Fundamentals of Non Destructive Testing & focus on electromagnetic methods

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This lecture uses the material

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https://www.nde-ed.org/

General concept for Non Destructive Testing

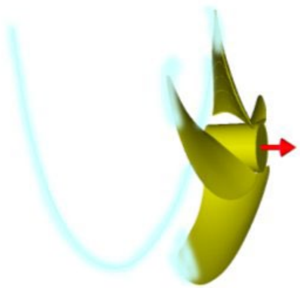
- A damaged material is unable to tell itself

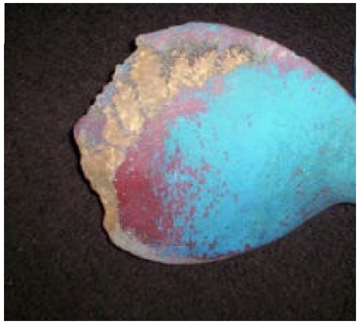
- The important question: for critical applications, what is the remaining lifetime of the system ? What should be replaced to extend it ?

- Numerous solicitations could be applied to the materials:
  - Light, sound, electromagnetic waves, contact liquids etc.

- Depending on the solicitation, it can be made « Non Destructive » and even « In Situ »

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

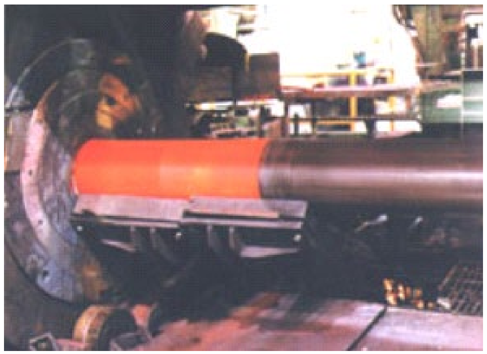




Examples of NDT applications

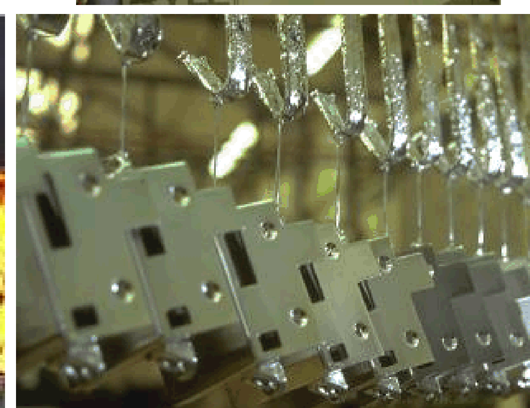
Inspection of Raw Products

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



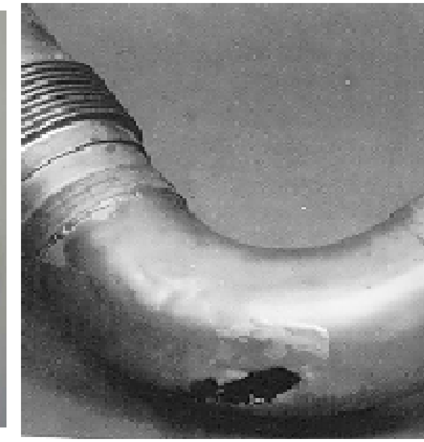
Inspection Following, secondary Processing

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



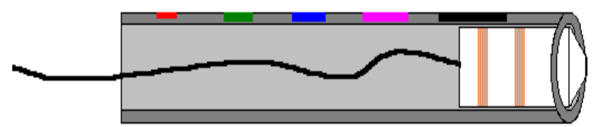
Inspection For In-Service Damage

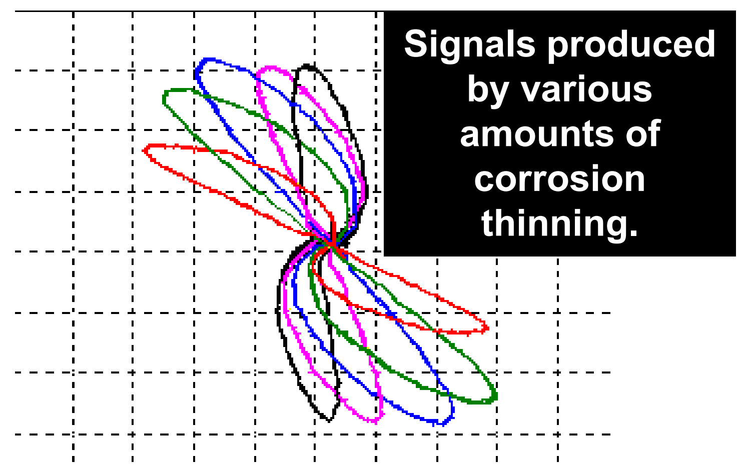
- Cracking
- Corrosion
- Erosion/Wear
- Heat Damage
- etc.

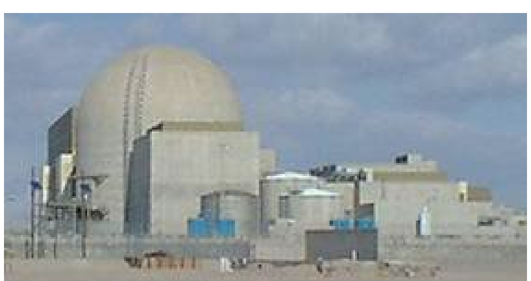


Power Plant Inspection

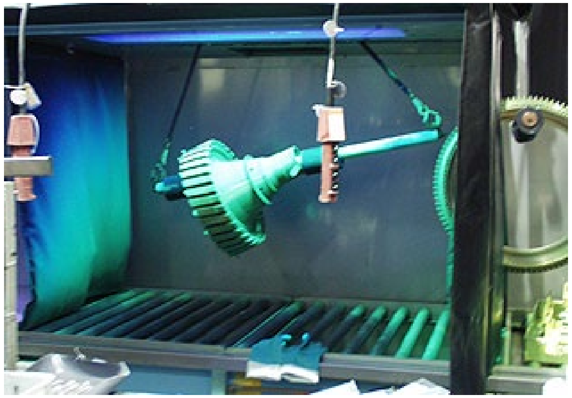
Periodically, power plants are shutdown for inspection.
Inspectors feed eddy current probes into heat exchanger tubes to check for corrosion damage.







Jet Engine Inspection



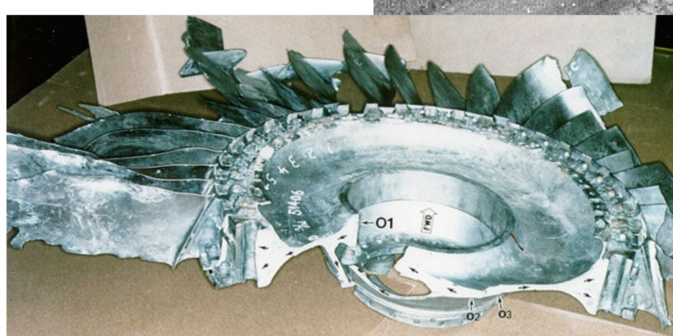
- Aircraft engines are overhauled after being in service for a period of time (e.g. $>10^4$ hours or $>10^3$ cycles).
- They are completely disassembled, cleaned, inspected and then reassembled.
- Fluorescent penetrant inspection is used to check many of the parts for cracking.

- Maintenance in aircraft industry represents 10% to 20% of the direct operating cost, engine maintenance representing around 40%

Crash of United Flight 232

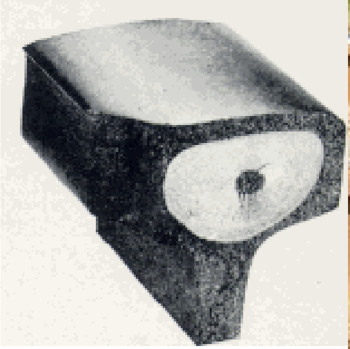
Sioux City, Iowa, July 19, 1989

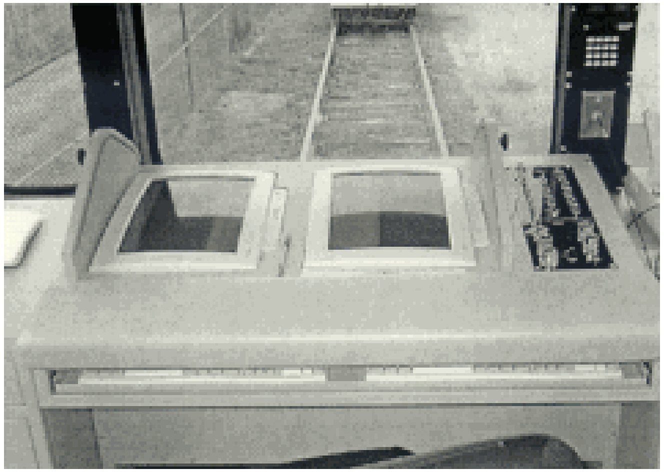
A defect that went undetected in an engine disk was responsible for the crash of United Flight 232.



Rail Inspection

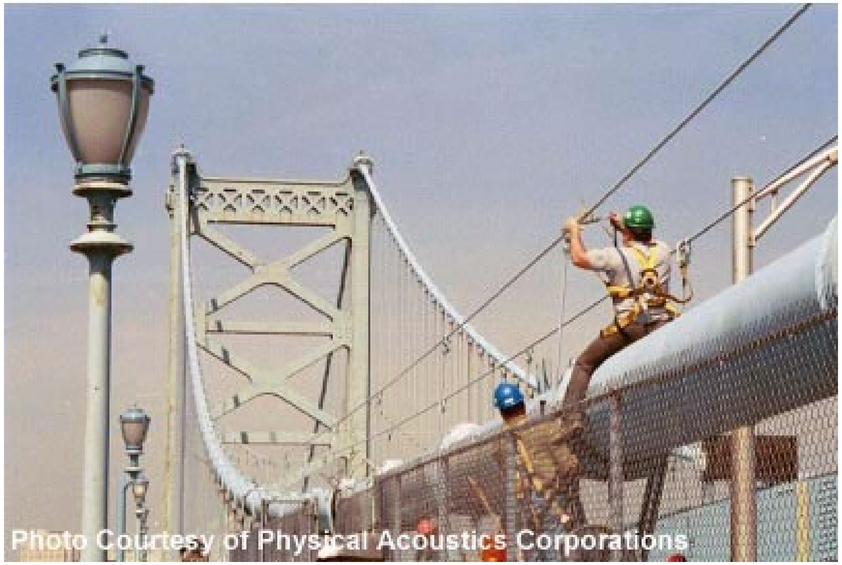
- Special cars are used to inspect thousands of kilometers of rail to find cracks that could lead to a derailment.

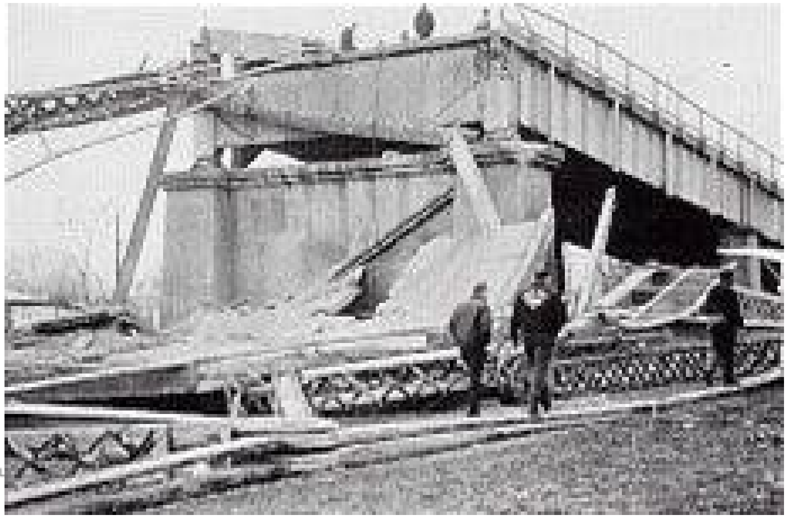




Bridge Inspection

- Corrosion, cracking and other damage can all affect a bridge's performance.
- 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.





