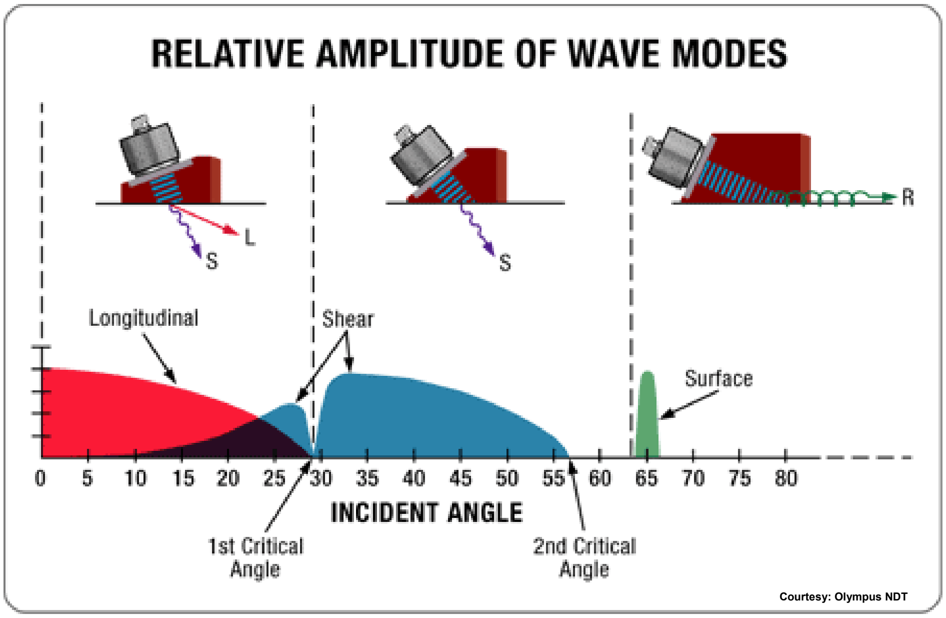
Amplitudes of Wave Modes



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6dB Drop Sizing Method

Used for sizing ultrasonic indications. It is based on the UT convention that a 50% decrease in signal amplitude is a 6dB change

Accomplished by:

Step 1. Move the probe over the flaw location and obtain the maximum signal amplitude from the flaw. Record the maximum signal amplitude.

Step 2. Move the probe in one direction until the signal amplitude decreases to 50% of the maximum amplitude found in Step 1. Make a reference mark on the part that coincides with the center of the sound beam.

Step 3. Move the probe in the opposite direction until the signal amplitude decreases to 50% of the maximum amplitude found in Step 1. Again, make a reference mark on the part that coincides with the center of the sound beam.

Step 4. Measure between the two reference marks to obtain the flaw dimension in the selected plane.

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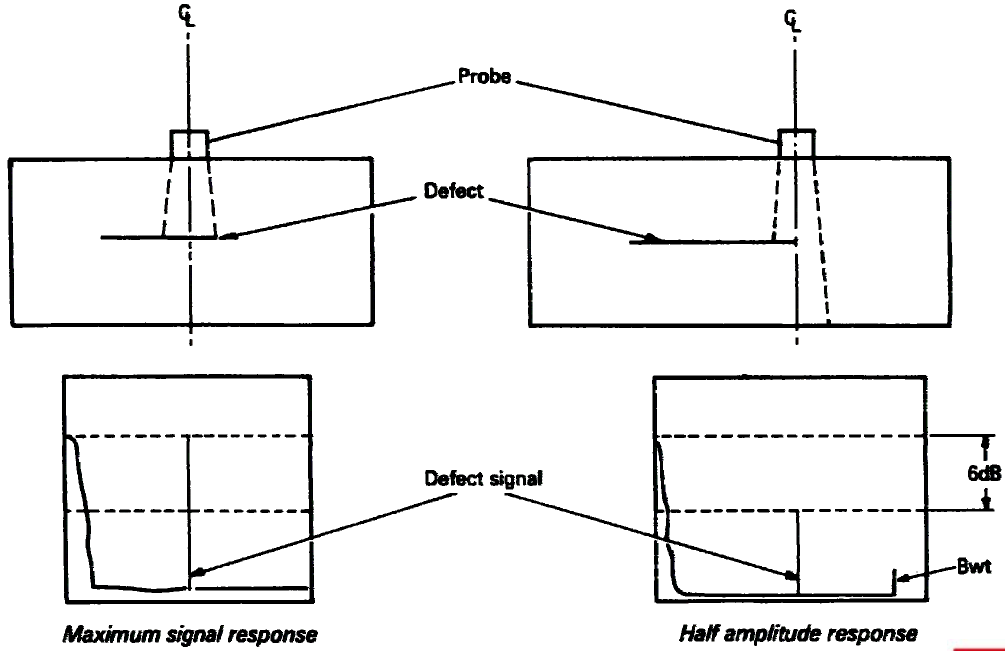
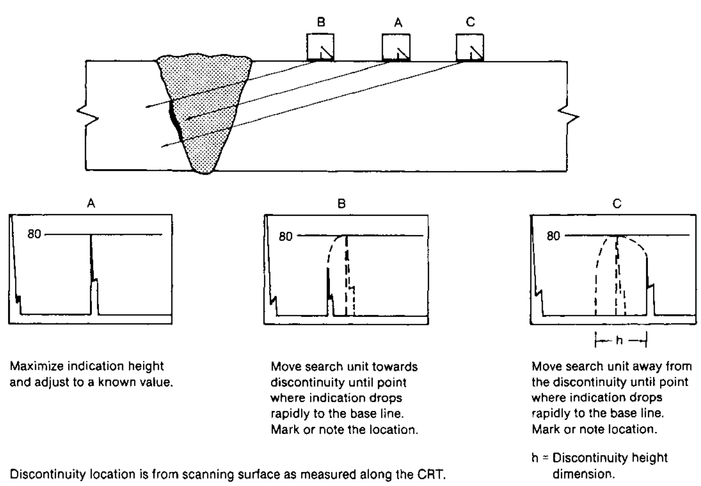
6dB Drop Sizing Method



THE MATERIALS JOINING EXPERTS

Sizing Weld Discontinuities

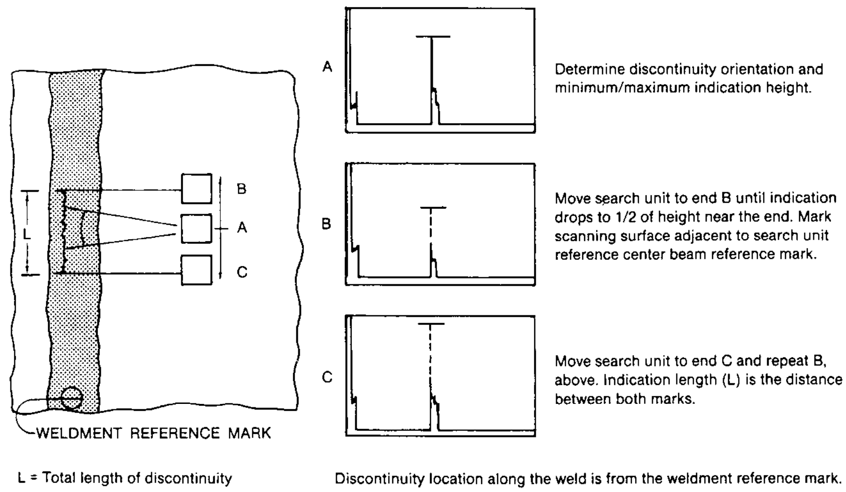
- Determining Weld Discontinuity Height (depth dimension)



THE MATERIALS JOINING EXPERTS

Sizing Weld Discontinuities

- Determining Weld Discontinuity Length Dir



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Difficulties with Discontinuity Evaluation

Type of Discontinuity	Relative UT Sensitivity
Incomplete fusion	Highest
Cracks (surface)	-
Incomplete joint penetration	-
Cracks (subsurface)	-
Slag (elongated)	-
Slag (scattered, globular)	-
Porosity (elongated)	-
Porosity (cluster)	-
Porosity (scattered)	Lowest

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Difficulties with Discontinuity Evaluation

- Discontinuity orientation
  - Orientation affects UT sensitivity since the highest sensitivity is obtained when sound is reflected directly back to the transducer
  - Orientation sensitivity can be increased by selection of an angle that most closely strikes the discontinuity at a right angle
  - For groove welds, selection of a probe having an angle based on the bevel angle will improve sensitivity to discontinuities along that plane

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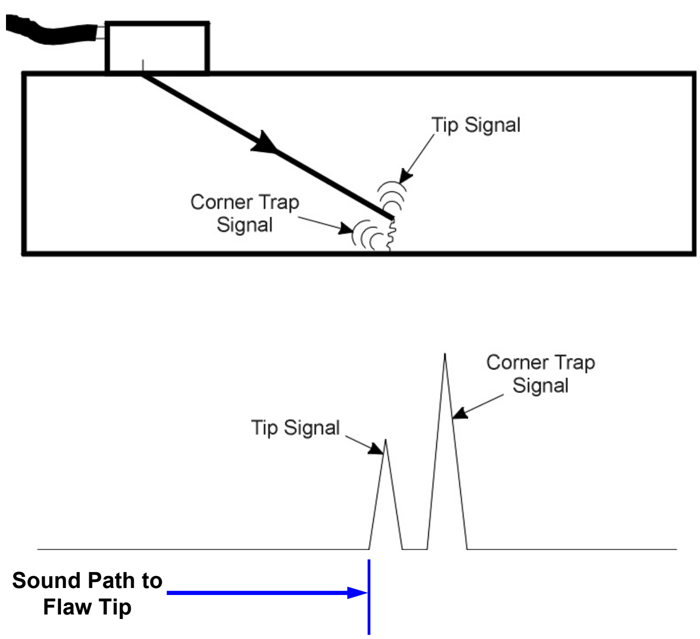
Pulse-Echo Tip Diffraction



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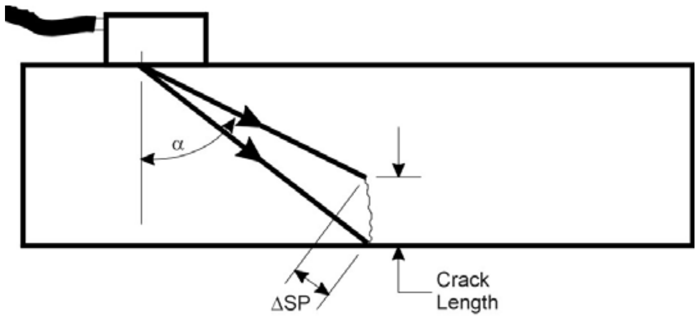
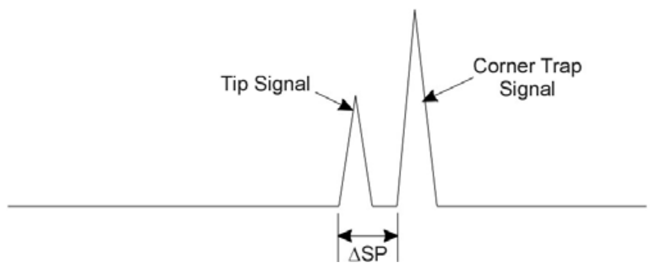
Relative Time of Flight Measurement



$$Height = \frac{\Delta SP}{Cos\alpha}$$



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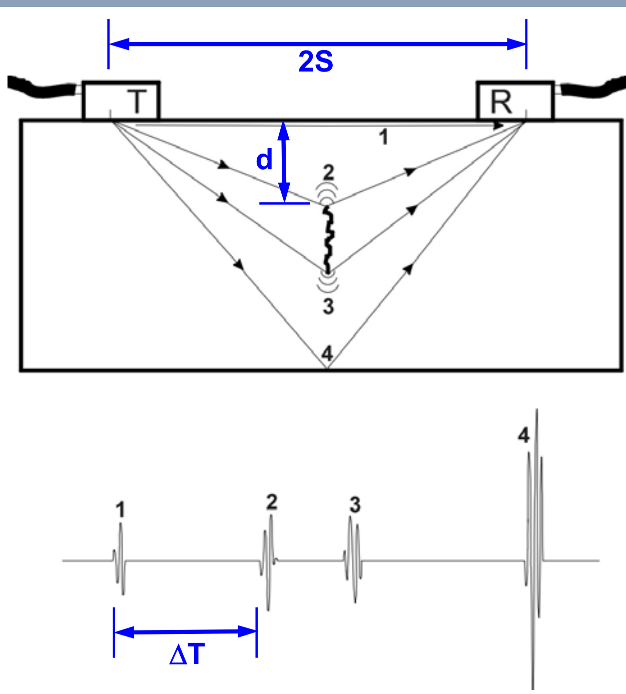
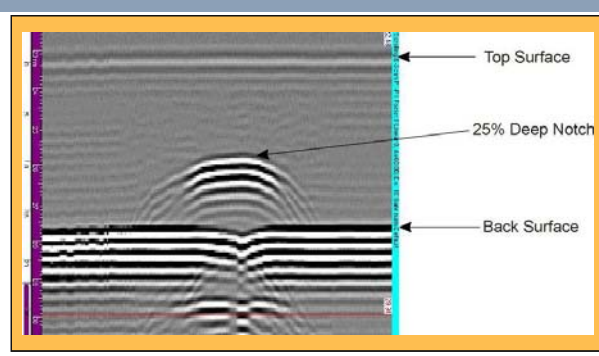
TOFD





$$d = 0.5\sqrt{(C\Delta T)^2 + (4C\Delta TS)}$$

d = Depth of crack tip from scanning surface

C = Sound velocity in the material

ΔT = Change in TOF between lateral wave and crack tip signal

S = Half the separation distance between the index points of the probes

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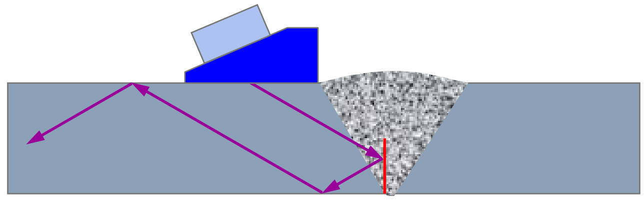
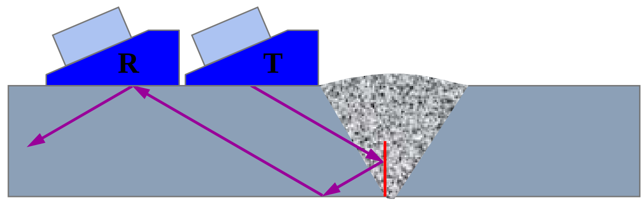
Reflection From Vertical Flaws

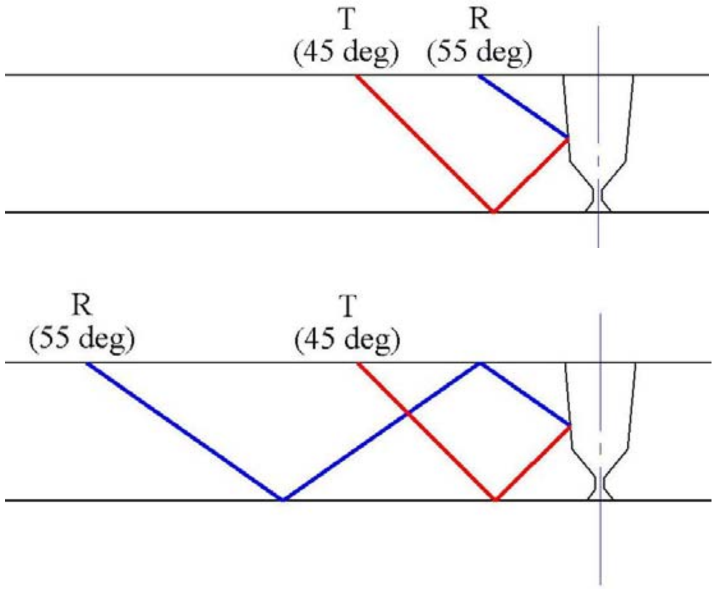
Pulse-Echo



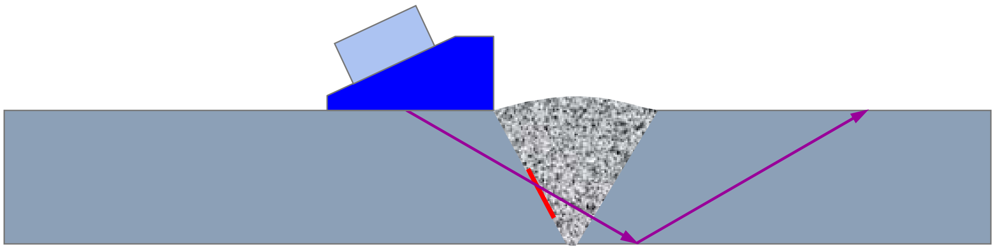
Tandem Pitch-Catch



Examples of Tandem Pitch Catch Techniques

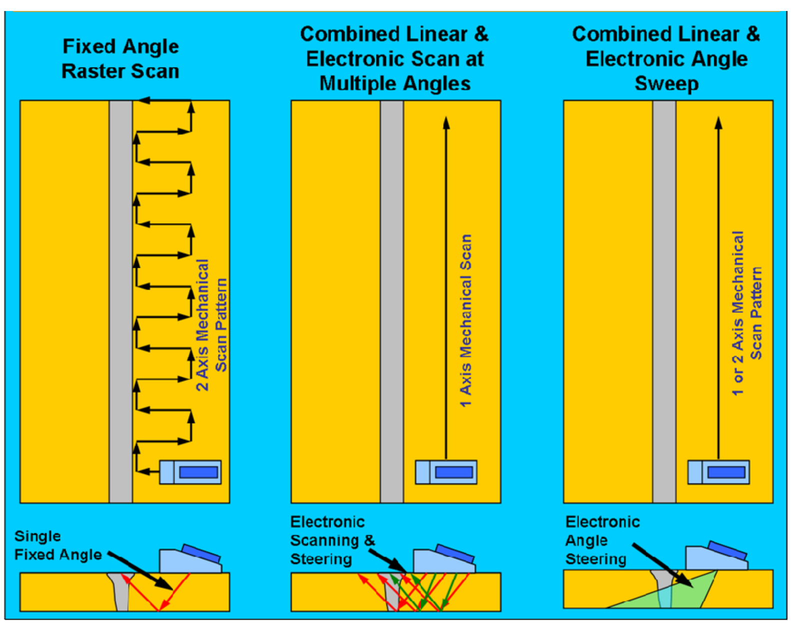


Conventional UT Weld Inspection Scan



Mechanical movement of probe provides good coverage of weld

Scanning Options



Phased Array ultrasonic inspection provides a means to combine conventional mechanical scanning with electronic focusing, steering, and scanning.

Eddy Current Inspection. Advanced Applications.

Exxon Mobil, March 2008

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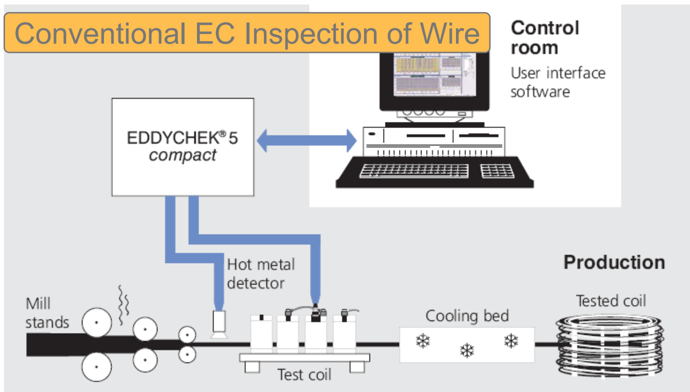
Outline

- Typical applications
- Advanced systems
- Weld inspection and material characterization
- Corrosion detection and sizing
- Magnetic permeability and electrical conductivity measurements used for material characterization
- Other techniques – MWM, RFEC, MFL, Pulsed EC
- Subsurface array inspection
- Current advanced applications

Typical Applications. Tube, Bar, Rod, Wire Mills

- Eddy current methods first large-scale industrial use during WWII
- Challenge – Detect flaws with 5% WT depth



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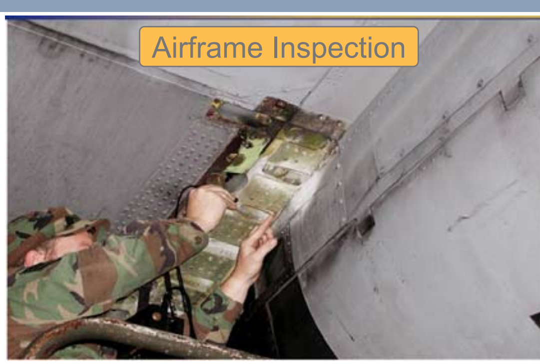
Typical Applications. Aerospace Frames and Jet Engines



- EC extensively used in Aerospace for inspection of airframes and engines – 50% to 80% of NDE
- Manual inspections for service and automated for manufacturing
- Typical inspections will look for surface and subsurface cracks and corrosion, small dents, inclusions, surface stress etc.

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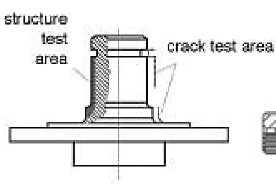
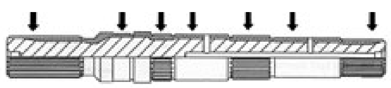
Typical Applications. Automotive Components





- Future applications related to introduction of new materials in high volume production
- Typical inspection tasks – sorting of materials, heat treatment control, case hardening depth, cracks, spot weld structure etc.

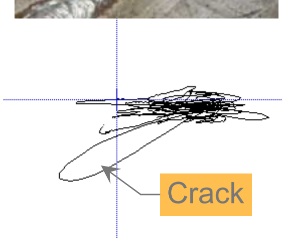
EWI THE MATERIALS JOINING EXPERTS

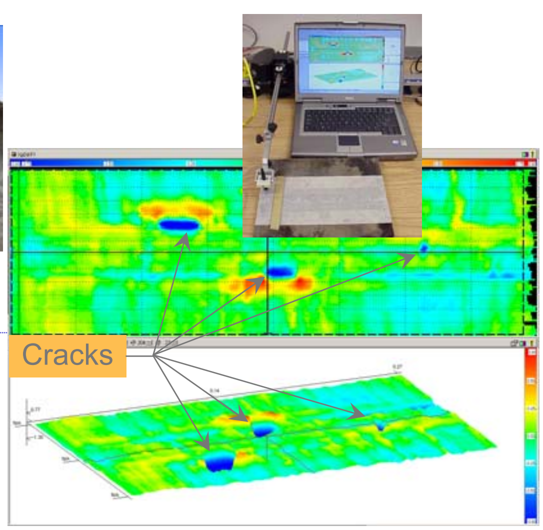
Conventional v. Advanced Eddy Current Techniques

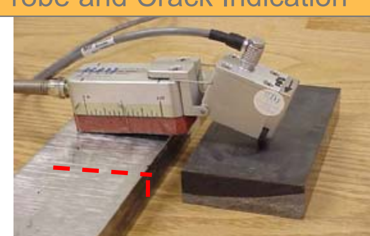
Conventional Probe and Crack Indication

Advanced Imaging - Same Probe and 3 Crack Indications

Fast Advanced Processing - Array Probe and Crack Indication

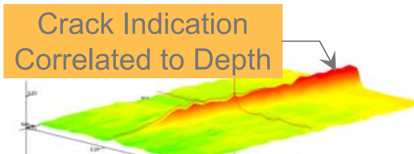






Crack in LF sample similar to crack in RH sample (sectioned)

Crack Indication Correlated to Depth



- Slow scanning
- Unreliable detection and sizing

- Reliable detection flaw sizing

- Fast and reliable detection and flaw sizing

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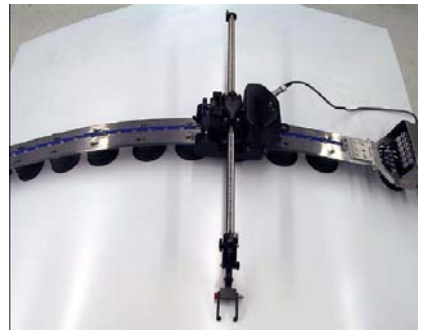
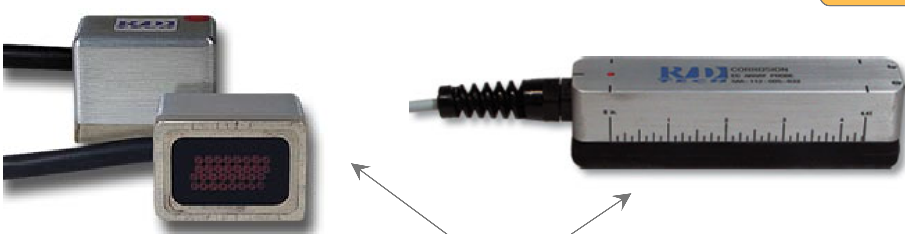
Eddy Current Multipurpose Array Systems

Up to 64 coils and 256 channels for conventional, array EC, magnetic flux leakage (MFL) and remote field eddy current (RFEC)

Portable eddy current array system for up to 32 coils

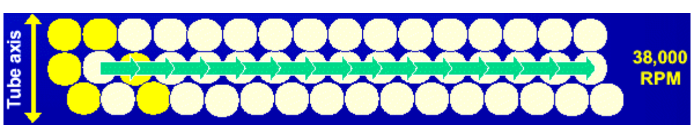


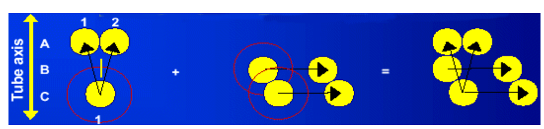
Scanner for Curved and Flat Surfaces

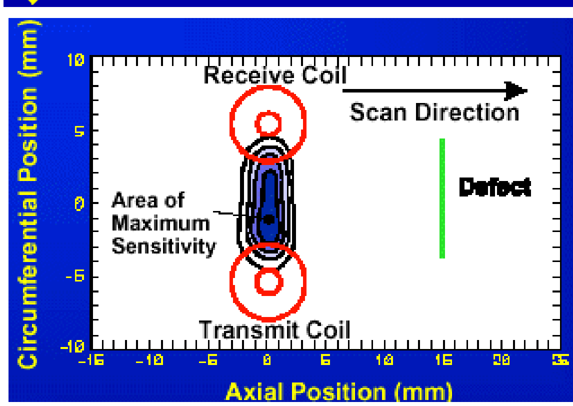


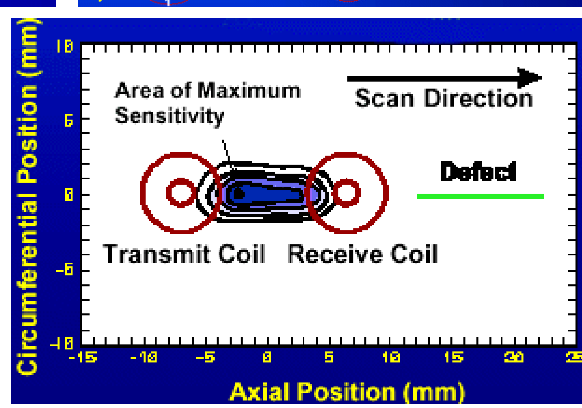
Array EC Probes

EC Array. Basic Principles





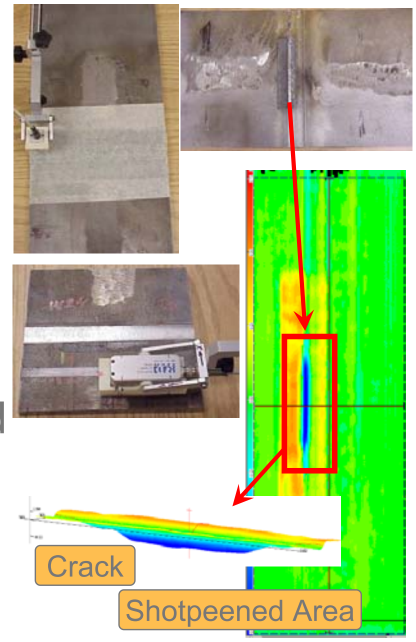




- Electronic scanning allows better and faster coverage
- Flaw at any orientation may be detected by electronically switching the coils
- Very high speed of scanning achieved

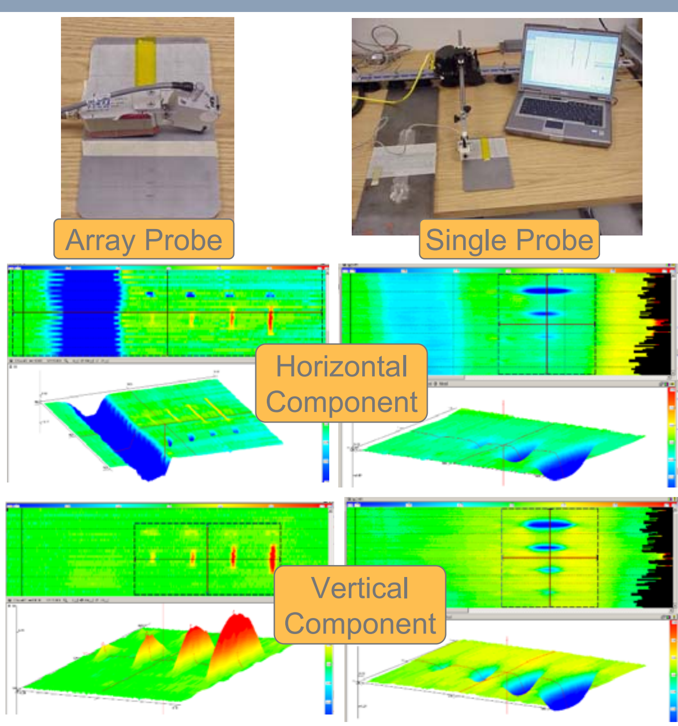
Fatigue Cracks in Heavy Structure

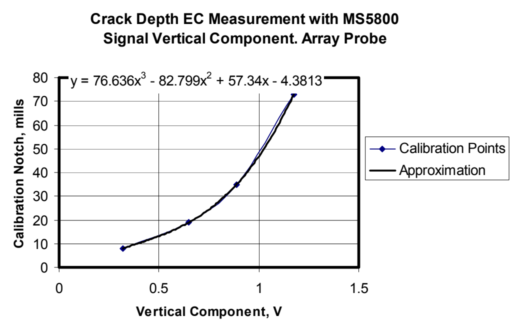
- **Problem** – Crack detection and sizing in HAZ with surface treatment under coating
- Inspection procedure modeled
- Seven welded specimens fatigued to produce cracks in area masked during shot peening
- Inspection area covered with tape to simulate paint
- Multiple scans performed with single and array probes at multiple frequencies for crack detection and sizing
- Three of specimens – crown removed, rescanned and fractured
- Performance of various EC technique validated and compared to magnetic particle and phased array ultrasonic