Presentation of NDT techniques and some physical insights behind

Thermography

Visual

Microwave

Magnetic Particle

Tap Testing

Acoustic Microscopy

X-ray

Acoustic Emission

Magnetic Measurements

Liquid Penetrant

Ultrasonic

Replication

Laser Interferometry

Eddy Current

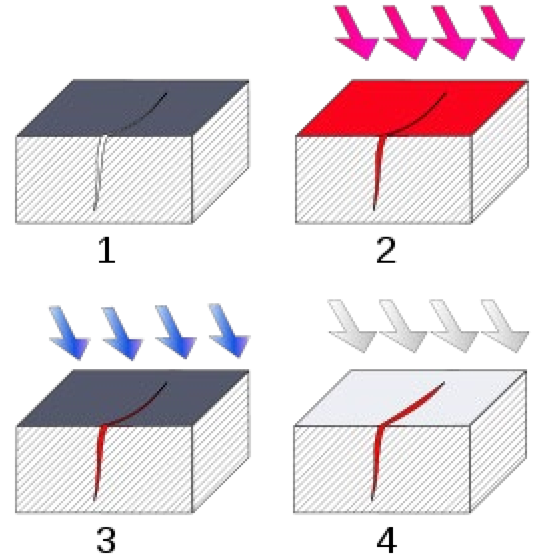
Flux Leakage

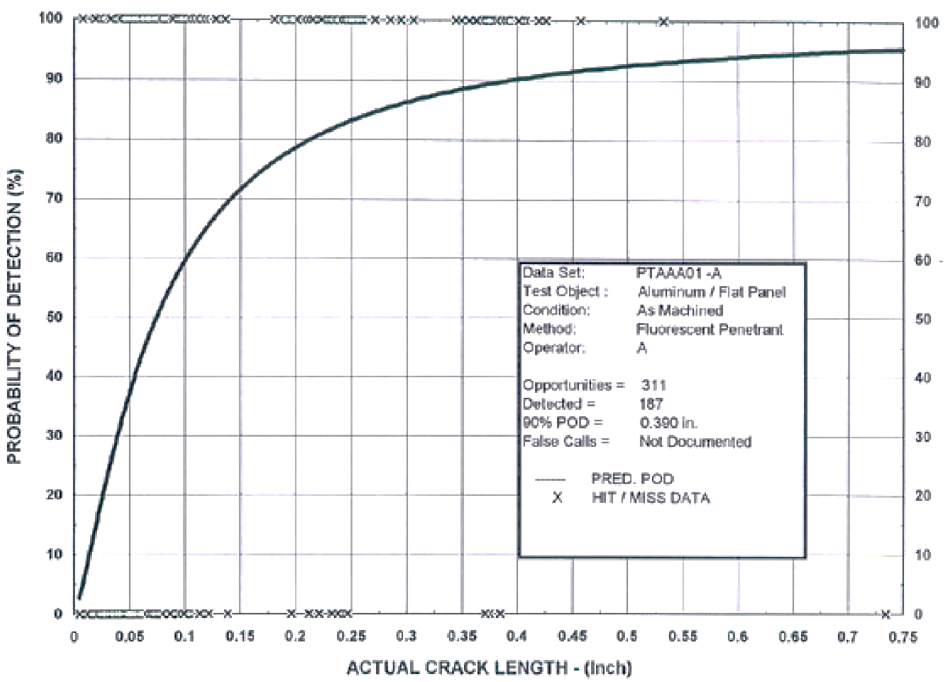
Visual and Optical Testing (VT)

- Simple and effective: just look at the parts to be checked.
- Most basic and common inspection method.
- Based on the knowledge of how it looks when it is damaged
- 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.

Penetrant Testing (PT): principle

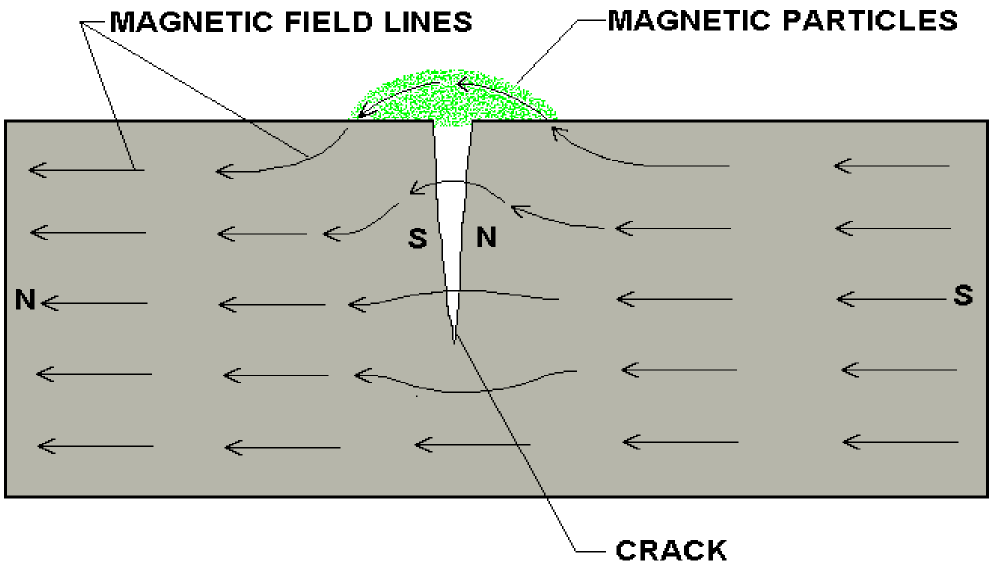
- When the eye is not accurate enough:
  - Small defects, lack of contrast for cracks visualization
- The penetrant testing is a way to increase eye accuracy
  - By increasing the crack contrast





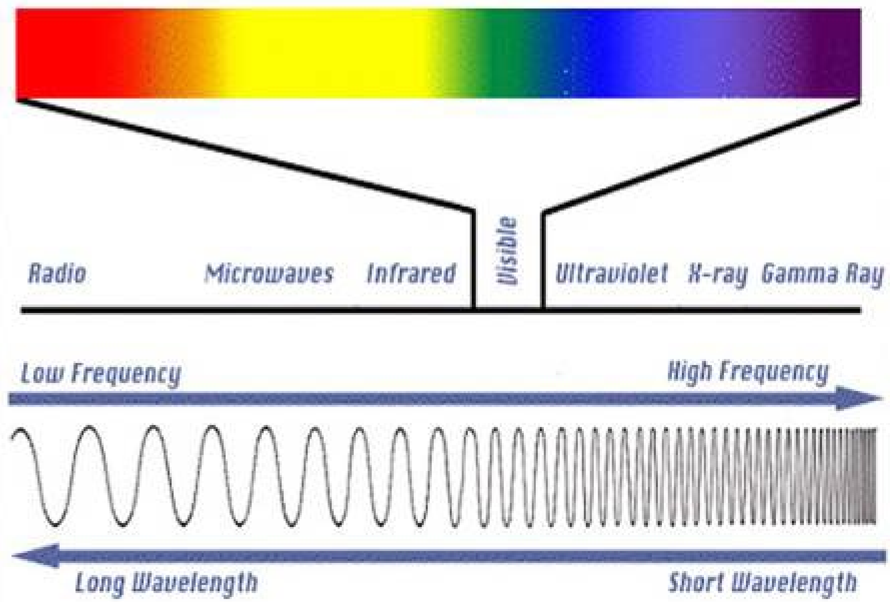
Magnetic Particle Inspection

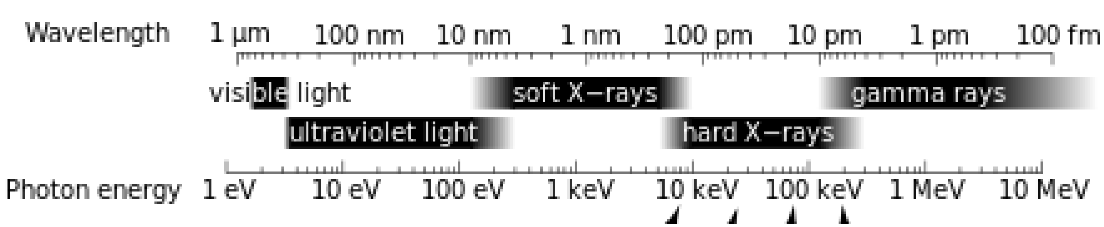
The part is magnetized. Finely milled iron particles coated with a dye pigment are then applied to the specimen. These particles are attracted to magnetic flux leakage fields and will cluster to form an indication directly over the discontinuity. This indication can be visually detected under proper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

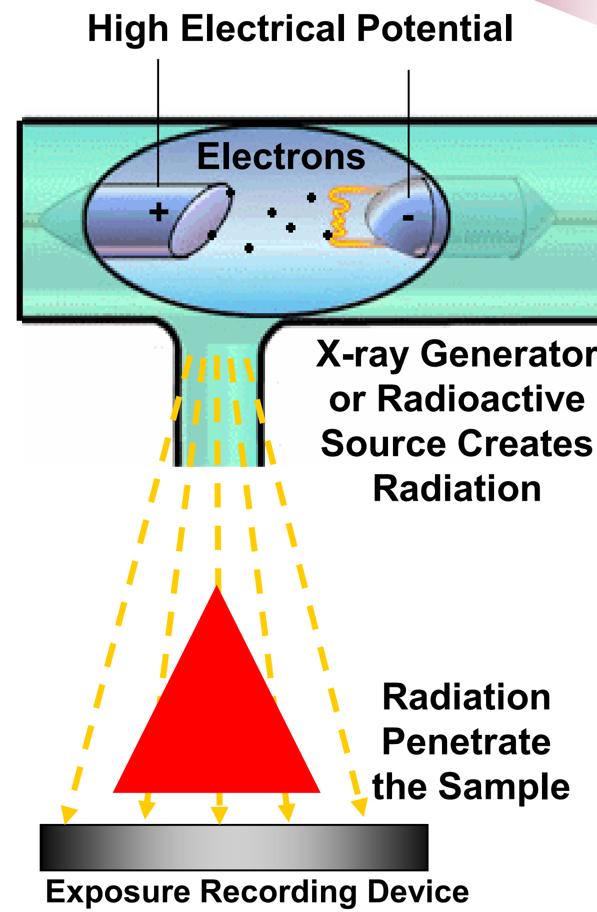


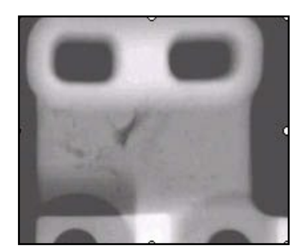
For defects inside the tested material: radiography

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.



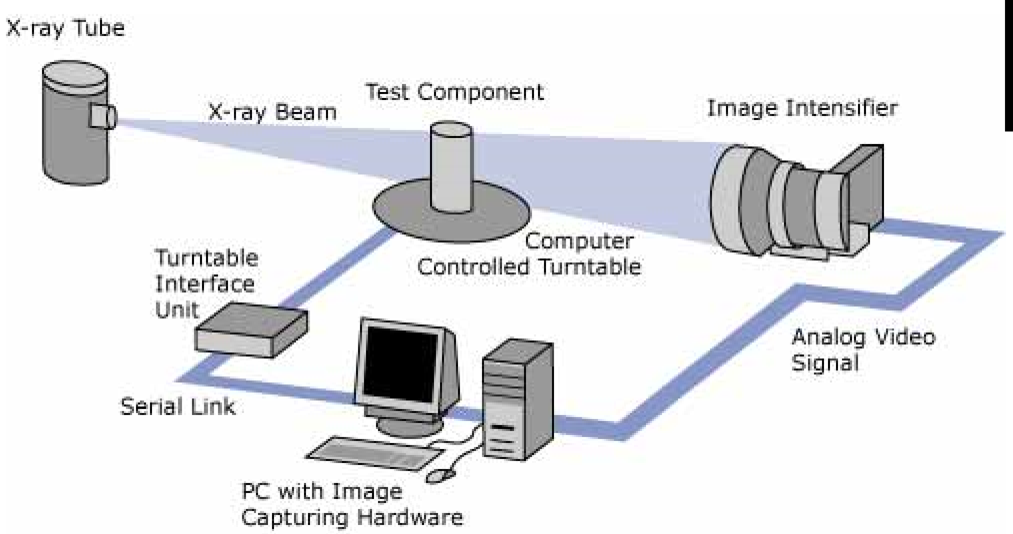


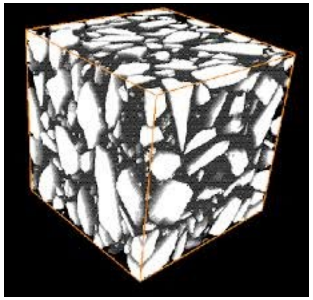


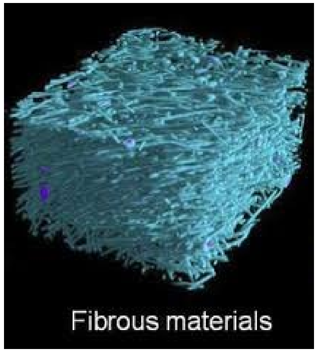


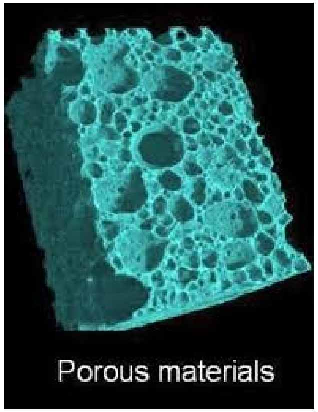
Tomography (not used as NDT but better material characterization)

- 3D reconstruction of internal structure









Provided by X Jia and Q Yuan. The University of Leeds

Concluding remarks

- A variety of techniques and applications
- Innovation is still possible in this field for a better safety
- 3D imaging using X-ray or acoustic microscopy further enhance the visualization
- But, always, the « end-user » knowledge about his application is of primary importance

Thermography

Visual

Microwave

Magnetic Particle

Tap Testing

Acoustic Microscopy

X-ray

Acoustic Emission

Magnetic Measurements

Liquid Penetrant

Ultrasonic

Replication

Eddy Current

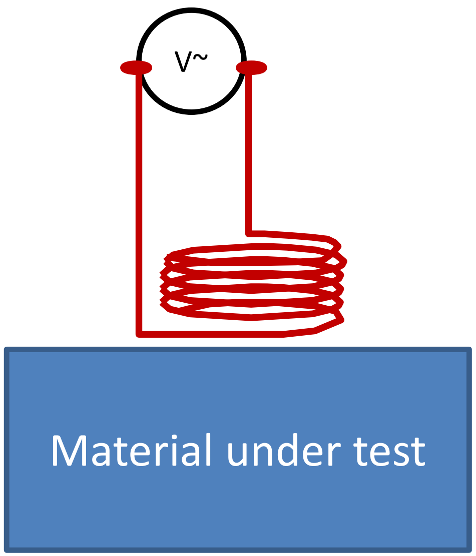
Laser Interferometry

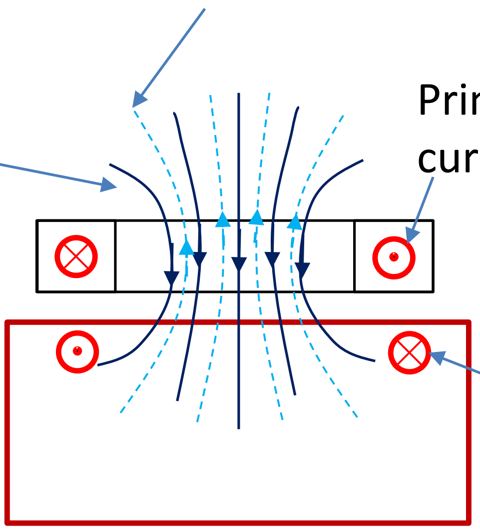
Flux Leakage

Focus on Eddy Current Testing and other electromagnetic techniques

Eddy current testing: signals from coils placed nearby tested material

- Alternative current supplied to the coil, measure of its voltage
- Signals depends on the medium nearby the coil, more precisely its magnetic permeability and electrical conductivity,





Back to some fundamental physics

- EM wave equation for electric field $\vec{E}$: $$\nabla^2 \vec{E} = \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} + \mu\sigma \frac{\partial \vec{E}}{\partial t}$$

- Case of metallic materials in harmonic regime:

$$\nabla^2 \vec{E} = \left(\mu\varepsilon (j\omega)^2 + \mu\sigma j\omega \right) \vec{E}$$

μ = magnetic permeability (H/m)

ε = dielectric permeability (F/m)

σ = electrical conductivity (S/m)

- If the frequency is low enough: $\sigma \gg \varepsilon\omega$

$$\nabla^2 \vec{E} = \mu\sigma j\omega \vec{E}$$

Example for copper: $\gamma=10^7$ S/m, $\varepsilon=8{,}85 10^{-12}$ F/m => true for f << 10^{17}Hz

- The wave equation becomes a diffusion equation

$$\underline{\vec{E}} = E_0 e^{j(\omega t - kx)} \hat{n}$$

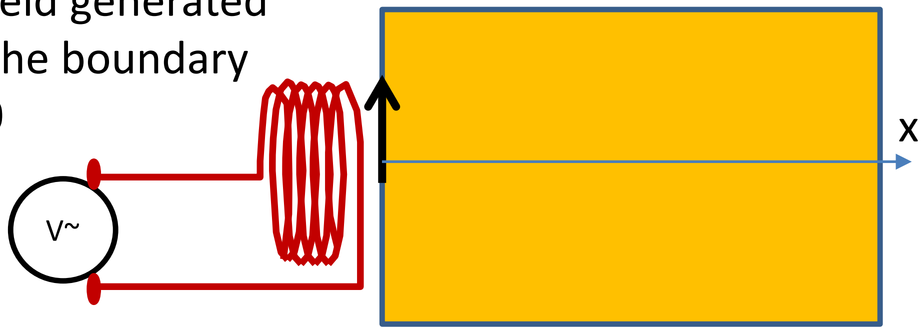
$$-k^2 = \mu\sigma j\omega \qquad k = \frac{1-j}{\delta} \qquad \delta = \sqrt{\frac{2}{\omega\sigma\mu}}$$

Solution for a Linearly Polarized Plane Wave

Animated plot of the E-field

E-field generated at the boundary x=0

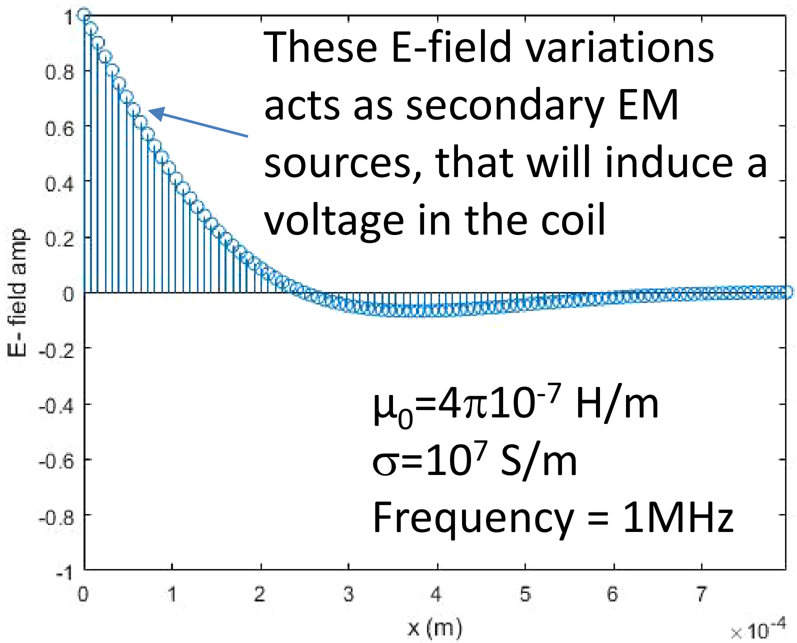
Copper semi-infinite medium



$$E = E_0 \,\mathrm{Re}\left\{ e^{j(\omega t - kx)} \right\}$$

$$k = \frac{1-j}{\delta}$$

$$\delta = \sqrt{\frac{2}{\omega \sigma \mu}}$$



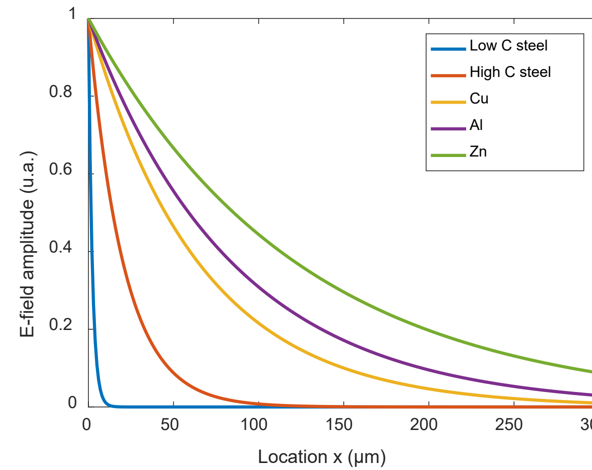
These E-field variations acts as secondary EM sources, that will induce a voltage in the coil

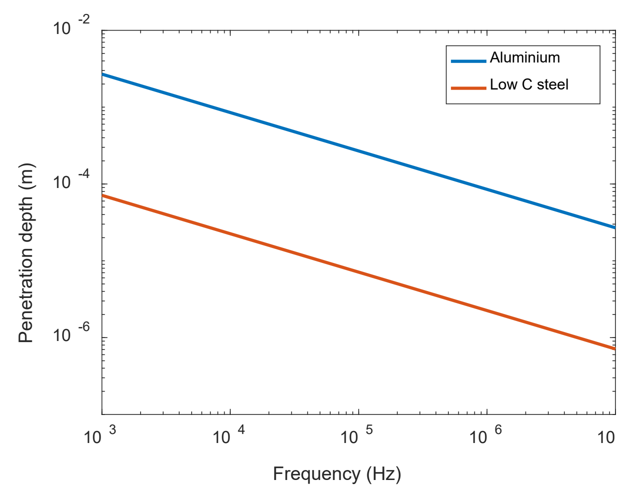
$\mu_0=4\pi 10^{-7}$ H/m

$\sigma=10^{7}$ S/m

Frequency = 1MHz

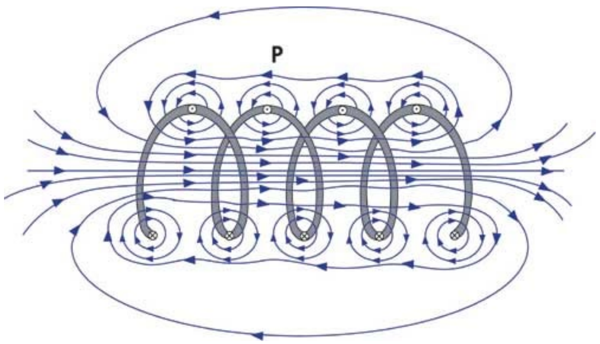
$$e(t) = -\iint_{coil\_surface} \frac{\partial \vec{B}}{\partial t} . \overrightarrow{dS}$$





Induction in coils

- Self-inductance: the magnetic flux generated by a coil is inducing electric field on the coil itself



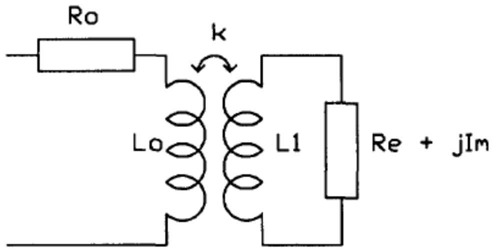
$$e(t) = -\iint_{coil\_surface} \frac{\partial \vec{B}}{\partial t} . \vec{dS} = -L \frac{di(t)}{dt}$$

- In the vicinity of a magnetic or conductive material, the value of the inductance L is modified, as well as the resistance of the coil.
- A conductive material is subjected to eddy currents. As a consequence, they will generate a magnetic field on the coil, counter-acting against the primary one => less flux in the coil => L decreases. Also, dissipated energy by the eddy currents will increase the losses of the coil => R increases.
- A magnetic material generates a new magnetic field that is added to that primarily generated (for the same current) => L increases
- The impedance of the coil in air is given by

$$Z_0 = \frac{V_0}{I_0} = R_0 + jX_0 = R_0 + j\omega L_0$$

Mutual inductance

- As the material under test acts as a new source of magnetic field, we can roughly consider the problem as two coils in interaction
- When the coil is very close to the surface of the material, the coupling factor k is closer to one. When far way, the value tends to zero



$$Z_0 = R_0 + jX_0$$

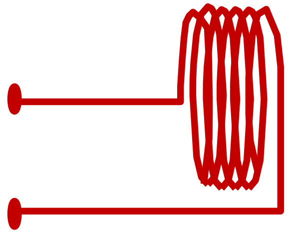
$$Z_C = R_C + jX_C$$

$$R_{CN} = \frac{R_C - R_0}{X_0} \qquad X_{CN} = \frac{X_C}{X_0}$$

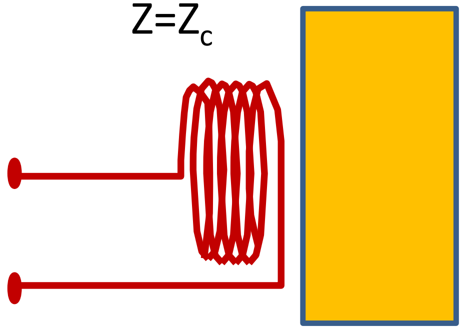
$$Z_C = R_0 + jL_0\omega + \frac{k^2 L_0 L_1 \omega^2}{R_e + jL_1\omega + jI_m}$$