THE MATERIALS JOINING EXPERTS

Calibration for Sizing





- Calibration for depth sizing performed on EDM notches with variable depth (0.01" to 0.08") and length
- Sizing curves built for each frequency and probe (single and array)

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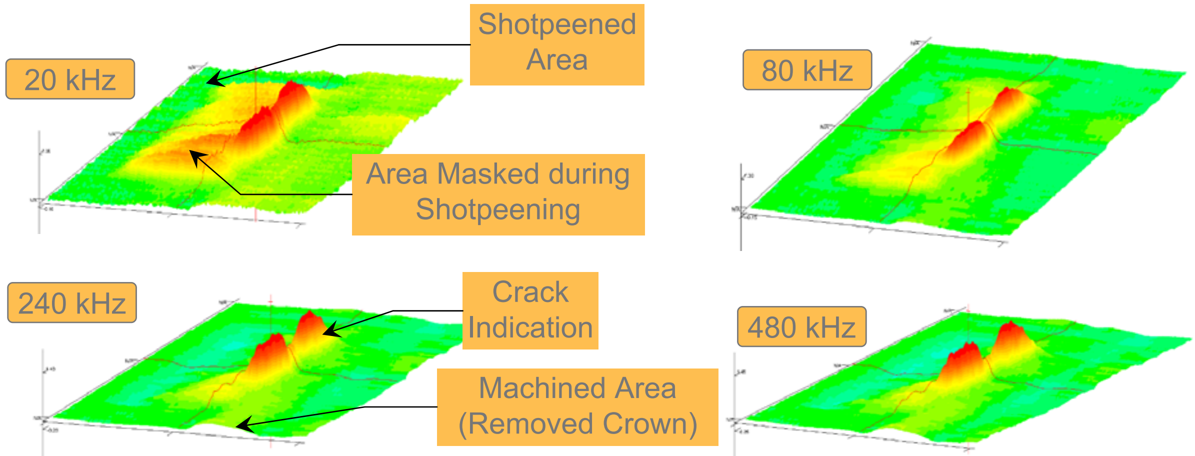
Multi-frequency Array Inspection



- Simultaneous 128 channel (32 coilsX4 frequencies) array inspection performed
- Signal to noise ratio and sensitivity to surface braking cracks improved at higher frequencies
- Lower frequencies better suited for deeper flaw measurements and surface treatment characterization

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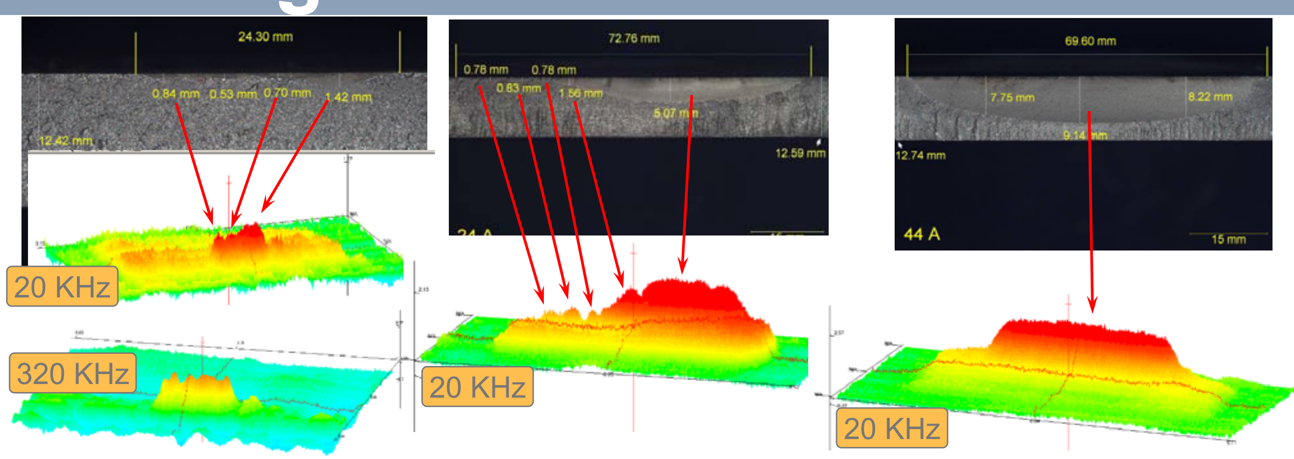
Detection and Sizing of Fatigue Cracks in HAZ



- Three specimens fractured and indications compared to crack topography and size
- High resolution demonstrated in detection, separation and sizing of small cracks <0.04” depth
- Deep cracks reliably classified due to limited depth of penetration <0.08” (truncated indications)
- Surface treatment detected and separated from cracks

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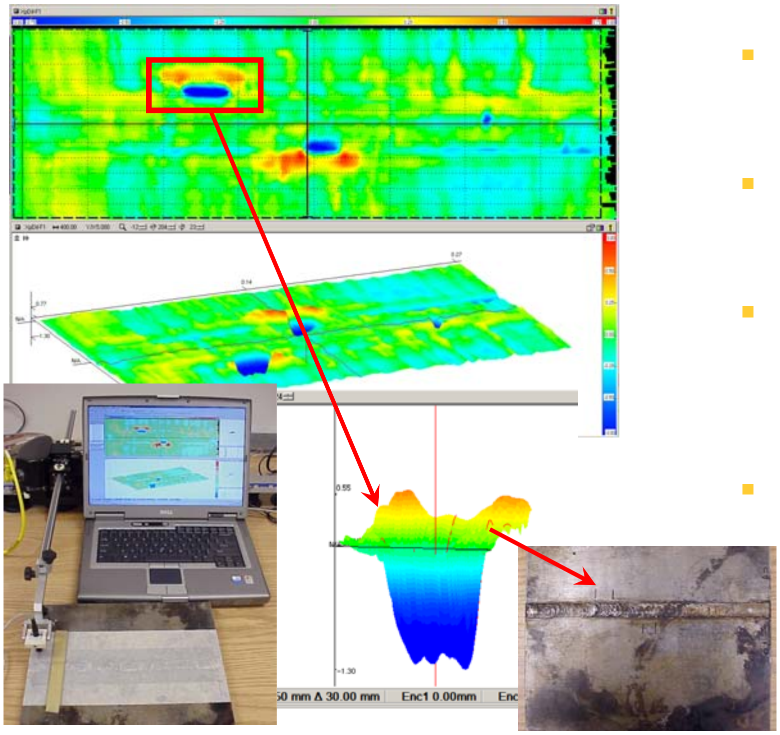
Thermomechanical Cracks in Pipes and Pressure Vessels



- **Problem** – Crack sizing in piping and pressure vessels under coating
- 3 cracks shape and location easily detectable (dark blue spots)
- Largest crack size as fabricated:
  - Length - 25mm,
  - Depth - 15mm
- Eddy current estimated crack size:
  - Length - 21mm,
  - Depth - > 2mm

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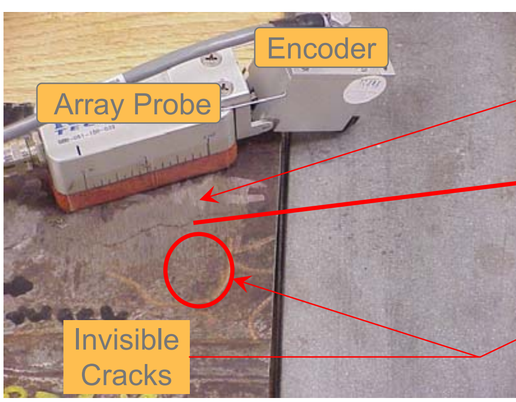
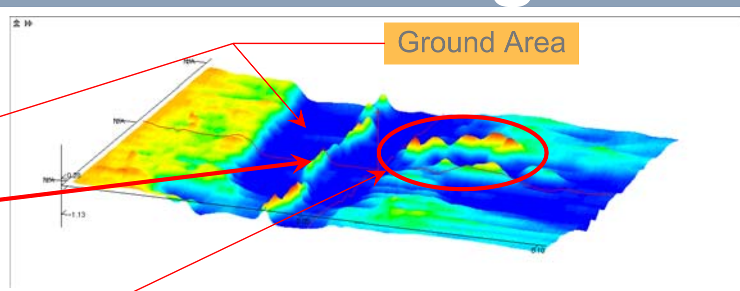
Thermomechanical Crack Detection after Grinding





- Ferromagnetic steel with rough surface after grinding – challenging application
- Crack shape and length are easily measured
- Depth measurements possible after adequate calibration
- Record available

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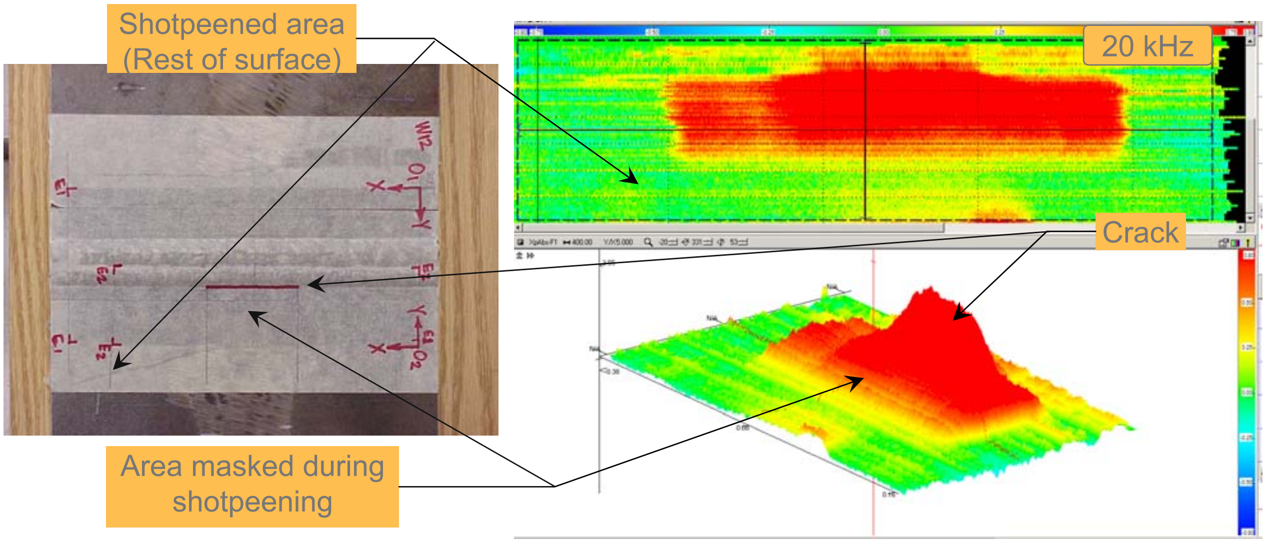
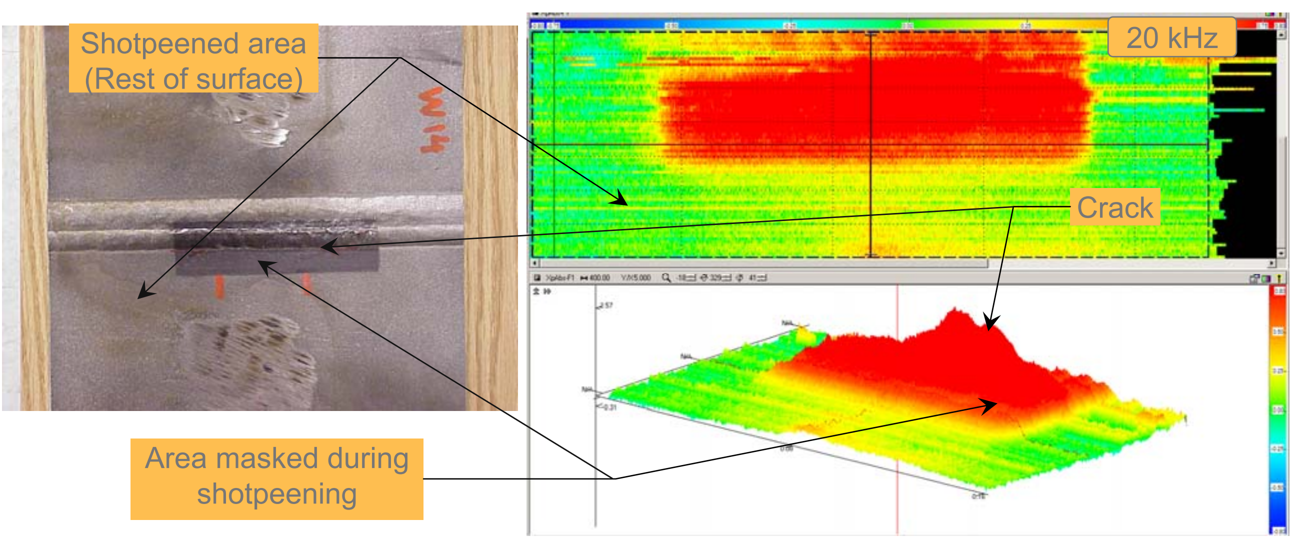
Specimen W12. Shotpeening Effect



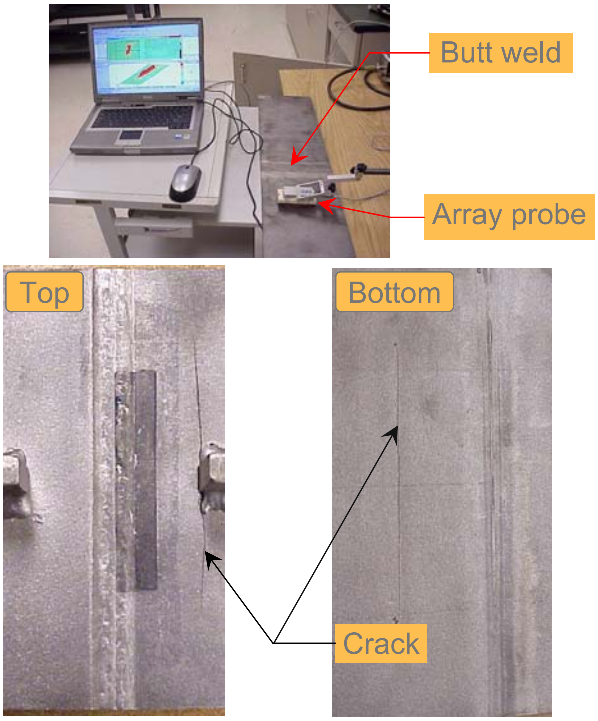
- Eddy current C-Scan and Isometric view of area with fatigue crack with and without shotpeening
- Absolute probe

Specimen W14. Shotpeening Effect



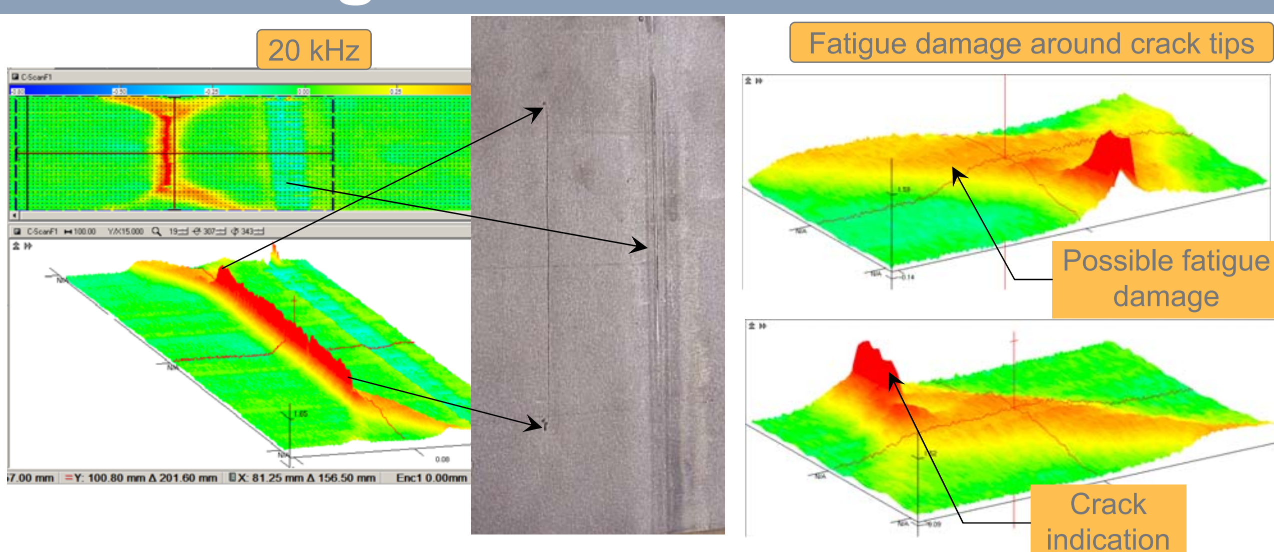
- Eddy current C-Scan and Isometric view of area with fatigue crack with and without shotpeening
- Absolute probe

Specimen W11 Tension Fatigue Damage. Slide 1



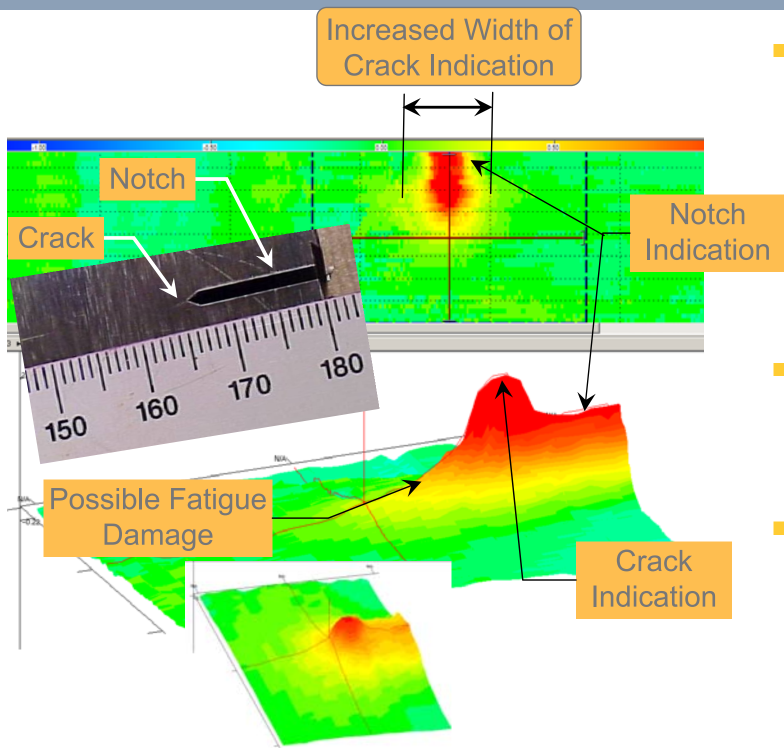
- Two welds loaded on tension
- Cracks initiated at attachment fillet welds
- Bottom surface of specimens inspected with array eddy current techniques

Specimen W11 Tension Fatigue Damage. Slide 2



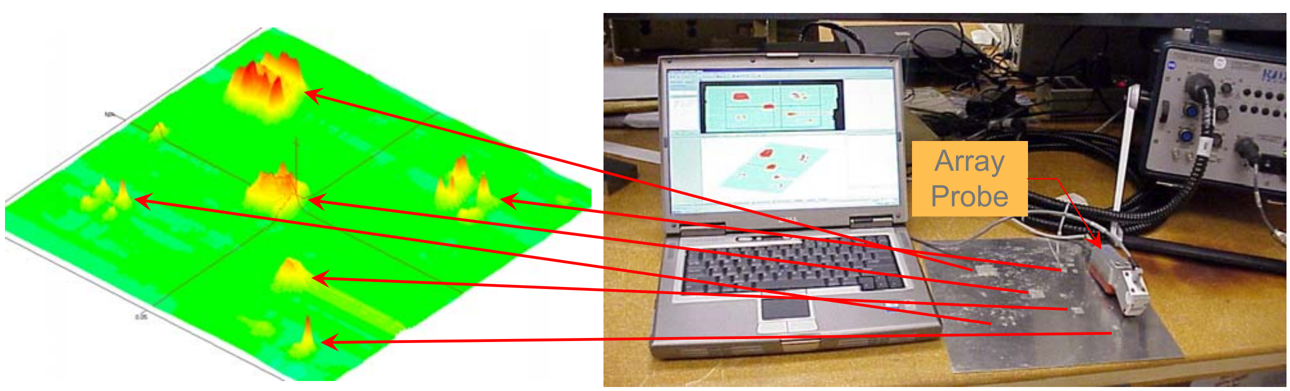
- Large crack and advancing fatigue damage clearly separated
- Early NDE detection of stress/strain metal will help prevent failures of critical elements

Fatigue Damage Detection



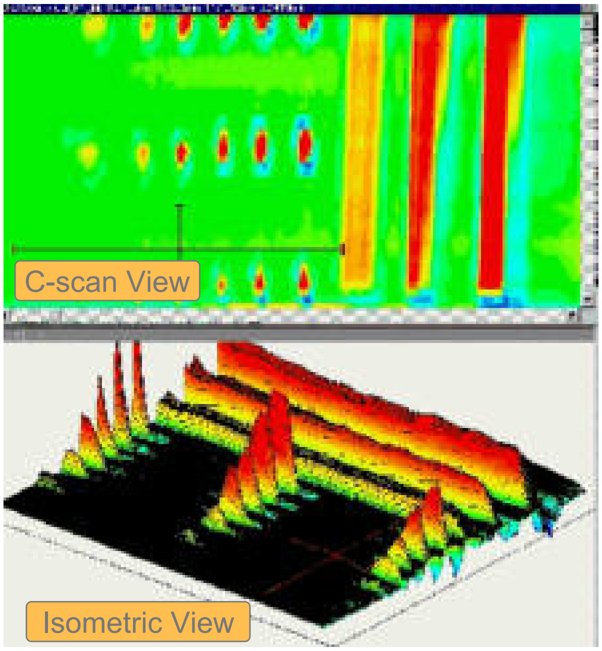
- **Problem** – Early detection of fatigue damage (stress, plastic deformation, microcracking)
  Starter notch and fatigue crack at notch tip well separated
- Affected area surrounding crack and notch tip larger than the rest of notch
- Possible to detect early fatigue damage (microcracks and stresses)

EC Array. Surface Corrosion Measurements



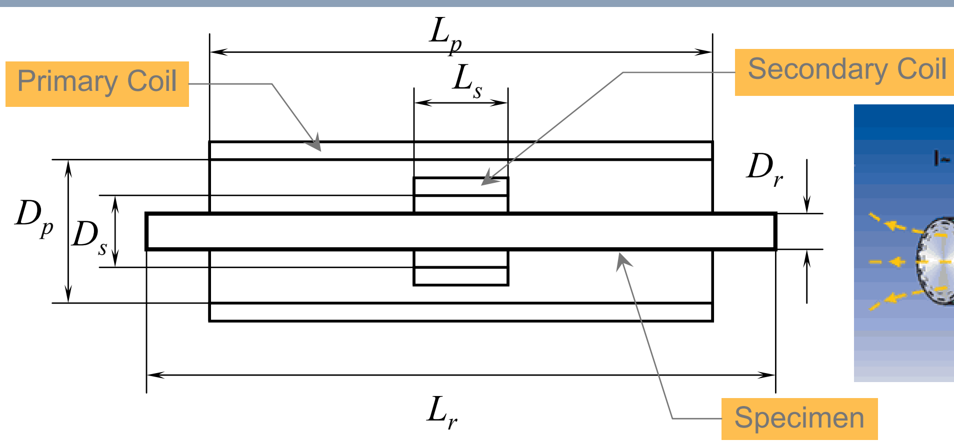
- **Problem** – Surface corrosion hidden under paint
- Eddy current techniques extremely sensitive to surface irregularities
- Very shallow (under 0.001 in.) surface corrosion is detectable and sizeable even under paint

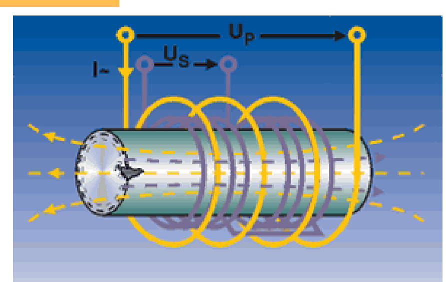
EC Array. Subsurface Corrosion Measurements



- Specimen simulating corrosion loss on bottom surface scanned from top surface with array probe
- C-scan and isometric view presentations intuitive and easy to interpret
- Color and height of images proportional to loss
- Very high speed of scanning

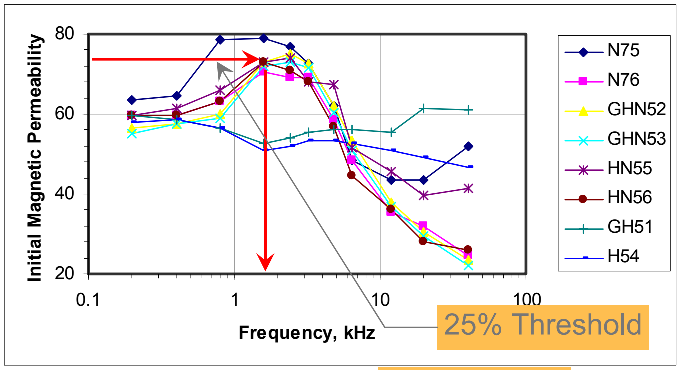
Electromagnetic Property Measurements

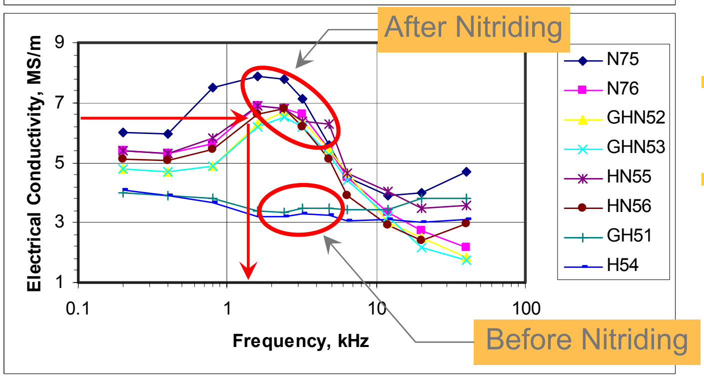




- Steel rods in uniform field of encircling probe
- Possible to solve inverse problem - find steel electrical conductivity and magnetic permeability measuring coil's electrical parameters
- Mathematical modeling involved to link coil's electrical parameters to steel electrical conductivity and magnetic permeability

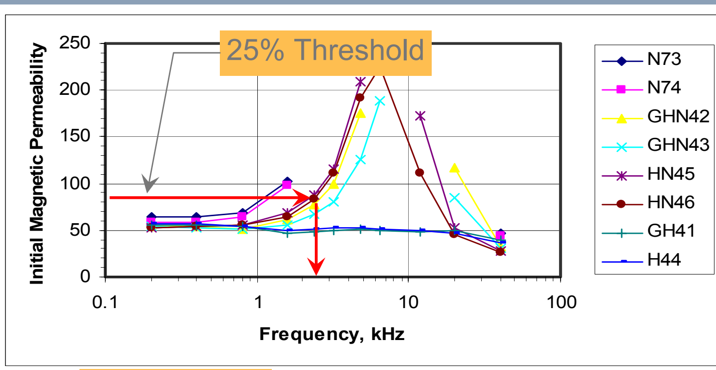
Electromagnetic Property Measurements. Case Hardening Depth. Long-time Nitriding Effect

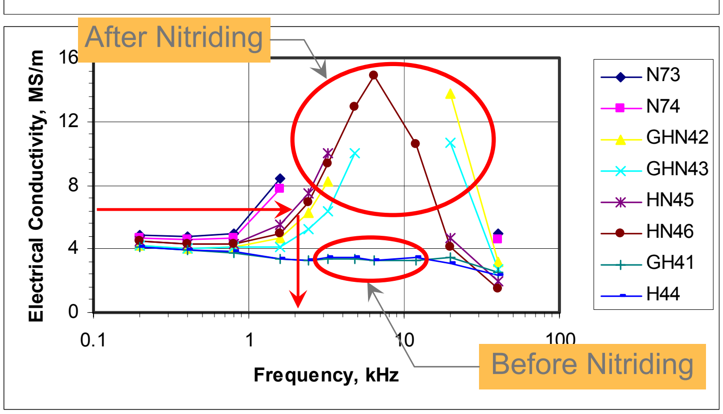




- **Problem** – NDE measurement of case hardening depth
- Ion nitriding for 18 hours at 540°C
- Significant difference in properties before and after nitriding
- Characteristic peak at certain frequency/depth
- 25% increase of electromagnetic properties at ~1.5 kHz

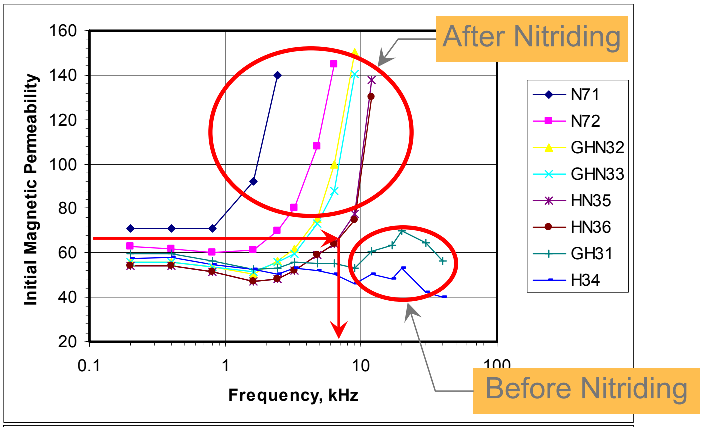
Electromagnetic Property Measurements. Case Hardening Depth. Mid-time Nitriding Effect