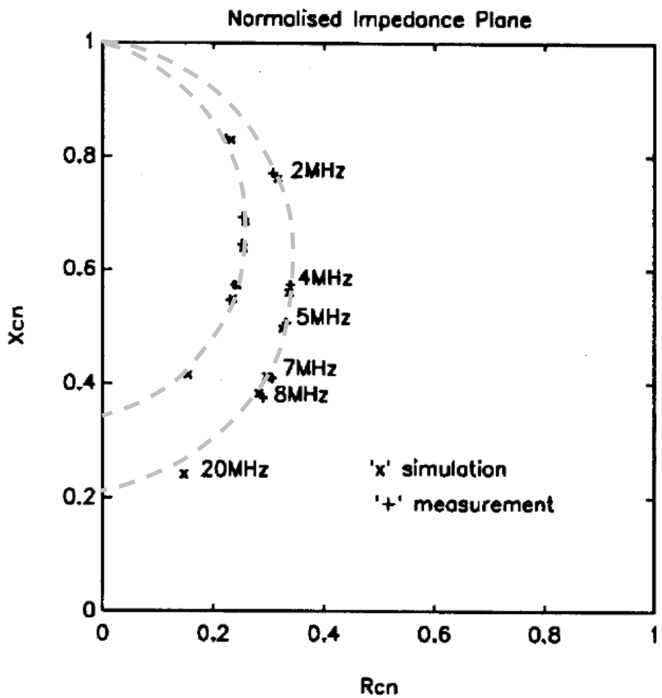
$$\left(R_{CN} + \frac{k^2 I_m}{2R_e}\right)^2 + \left(X_{CN} - 1 + \frac{k^2}{2}\right)^2 = \frac{k^4}{4}\left(\frac{I_m^{\ 2}}{R_e^{\ 2}} + 1\right)$$

$Z = Z_0$



$Z = Z_c$





Placko et al. 1992 IEEE IAS Meeting

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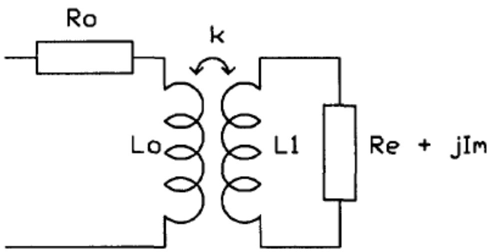
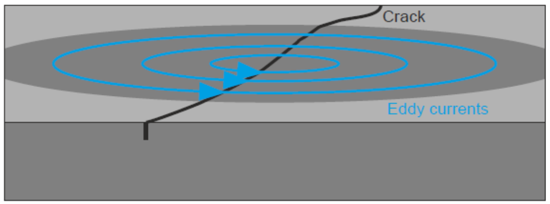
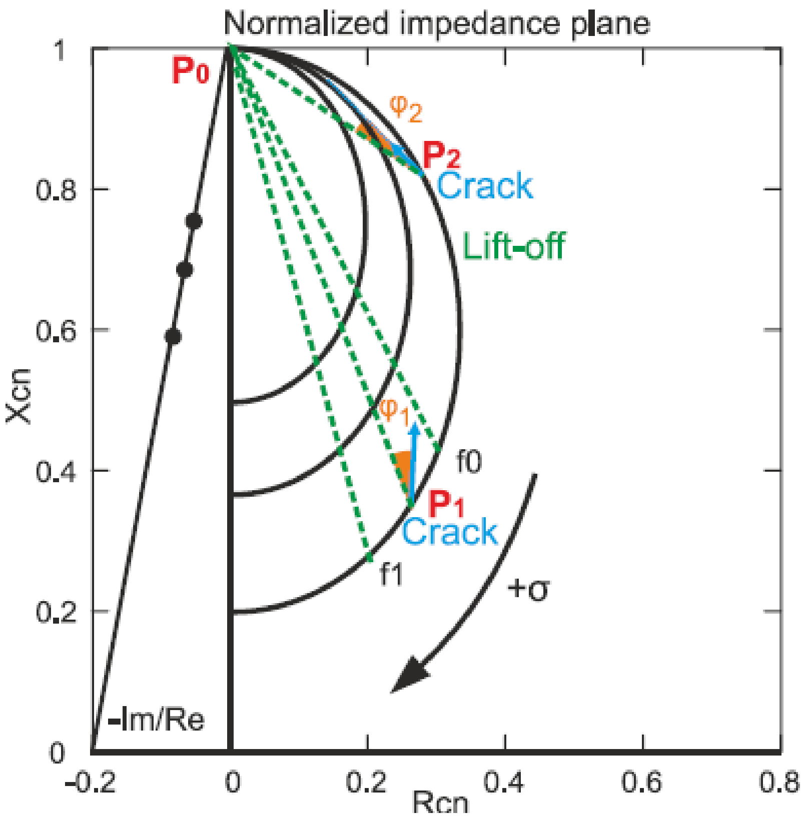
Complex impedance plane

- Representation of the coil impedance putting real component as x axis (~resistive part), and imaginary component as y axis (~inductive part)

$$\left(R_{CN}+\frac{k^2 I_m}{2R_e}\right)^2+\left(X_{CN}-1+\frac{k^2}{2}\right)^2=\frac{k^4}{4}\left(\frac{I_m{}^2}{R_e{}^2}+1\right)$$







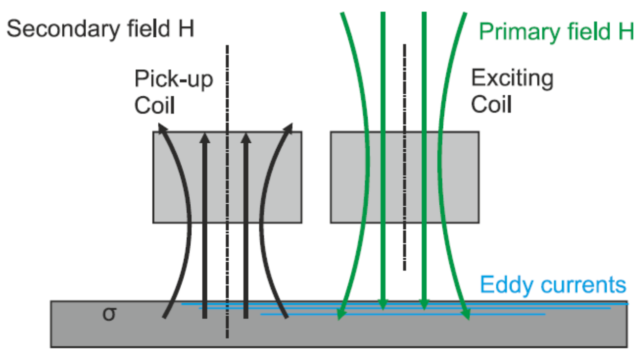
- When coil is far from the sample, point P_0
- Approaching to the material, we move along the green dotted line down to P_1 (this is the lift off line):
  - R_{CN} increases, because additional losses appear (dissipated Joule loss by the eddy currents)
  - X_{CN} decreases: the eddy current generate a B-field opposite to that generated by the coil => less flux in the coil, smaller inductance value.
- When above a crack: we need to move to another lift off line, inducing a variation in both R_{CN}(↓) and X_{CN}(↑)

Garcia-Martin et al. 2011, Sensors

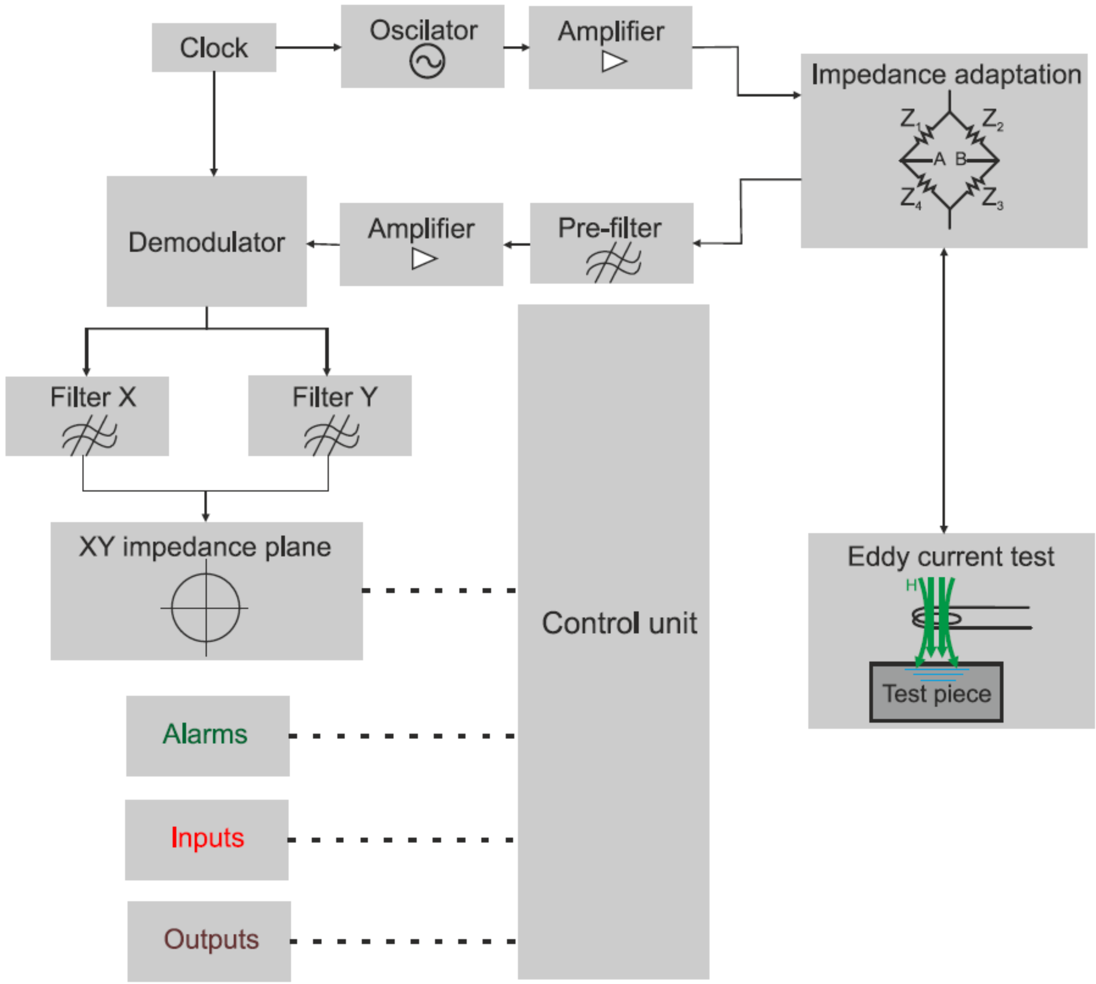
Inspection techniques

Garcia-Martin et al. 2011, Sensors

- Single coil require heavy signal processing, since the variations in impedance are small compared to initial ones
- Double-coil configurations are also proposed, working in transmission or differential mode

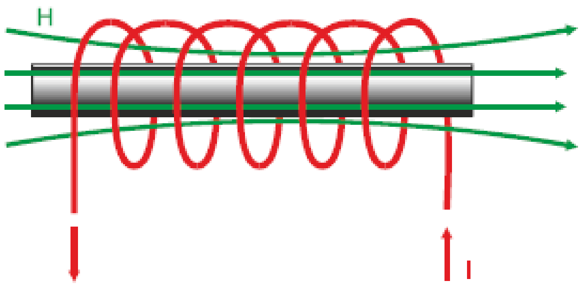


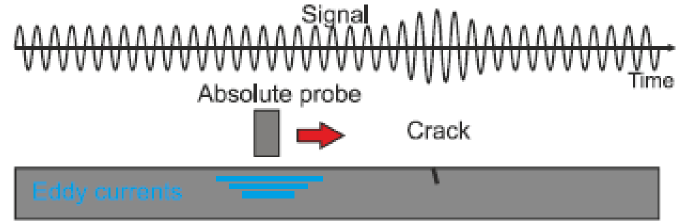
Yin et al. Proc. IEEE Instr Meas Tech Conf. 2005



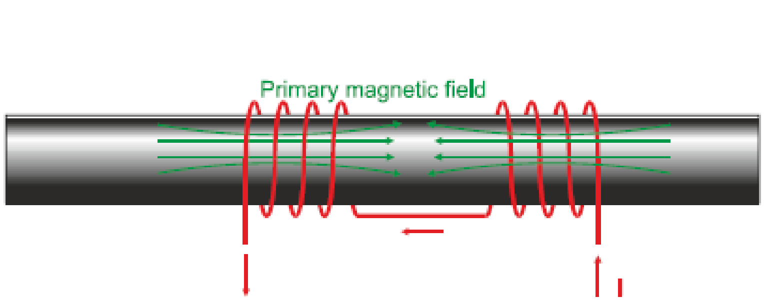
Absolute vs. differential probe

- Absolute probe





- Differential probe



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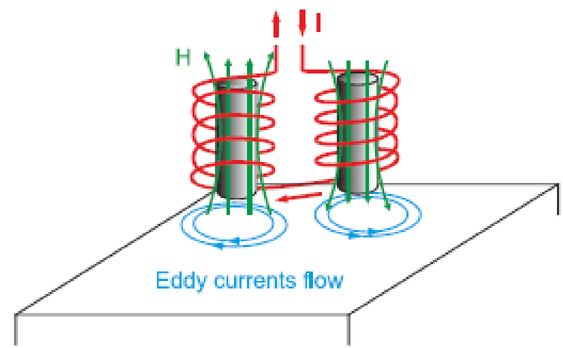

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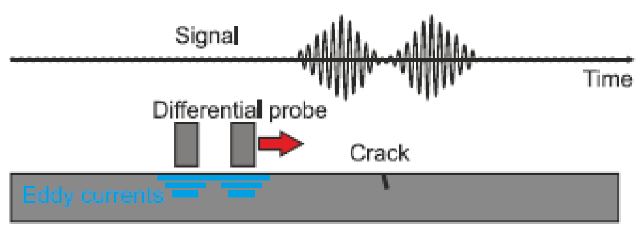

(c)

Garcia-Martin et al. 2011, Sensors

- It is also possible to replace the secondary probe by another magnetic field sensor, such as Hall sensor, SQUID, GMR, for very precise magnetic field measurement.

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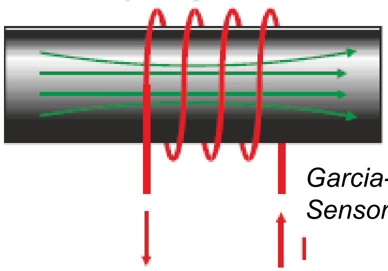
Probe configurations

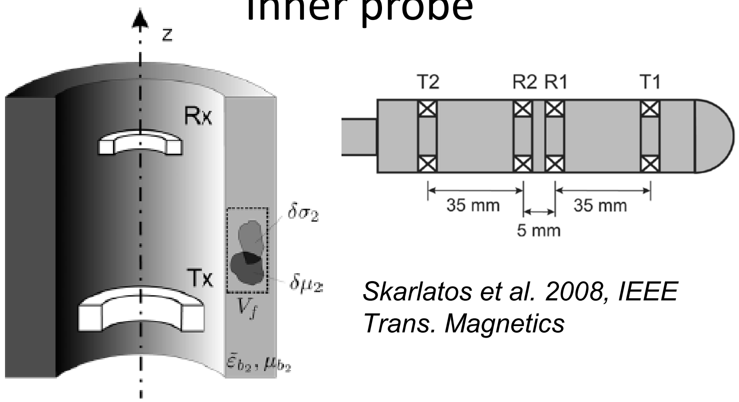
- For tubes:

Encircling probe



Garcia-Martin et al. 2011, Sensors

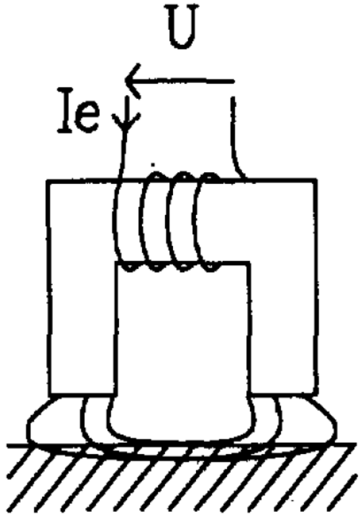
Inner probe



Skarlatos et al. 2008, IEEE Trans. Magnetics

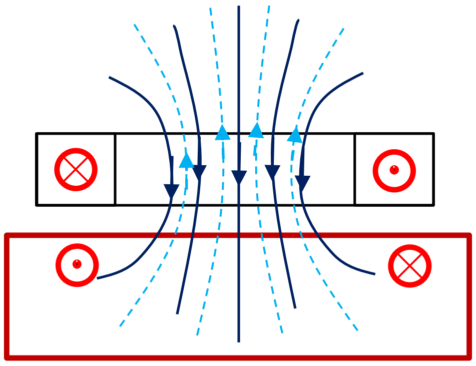
- For plates:

Horseshoe-shape coil probe



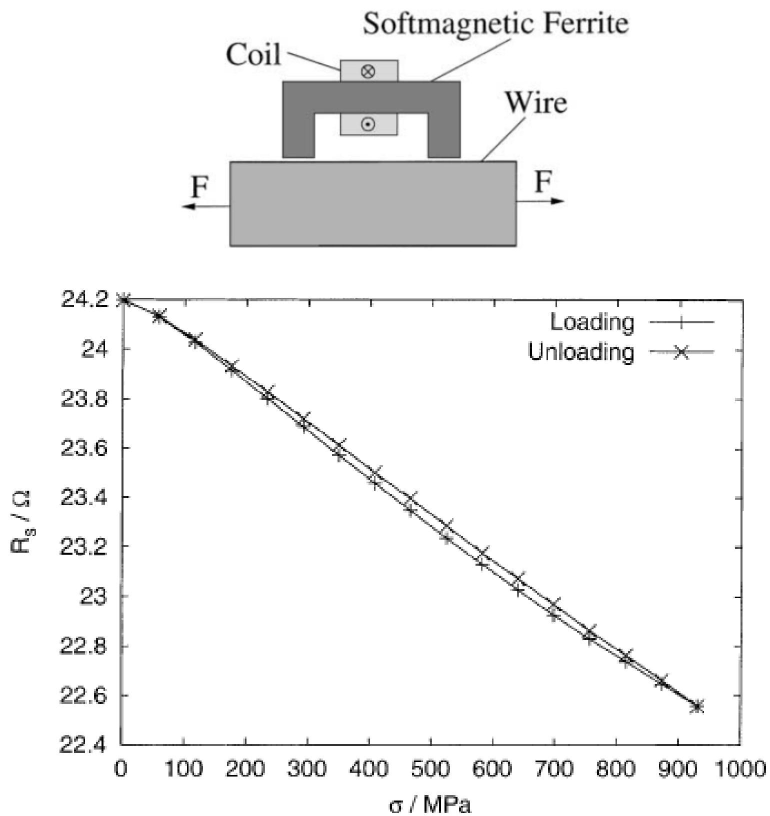
Placko et al. 1992 IEEE IAS Meeting

Pancake coil



Some applications of eddy current testing

- Very important application: detection of cracks, especially in aeronautical and nuclear industries
- Characterization of microstructural state: absolute probes are able to estimate the value of the conductivity and permeability of the material, which is a function of heat treatment or stress level.
- Hardness may be also correlated to the response of eddy currents
- The effect of lift off on the signals may be used to determine insulating coating condition
- Various applications in metallurgy, in production lines, check of the quality of parts at each step of the manufacturing
- Estimation of residual stresses due to the magneto-elastic coupling.



Ricken et al. Sens & Actuator A, 2001

ECT, as for other NDT techniques, is a highly standardized method

British Standards (BS) (examples)

- BS 3889 (part 213): 1966 (1987) **Eddy current testing of nonferrous tubes**
- BS 5411 (part 3):1984 Eddy current methods for measurement of coating thickness of nonconductive coatings on nonmagnetic base material.

American Society for Testing and Materials (ASTM) (examples)

- ASTM B 659 **Recommended practice for measurement of thickness of metallic coatings on nonmetallic substrates**
- ASTM E 690 **In-situ electromagnetic (eddy current) examination of nonmagnetic heat-exchanger tubes**
- ASTM E 1004 Electromagnetic (eddy current) measurements of electrical conductivity
- ASTM G 46 **Recommended practice for examination and evaluation of pitting corrosion**

French - EU standards (examples)

- NF EN ISO 15548-1 to 15548-3 : **Non-destructive testing - Equipment for eddy current examination Instrument characteristics and verification**
- NF EN ISO 20339: Non-destructive testing - Equipment for eddy current examination - Array probe characteristics and verification

The operators of ECT also are "certified" by independent bodies after appropriate training (e.g. COFREND in France, ASNT in US, ISNT in India, JSNDI in Japan…)

To go beyond, solving penetration depth issues

- For highly conductive materials and/or ferromagnetic ones, the penetration depth becomes very small, only very close to the surface defects may be detected

- Another issue: double or multi-layer structures (coatings…)

- The only way to enrich the information is to test different frequencies $$\delta = \sqrt{\frac{2}{\omega\sigma\mu}}$$

- Consequences of low frequencies:

⇒ Imaginary part of the coil impedance decreases

⇒ The influence of the material under test becomes negligible (term with k^2)

$$Z_C = R_0 + jL_0\omega + \frac{k^2 L_0 L_1 \omega^2}{R_e + jL_1\omega + jI_m}$$

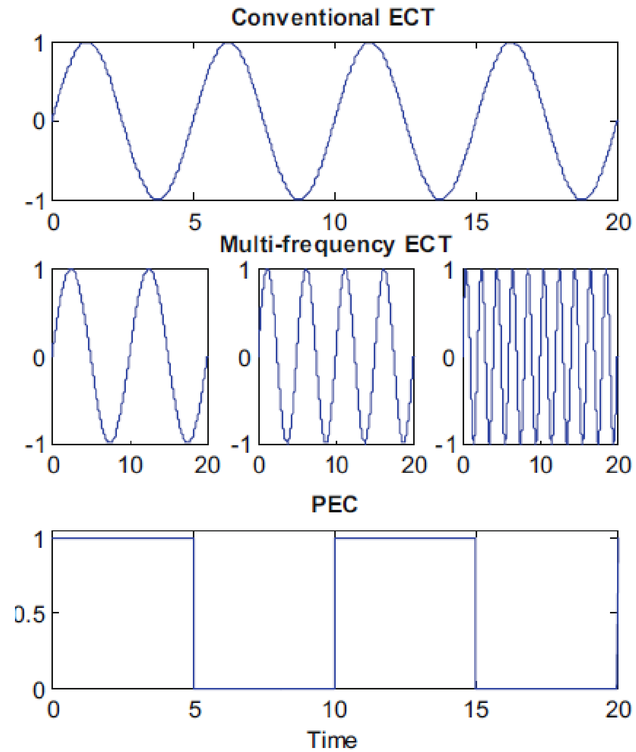
⇒ For differential probe systems, the signals becomes of very small amplitude

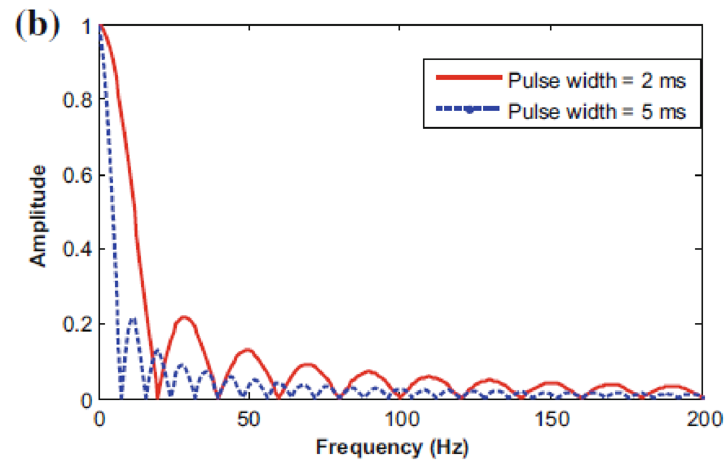
- One solution: increase by a lot the currents in the coil (without over heating !)