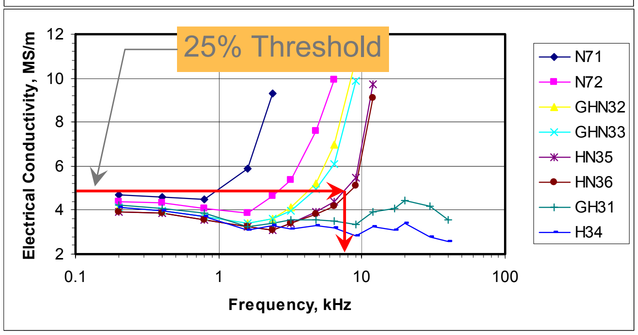




- Ion nitriding for 12 hours at 540°C
- Significant difference in properties before and after nitriding
- Characteristic peak at certain frequency/depth
- 25% increase of electromagnetic properties at ~2.1 kHz

Electromagnetic Property Measurements. Case Hardening Depth. Short-time Nitriding Effect

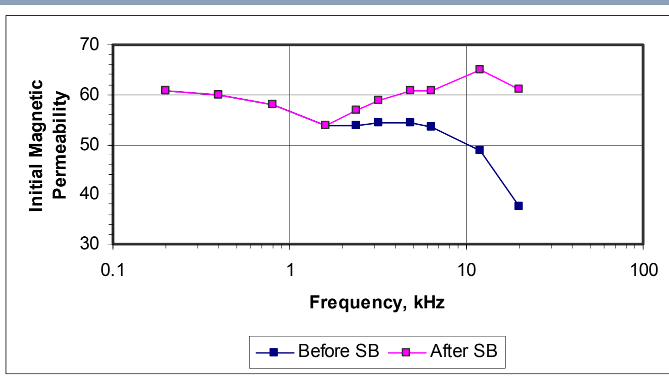


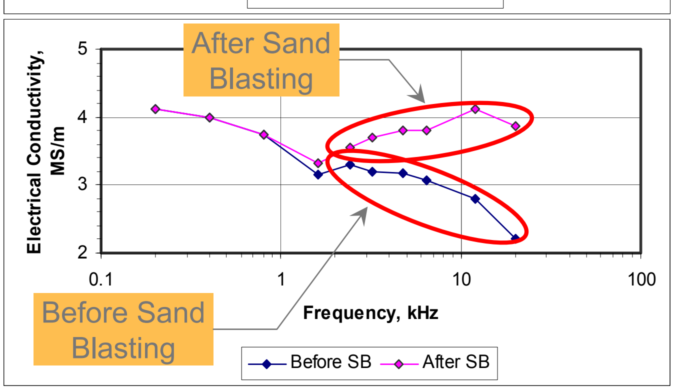


- Ion nitriding for 4 hours at 520°C
- Significant difference in properties before and after nitriding
- Characteristic peak might be outside of used frequency range
- 25% increase of electromagnetic properties at ~7 kHz

THE MATERIALS JOINING EXPERTS

Electromagnetic Property Measurements. EC Depth Scan. Sandblasting Effect

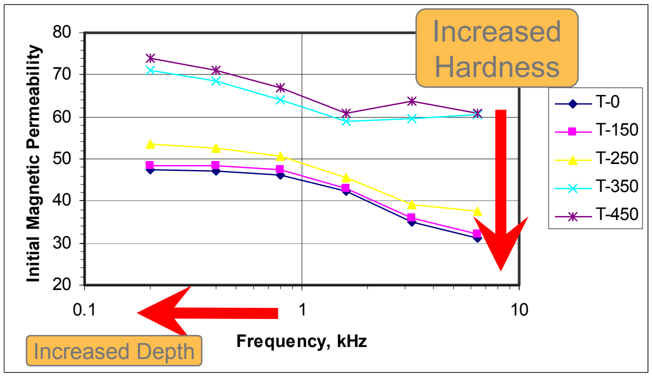


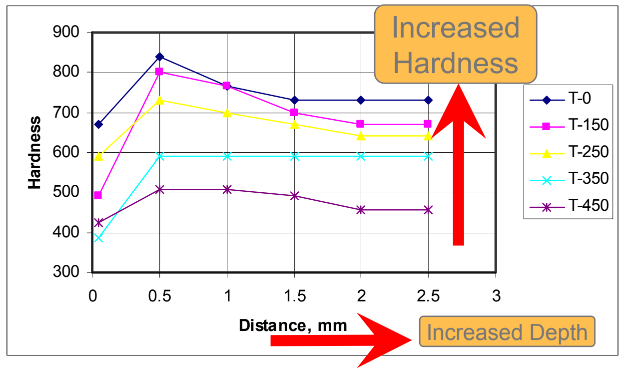


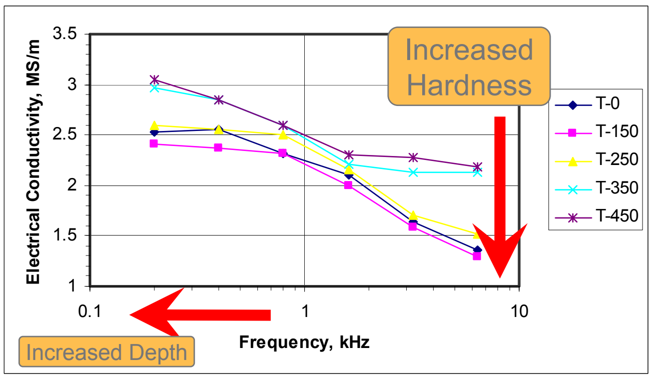
- Sand blasting (SB) performed on specimens to remove oxide after hardening and tempering before nitriding
- Noticeable increase in properties close to surface before and after SB
- EC techniques sensitive to degree of SB

THE MATERIALS JOINING EXPERTS

Main Applications of EC Testing. Part Composition. Hardness Scan

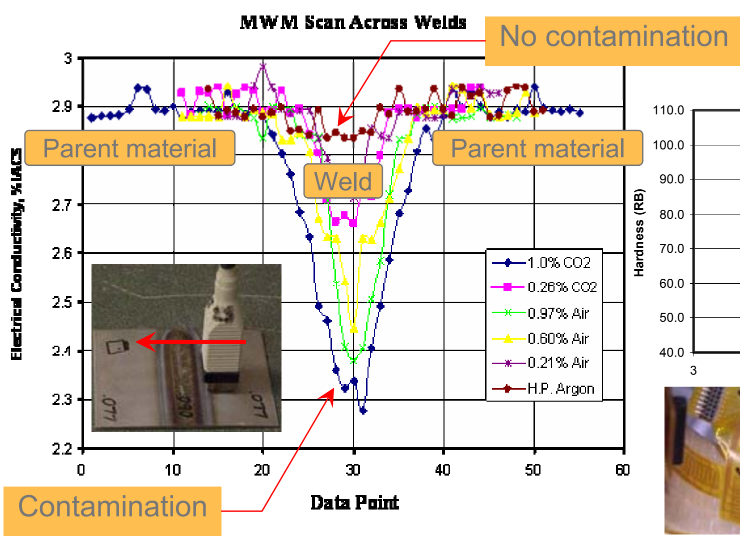






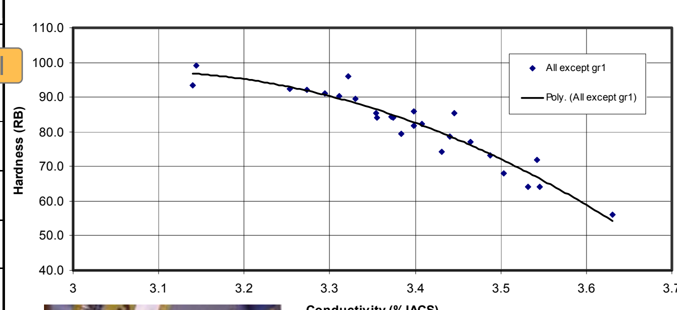
- **Problem** – NDE measurement of hardness
- 5 groups with increased hardness (HV) from group to group
- EC measurements strongly correlated to hardness

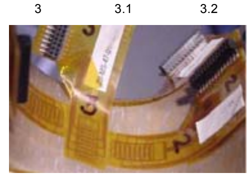
Electromagnetic Property Measurements. Detection of Air Contamination in CP Titanium with MWM



Hardness vs Conductivity

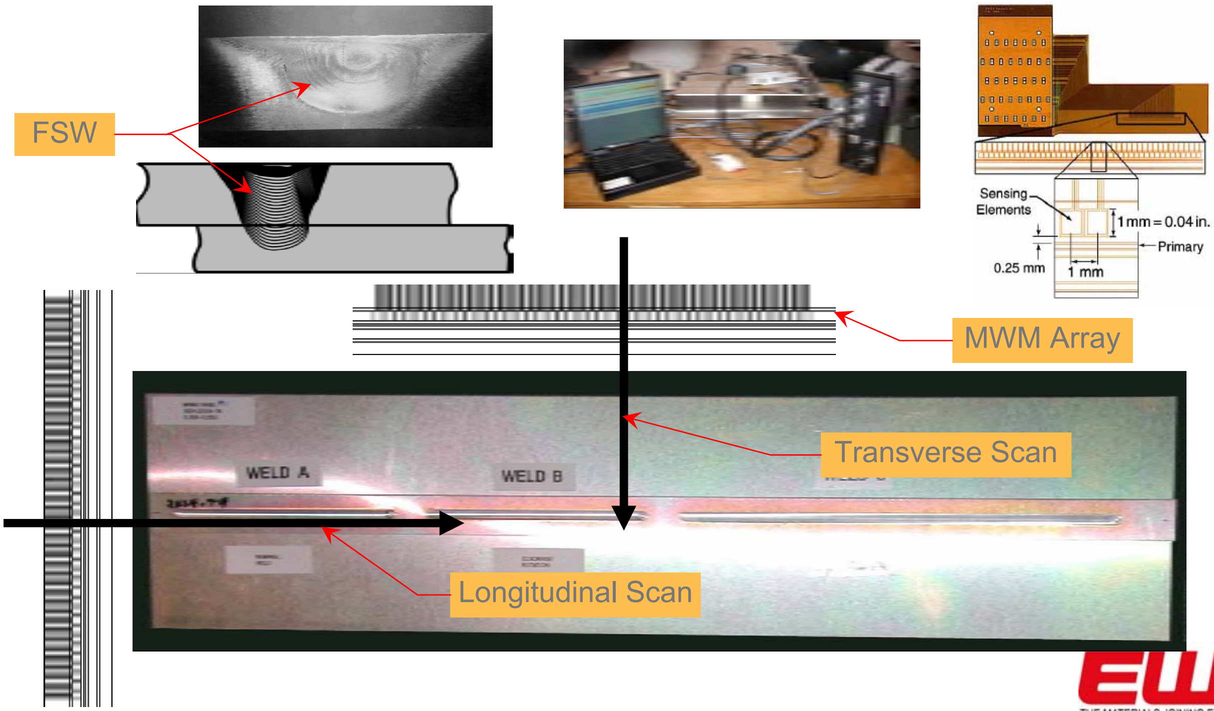
(Combined Data for Gr. 2 & Gr. 4 Base Metal)



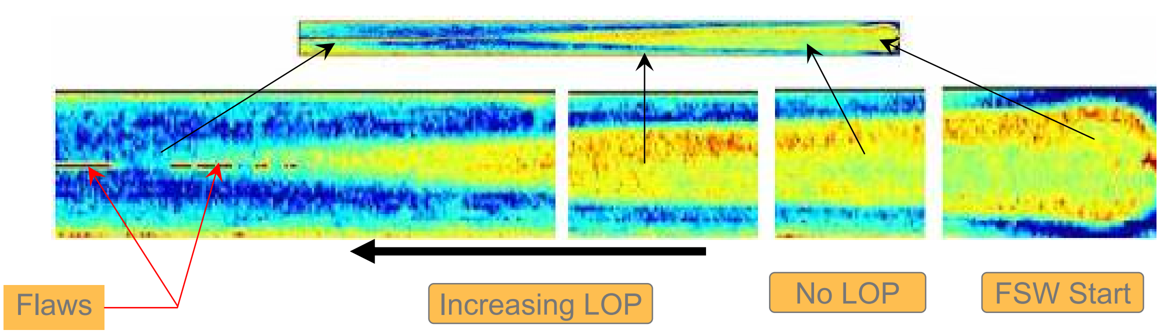


- Use of EC conductivity measurements for air contamination detection in CP titanium alloys welds demonstrated in the past at EWI
- Strong correlation established between conductivity and hardness
- Previous experience used to solve similar problem in reactive alloy welds

Electromagnetic Property Measurements. MWM for FSW Inspection

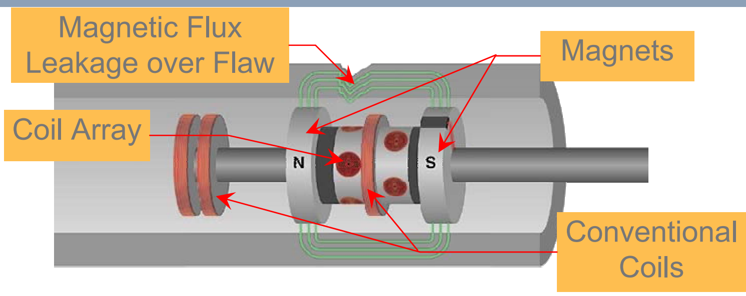


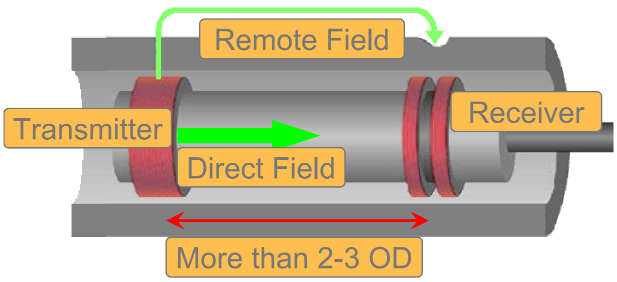
Electromagnetic Property Measurements. MWM C-Scan Conductivity Profile of FSW



- Study indicated that property/conductivity profile might be indicative of weld quality

MFL and RFEC Basics





- Ferromagnetic tube inspection requires different approach
- Both techniques used extensively for heat exchanger tubes and pipeline inspection

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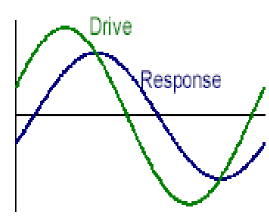
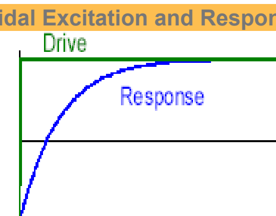
Pulsed Eddy Currents (PEC). General

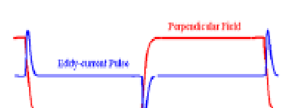
- Pulsed eddy currents created by pulsed excitation voltage
- Pulsed signals contain many frequencies simultaneously
- Different frequency components have different penetration in material
- Additional automated signal processing required to extract data from different depths



Sinusoidal Excitation and Response



Pulsed Excitation and Response



Eddy Currents and Magnetic Field (Red)

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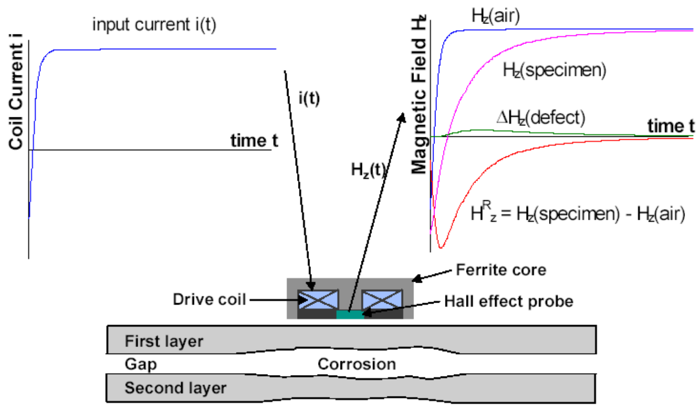
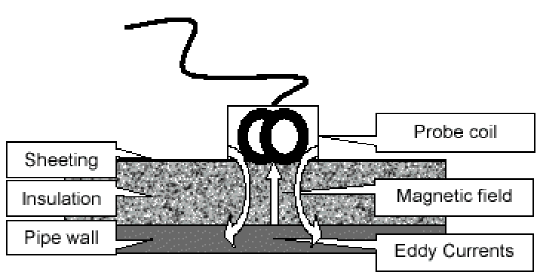
PEC. Basic Principles

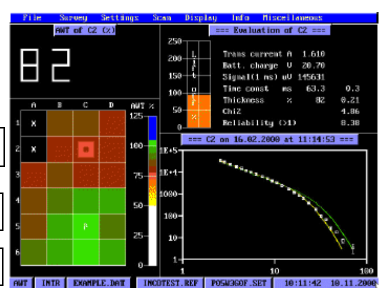
- Similarities with other eddy current techniques
  - Signals depend on part conductivity and magnetic permeability, distance between the coil and material and part thickness if penetration through the thickness is possible
  - Signal from air or on defect free area can be used as reference to provide necessary sensitivity and resolution
- Hall effect devices/probes used as receivers instead of coils to take advantage of broad-band frequency signal content

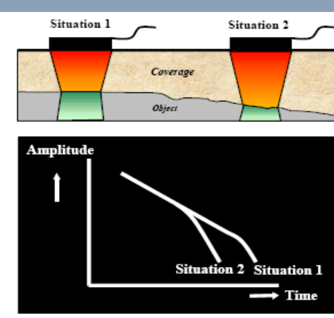


THE MATERIALS JOINING EXPERTS

PEC. Measurement of Pipeline Corrosion through Insulation







- Specialized instrument developed mostly for OD corrosion
- Claimed to work through nonconductive and nonmagnetic insulation up to 6”
- Due to low pulsing frequency, thin metal sheets in insulation may have little effect on measurements (subject to verification)
- Applicable to ferromagnetic substrate materials only
- Test spot min diameter is approximately 1” at optimal distance and insulation material
- Resolution and sensitivity are insufficient to detect small flaws in substrate

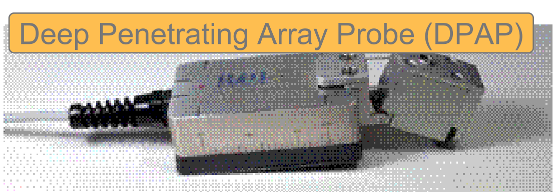
Robers, M.A., R. Scottini, Pulsed Eddy Current In Corrosion Detection, Röntgen Technische Dienst bv, 8-th European Conference on NDT, Barcelona, June 2002

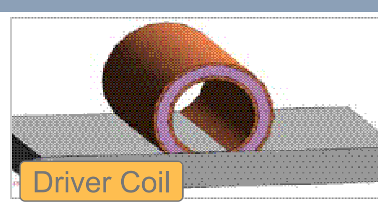
THE MATERIALS JOINING EXPERTS

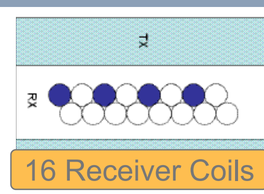
PEC. Advantages and Disadvantages

- Advantages
  - Pulsed excitation offered certain advantages in the past when fast multiplexing and processing of single frequency signals was technological challenge (not any more)
  - Post-processing used to extract different parameters (surface and subsurface) from the same set of data
  - Fast scanning and reduced cost for hardware
- Disadvantages
  - Broadband signal does not allow to achieve levels of sensitivity and resolution typical for many of multi-frequency (multiplexed or parallel) sinusoidal excitation techniques
  - Frequency contents of pulse excitation current (not voltage) is difficult to control which also reduces sensitivity and resolution to some flaws and conditions

Jet Subsurface Wing Spar Inspection

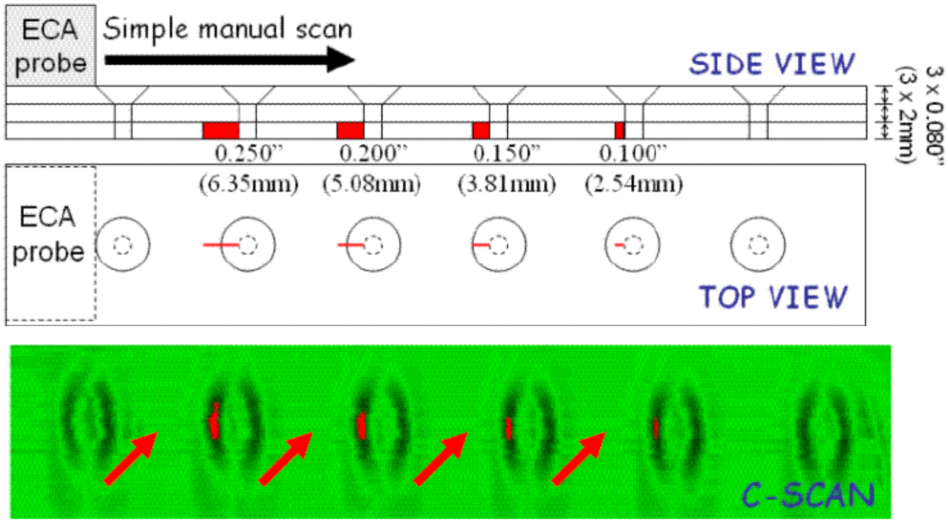






- In-service wing inspection required
- Small flaws (0.1”-0.25”) under thick first layer targeted
- Experimental specimens and modeling critical to optimize technique performance

Scan of Aircraft Structure with DPAP



- New technique capable of detecting small flaws under ~0.16" thick layers
- Challenge – Skin may even be thicker than this

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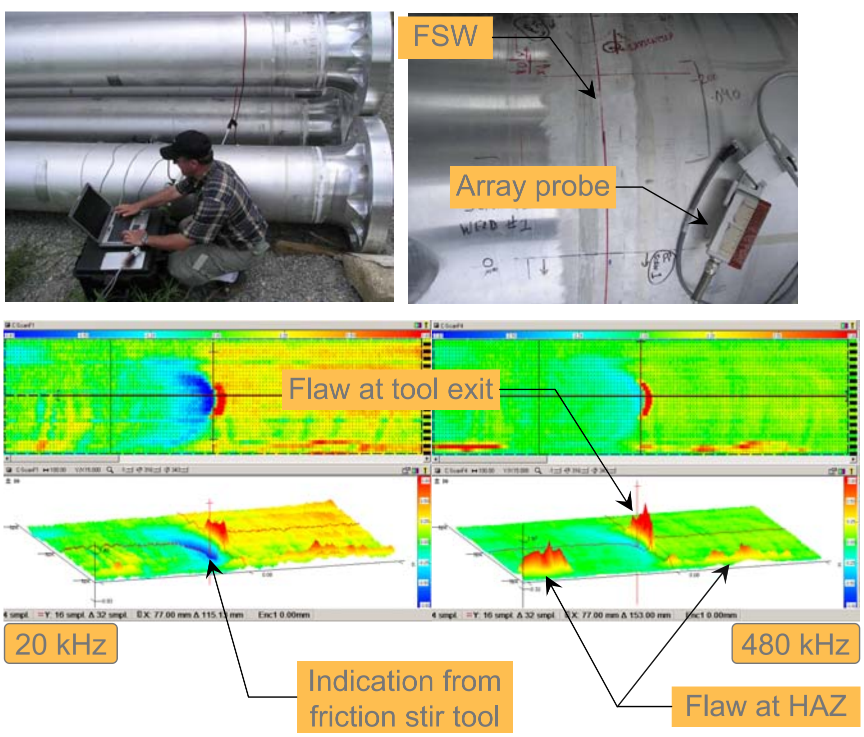
Multi-frequency EC Array Inspection of FSW in Aluminum Alloys



- Weld joints failed pressure test
- Several conventional (UT, TOFD, PT) and advanced (phased array 10MHz UT, ACFM) NDE failed to detect any surface flaws
- Only array EC advanced techniques detected and mapped flaws

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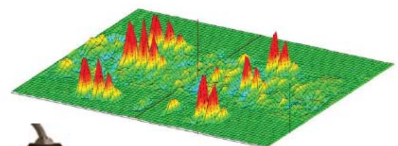
Current Development at EWI (50929GTO)

Flexible array for smooth transitional areas

- Currently, arrays for smooth transition and low conductivity areas available. Need customization for specific tasks
- Need for flexible eddy current arrays for sharp transitional areas (weld toe, fillet welds etc) and carbon steel
- No removal of crown required
- Increased speed and reliability
- Superior data presentation



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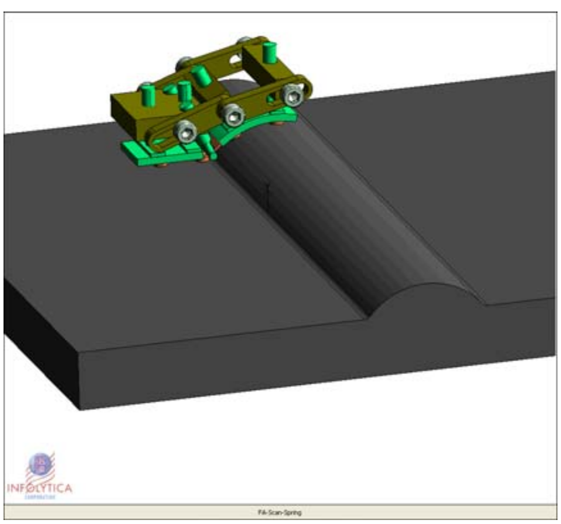
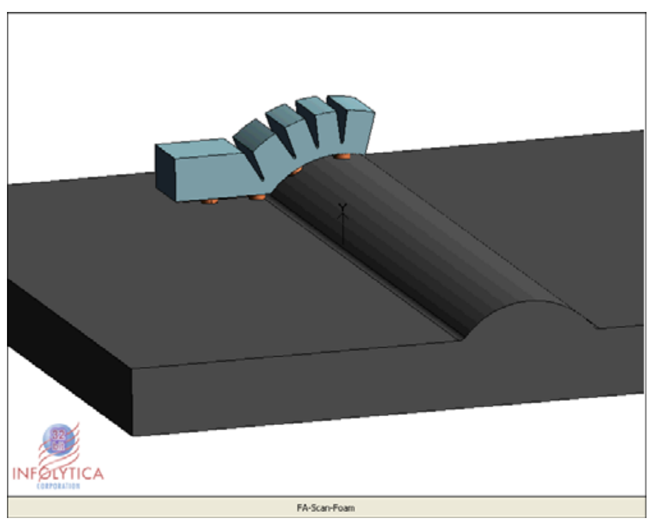
Scan Patterns Animations





- Next steps
  - Prototyping
  - Demonstration and validation of approach, detection and sizing capabilities
  - Service application

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Conclusions

- Eddy current inspection method covers broad range of inspection applications
- New array technology makes inspection faster and more reliable
- Multi-parameter examination – flaw detection, material characterization, surface and subsurface
- Modeling takes on new roles for material characterization
- New challenging applications will emerge with introduction of advanced technologies

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Eddy Current Inspection. Modeling of EC Techniques

Exxon Mobil, March 2008

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Outline

- Introduction
- Model verification
- Surface inspections
  - Lift-off modeling
  - Modeling of notch opening width effect
  - Pencil probe over aluminum coated steel substrate
- Subsurface Inspections
  - Sliding probe over multilayer structure modeling
  - Spot probe over multilayer structure
- Tube inspection
- Property measurement through modeling
- Conclusions

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Why Model?

- Limited resources to justify technique performance
- Long time between specimen development, order, delivery and physical trials (6 to 12 months)
- Possible overlooks during specimen development and manufacture
- Impossible to optimize the equipment, probe performance, and inspection procedure before the physical trials
  - Lack of versatility once the specimens are built
- Expensive and time consuming to justify "worst case scenario" and "false calls"

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Modeling Approach

1. Analyze the inspection task
2. Determine geometry and instrumentation critical modeling parameters
3. Build models of the probe, inspection area, and scanning pattern
4. Interact the probe with areas with and without flaws and geometry features
5. Interpret the modeling results. Compare and verify the model predictions with experimental data and previous experience
6. Improve the model if necessary

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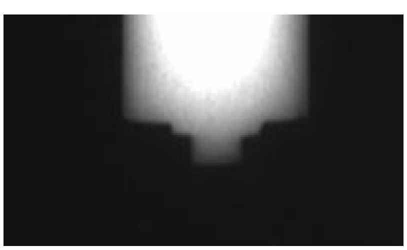
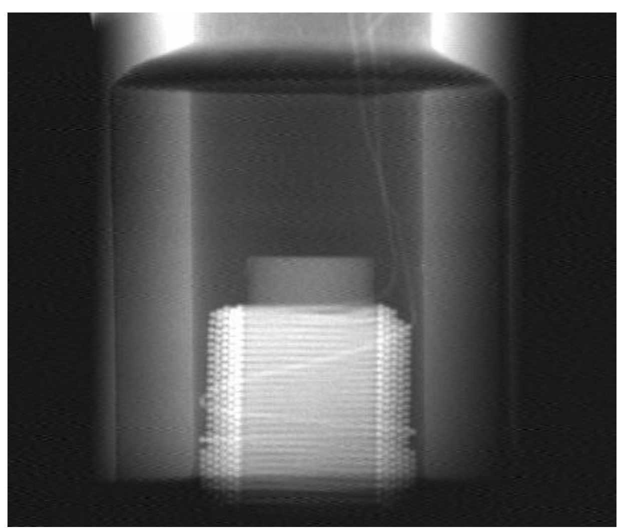
Probe Characterization

Picture of 1/8" Probe



Conventional X-Ray of Probe Tip



Micro-focus X-Ray

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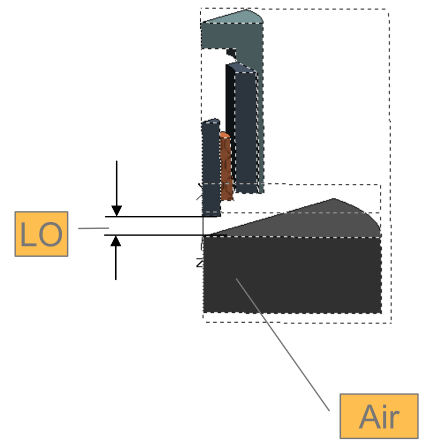
2D FEM. Model Validation in Air

	Freq	Rs	Ls
	kHz	Ω	µH
Measured	75	8.9212	111.943
Modeled	75	8.208	113.488
Error,%		**7.99**	**-1.38**
Measured	100	9.4835	111.941
Modeled	100	9.115	112.960
Error,%		**-3.89**	**-0.91**
Measured	200	13.182	111.897
Modeled	200	13.787	111.433
Error,%		**-4.59**	**0.41**
Measured	400	26.029	112.17
Modeled	400	26.476	109.910
Error,%		**-1.72**	**2.01**



- High accuracy of modeling achieved

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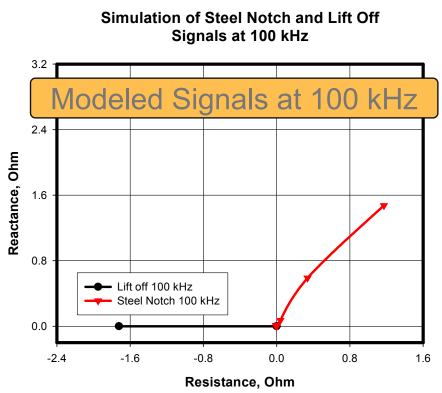
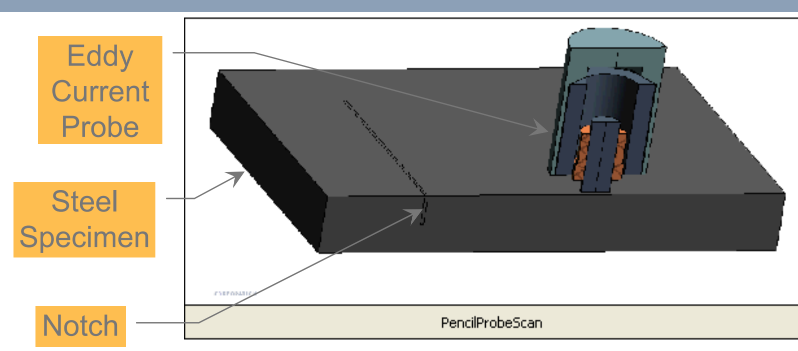
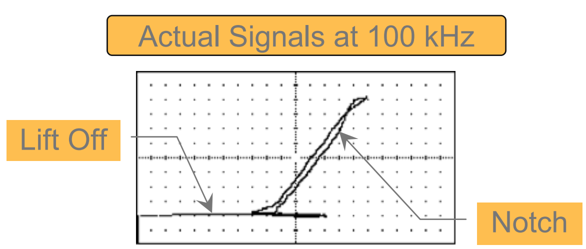
3D FEM. Model Verification on Material with Notch







- Modeled complex probe geometry
- Modeled signals compared well with actual signals

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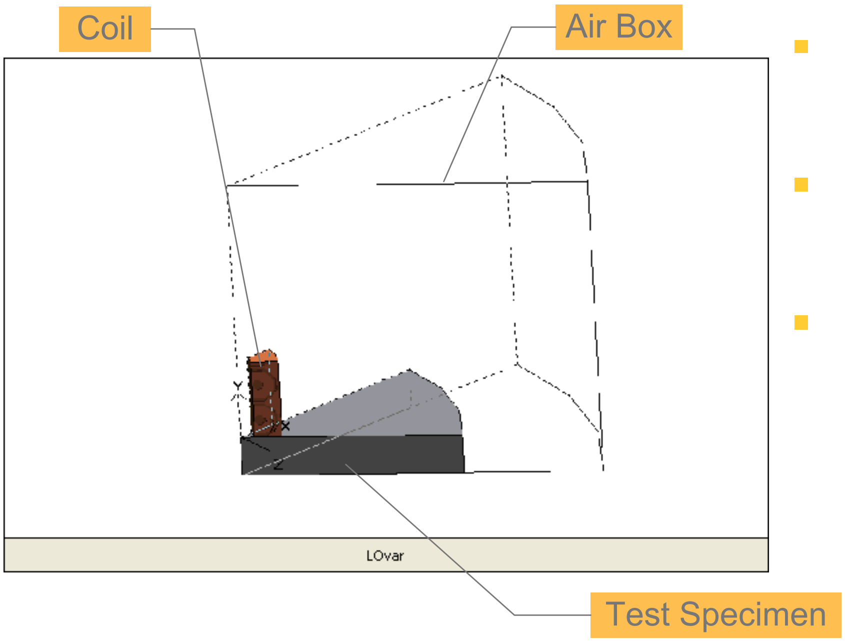
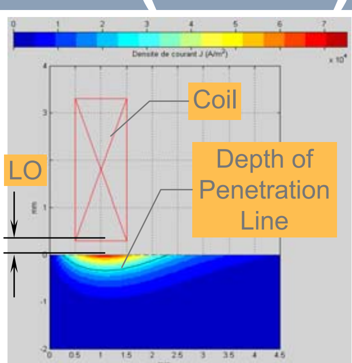
Lift Off (LO) Modeling



Animation of LO

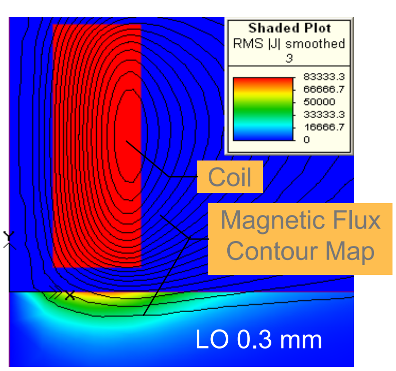
- LO – Distance between probe face and test piece
- In procedures, LO signal reference to other signals
- Top surface corrosion, nonconductive and nonmagnetic coatings increase LO

LO. Eddy Current Density (ECD) Distribution



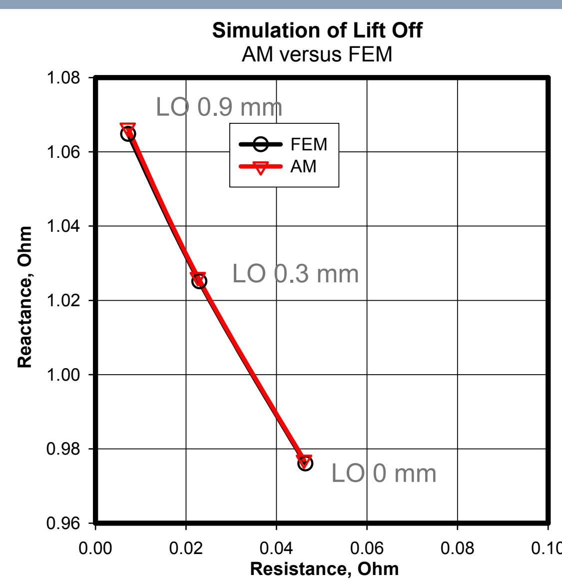
Analytical modeling of LO and ECD

No account for currents in the coil on the map



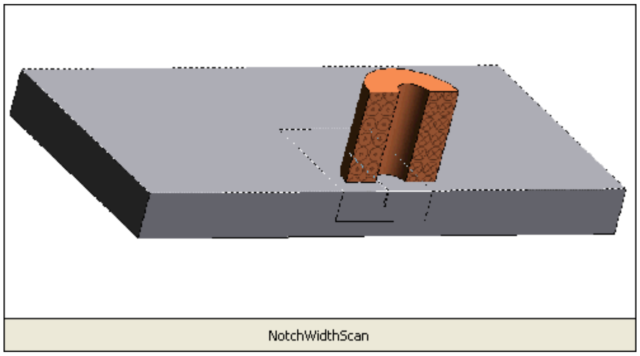
Finite element modeling of LO and ECD

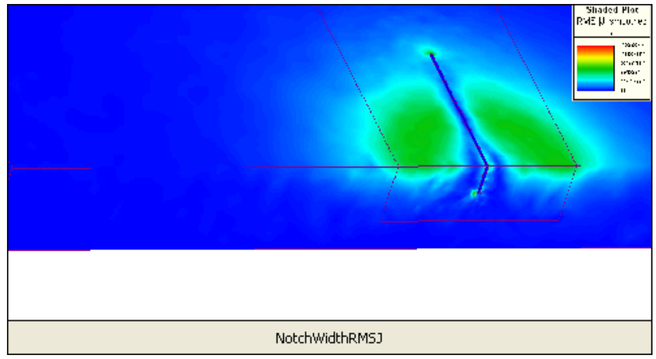
Currents in the coil shown on the ECD map



Impedance values calculated with the AM and FEM almost identical

Modeling of Notch Opening or Width





Animation of scan path and notch width

Animation of ECD versus notch position and width

- Artificial notches used for calibration for surface inspection have width larger than the cracks to be detected
- At horizontal LO, studies and field experience indicate:
  - Small variations of notch width do not affect significantly reactance component
  - Notch decreasing width at constant depth and length causes resistance component of the notch signal to decrease

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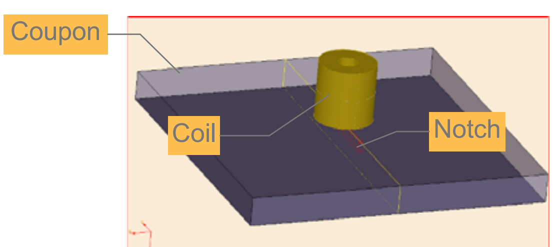
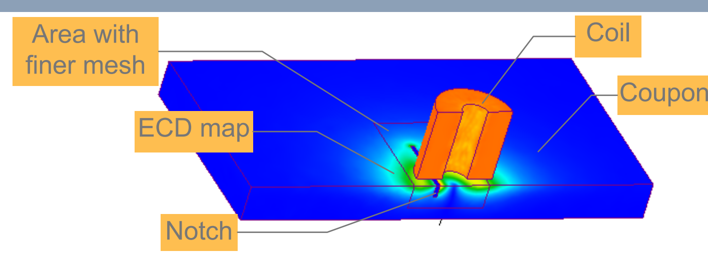
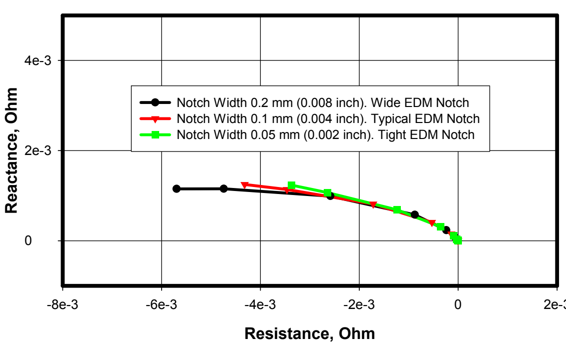
Notch Opening. Comparison of AM and FEM

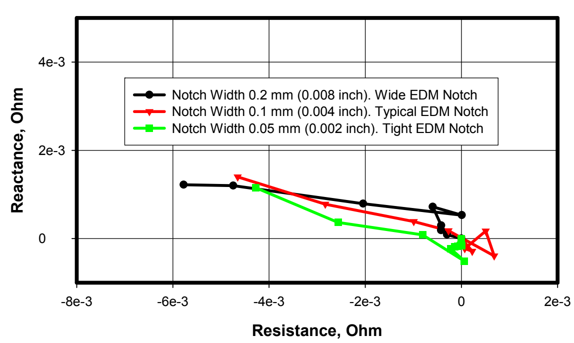




Simulation of Calibration Notch Width Effect (AM)
Notch Depth Constant at 0.5 mm (0.02 inch)



Simulation of Calibration Notch Width Effect (FEM)
Notch Depth Constant at 0.5 mm (0.02 inch)



Comparison between amplitude and phase for the various widths is very good

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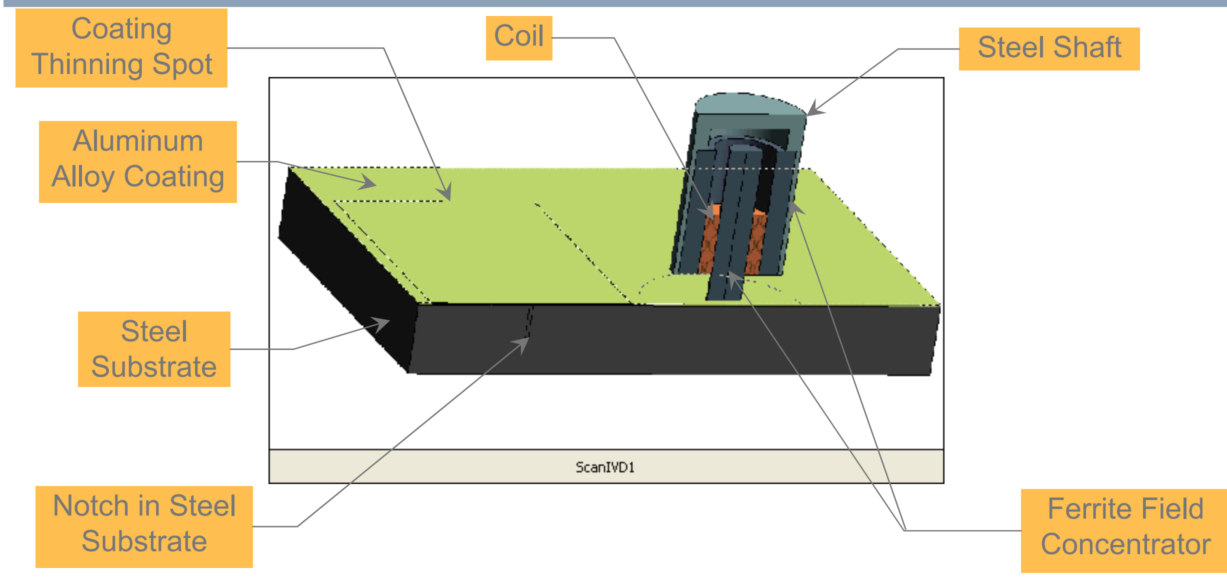
Surface Probe (SP) over Aluminum Coated Steel Substrate



- Difficult problem to study with specimens
- Relatively large flaws might be missed under the coating at high frequencies

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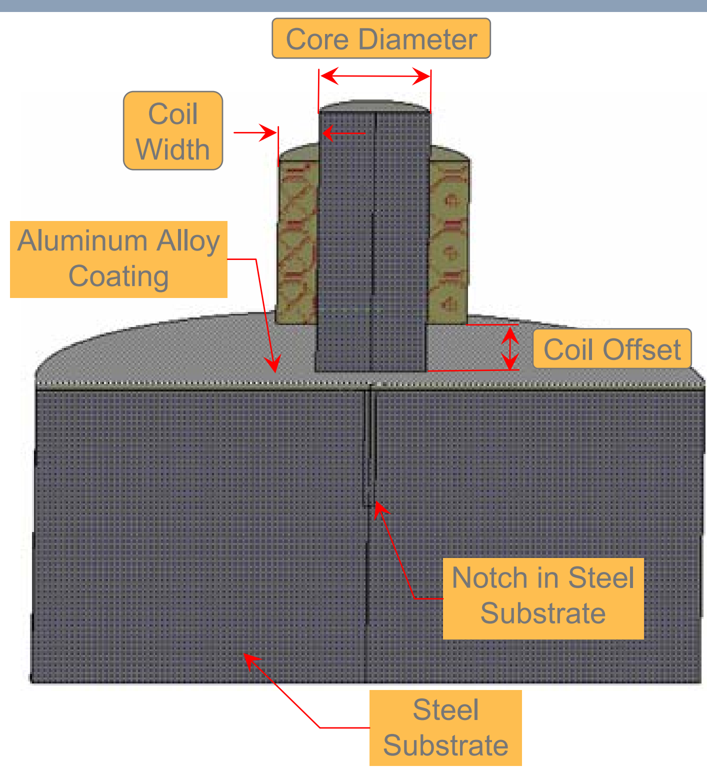
SP. Shape Optimization Parameters



- Simplified static model built for optimization
- Factorial (2^3) experiment conducted for 3 parameters:
  - Core diameter
  - Coil width
  - Coil offset
- Coil electromotive force maintained constant
- Coil impedance change with and without notch analyzed

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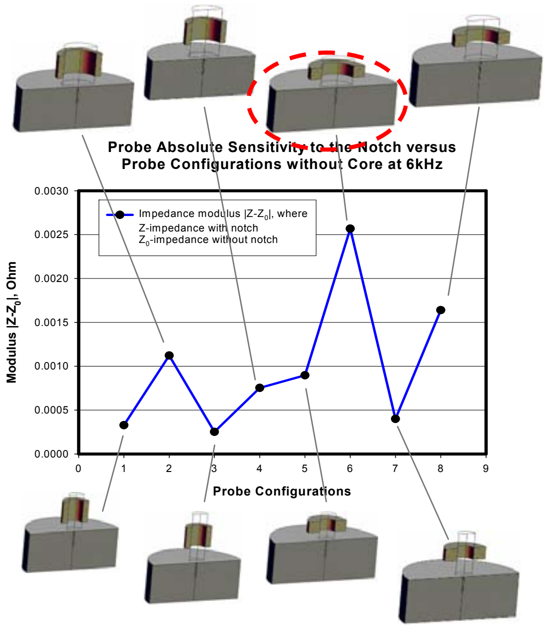
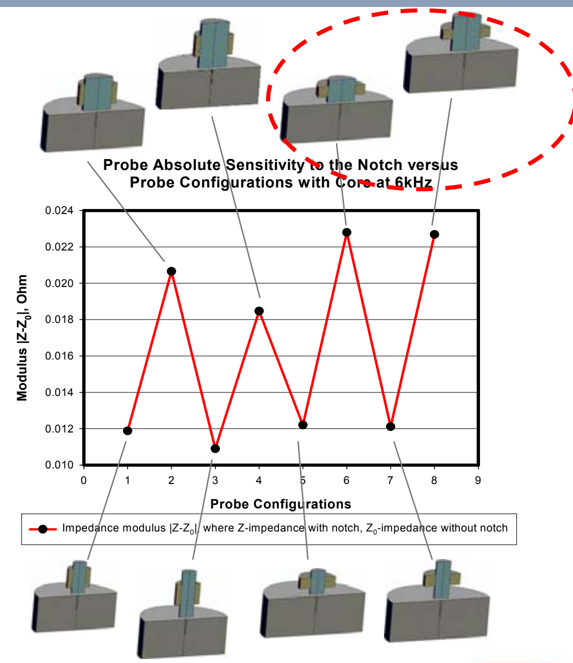
SP. Shape Optimization Results





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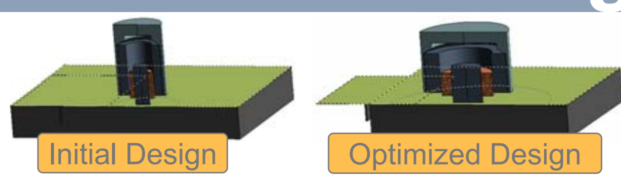
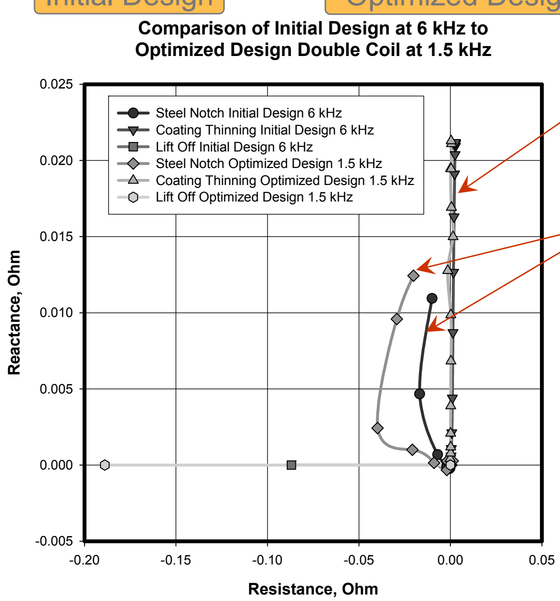
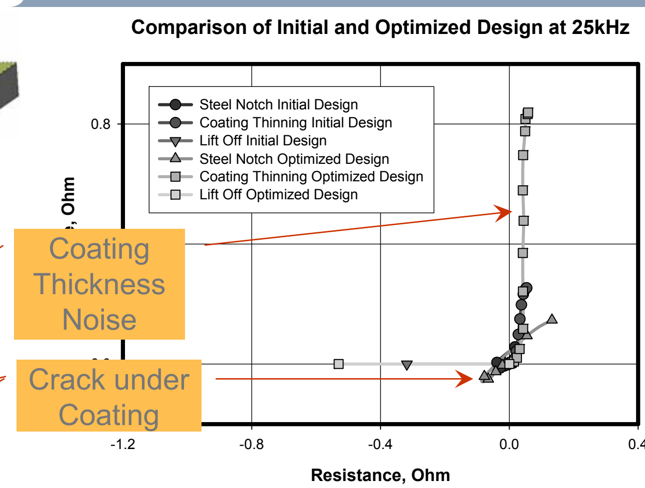
SP Optimization. Cracks under Coating







- Recommended frequencies below 6 kHz for steel cracks under aluminum coating
- Probe shape optimization required

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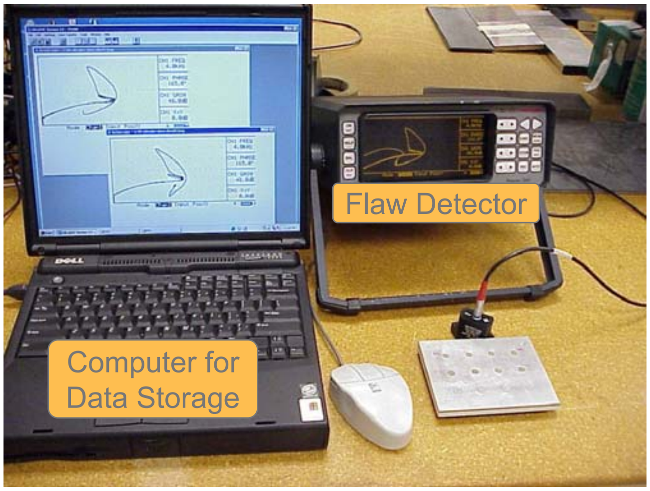
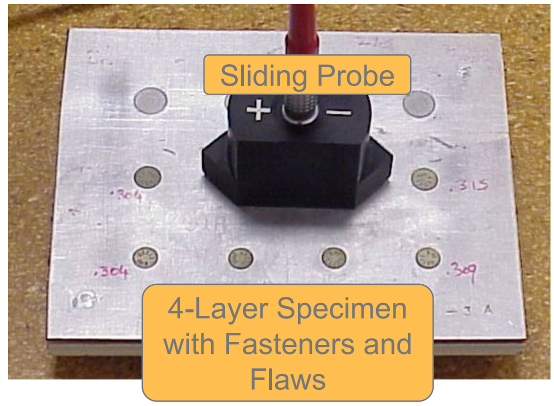
Subsurface Probe (SSP) Inspection





- Complex multilayer inspection area
- Many parameters affect performance
- Current field procedure exists

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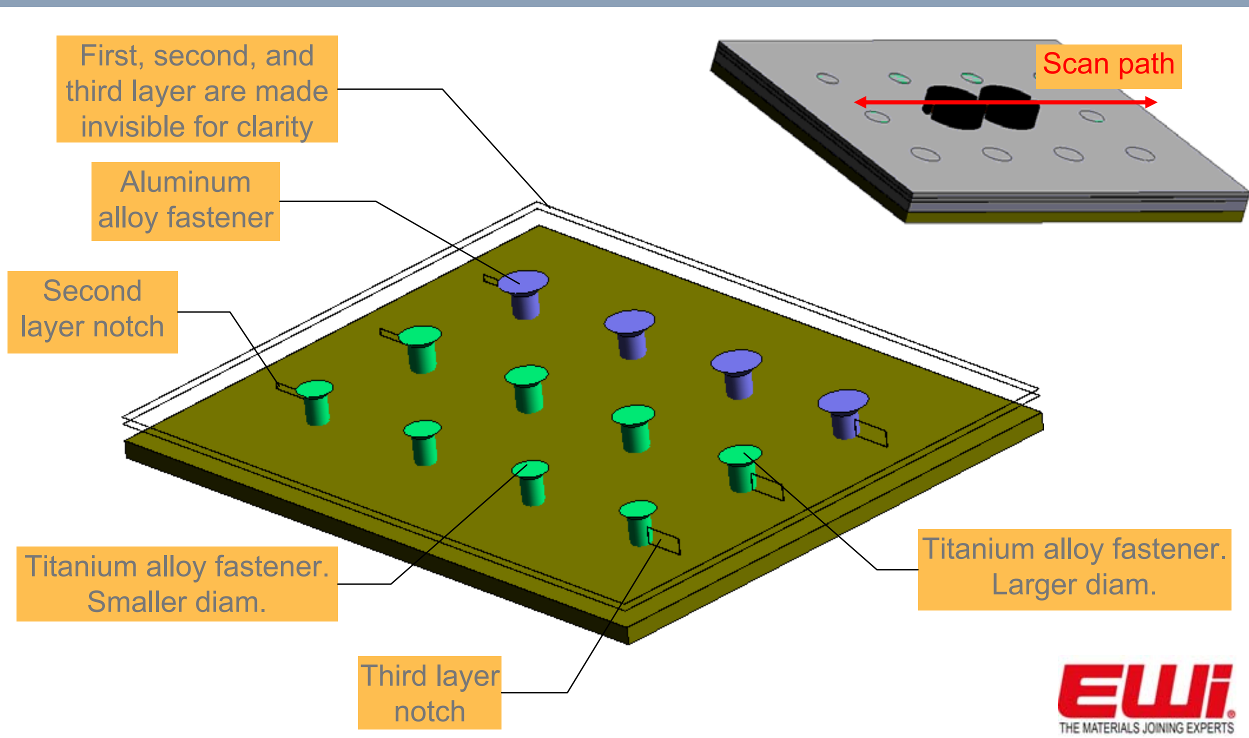
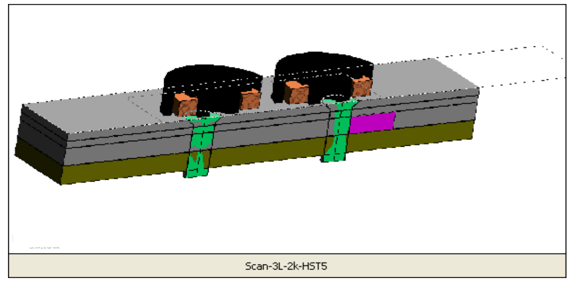
Complex Multilayer Specimen for Simulation



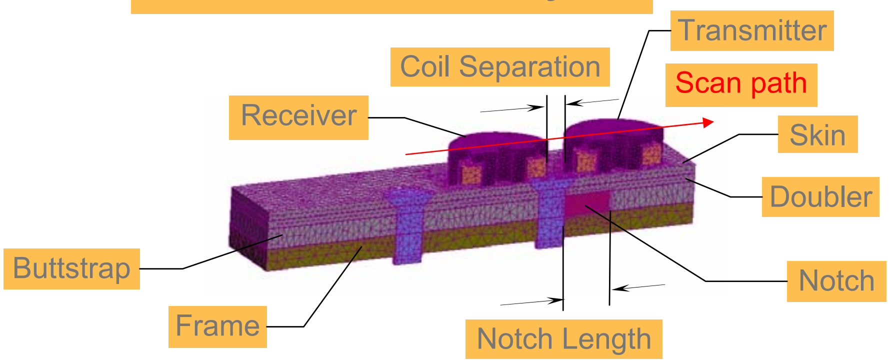
THE MATERIALS JOINING EXPERTS

Sliding Probe over Multilayer Structure



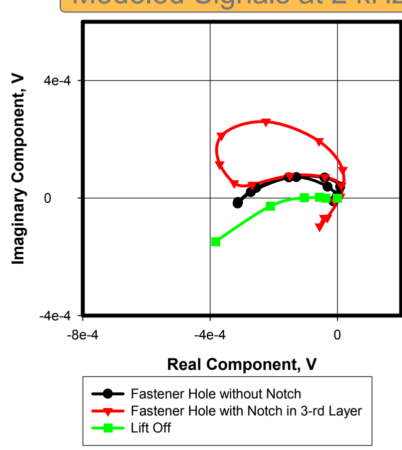
Geometry and Mesh Pattern for Notch in Third Layer