⇒ Pulse Eddy Currents Testing (PECT) may be used with higher currents and multiple frequency components

Pulsed Eddy Current

- The analysis of the frequency-rich signal of the coil voltage can give information on:
  - The conductivity and permeability of the material under test
  - The thickness of insulation and coating
  - Evaluation of thickness and corrosion state
  - Detection of defects





Sophian et al. Chin. J. Mech. Eng., 2017

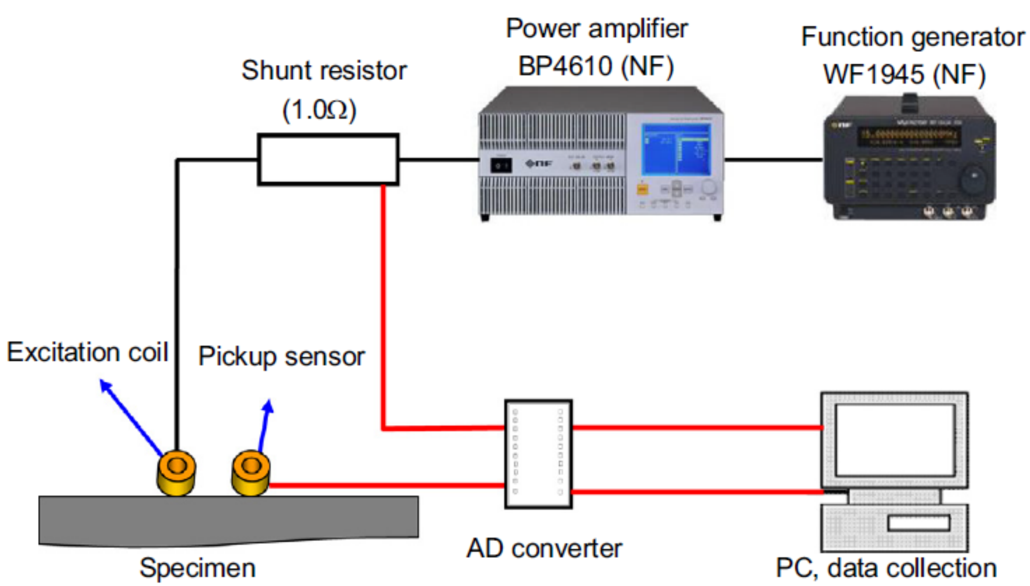
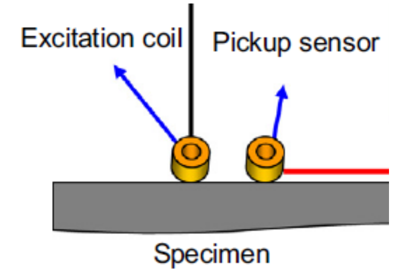


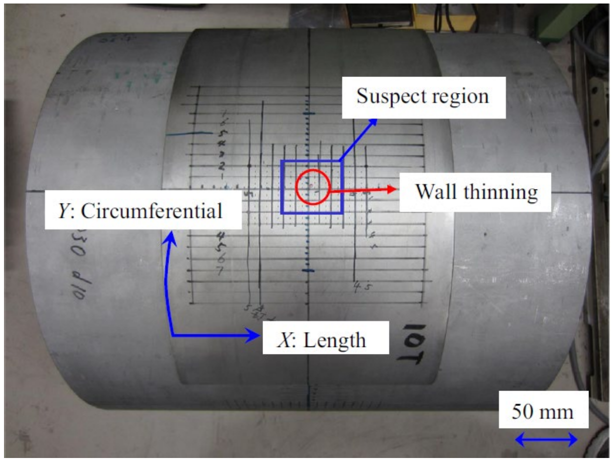
Fig. 6. Schematic of pulsed ECT experiment setup.

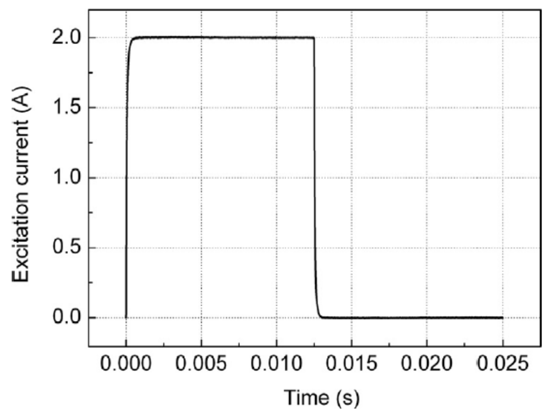
Xie et al. NDT&E International, 2015

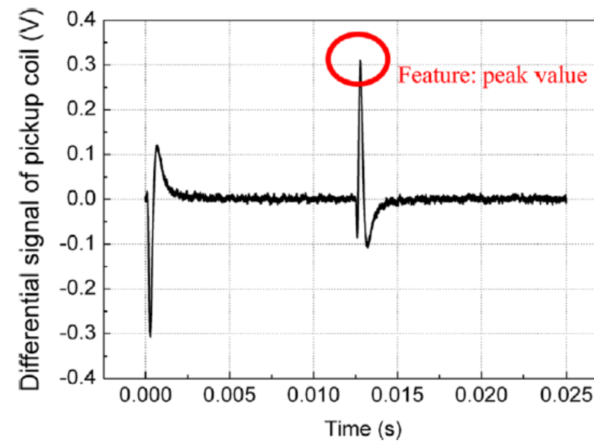
Example: pipe wall thinning determination using PECT

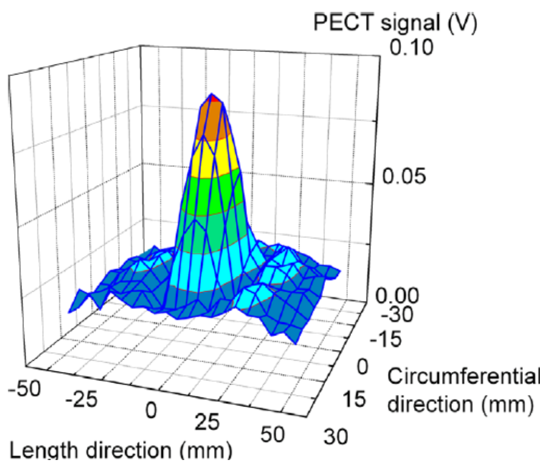
- Estimation of both thickness and the area of the thinning zone

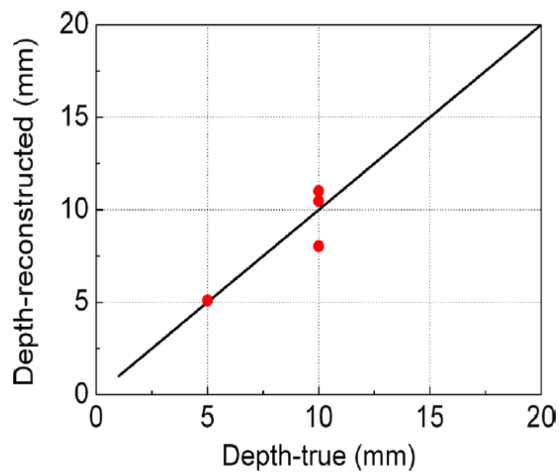


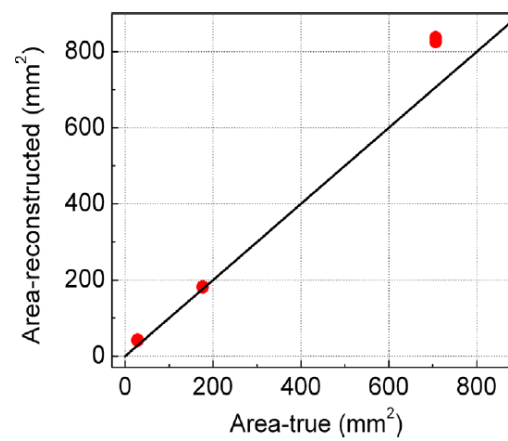








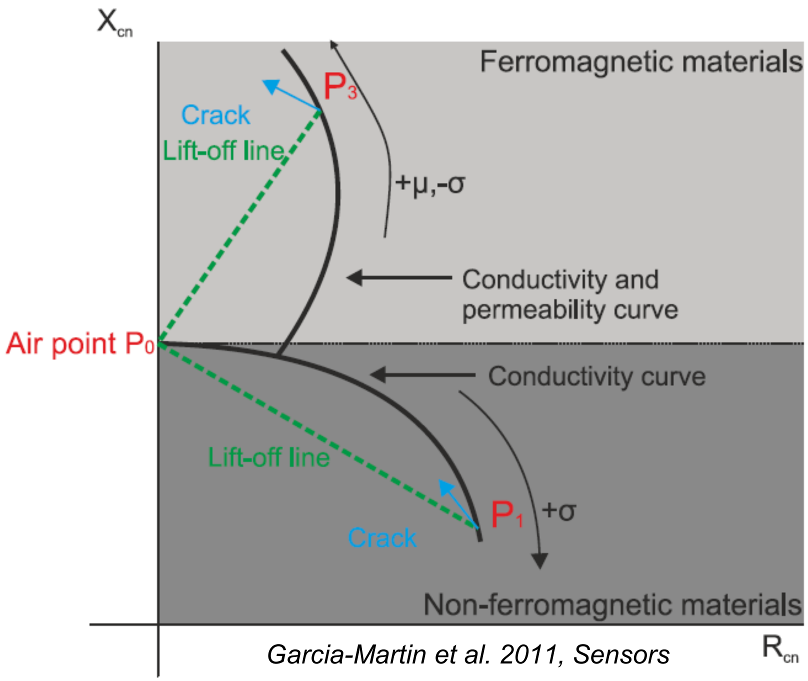




Xie et al. NDT&E International, 2015

Focus on ferromagnetic materials

- In principle, ferromagnetic materials induces a different response of the material compared to a non-ferromagnetic one: B field is increased by the permeability, whereas it is decreased by eddy currents
- Hopefully, a crack will have a similar effect (R_{CN} decreases and X_{CN} increases)
- But the issue is that the penetration depth is strongly decreased $\delta = \sqrt{\frac{2}{\omega\sigma\mu}}$
- In some work, a strong magnet is used in order to magnetically saturate the material, making it reach back quasi-vacuum permeability
- But one can also try to use the advantages of ferroelectric materials…