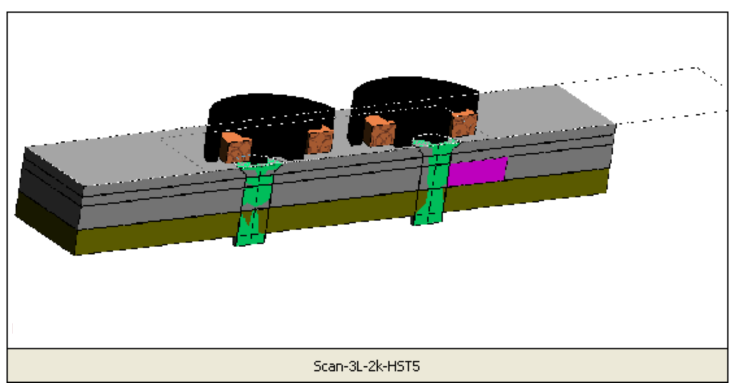
Animation of Scan Path



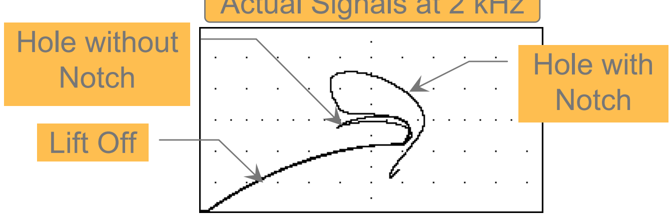
SSP. Inspection Simulation

Modeled Signals at 2 kHz



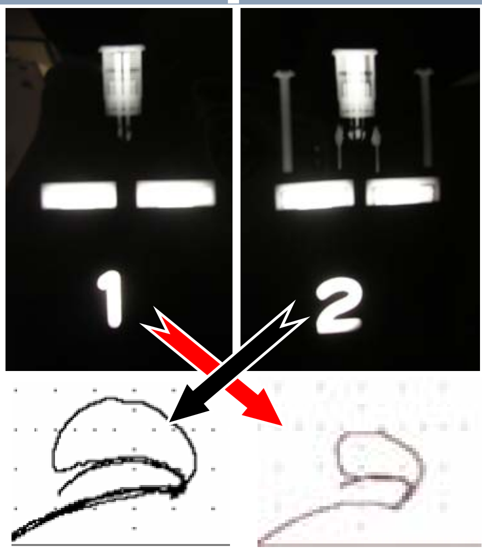


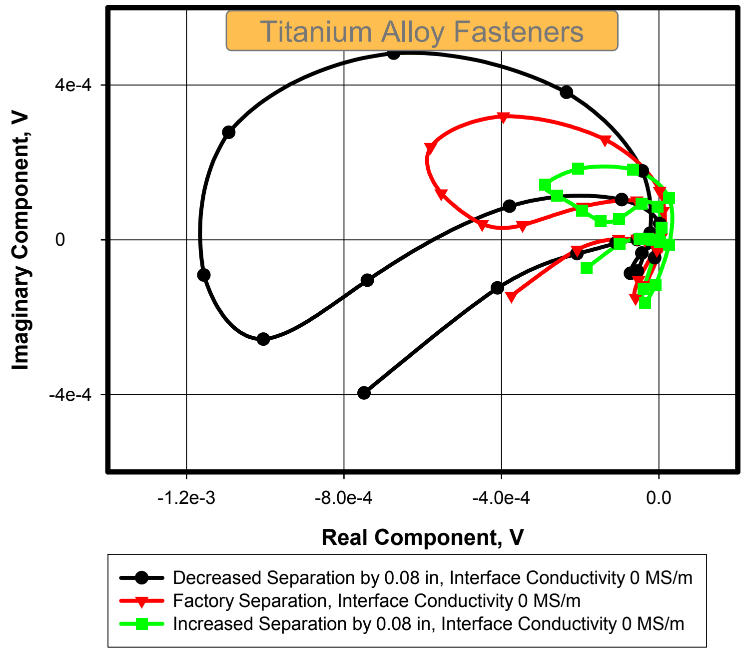
Actual Signals at 2 kHz



- Sliding probe and inspection area with fasteners are modeled for the first time in NDE industry
- Modeled signals compared well with actual signals

SSP. Optimization of Coil Separation Distance at 2kHz





- Modeling indicated better performance for smaller separation
- Field personnel confirmed the model predictions through characterization of probes

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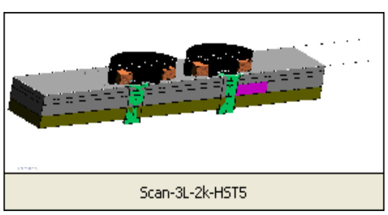
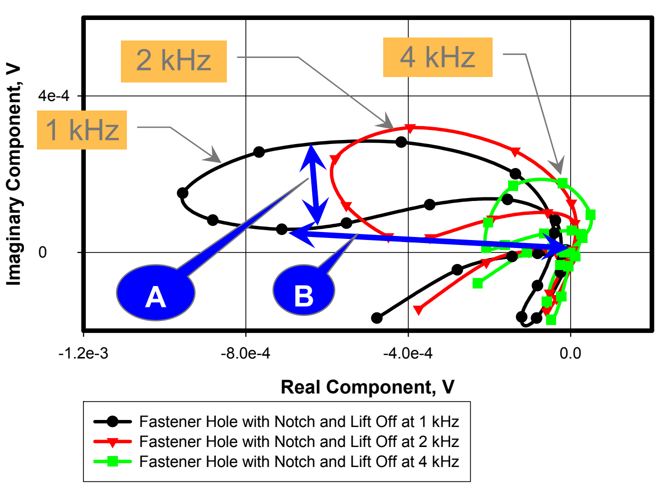
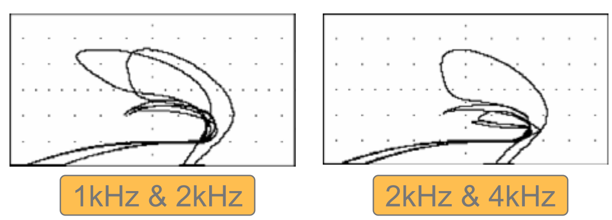
SSP. Frequency Optimization for Cracks in Third Layer





Actual Signals at Constant Instrument Gain



- Ratio A/B maximum for frequency of 2kHz
- The model proves 2kHz is the optimal frequency for the application
- Same frequency is used in current field inspection procedure
- Actual signals agree well with the model

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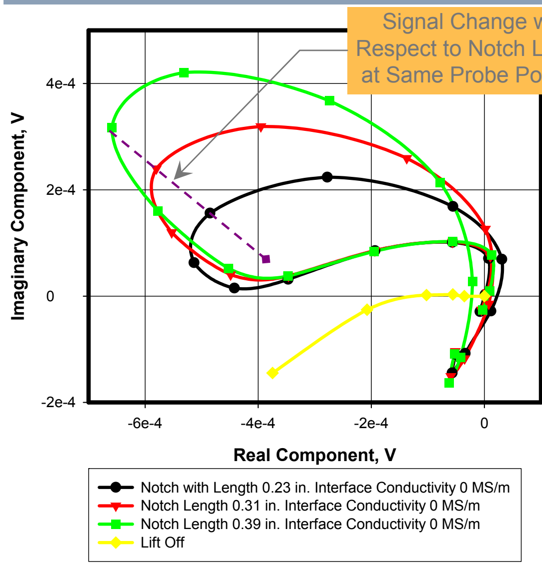
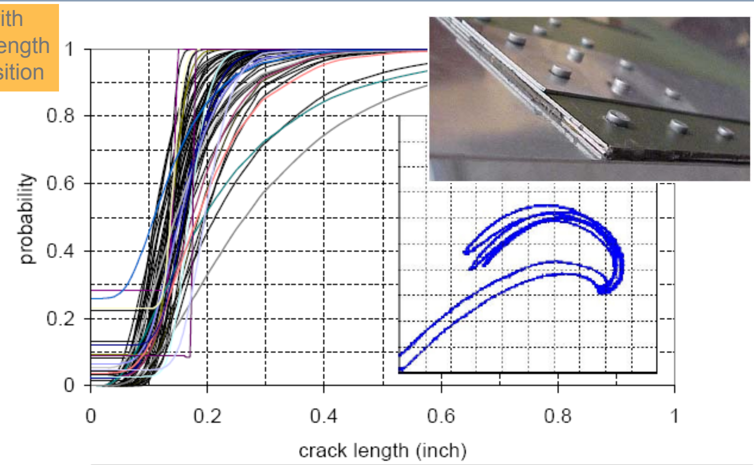
SSP. Flaw Size Effect at 2kHz





POD Study – FAA Validation Center, Sandia NL

- Model predicts flaws with size down to 0.25” might be detectable with this probe
- Flaws with size 0.15” might be missed

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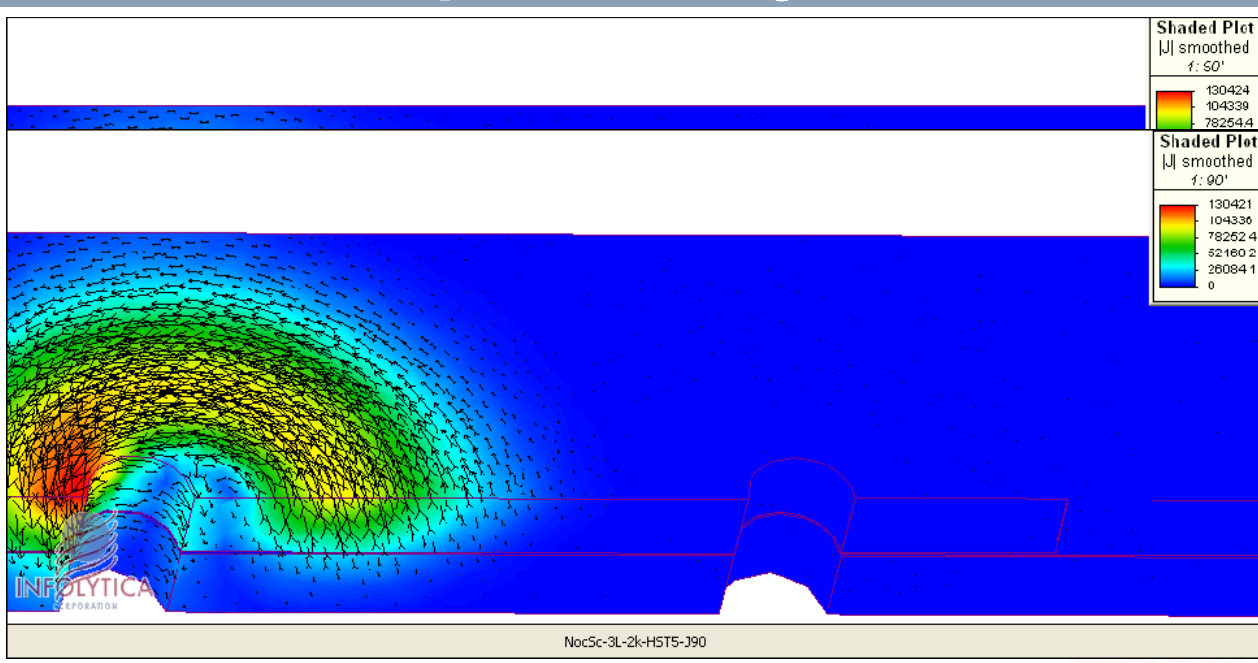
SSP. Animated Color and Arrow Maps of Eddy Currents



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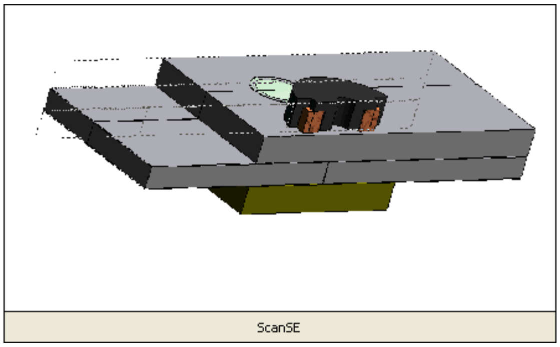
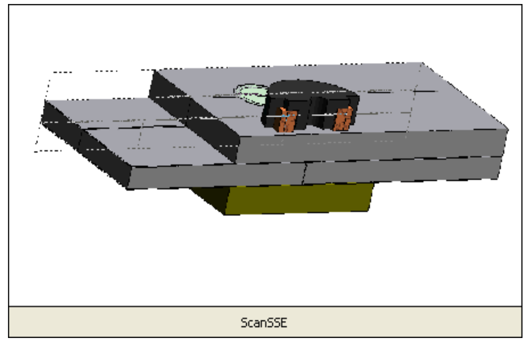
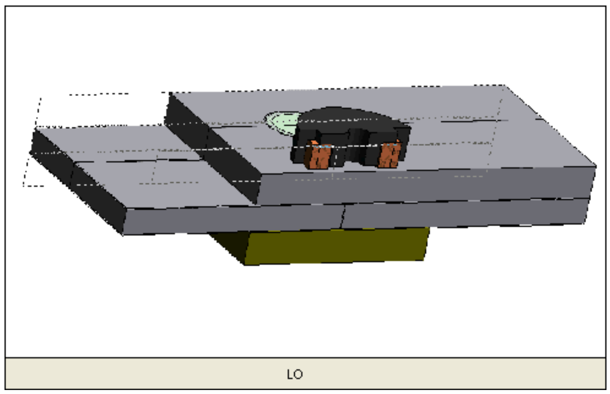
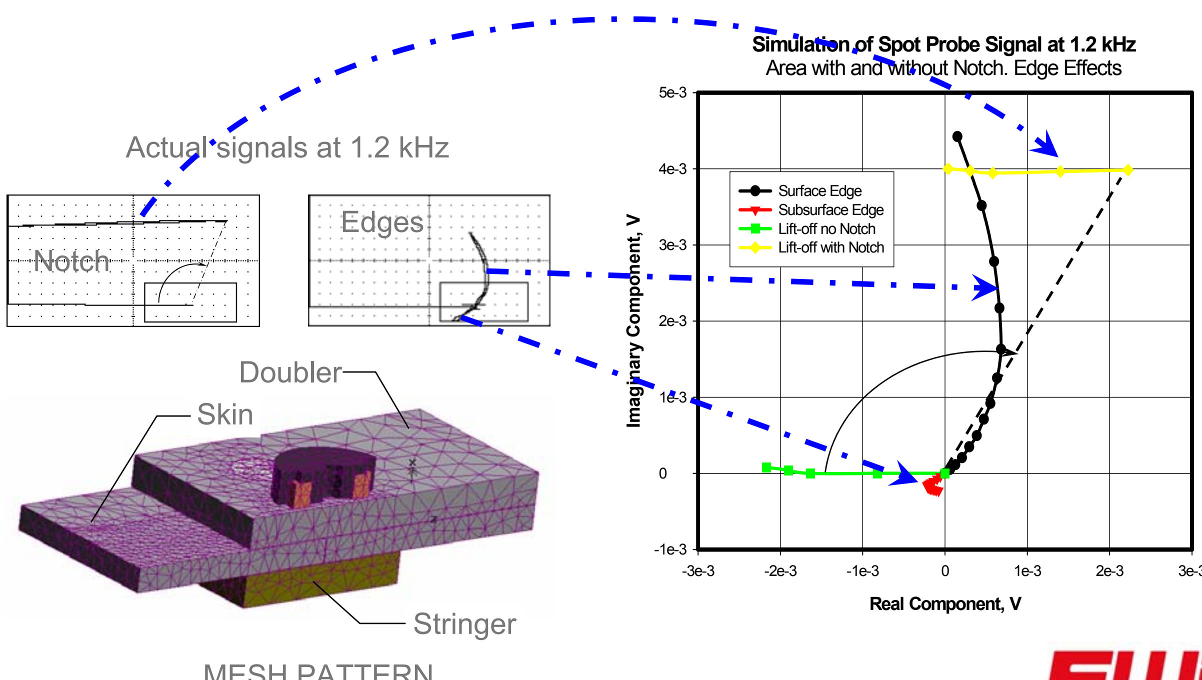
Spot Probe over Multilayer Structure. Animated Scan Paths



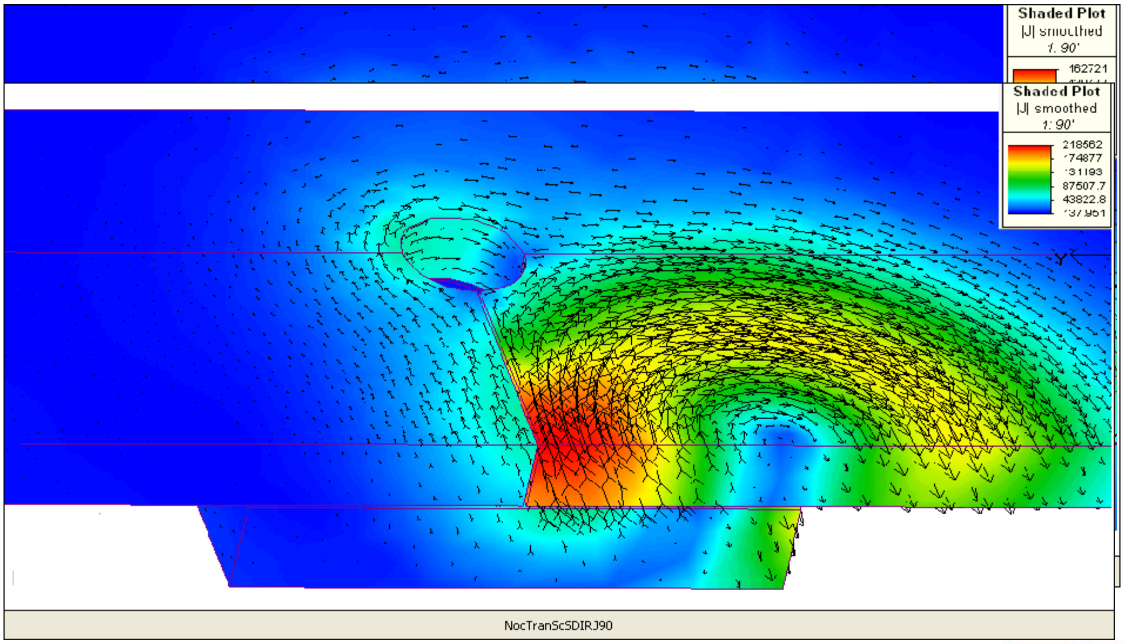




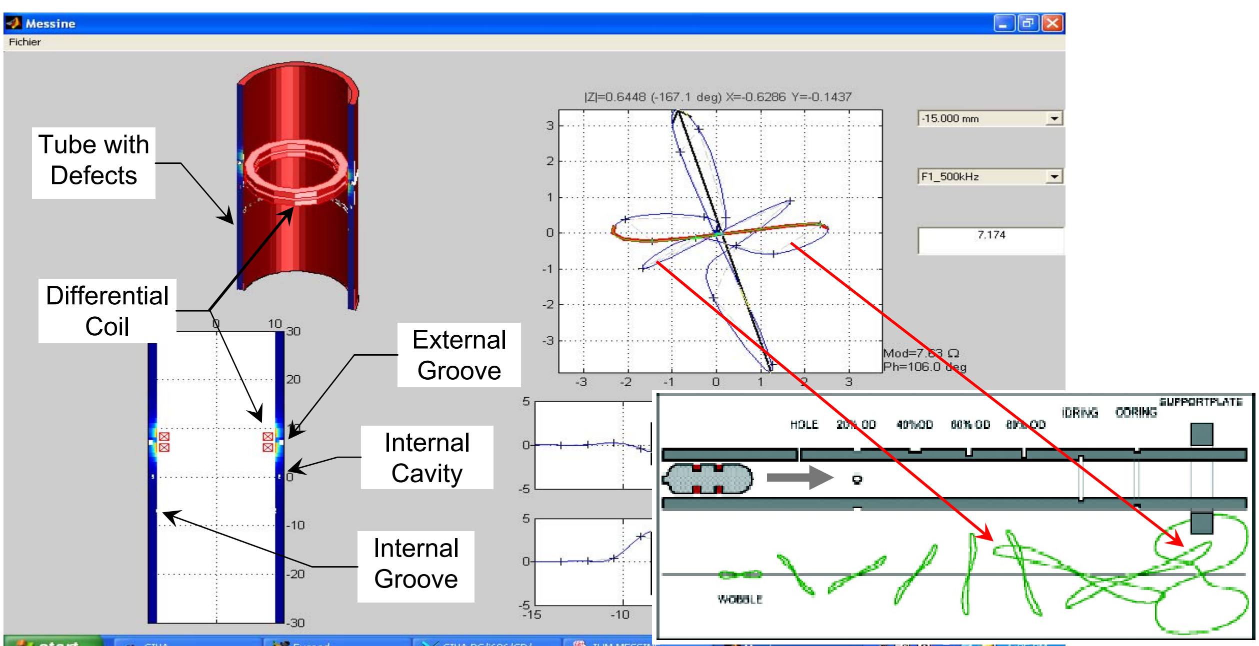
3D FEM. Spot Probe over Multilayer Structure



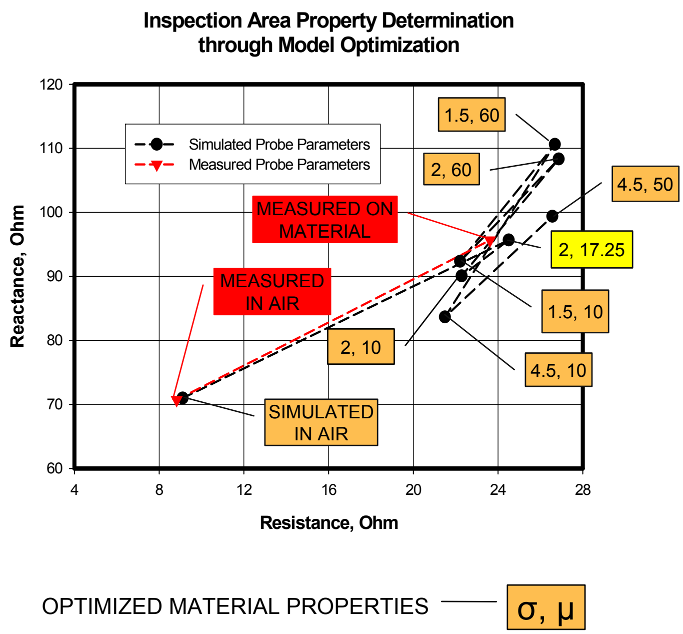
Spot Probe. Animated Color and Arrow Maps of Imaginary Component of ECD Solution with and without Notch at 1.2 kHz



ET Modeling Inconel Tube Inspection Differential Probe



Property Determination through Optimization/Best Fit



- Steel electrical conductivity and magnetic permeability needed for eddy current inspection optimization
- Magnetic permeability data unavailable
- Accurate models allow new algorithms and approaches to be investigated
- Steel properties varied in the probe-material model until best fit achieved

Conclusions

- Significantly reduced time for development and validation of procedures used for inspection of complex geometry structures where NDT technique performance is unknown
- Significant cost benefits due to elimination and reduction of experimental specimens and mock-ups needed for technique and procedure validation
- Increased inspection reliability and repeatability
- Fast interpretation of field NDE data and reduction of unnecessary repairs
- Quick customer support turnaround

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THE MATERIALS JOINING EXPERTS

Eddy Current Inspection. Theory and Applications.

Exxon Mobil, March 2008

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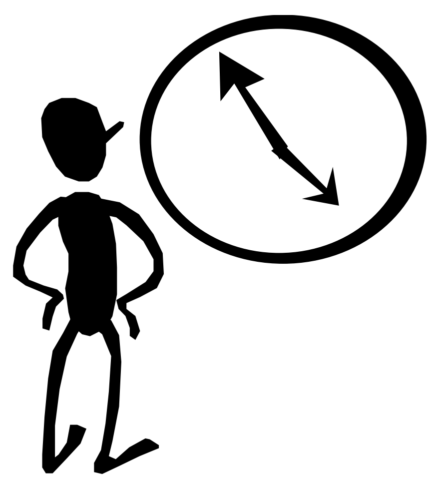
Course Agenda.

- Welcome
- Eddy Current (EC) Theory
- EC Techniques and Applications
- Modeling of EC Techniques and Procedures
- Advanced Techniques
- Lunch Break
- Demonstration of Typical EC Techniques
- Demonstration of Advanced EC Techniques



EWI
THE MATERIALS JOINING EXPERTS

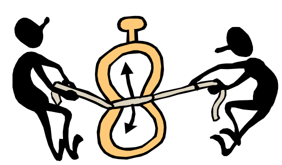
Course Objectives

- Course designed to familiarize participants with major advanced eddy current NDT techniques

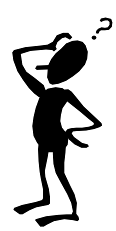
- Useful for technical personnel considering NDT for manufacturing and service processes
- On the completion of the course participants should:
  - Understand advanced eddy current NDT techniques and typical applications
  - Understand the inspection process and factors that affect it

THE MATERIALS JOINING EXPERTS

Ground Rules



- Difference in Opinion is OK!
- Be On Time!
- Misery is Optional!
- Have Fun!
- Feel Free to Ask Questions!



THE MATERIALS JOINING EXPERTS

Outline

- Physics – basic principles
- Theory of eddy currents
- Probes
- Equipment
- Materials and products
- Influence of different parameters on measurement
- Inspection process
- Main applications of eddy current testing

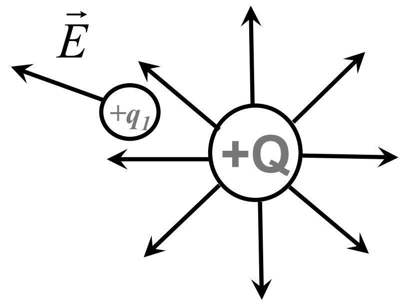
History

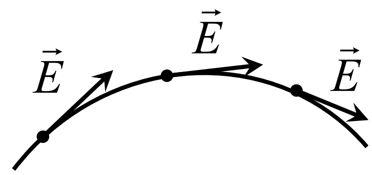
- 1879 - D. Hughes sorting of coins with coils and phone - %IACS
- 1881 – A. Bell induction sensing device for bullet in President J. Garfield (missed)
- 1950 - F. Förster theory and instrumentation
- 1960-s proliferation of testing equipment

Moore, P., *Nondestructive Testing Handbook,* third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

Electricity. Electrical Field.

- Electrical field – Field created around electrically charged **+Q** body
- Field characterized by electrical intensity ***E*** – Force acting on single unit charge $+q_1$ at unit charge position
- Line of force in electrical field – Imaginary line in space where the electrical intensity vector ***E*** is tangent to the line at any point of it

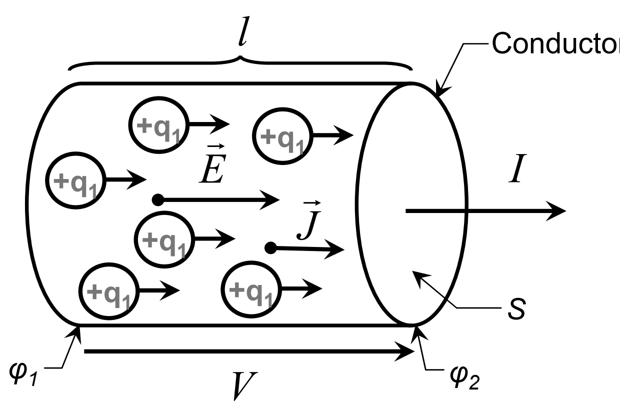




THE MATERIALS JOINING EXPERTS

Electricity. Direct Current (DC).

- Amperage and voltage
  - Amperage or Current I [A]- Amount of electrical charges $\Sigma+q$ passing through conductor cross section S for unit time t
  - Voltage V [V]–Difference (φ_1 and φ_2) of electrical potentials at two points of electrical conductor or circuit
- Ohm's law and resistance
  - Ohm's law –Current through conductor proportional to voltage drop across the conductor
  - Resistance R [Ω] –Conductor's capability to resist flow of electrical charges or current
  - Resistivity ρ [Ωm] –Characteristic specific to given material. Does not depend on conductors geometry.
- Conductivity σ [Siemens(S)/m] and resistivity ρ –Conductivity inversely proportional to resistivity



$$I = \frac{\sum_S +q}{t}$$
Current

$$\vec{J} = \frac{I}{S}$$
Current Density

$$V = \varphi_1 - \varphi_2$$
Voltage

$$\sigma = \frac{1}{\rho}$$
Conductivity

$$I = \frac{1}{R}V$$
Ohm's Law

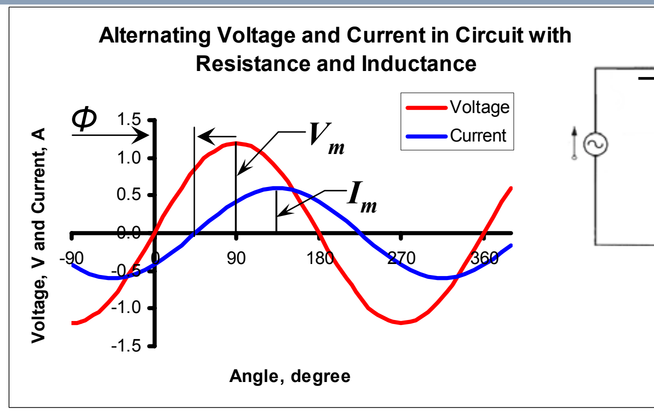
$$R = \rho\frac{l}{S}$$
Resistance

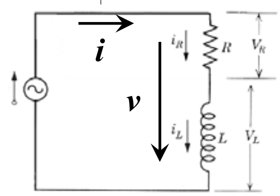
$$\vec{J} = \sigma\vec{E}$$
Another Form of Ohm's Law

THE MATERIALS JOINING EXPERTS

Electricity. Alternating Current (AC).

- Amplitude and phase – Usually sinusoidal AC with frequency f
  - Amplitude (V_m, I_m) or modulus is maximum reached with time
  - Phase (Φ) is angle at initial moment t=0
- Complex presentation used to simplify the analysis of AC circuits
- Ohm's law for AC similar to DC except impedance used in AC instead of resistance only for DC





$$v = V_m \sin \omega t$$

Instantaneous Voltage

$$i = I_m \sin(\omega t - \phi)$$

Instantaneous Current

$$v = V_m \sin \omega t \Leftrightarrow \dot{V}_m e^{j\omega t} = V_m e^{j0} e^{j\omega t}$$

$$j = \sqrt{-1}$$

$$i = I_m \sin(\omega t - \phi) \Leftrightarrow \dot{I}_m e^{j\omega t} = I_m e^{-j\phi} e^{j\omega t}$$

Imaginary Unit

Complex Presentation of AC Current and Voltage

$$\dot{I}_m = \frac{1}{\dot{Z}} \dot{V}_m$$

Ohm's Law for AC

$$\omega = 2\pi f$$

Cyclic Frequency

THE MATERIALS JOINING EXPERTS

Electricity. Alternating Current.

- Impedance – Capability of AC element or circuit to conduct AC current
- Vectorial representation – Vectors (usually space related) or rather phasors (time related vectors) are used to represent currents, voltages and impedances in AC circuits

$$\dot{Z} = |\dot{Z}| e^{j\phi} = |\dot{Z}| (\cos\phi + j \sin\phi)$$

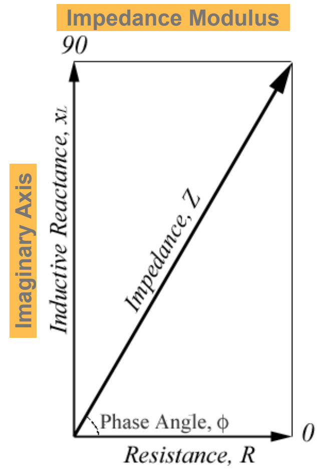
Complex Impedance

$$|\dot{Z}| = \sqrt{R^2 + X_L^2}$$

Impedance Modulus

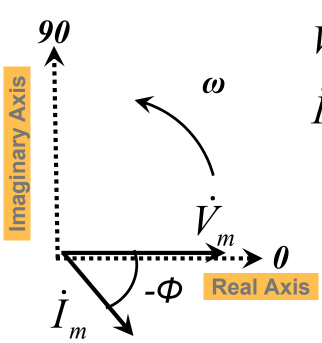
$$X_L = \omega L$$

Inductive Reactance



$$\tan\phi = \frac{X_L}{R}$$

Phase Angle Calculated from Vectorial Presentation



$$\dot{V}_m = V_m e^{j0}$$

$$\dot{I}_m = I_m e^{-j\phi}$$

$$V_{eff} = V_{RMS} = \frac{V_m}{\sqrt{2}}$$

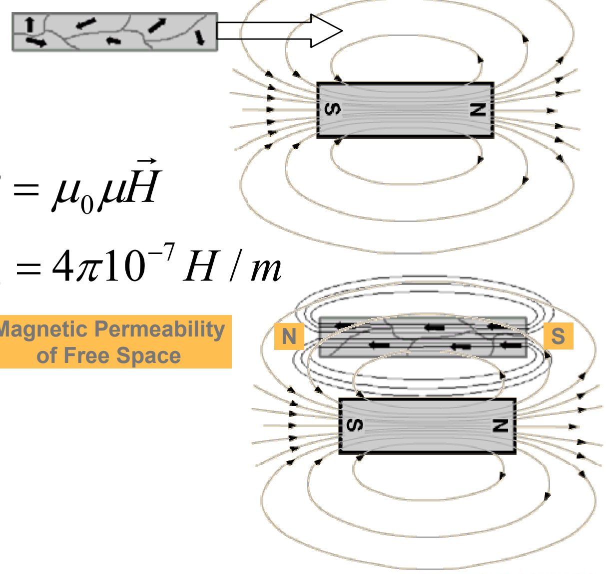
$$I_{eff} = I_{RMS} = \frac{I_m}{\sqrt{2}}$$

Moore, P., *Nondestructive Testing Handbook*, third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

THE MATERIALS JOINING EXPERTS

Magnetism. Magnetic Data

- Induction and magnetic fields
  - Permanent magnets, compass, earth magnetic field
  - Magnetic field density ***B*** or magnetic induction indicates how material magnetizes when placed in external field with Magnetic field intensity ***H***
- Magnetic permeability (μ) – Describes ability of material to magnetize when placed in external magnetic field
  - Diamagnetics - μ <1
  - Paramagnetics – μ ≈1
  - Ferromagnetics - μ >>1



$$\vec{B} = \mu_0 \mu \vec{H}$$

$$\mu_0 = 4\pi 10^{-7}\, H/m$$

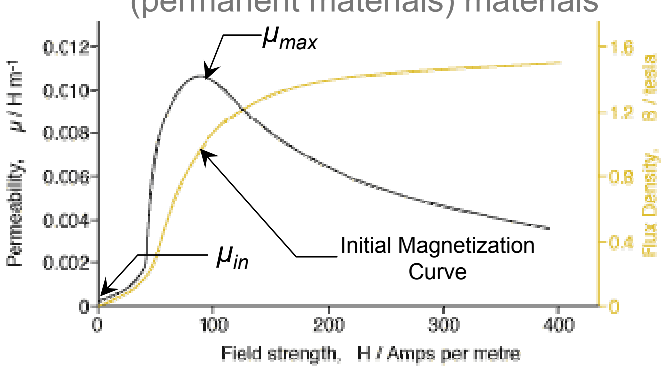
Magnetic Permeability of Free Space

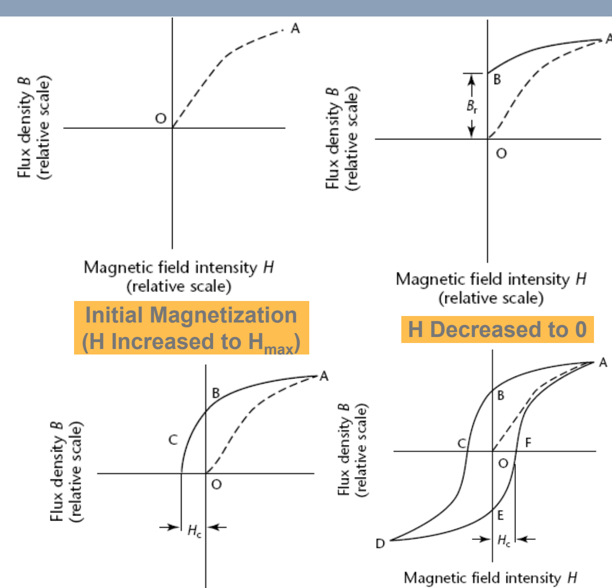
http://hyperphysics.phy-astr.gsu.edu/l

THE MATERIALS JOINING EXPERTS

Magnetism. Magnetic Data

- Iron magnetization
  - Initial magnetization curve
  - Hysteresis loop-H_c, B_r, B_s
  - Curie point-Temperature of loosing magnetic properties
  - Saturation
- Residual magnetization-Magnetic flux density at H=0 or permanent magnetism
- Magnetically soft and hard (permanent materials) materials





Initial Magnetization (H Increased to H_{max})

H Decreased to 0

B Decreased to 0 at H = $-H_c$

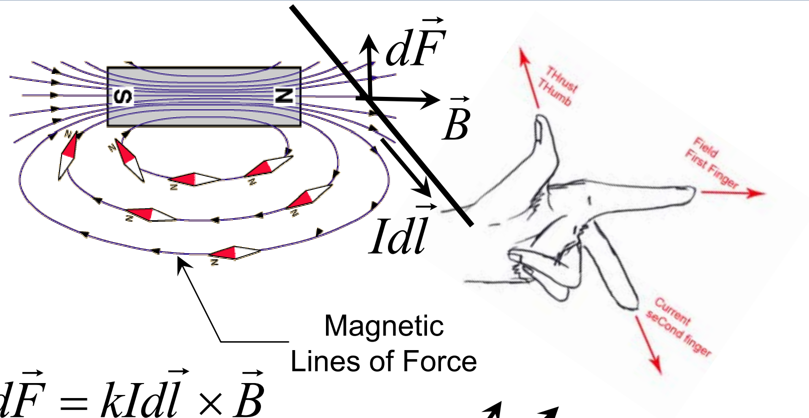
Loop Closed (H Increased to H_{max})

Moore, P., *Nondestructive Testing Handbook*, third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

THE MATERIALS JOINING EXPERTS

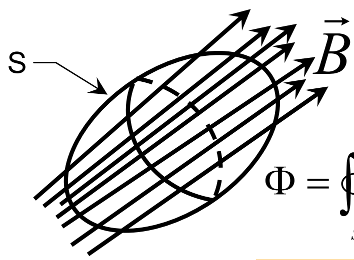
Magnetism. Magnetic Data

- Magnetic flux
  - Lines of forces and force fields- ***B*** tangent at any point of a line of force
  - Definition
  - Flux conservation, residual magnetization – permanent magnets based on this



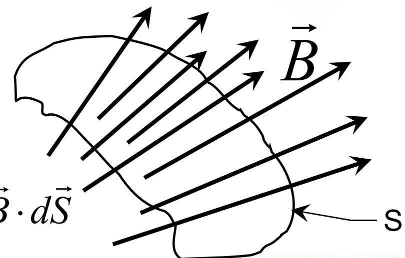
$$d\vec{F} = kId\vec{l} \times \vec{B}$$

Force in Magnetic Field



$$\Phi = \oiint_s \vec{B} \cdot d\vec{S} = 0$$

Flux Conservation



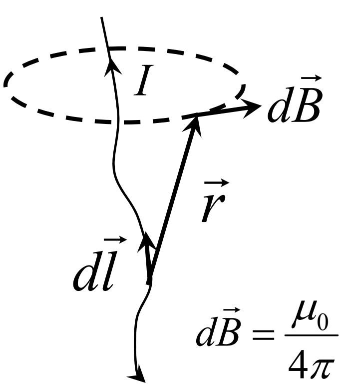
$$\Phi = \iint_s \vec{B} \cdot d\vec{S}$$

Magnetic Flux

http://en.wikipedia.org/wiki/Magnetic_field
http://hyperphysics.phy-astr.gsu.edu/l

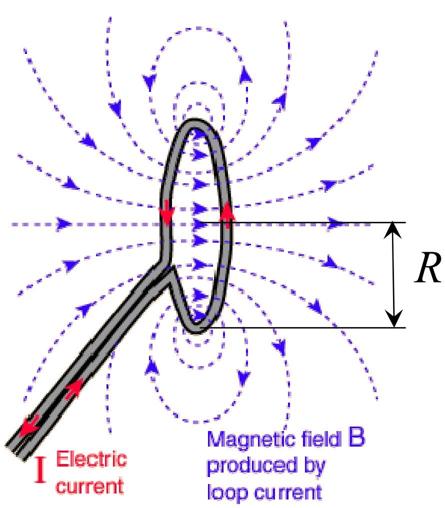
Magnetic Field Produced by Current. Biot and Savart law.

- Definition
- Practical rules (right hand rule)



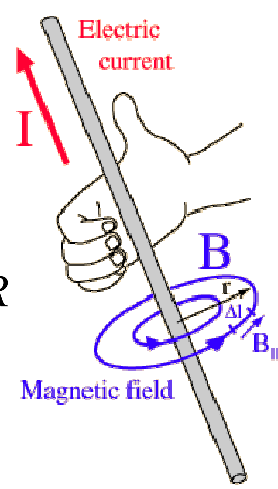
$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l} \times \vec{r}}{r^3}$$

Magnetic Induction at Point next to Conductor with Current



$$B = \frac{\mu_0}{4\pi}\frac{2\pi I}{R}$$

Circular Conductor



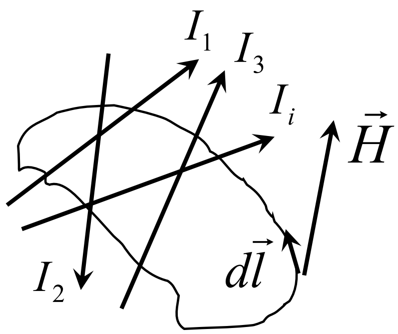
$$B = \frac{\mu_0}{4\pi}\frac{2I}{r}$$

Long Straight Conductor

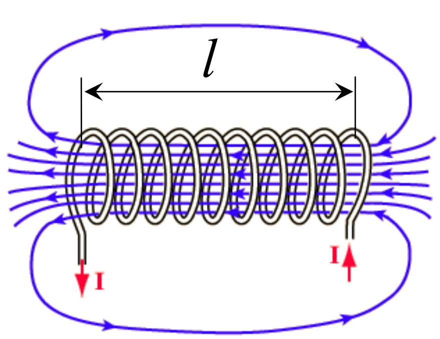
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfie.html

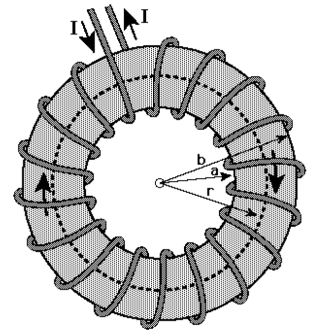
Magnetic Field Produced by Current. Ampere's law.

- Ampere's law
- Definition
- Applications (toroid, long coil)



$$\oint_l \vec{H} \cdot d\vec{l} = \sum_{i=1}^{n} I_i$$





$$H = \frac{nI}{l}$$

Magnetic Field Intensity away from Coil Ends

$$H = \frac{nI}{2\pi r}$$

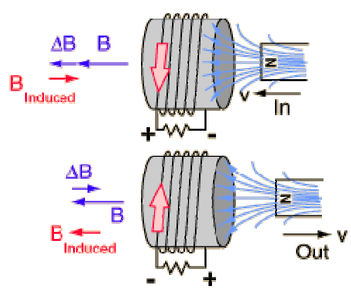
Magnetic Field Intensity on Coil Center Line

n – Number of Turns

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfie.html

Electromagnetic Induction. Faraday's and Lenz's Laws.

- Definition – Changing flux causes emf (e) in contour. Induced current creates field that opposes the change of magnetic flux.
- Auto-induction factor (L) – Links flux through contour (coil) with current through it. Depends on media property and contour geometry
- Mutual induction factor (M) – Links flux in one contour with current in another and vice versa. Depends on media properties and shapes of both contours.
- Coupling factor



$$e = -\frac{d\Phi}{dt} = -\frac{d\iint_s \vec{B} \cdot d\vec{S}}{dt}$$

$$\Phi = Li$$

Auto-induction

$$\Phi_{2M} = M_{21} i_1$$

Mutual Induction of Contour 2 to Current in Contour 1

$$e = -\frac{d\Phi}{dt} = -L\frac{di}{dt} - i\frac{dL}{dt}$$

Change from Current | Change from Shape

$$e = -\frac{d\Phi_{2M}}{dt} = -M_{21}\frac{di_1}{dt} - i_1\frac{dM_{21}}{dt}$$

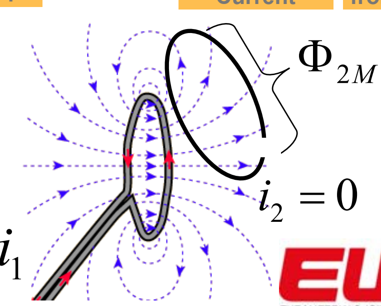
$$M_{21} = M_{12} = M$$

$$\Phi_{1M} = M_{12} i_2$$

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

Coupling Factor

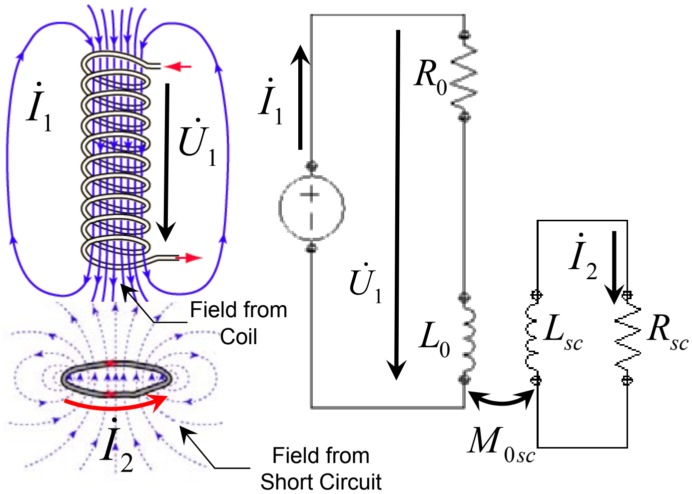
MOVIE
SelfinductFaradLaw



http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfie.html

Electromagnetic Induction. Induced Currents in Short Circuit.

- Current induced in short circuit when placed in changing field created by a coil
- Current I_2 induced in short circuit
- Short circuit electrical parameters:
  - Resistance – R_{sc}
  - Inductance – L_{sc}



$$\dot{U}_1 = (R_0 + R_{ad})\dot{I}_1 + j\omega(L_0 - L_{ad})\dot{I}_1$$

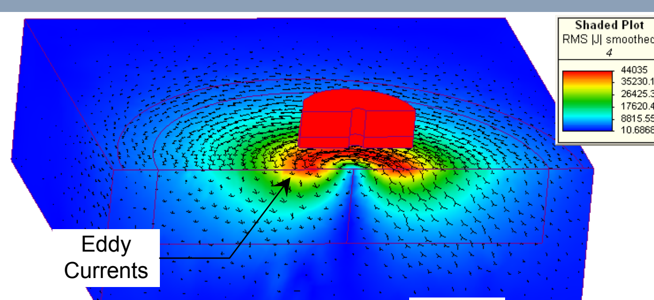
$$R_{sc} = \rho_{sc}\frac{l_{sc}}{S_{sc}} \qquad L_{sc} = \frac{\Phi_{sc}}{I_2}$$

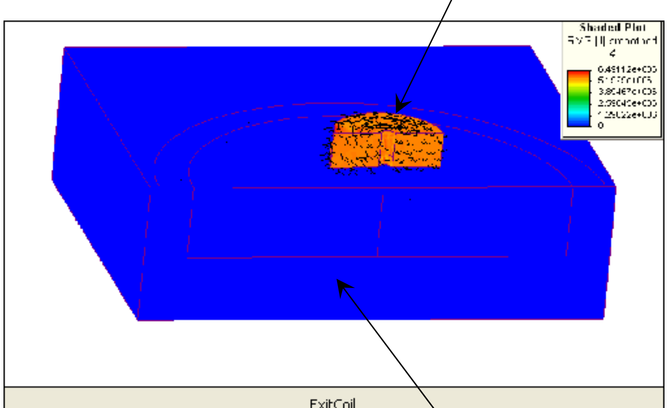
Circuit Length (l_{sc}); Circuit Resistivity (ρ_{sc}); Circuit Cross Section (S_{sc})

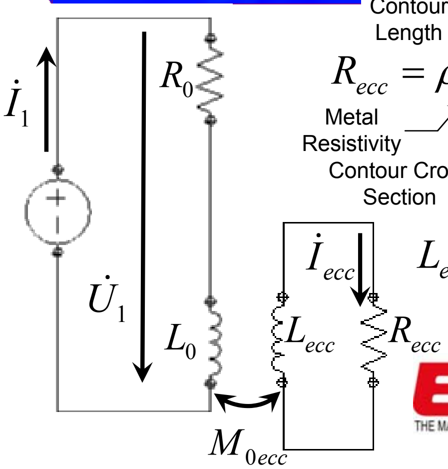
THE MATERIALS JOINING EXPERTS

Electromagnetic Induction. Induced Currents in Metal Mass. Slide 1.

- Eddy currents induced in metal when magnetic flux changes
- Eddy currents effect similar to equivalent short circuit contour with current I_{ecc} and electrical parameters:
  - Resistance – R_{ecc}
  - Inductance – L_{ecc}







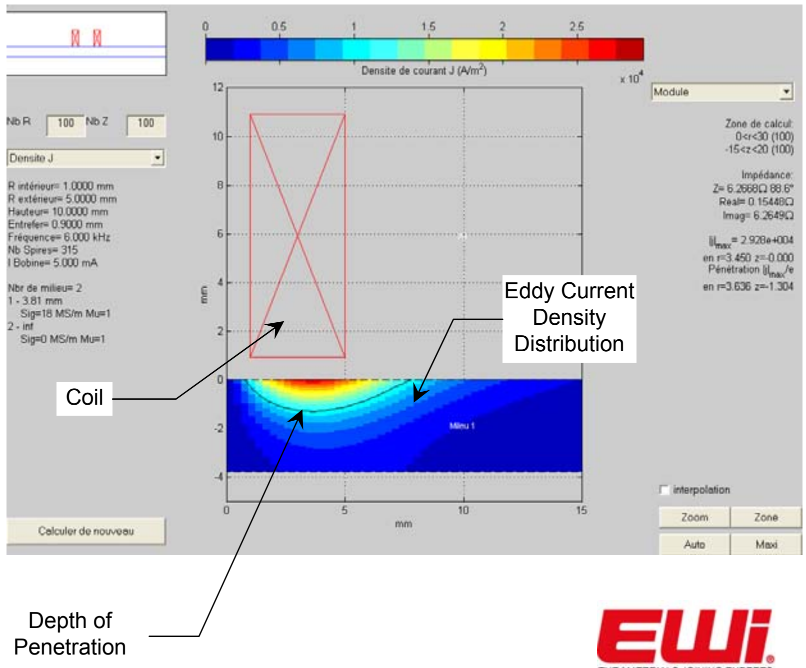
$$R_{ecc} = \rho_{met}\frac{l_{ecc}}{S_{ecc}} \qquad L_{ecc} = \frac{\Phi_{ecc}}{I_{ecc}}$$

Contour Length (l_{ecc}); Metal Resistivity (ρ_{met}); Contour Cross Section (S_{ecc})

THE MATERIALS JOINING EXPERTS

Electromagnetic Induction. Induced Currents in Metal Mass. Slide 2.

- Skin effect – Highest density of eddy currents on the surface. Attenuate exponentially away from surface
- Depth of penetration defined as depth where density attenuates e-times (2.71… times) compared to density on surface



Electromagnetic Induction. Coil Impedance Change.

- Eddy current field interacts with coil field
- Coil parameters changed accordingly

$$\dot{U}_1 = (R_0 + R_{ad})\dot{I}_1 + j\omega(L_0 \pm L_{ad})\dot{I}_1$$

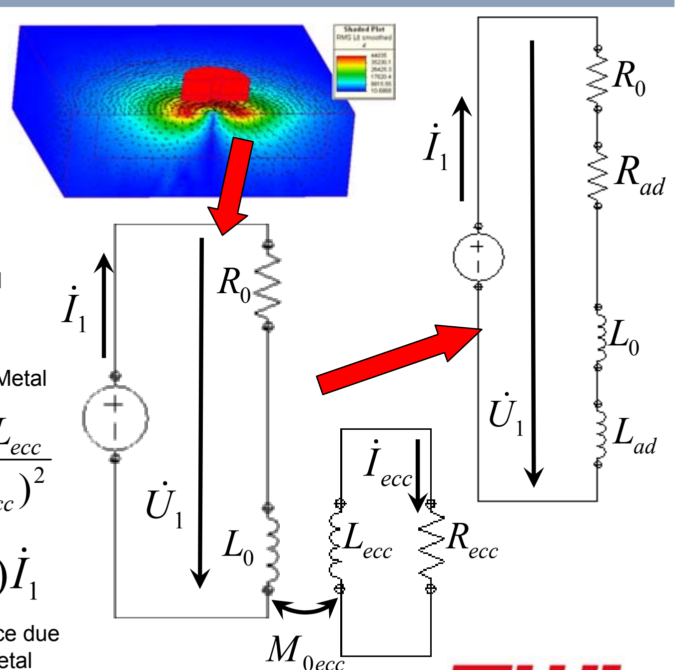
Magnetic Metal (+); Nonmagnetic Metal (−)

$$R_{ad} = \frac{(\omega M_{0ecc})^2 R_{ecc}}{R_{ecc}^2 + (\omega L_{ecc})^2} \qquad L_{ad} = \frac{(\omega M_{0ecc})^2 L_{ecc}}{R_{ecc}^2 + (\omega L_{ecc})^2}$$

$$\dot{U}_1 = (R_0 + j\omega L_0)\dot{I}_1 + (R_{ad} \pm j\omega L_{ad})\dot{I}_1$$

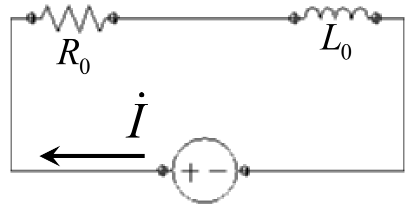
Change of Coil Impedance due to Eddy Currents in Metal

$$\dot{U}_1 = \dot{Z}_0\dot{I}_1 + \dot{Z}_{ad}\dot{I}_1$$



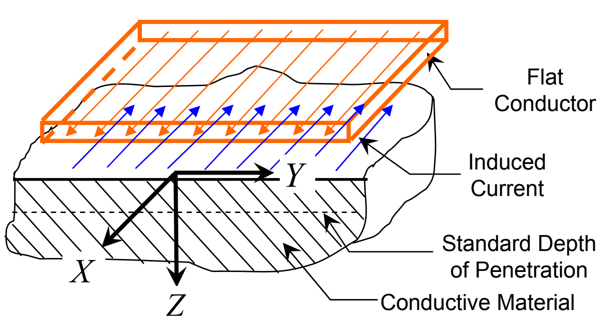
Exercises 1

- Ex. 1. Calculate impedance modulus of an eddy current probe in air represented by typical *RL*-equivalent electrical circuit where – R_0=10 Ω, L_0=150μH, and frequency is 100 kHz.
- Ex. 2. Calculate the amplitude of a sinusoidal current with effective or RMS value of 10 mA



Theory of EC. Plane Conductors

- Variation of amplitude and phase of current – Amplitude attenuates exponentially and phase changes linearly with depth in material
- Depth of standard penetration – Depends on material properties and frequency
- Defect signal with increasing depth
  - Signal from identical defects at different depths will decrease
  - Signal phase angle from defect will increase



Amplitude — Phase

$$\vec{J}(z,t) = \vec{J}_0 e^{-kz} \sin(\omega t - kz)$$

Eddy Current Density

$$|\vec{J}| = \frac{J_0}{e}$$

Eddy Current Density at Standard Depth

$$k = \sqrt{\frac{\omega\sigma\mu_0}{2}}$$

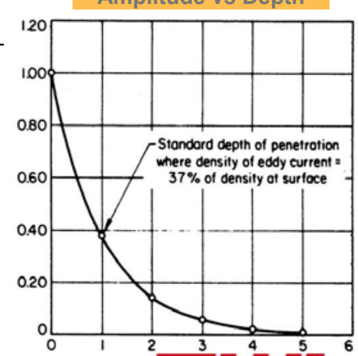
$$\delta = \frac{1}{k} = \sqrt{\frac{2}{\omega\sigma\mu_0}}$$

Standard Depth of Penetration. Nonmagnetic Material.

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu_0\mu_r}}$$

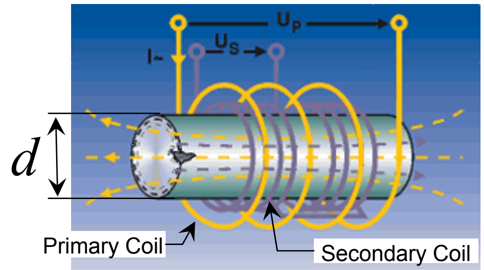
Standard Depth of Penetration. Magnetic Material.