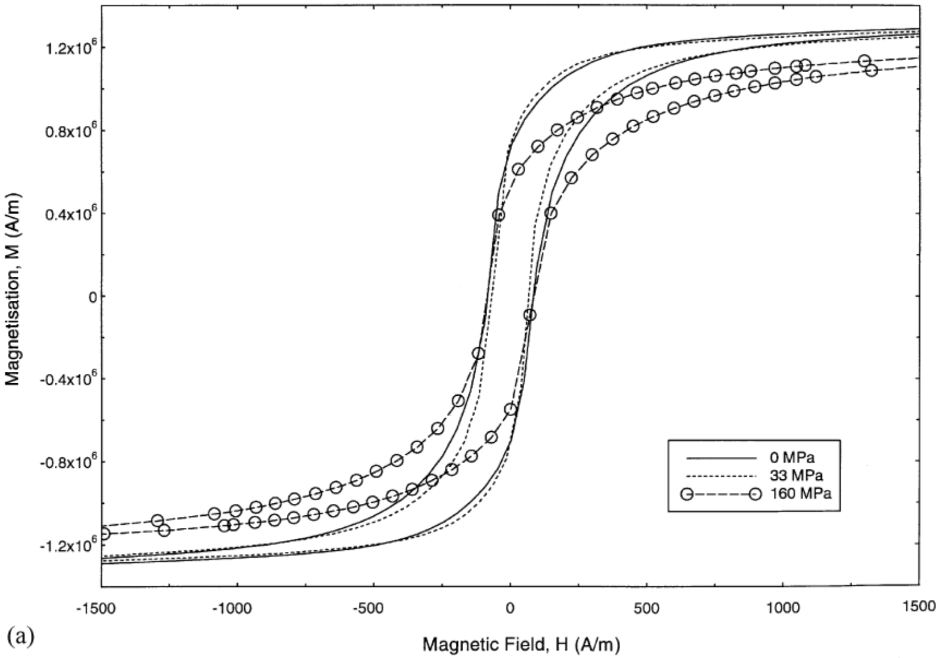
Garcia-Martin et al. 2011, Sensors

For ferromagnetic materials: additional possible techniques

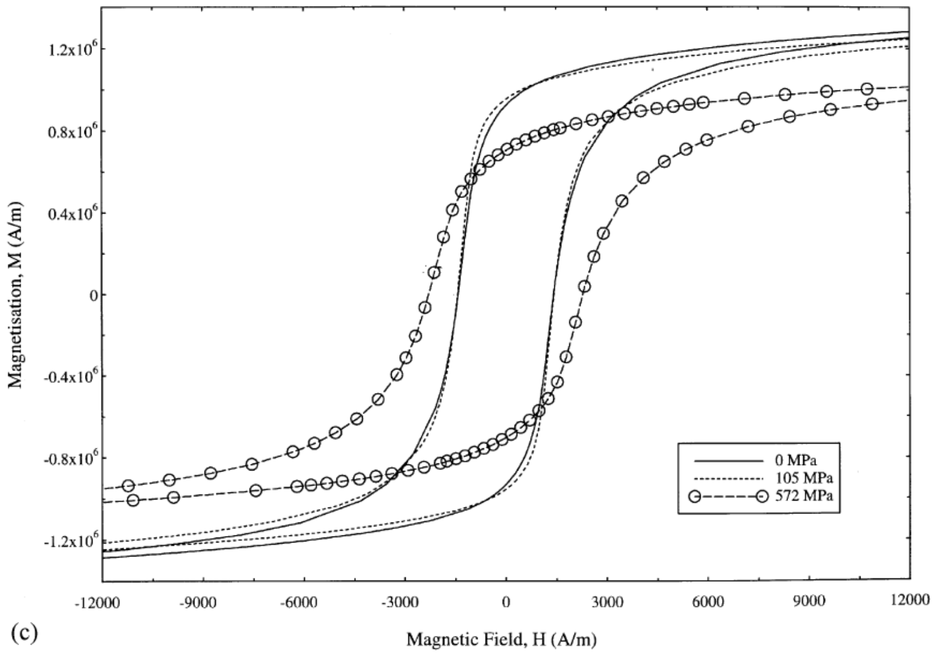
- Ferromagnetic materials exhibit very specific magnetic behavior (Magnetic induction B or magnetization M as a function of magnetic excitation field H)
- The hysteresis loops is dependent on mechanical conditions, i.e. sensitive to cracks, residual stress, fatigue, precipitations…

Hysteresis loop as a function of maximal applied stress (measurement done at rest)

Makar et al, J. Magnetism Magnetic Materials, 1998



Low carbon steel



High carbon steel

Measuring magnetic properties as an indicator of material state

- One may find many attempts to (successfully) link the microstructure, and residual stress level, damaging (etc.) to the magnetic hysteresis loop,.
- But how to measure it ?

1. Standard Epstein frame geometry:
Assembly of plates of material to be tested, with symmetric excitation coils

Bramerdorfen et al., Technisches Messen 2019

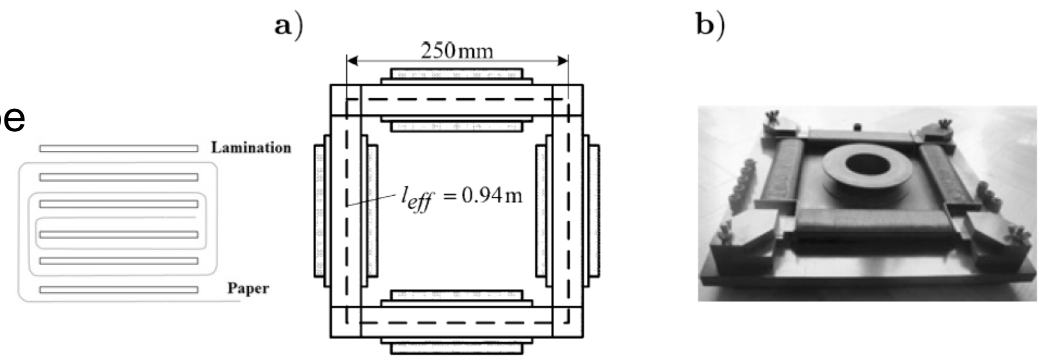
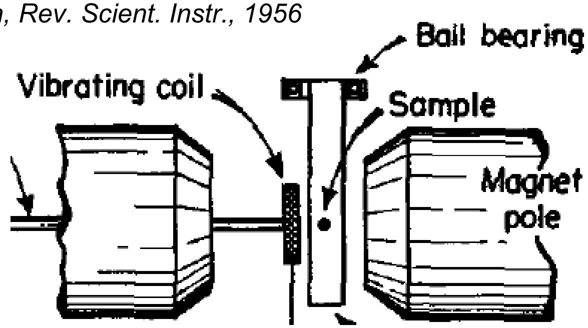


Figure 6: a) Typical geometry of an Epstein frame with its dimensions. b) Photograph of an Epstein frame.

2. Vibrating Sample Magnetometer:
Very small sample place in a uniform magnetic field. A vibrating coil nearby the sample see its voltage vary due to the magnetization of the sample

Smith, Rev. Scient. Instr., 1956



⇒ In both cases, samples has to be cut in specific dimensions to be characterized properly

⇒ **Not really suitable for NDT, in-line, in-situ or in-service inspection…**

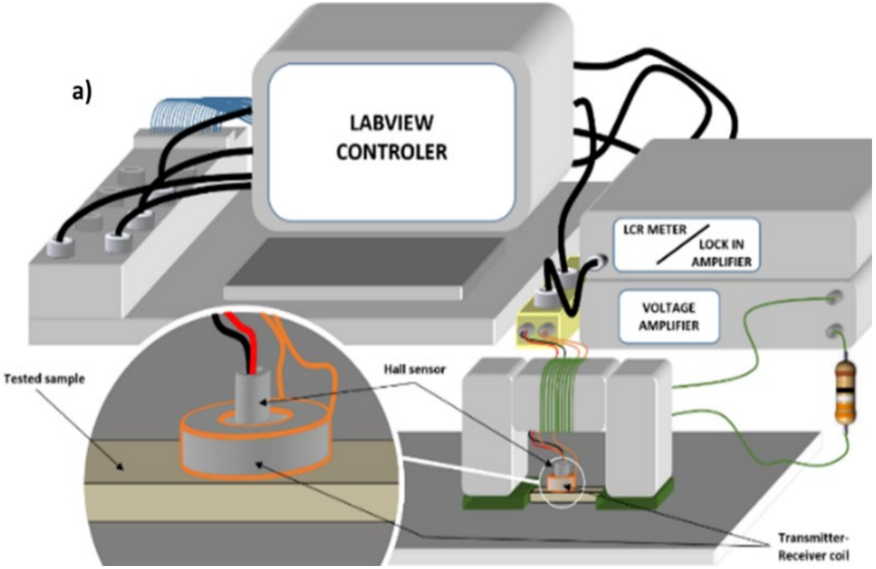
Horse-shoe configuration to measure hysteresis (and more)

- In the horse-shoe configuration
  - Magnetic yoke with encircling coil
  - In contact with a plate under test
  - A small sensor may contain, Hall sensor, coils etc.

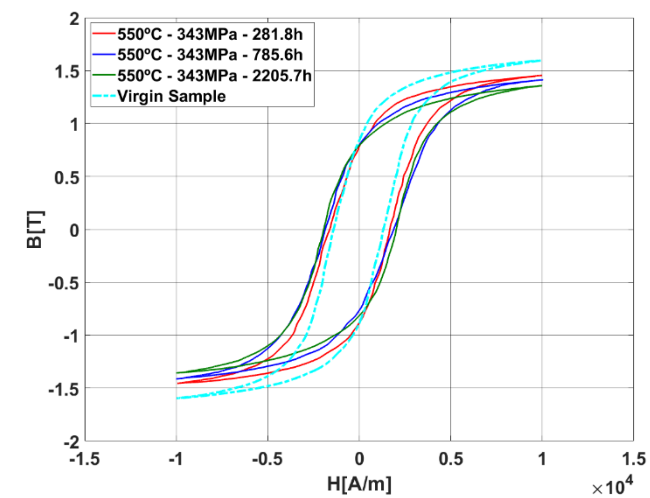
- Basic operation consist of supplying low frequency current to the primary coil, and to measure tangential excitation field using a Hall sensor.

- A secondary encircling coil around the sample is measuring the average induction field

- From the literature, this was attempted to estimate residual stresses, creep damage, or phase transitions



Courtesy Prof B. Ducharne, INSA Lyon



B. Gupta, PhD dissertation, 2019

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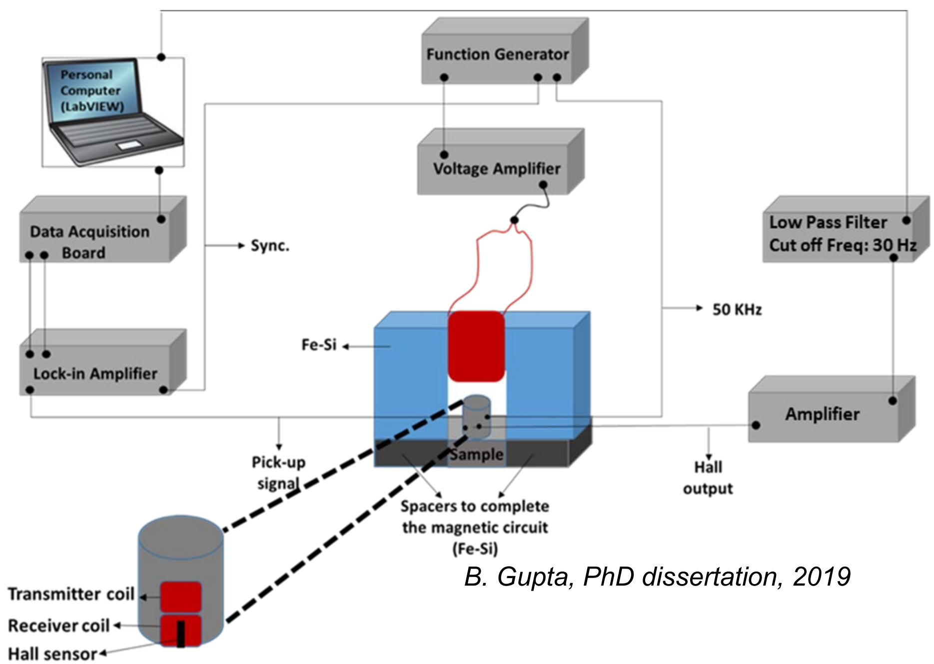
Investigating more closely the magnetic behavior

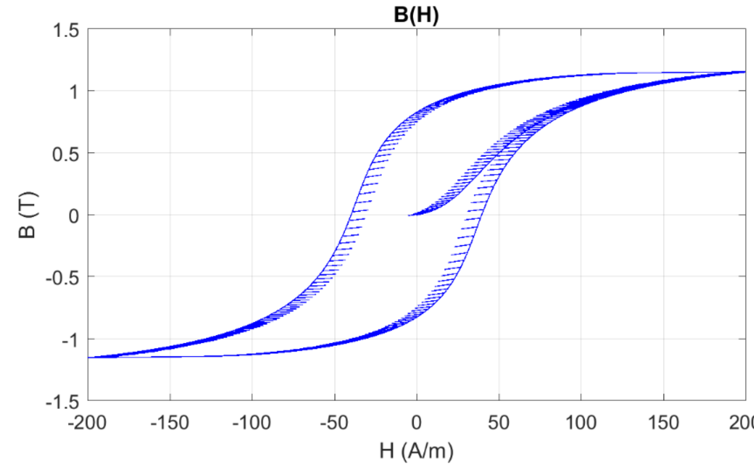
- Hysteresis loop result from the averaging of all magnetic domains response, and depends only weakly on microstructure variations and other phenomenon under consideration in NDT
- In addition, the measurement of induction field is rather difficult since no sensors can be inserted inside the material
- Alternatively, by joining eddy current techniques and hysteresis loop measurement it is possible to estimate the local and dynamic magnetic permeability
- Technique known as Magnetic Incremental Permeability