Current Density Amplitude vs Depth



Theory of EC. Cylindrical Bars

- Characteristical or Limit frequency – Frequency f_g at which ratio *A* equals 1. Unique for material and diameter. Introduced by Förster
- Inspection frequency selected to obtain certain ratio of f/f_g
- Generalized parameter *P* often used instead of frequency ratio
- Variation of amplitude and phase of currents – Very similar to flat conductors and material except eddy current density at cylinder center is always "0" regardless of frequency and material properties.
- Depth of standard penetration δ – Similar to flat conductor when $d \geq 20\delta$
- Defect reaction according to its position – Similar to flat conductor and material



$$A = \frac{f\mu_r\sigma d^2}{5066} = 1 \qquad f_g = \frac{5066}{\mu_r\sigma d^2}$$

Characteristical Frequency

$$f/f_g = \frac{f\mu_r\sigma d^2}{5066}$$

Diameter d in cm and Conductivity in m/(Ω.mm²)

$$P = dk = d\sqrt{2\pi f\mu_0\mu_r\sigma}$$

$$\mu_0 = 4\pi 10^{-7}\ H/m \text{ and } \mu = \mu_0\mu_r$$

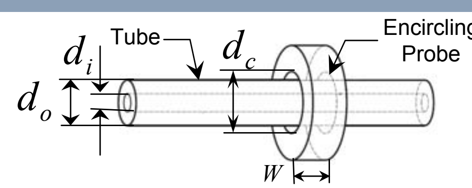
Generalized Parameter

$$f/f_g = (dk)^2 = P^2$$

Link between Frequency Ratio and Generalized Parameter

Theory of EC. Tubes

- Characteristical or Limit frequencies
- Variation of amplitude and phase of currents
- Depth of standard penetration
  - Thick tube – Similar to cylinder and plane conductor
  - Wall thickness (T) changes affect the eddy current signals for thin tubes
- Defect reaction according to its position – OD and ID flaw signals are at ~90⁰ at frequency f_{90} for thin tubes



Limit Frequency for Thin Tube

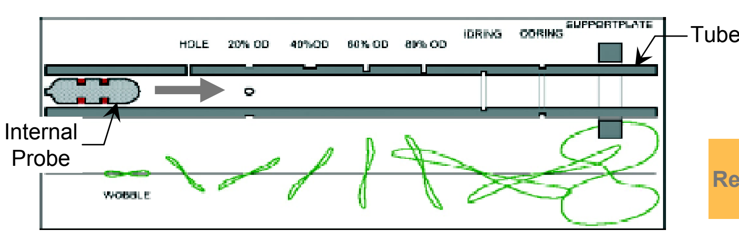
$$f_g = \frac{5066}{\mu_r\sigma d_i T}$$

Limit Frequency for Thick Tube

$$f_g = \frac{5066}{\mu_r\sigma d_o^2}$$

$$f/f_g = \frac{f\mu_r\sigma d_i T}{5066} \qquad f/f_g = \frac{f\mu_r\sigma d_o^2}{5066}$$

Diameters and Wall thickness in cm, Conductivity in m/(Ω.mm²)



$$f_{90} = \frac{3\rho}{T^2\mu_r}, kHz$$

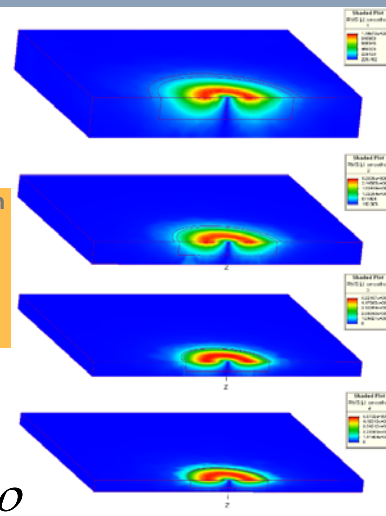
Wall thickness "T" in mm, Resistivity "ρ" in μΩ.cm, Magnetic permeability "μr" unitless

Exercises 2

- Ex. 1. Calculate the standard depth of penetration for surface eddy current inspection of aluminum alloy with electrical conductivity of 33.1%IACS at 4 frequencies 20, 80, 240 and 480 kHz. Compare with actual depth of penetration (0.022”, 0.015”, 0.0093” and 0.0066”) obtained through computer modeling (four plots right) of actual probe with diameter approximately 0.125”. Explain the difference if any.
- Ex. 2. Calculate the f_{90} for a tube made of austenitic stainless steel with electrical resistivity of 72 μΩ.cm and thickness of 2 mm. Repeat the calculation for a tube made of typical carbon steel with electrical resistivity of 25 μΩ.cm and relative magnetic permeability of 60 with the same wall thickness. Explain the difference.

$$\delta = \frac{26}{\sqrt{f\sigma\mu_r}}$$

Depth of penetration “δ” in inch, Conductivity “σ” in %IACS, Magnetic permeability “μ_r“ unitless



$$f_{90} = \frac{3\rho}{T^2\mu_r}$$

Separation frequency “f_{90}“ in kHz, Wall thickness “T” in mm, Resistivity “ρ” in μΩ.cm, Magnetic permeability “μ_r“ unitless

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Theory of EC. Geometric Flaw Characterization. Current Interruption

- Hypothesis of interrupted currents
  - Increased resistance
  - Changed inductance
- Case of point defects
  - Point defect will cause small interruption of eddy current contours if point defect size is relatively small compared to size of coil
  - **Solution** – Reduce size of coil which will in turn lead to longer inspection times with single probe or better build array probe with high resolution
- Case of large defects
  - Larger defects will cause large interruption of eddy current contours and will easily be detected
  - Interruption will also depend on defect orientation. If defect is parallel (delaminations) to EC contours it may be missed even if large
  - **Solution** – Collect defect data and design probes and scanning paths (preferably through modeling) that will allow maximum interruption of EC contours
- Case of multiple defects
  - Multiple defects will be easy to detect but may be difficult to separate.
  - **Solution** - Modeling can successfully be used to aide signal interpretation and reduce significantly the cost of manufacturing multiple specimens with multiple defect combinations

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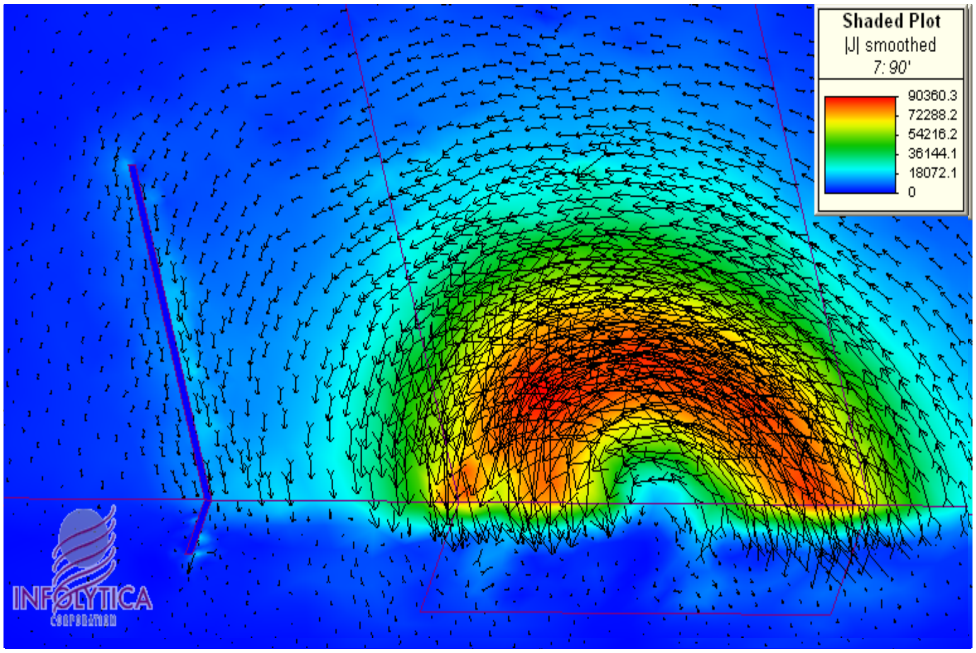
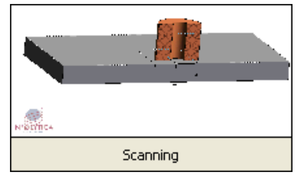
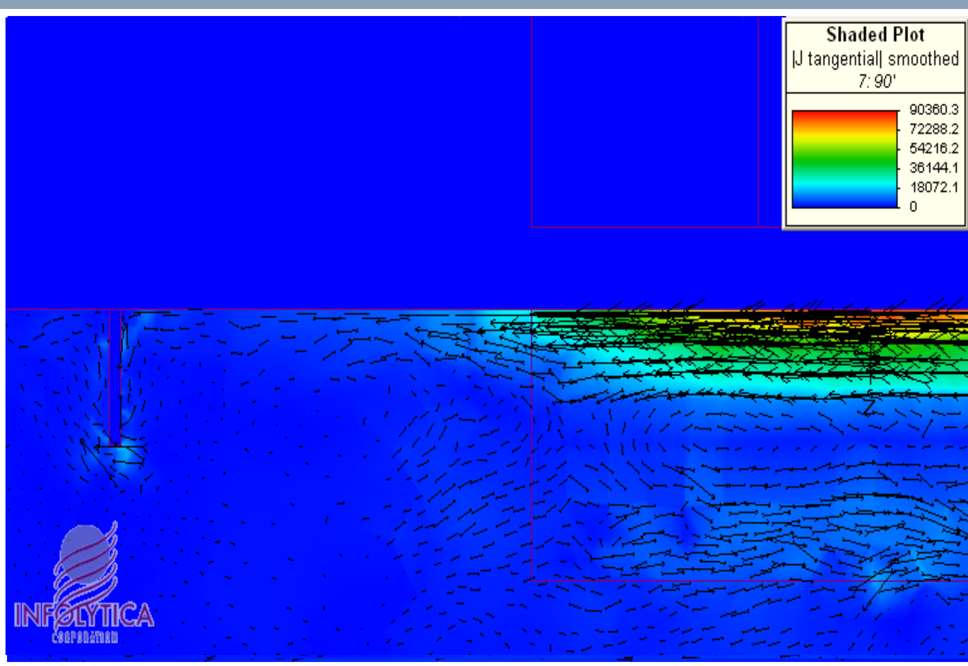
ET Interaction with Flaw. Current Interruption. 3D View.

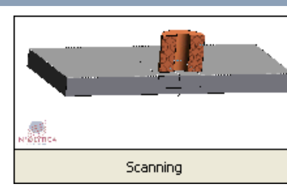




THE MATERIALS JOINING EXPERTS

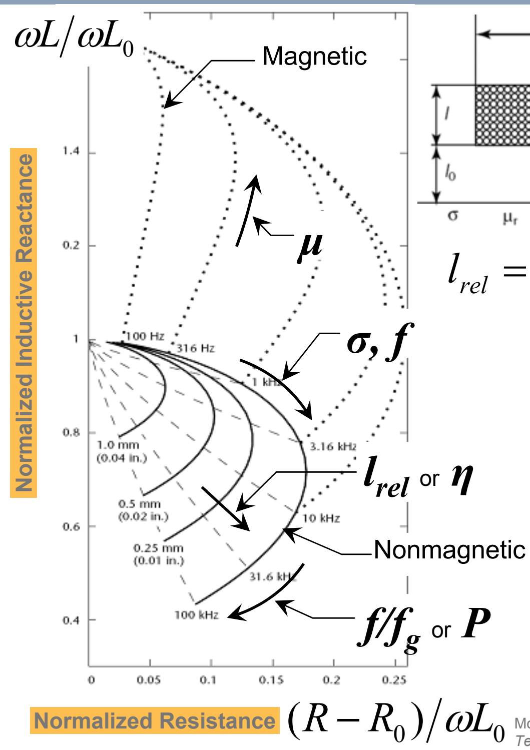
ET Interaction with Flaw. Current Interruption. 2D View.

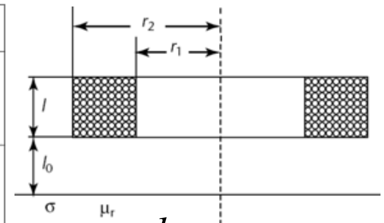




THE MATERIALS JOINING EXPERTS

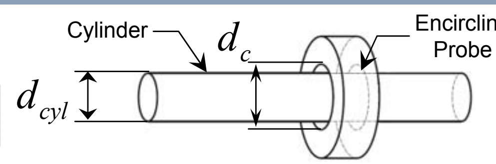
Theory of EC. Impedance Diagram of Surface or Encircling Coil





$$l_{rel} = \frac{l_0}{r_{aver}}$$

Relative Probe Lift Off



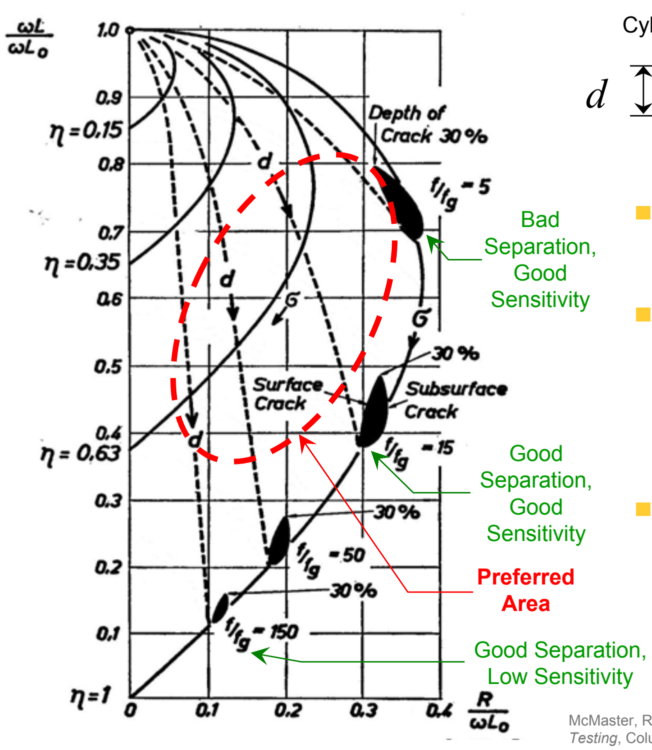
$$\eta = \frac{d_{cyl}^2}{d_c^2}$$

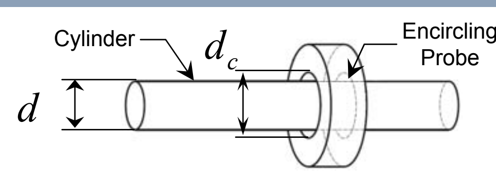
Probe Fill Factor

- Diagram drawing – Function of generalized parameter P or f/f_g at various lift off l_{rel} or fill factor η
- Influence of various parameters
  - Nonmagnetic and magnetic
  - Conductivity, permeability, lift off/fill factor, frequency
- Ferromagnetic products

Moore, P., *Nondestructive Testing Handbook*, third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

Theory of EC. Use of Impedance Diagrams





$$\eta = \frac{d^2}{d_c^2}$$

- Definition of operating point - Determined by frequency, material properties and geometry
- Choice of operating point according to sensitivity of parameters separation – Best operating point for example is where changes in conductivity or crack signals are separated from geometry changes
- Frequency and probe configuration is optimized to ensure operating point falls in the preferred area (actual Lift off or Fill factor is never 1)

McMaster, R., *Nondestructive Testing Handbook*: Volume 2, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 1959

Probes. Principles and Basic Characteristics

- Induction and reception functions
  - Parametric – one coil creates eddy currents (EC) and measures effect on EC contours due to flaws, material variations and geometry. Coil impedance parameters (R and L) are measured hence the name parametric.
  - Transformer – a primary coil act as transmitter creating EC and secondary coil (receiver) measures the field from EC. The probe is electrical transformer where the inspected material affects the transforming function. The voltage in secondary coil is measured.
- Absolute and differential measure
  - Absolute – Measures absolute properties of materials. Suitable for long flaws. Low sensitivity. Material variations may obscure discontinuities/cracks. Temperature and external electromagnetic noise (EMN) may affect measurements.
  - Differential – Usually has two coils that measure difference in properties between two spots of the same specimen (self comparison) or two different specimens with one being reference (comparator). Self comparison has high sensitivity to short flaws, only start and end will be detected for long flaws, insensitive to temperature and external EMN or gradual property changes. Comparator acts as absolute with reduced effect of temperature and external EMN compared to absolute.
- Types of probes – parametric and transformer, absolute and differential, surface and encircling or internal, any combination of above.

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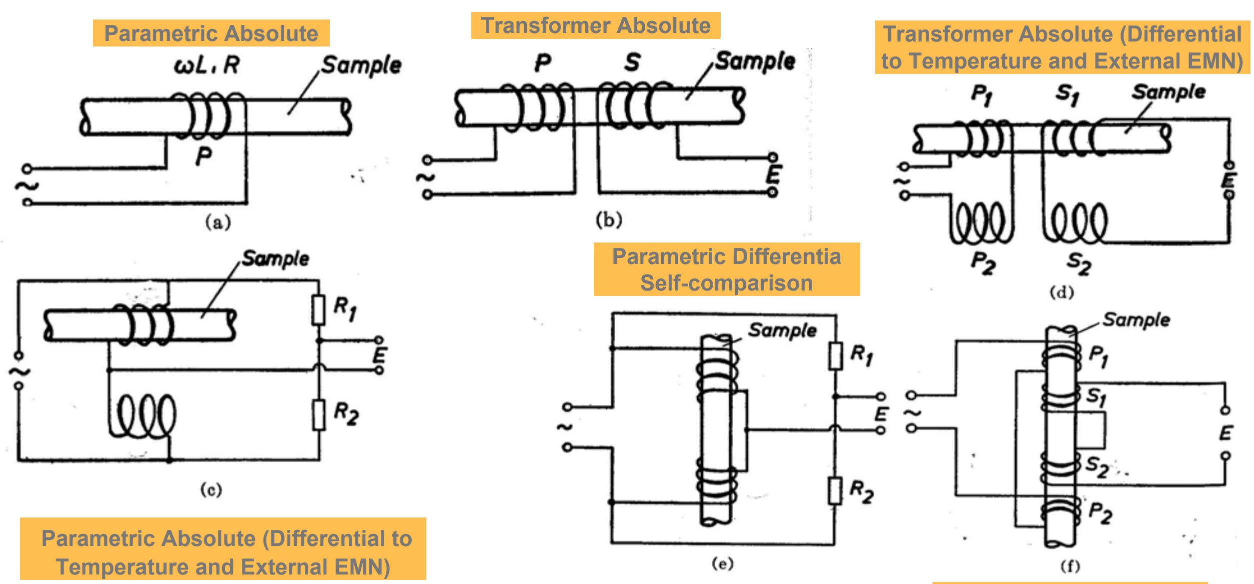
Probe Arrangements for Long Bars



MOVIE Encircling

P – Primary Or Transmitter
S – Secondary Or Receiver

McMaster, R., *Nondestructive Testing Handbook*: Volume 2, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 1959

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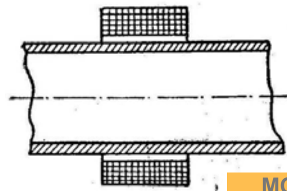
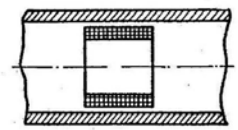
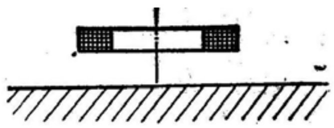
Probe Arrangements for Plates, Sheets and Tubes

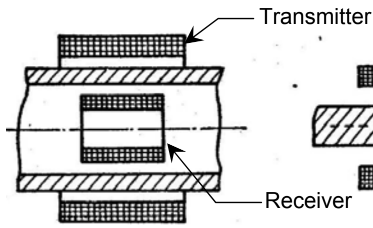
- Surface and tube probe arrangements are similar to those for long bars
- Variety of probes and arrangements necessary to ensure optimal inspection conditions

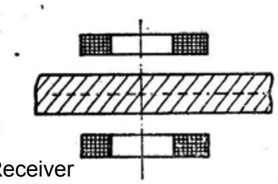


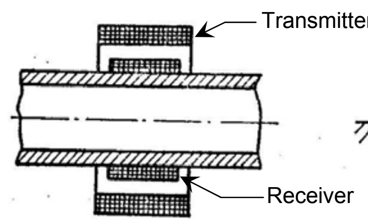


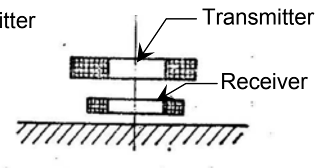
MOVIE BobbinProbe





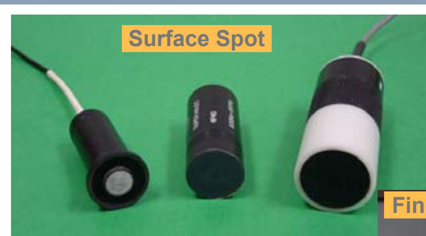


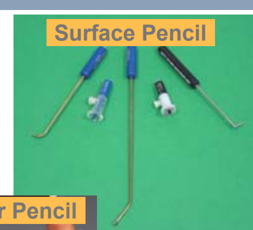


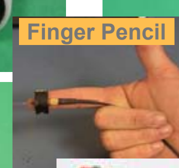


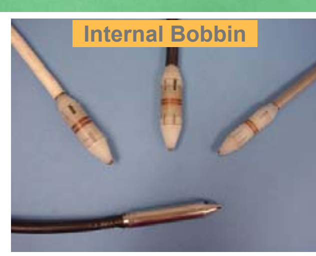
Different Probe Designs and Applications

- Surface spot probes used for inspection of flat areas
- Pencil probes good for tight areas and close proximity of inspection area to edges and corners
- Aerospace multilayer structure with fasteners often inspected with sliding and ring probes
- When fasteners are removed, fastener holes inspected with rotating bolt hole probes
- Encircling probes with various shapes employed for examination in automotive and primary metal industries
- Internal or bobbin probes extensively used for tube inspection of heat exchangers in conventional and nuclear power plants









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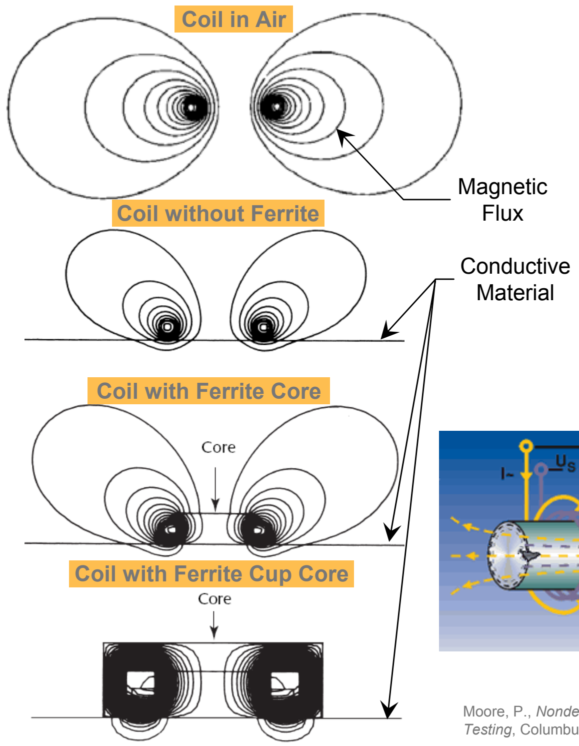
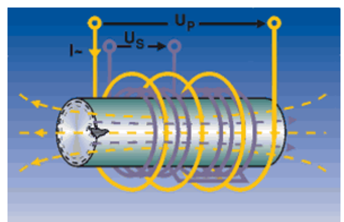
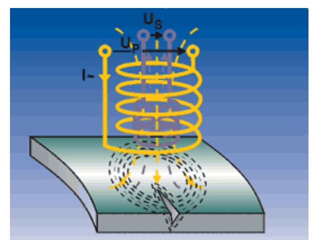
Probes. EC Distributed Related to Coil Position



- Field generated by non-load inductor coil
- EC contours in the part related to juxtaposition between the coil and the part – EC paths mirror approximately shape of transmitter coil creating the field
- Distance/Lift off effect on coupling in various probes – Reduces sensitivity and resolution when increased. The smaller the probe the higher the effect.
- Focusing means – Ferrite, electrical steel, copper, aluminum. Shield the coil, increase sensitivity, decrease depth of penetration, inspect material next to edges or corners





Moore, P., *Nondestructive Testing Handbook*, third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

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Probes. Reaction of Different Coils According to Coil Shape

- Reaction to small flaws
  - Reaction strongly depends on the ratio of flaw-to-probe size. The higher the ratio the better the sensitivity to flaw but worse the sensitivity to lift off.
  - Differential probes with self-comparison are better for detection of small flaws than absolute.
- Reaction to long flaws
  - Long flaws are those that are longer than the diameter of surface or pencil probes or longer than the width of encircling/internal probes.
  - Differential probes will only indicate the begging and the end of long flaws whereas the absolute will indicate the entire length of long flaws.
- Reaction to continuous (e.g. seam weld) flaws
  - Absolute or self-comparison differential probes may not be adequate for this application
  - May require differential arrangement with separate reference specimen

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Probes. Technology and Practical Characterization

- Critical design factors
  - Material penetration requirements (surface vs. subsurface)
  - Sensitivity requirements
  - Type of probe connections on eddy current instrument (many variations)
  - Probe and instrument impedance matching (will probe work with instrument)
  - Probe size (smaller probes penetrate less)
  - Probe type (absolute, differential, parametric, transformer others)
- All possible to simulate through modeling
- Manufacturing/Design technology
  - Trial and error
  - Advanced modeling tools available currently to simulate performance before order and practical trials
  - Copper wire used to wind the coil
  - Body made of plastic. Wear resistant plates or resins used for probe tips or contact surfaces
  - Ferrite cores, cups and tubes used for focusing
  - Metal used for shielding mainly
- Electric parameters
  - Resistance (R) and inductance (L)
  - Induced voltage
  - Parasitic capacitance (C)
  - Frequency range
  - Resonance
- Maintenance
  - Check cables and connectors
  - Visually inspect for wear and tear
  - Measure electrical parameters regularly
  - Use protective tape on probe tip to avoid damage during scanning of rough surfaces

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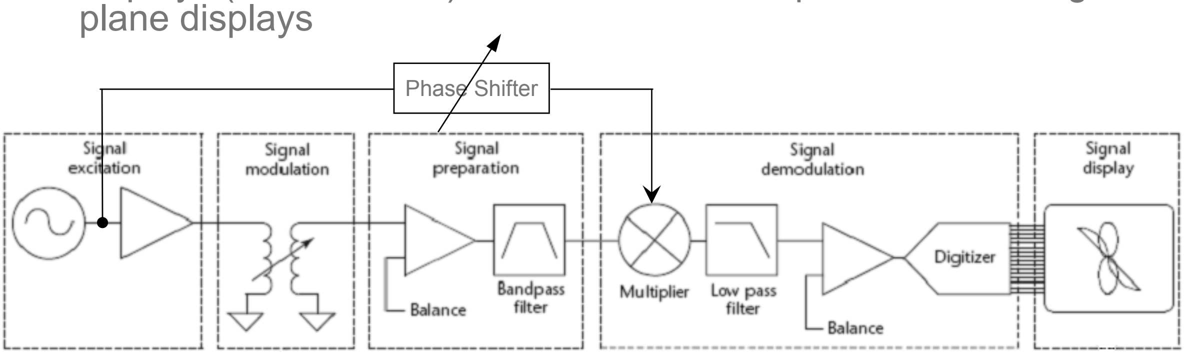
Equipment. Working Principles of EC Equipment

- Transmission – Sinusoidal generator with adjustable frequency using power amplifier to excite the transmitter coil
- Reception – Usually differential amplifier with full or semi-bridge input circuit followed by signal conditioning and demodulation
- Data presentation – Various devices ranging from needle analogue displays (older models) to more common impedance or voltage plane displays



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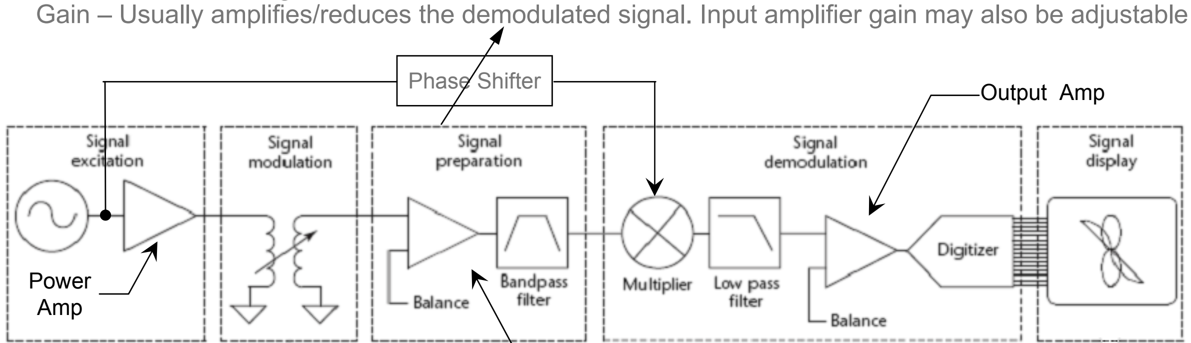
Equipment. Adjustment of EC Equipment

- Frequency – Control the sensitivity and separation of parameters (operating point). Important for adequate depth of penetration.
- Generator – In addition to frequency adjustment it allows control of exciting current or voltage applied to the transmitter coil
- Balancing – Compensates the signal bias to avoid saturation of reception circuits. Position signal point on the screen at a location referred to as "Balance Point"
- Phase rotation – Orientation of signals to facilitate signal interpretation. Lift off usually from right to left from the balance point.
- Output filter – High pass, band pass and low pass. Used to improve signal during scanning of materials with varying properties and geometry. Should not be mixed with low pass demodulation filter shown in the diagram below.
- Gain – Usually amplifies/reduces the demodulated signal. Input amplifier gain may also be adjustable



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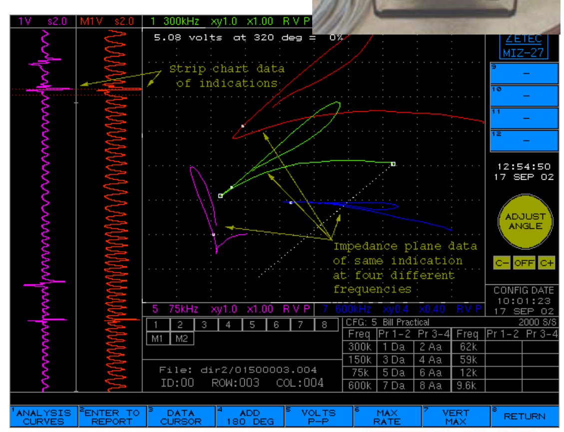
Equipment. Different Types of EC Equipment

- Mono-parameter, mono-channel and specialized
  - Meters simplest form of eddy current instrumentation
  - Conductivity meters - another category of specialized EC
  - Impedance plane most widespread typical instruments
- Multi-parameter and multi-channel
  - Drive inspection coils at more than two frequencies either sequentially (multiplexing) or simultaneously
  - Used extensively for tubing inspection in the power generation, chemical and petrochemical industries
  - Capable of being computer networked and may have as many as 256 coils attached to them at one time
- Advantages of multi-parameter
  - Allows increased inspection information to be collected from one probe pulling
  - Provides for comparison of same discontinuity signal at different frequencies
  - Allows mixing of frequencies which helps to reduce or eliminate sources of noise
  - Often improves detection, interpretation and sizing capabilities of discontinuities



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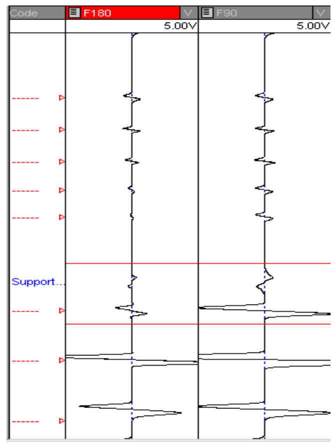
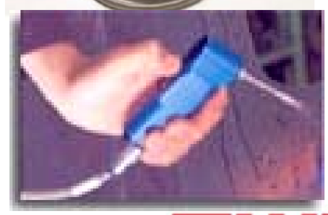
Equipment. Auxiliary Devices

- Auxiliary devices for signal acquisition
  - Encoders
  - Scanners
- Driving mechanism, Saturating unit, Demagnetizer
- Equipment of signal storage
  - Strip-chart recorders
  - Magnetic tape recorders
  - Numerical memories
- System for automatic processing of signals
  - Enhancement – averaging, filtering
  - Classification – K-means clustering, neural networks
  - Characterization – flaw size and shape reconstruction, material properties estimate





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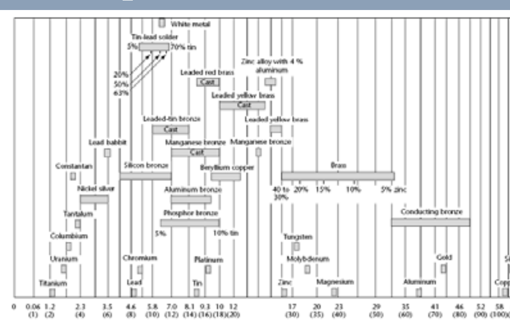
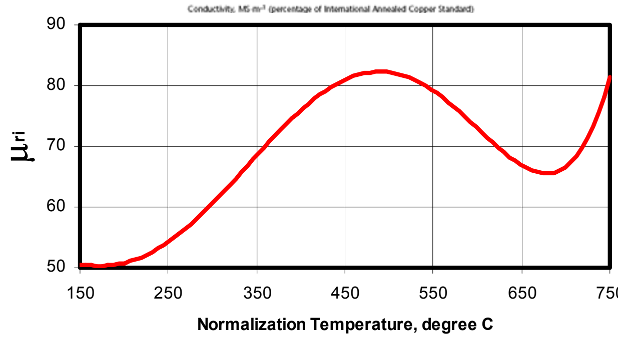
THE MATERIALS JOINING EXPERTS

Materials and Products. Electromagnetic Properties

- Electric conductivity
  - Chemical analysis-Conductivity affected strongly by chemical composition
  - Temperature-Resistivity increases with temperature
  - Grain size-Hardness is usually correlated with conductivity
  - Texture-Rolling and drawing may lead to conductivity anisotropy
  - Structure-Phase composition may affect it
- Magnetic permeability
  - Chemical analysis-Different materials have different magnetic properties
  - Temperature-Magnetic properties lost at Curie point
  - Grain size-Strongly affect permeability
  - Texture-Permeability is anisotropic and depends on rolling and drawing direction
  - Structure-Phase composition (ferromagnetic vs nonmagnetic) is strongly correlated with permeability





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THE MATERIALS JOINING EXPERTS

Materials and Products. Main Discontinuities Detected by EC

- Production – surface and slightly subsurface
  - Solidification cracks
  - Pores
  - Chemical and phase composition
  - Welding
    - LOF
    - LOP
    - Cracks
    - Undercut
    - Pores
    - Seam tracking
- Processing (hot or cold)
  - Discontinuities – Cracks, laps, stringers, chevron marks
  - Heat treatment
  - Residual stresses and hardness
  - Phase composition
- In-services
  - Creep – Leading to change of electromagnetic properties
  - Fatigue – Fatigue cracks and strain. Multilayer structure for surface and subsurface cracks in aerospace
  - Corrosion – Loss of material (oxides non-conductive), inter-granular changes electromagnetic properties

Influence of Parameters. Flaw Position and Orientation

- EC contour – Contours must be as close to perpendicular to the flaw plane as possible to generate max response
- Penetration depth – best detection and sizing possible in one to two standard depth of penetrations
- Zone of probe action
  - Non-shielded - Extends several depths of penetration around probe tip on inspected surface
  - Shielded – Area around the probe is significantly reduced due to focusing ferrite and soft magnetic iron means

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Influence of Parameters. Material Temperature

- Heating – Temperature affects material properties
  - Resistivity increases with the temperature increase
  - Magnetic properties are lost above Curie temperature
  - Local areas of spontaneous magnetization may appear on surface of hot rolled materials due to local cooling
- Compensation
  - Differential and particularly transformer differential probes are best temperature compensated
  - Probes may need cooling or must be cooled when testing materials after the furnace or hot rolling processing

Influence of Parameters. Geometry and Structure of Part

- Choice of test frequency – Very important to optimize the operating point on the impedance plane diagram for best separation and sensitivity
- Phase discrimination – Flaw depth measurements is better done with phase measurements in many cases. Frequency selection important for better signal separation/discrimination by phase.
- Filtering – Reduces noise from fluctuating properties, vibration, electrical sources etc
- Magnetic saturation – Used mainly for inspection of thin wall magnetic tubes as nonmagnetic (improved penetration) during saturation

Influence of Parameters. Coupling

- Vibration – Must be eliminated through mechanical means or filtered electronically
- Centering – For encircling, internal tube and bolt hole probes, ensures the sensitivity is uniform along the tube or hole circumference
- Sensitivity – Sensitivity is reduced when the coupling (usually increased distance) is reduced.
- Compensation –
  - Use means for centering and stabilization of probe movement as close to inspected surface as possible
  - Design probes less sensitive to coupling variations

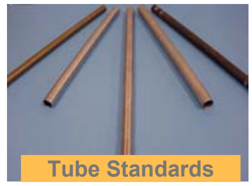
Influence of Parameters. Speed Relative Part vs Probe

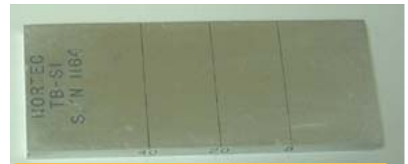
- Defect spatial frequency (f_{defect}) – Ratio of inspection or testing speed (V_{test}) to coil diameter (D_{coil}) for surface probes assuming flaw length is normal to probe scan and flaw width is very small relative to probe diameter and parallel to probe scan.
- Examples of defect frequency at different inspection speeds
  - Defect frequency of 100 Hz is obtained at testing speed of 0.3 m/s (1 ft/s) with probe diameter of 3 mm
  - Defect frequency of 1 kHz is obtained at testing speed of 3 m/s (10 ft/s) with probe diameter of 3 mm
- Bandwith of equipment according to testing speed
  - Bandwith is increased with increased inspection speed
  - Further bandwidth increase is required when several probes are simultaneously used in multiplex arrangement
  - Important to select adequate equipment for the expected inspection speeds
  - Filter settings must be adjusted correctly for automated inspection applications

$$f_{defect} = \frac{V_{test}}{D_{coil}}$$

Inspection Procedures. Reference Standards

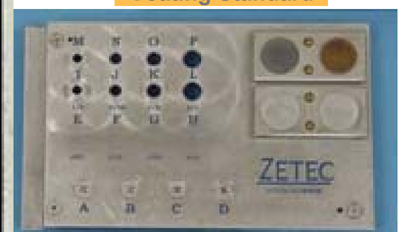
- Function of reference standards
  - Ensure repeatable inspection and establish accept/reject criteria
  - Signals generated from inspection must be compared with known values
  - Reference standards manufactured from same or similar material as inspected material
  - Structural features may be represented (aerospace multilayer)
  - Should not be mixed with experimental for qualification
- Choice of reference standards-Very important
  - Many different types of standards due to variety of eddy current inspections
- Various types of reference standards – fabrication, reproducibility
  - EDM notches
  - Actual flaws – fatigue cracks, corrosion
  - Drilled holes or machined grooves
  - Artificial flaws better reproduced and cheaper, although, less representative


Tube Standards


EDM Notches (Crack Simulation)


Corrosion Standard


Coating Standard



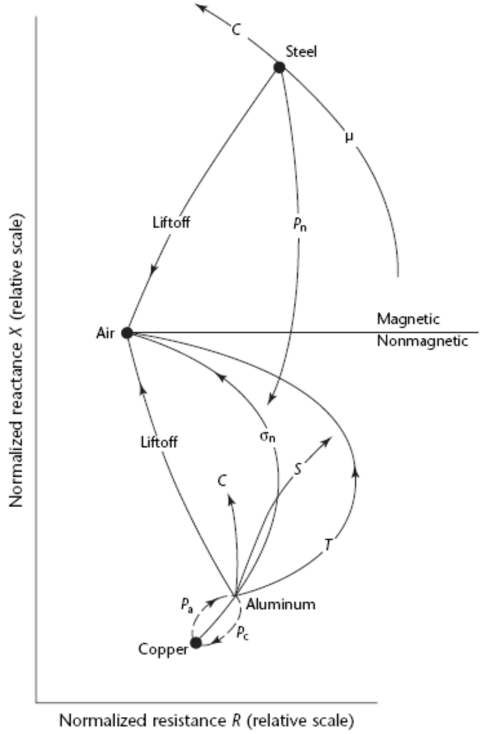
Multipurpose - EDM Notches and Conductivity

MOVIE
TubCalibrSpec

Inspection Procedures. Inspection

- Access – Needs verification before preparation of procedure. Accessories (holders, scanners, fixtures) may be required.
- Surface preparation – Although EC application does not require paint removal, cleaning of loose paint, corrosion products, dirt is performed as necessary.
- Speed – EC inspection speed may reach up to 100 m/s. Filter settings are correlated with speed and must be readjusted if speed is changed.
- Use of auxiliary devices – Required to increase inspection reliability (e.g. saturation coils/magnets, scanners)
- Inspection range – Must be clearly specified in procedure (e.g. thickness of material and coating, magnetic or nonmagnetic metals, tube diameters, fastener type)
- Indication recording – Usually, indications that exceed a threshold are recorded. In other cases, all data is recorded and analyzed later.

Main Applications of EC Testing. Impedance Plane



PARAMETERS ON IMPEDANCE PLANE

C - Crack in aluminum or steel

Pa - Plating aluminum on copper

Pc - Plating copper on aluminum

Pn - Plating nonmagnetic on steel

S - Spacing between aluminum layers

T - Thinning in aluminum

μ - Permeability

σ_n - Conductivity nonmagnetic materials

- Signal analysis usually conducted on impedance plane
- Specimen preparation critical to identify operating point and optimize performance
- Applications
  - Flaw detection and sizing
  - Electromagnetic property measurement
  - Thickness of metal sheet and coating measurement

Moore, P., *Nondestructive Testing Handbook,* third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

Main Applications of EC Testing. Flaw Detection

- Absolute measurements - Inspection for properties that change gradually (see slides with probe types)
  - Material characterization – conductivity and permeability measurements
  - Material sorting
  - Inspection for flaws and conditions relatively larger that probe size
  - Sheet, tube wall (corrosion) and coating thickness measurement
- Differential measurements – Detection of relatively small and localized discontinuities (see slides with probe types)
  - Small flaws
  - Surface scratches and score marks
  - Small cracks close to edges and corners
  - Detection of small flaws where electromagnetic properties or surface conditions gradually fluctuate (e.g. weld crown surface and volume)
  - Dissimilar materials joints
  - Material sorting using reference coil with standard for comparison
  - Inspection in areas with high level of environmental EMN
  - Inspection in areas where temperature is expected to fluctuate

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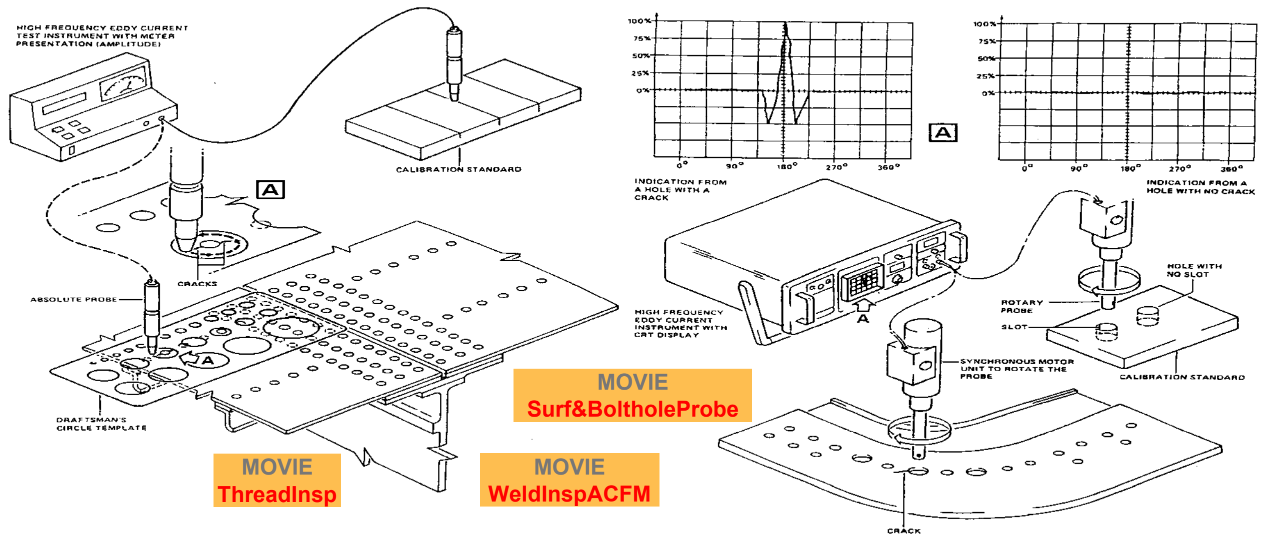
Main Applications of EC Testing. Surface Flaw Detection.



- One of the most wide-spread applications
- Conducted manually, semi- or fully-automated
- In many cases, superior to other surface inspection methods (LPI, MPI, UT)
- Performed through paint, coatings or at a distance from surface

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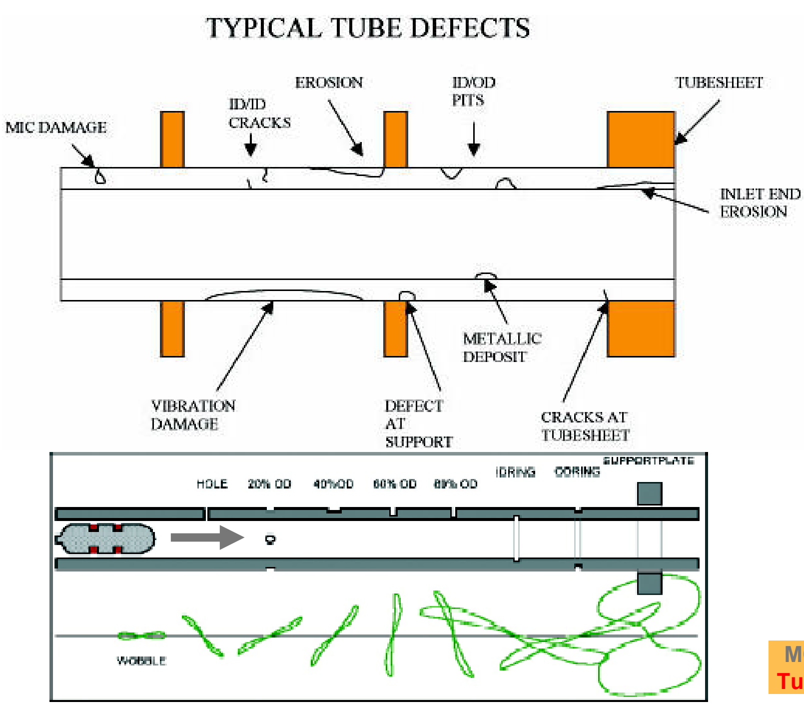
Main Applications of EC Testing. Tube Flaw Detection



The Collaboration for NDT Education, www.ndt-ed.org

- Typical inspection tasks – cracks, corrosion and other fabrication and service damage
- Renaissance of nuclear power plants will require more inspections
- Weld surface inspection

MOVIE TubInsp

MOVIE TubInspDiffer

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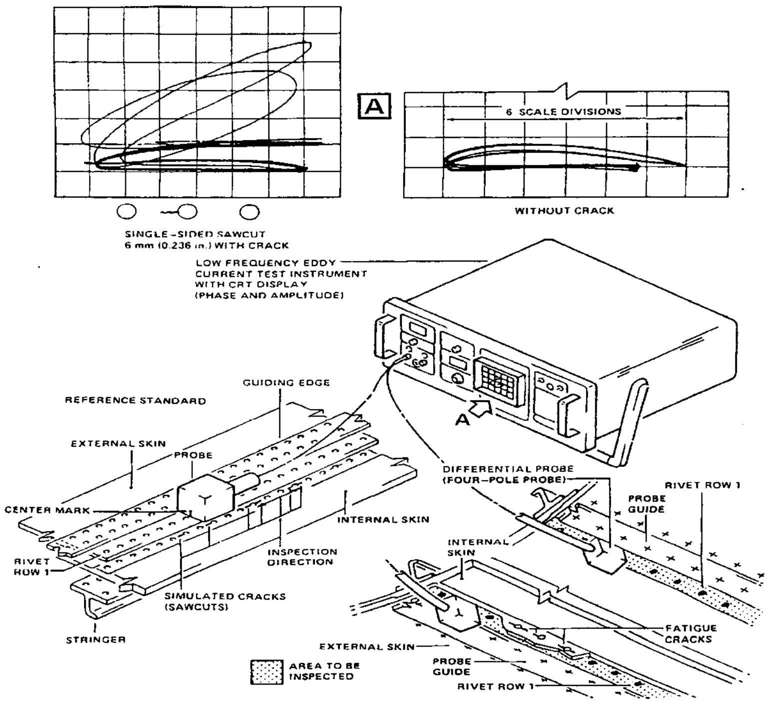
Subsurface Crack Inspection. Multilayer Structure



- Used extensively in aerospace
- Depths up to 6-10 mm are common
- In general, detectable flaw size increases with depth increase
- Representative calibration specimens are critical for reliable inspection
- Lately, modeling reduces significantly the time and cost for development and increases the inspection reliability

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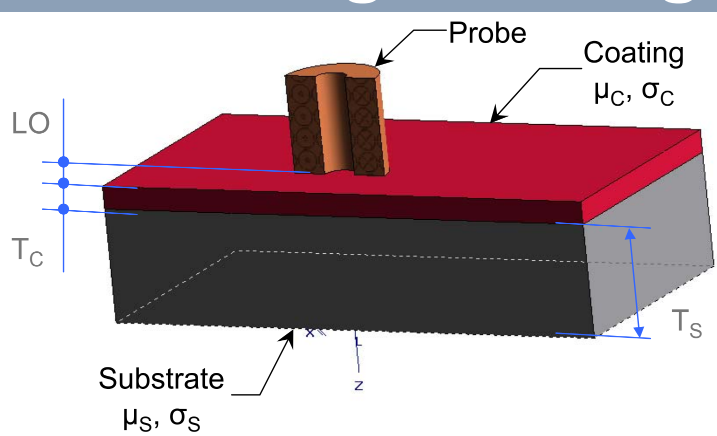
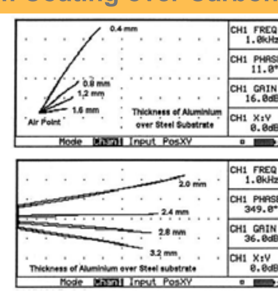
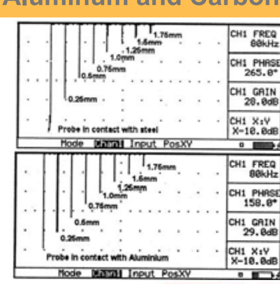
Main Applications of EC Testing. Coating Thickness



Aluminum Coating over Carbon Steel



Paint over Aluminum and Carbon Steel



LO - Lift off
T_C – Coating thickness
T_S – Substrate thickness
μ_S, σ_S – magnetic permeability and electrical conductivity of substrate
μ_C, σ_C – magnetic permeability and electrical conductivity of coating

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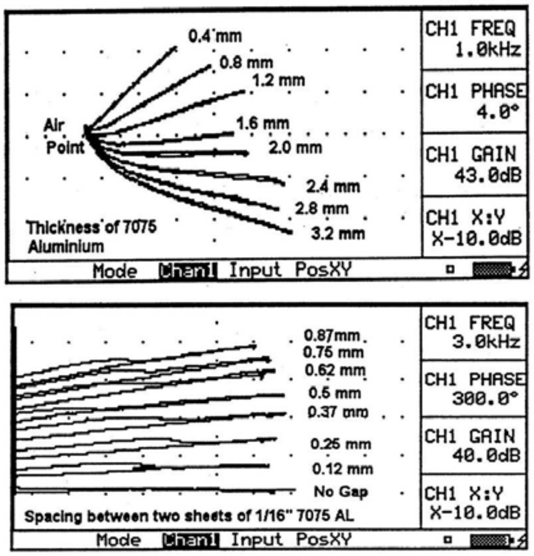
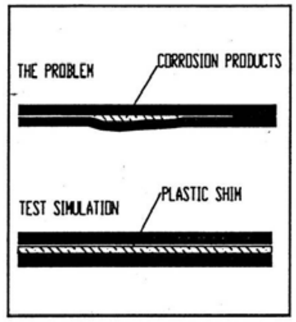
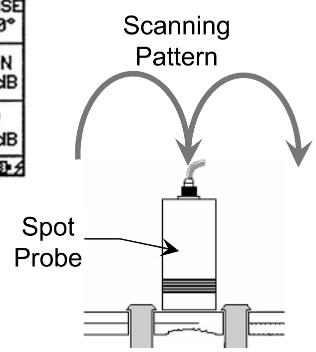
Main Applications of EC Testing. Thickness Test



Impedance Plane Indications





- Thickness of sheet measurements are required for quality purposes during manufacture
- Thickness of sheet measurement approach is used in service for corrosion testing
- Sheet spacing may also be used for corrosion detection
- Depth of penetration in first and second layers shall be sufficient to detect back surface variations due to corrosion or sheet spacing

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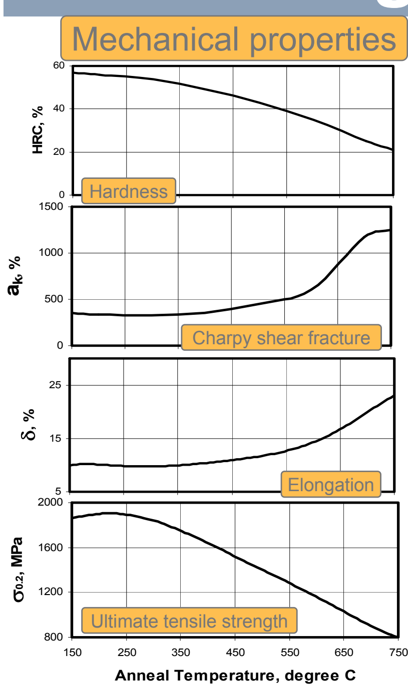
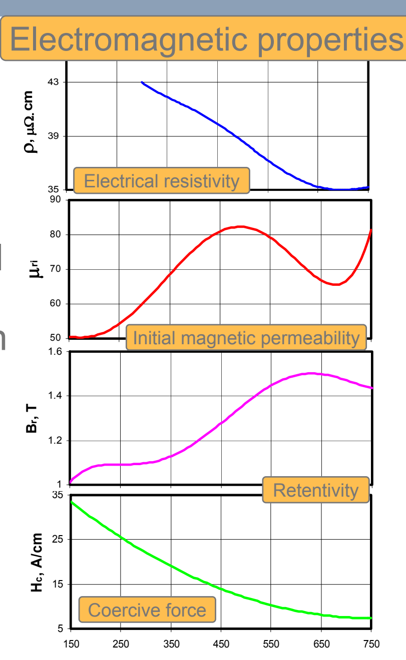
Main Applications of EC Testing. Part Composition.



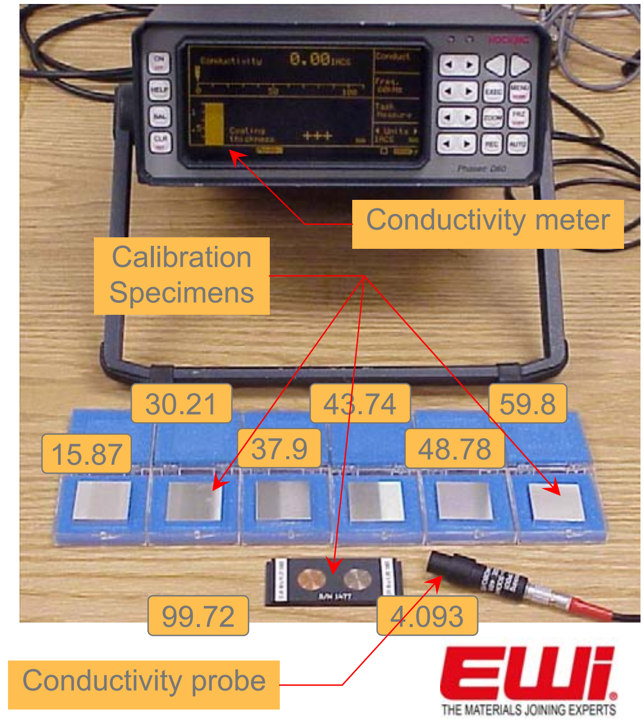
CORRELATION?
YES/NO

- Electromagnetic NDE used extensively for metal inspection
- Based on good correlation between mechanical and electromagnetic properties
- 100% NDE of critical materials and parts for any deviation in quality and properties possible



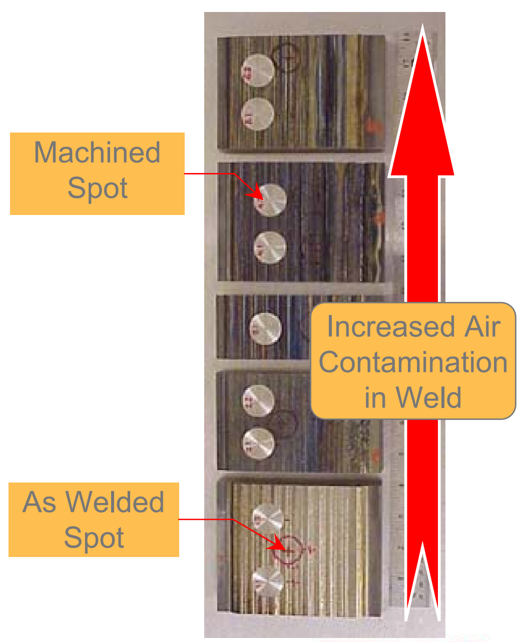
Main Applications of EC Testing. Part Composition. Conductivity Measurement of Nonferrous Metals

- Conductivity meters available for direct measurements of electrical conductivity
- Equipment calibrated on specimens with known conductivity
- Lift off measurements provided in addition to conductivity

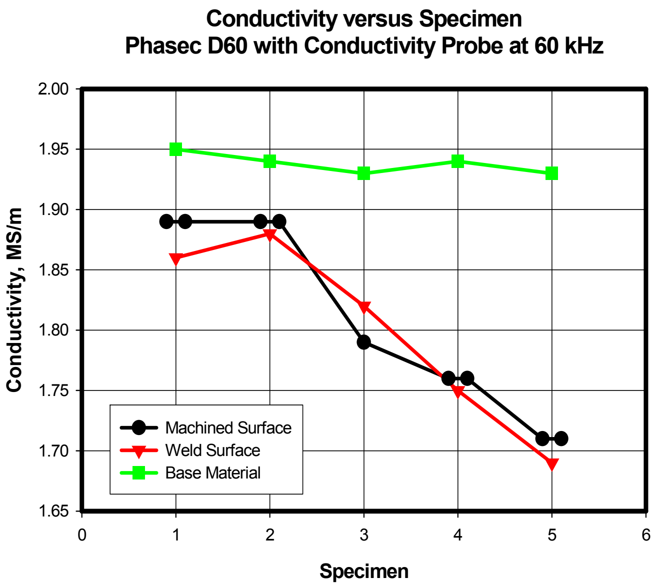


Main Applications of EC Testing. Part Composition. Reactive Material Weld Contamination Detection.

- **Problem** – Air contamination of reactive material clad welds. Color of weld may not always be indicative of contamination.
- Five specimens prepared with increased air contamination in weld. Substrate unchanged.
- Conductivity measured on machined, as-welded clad spots and substrate material



Main Applications of EC Testing. Part Composition. Conductivity Measurements at 60 kHz



- Sorting conducted with conductivity spot probe, 12 mm diameter
- Conductivity dropped almost linearly from Sp1&2 to Sp5
- All specimens separated except Sp1 and Sp2 on machined surfaces
- Base/substrate material conductivity did not change
- Conductivity on machined and as welded surfaces very close

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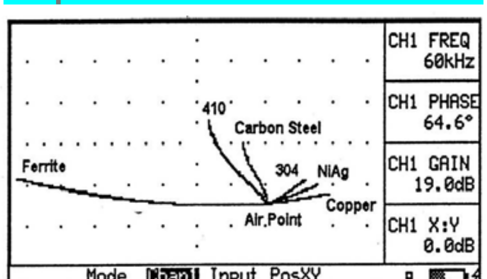
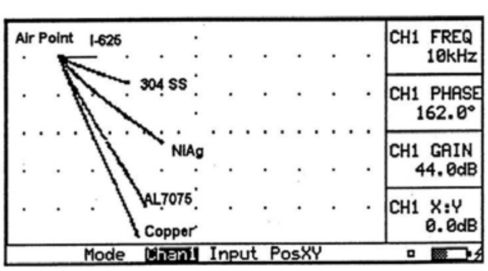
Main Applications of EC Testing. Part Composition. Material Sorting.

Impedance Plane Indications



Sorting of Ferromagnetic and Nonferromagnetic Materials



Sorting of Nonferromagnetic Materials

Set of Conductivity Specimens

- Common procedure for primary metal and automotive industries
- Performed manually, semi- or fully-automated
- Very reliable tool for heat treatment, case hardening depth, hardness, metal phase composition, stress and strain measurement and detection and other metal conditions

MOVIE Sorting

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Advantages of Eddy Current Inspection

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

Limitations of Eddy Current Inspection

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

Glossary of Terms

- **Alternating Current**: Electrical current that regularly reverses direction.
- **Analog**: Being or relating to a mechanism in which data is represented by continuously variable physical quantities such as a watch with hour and minute hands.
- **ASME**: Acronym for American Society of Mechanical Engineers. This society is highly involved in establishing and maintaining industrial standards.
- **CRT**: Acronym for Cathode Ray Tube. Vacuum tube that uses one or more electron guns for generating an image.
- **Calibration**: Adjustment of a test systems response using known values so that unknown quantities may be derived.
- **Conductor**: Material capable of allowing electrical current to flow through it.
- **Discontinuity**: An interruption in the physical structure of a part. Cracks are examples of discontinuities.

Glossary of Terms

- **EDM**: Acronym for Electrical Discharge Machine. Machining technique which uses an electrode and electrical current to remove metal. Sometimes used to prepare calibration standards for eddy current testing.
- **Electromagnetic Induction**: Process which creates electrical current flow when a dynamic magnetic field is brought into close proximity with an electrical conductor.
- **Extrapolation**: To project or predict unknown values from know quantities.
- **I.A.C.S.**: Acronym for International Annealed Copper Standard. Standard unit of measurement of electrical conductivity in eddy current testing with pure annealed copper as the standard, measuring 100% at 20 degrees Celsius.
- **Impedance Plane Diagram**: A diagram that depicts the changes in electrical impedance that occur in an eddy current coil as test variables change.

Glossary of Terms

- **Multiplexing**: Use of a time sharing system in which a coil is stimulated at several different frequencies one after another for a certain amount of time. Results from each stimulation can then be processed and displayed.
- **Permeability**: The ease with which a material can be magnetized.
- **Probe or Sensor**: Common term used in eddy current inspection that refers to the test coil.
- **RAM**: Acronym for Random Access Memory. Most modern eddy current instruments have some form of memory used as a data buffer to store information.

References

1. Moore, P., *Nondestructive Testing Handbook,* third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004.
2. ASM Metals Handbook, Volume 17, Nondestructive Evaluation and Quality Control
3. MIL-HDBK-1823, Nondestructive Evaluation System Reliability Assessment
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5. EWI NDT Projects and Reports