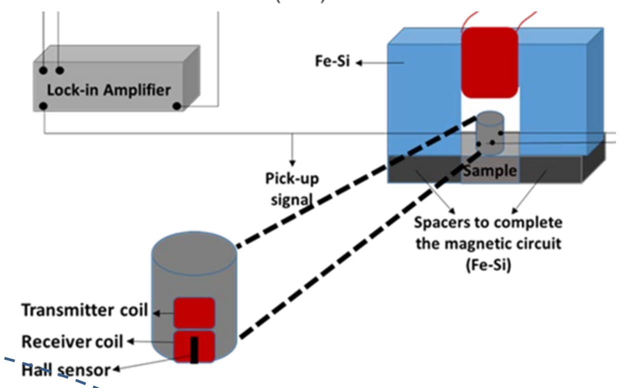


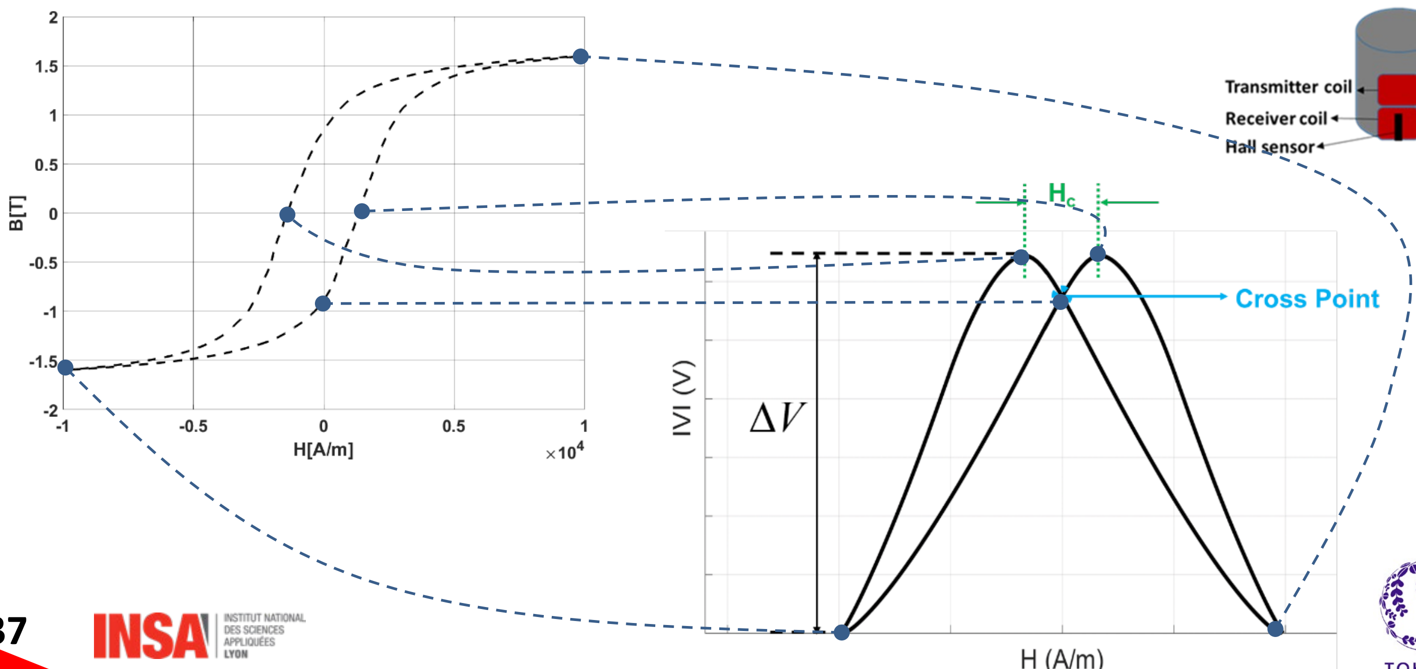
B. Gupta, PhD dissertation, 2019

Magnetic Incremental Permeability

- The main coil is supplied with a low frequency, large amplitude current
- Excitation field H is varied enough to fully saturate the magnetic material under test
- Transmitter coil is supplied with high frequency, low voltage signal
- Receiver coil voltage is measured, it is closely linked to material conductivity and permeability.
- Due to the low frequency variation of excitation field, travel over the whole hysteresis cycle

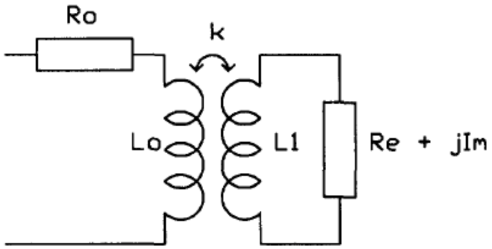




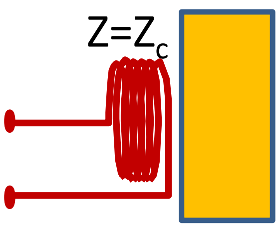


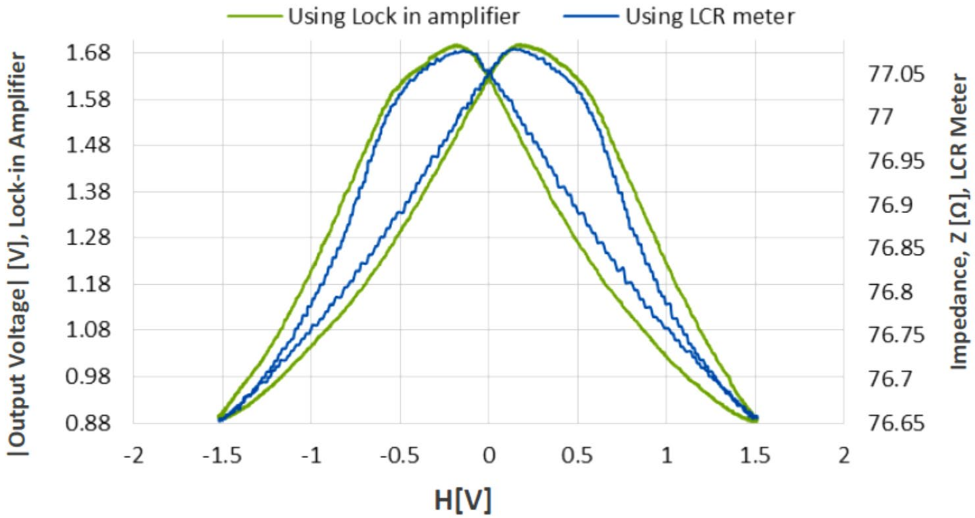
Magnetic Incremental Permeability and eddy current testing

- The measurement coil system (single or dual probe) work as for eddy current
- As a result, the coil signal reveals conductivity and permeability as a function of excitation low frequency H field
- **We replace a signal measurement point by a full curve**, giving much more information
- Example with a single coil impedance $Z_0 = R_0 + jX_0$ $Z_C = R_C + jX_C$



$$Z_C = R_0 + jL_0\omega + \frac{k^2 L_0 L_1(H_{DC})\omega^2}{R_e(H_{DC}) + jL_1(H_{DC})\omega + jI_m(H_{DC})}$$

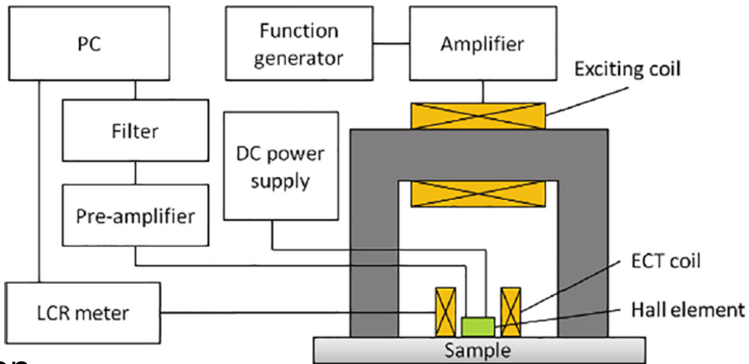


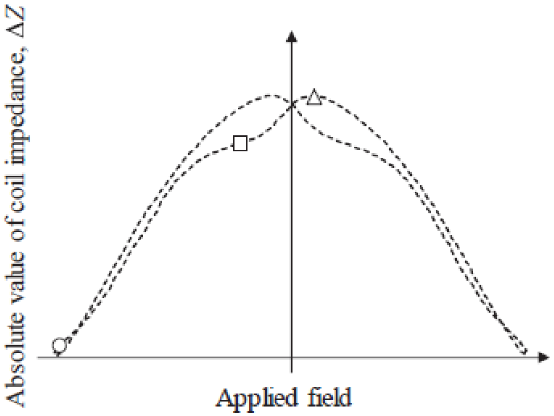


B. Gupta, PhD dissertation, 2019

Study of coil impedance as a function of magnetic state

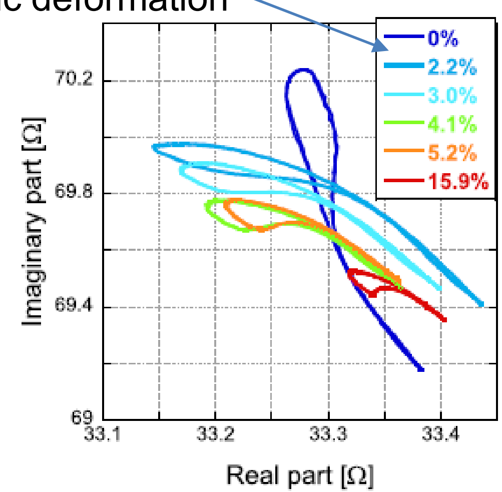
- With similar horse-shoe magnetic core for applying low frequency magnetic excitation field H
- Investigation of the coil impedance (imaginary part vs real part) as for ECT analysis
- Example on the determination of plastic strain

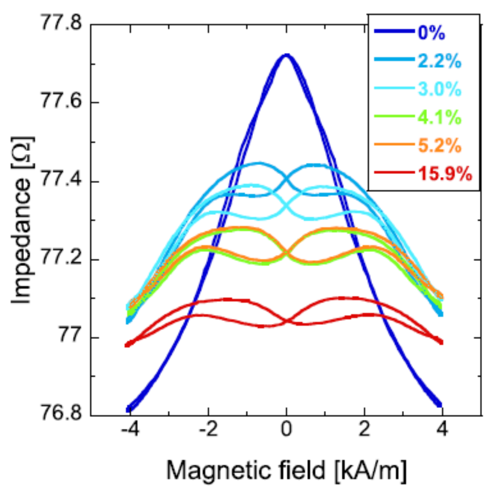


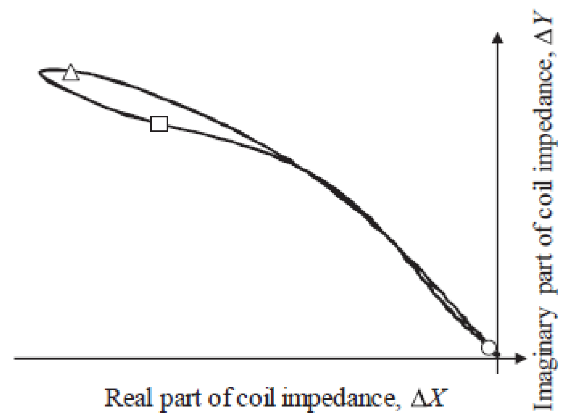


(a) Coil impedance as function of applied field

Plastic deformation



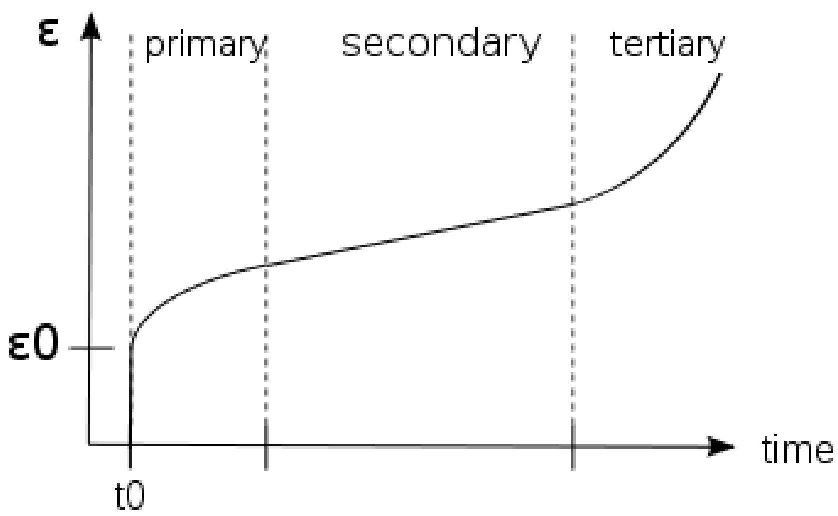


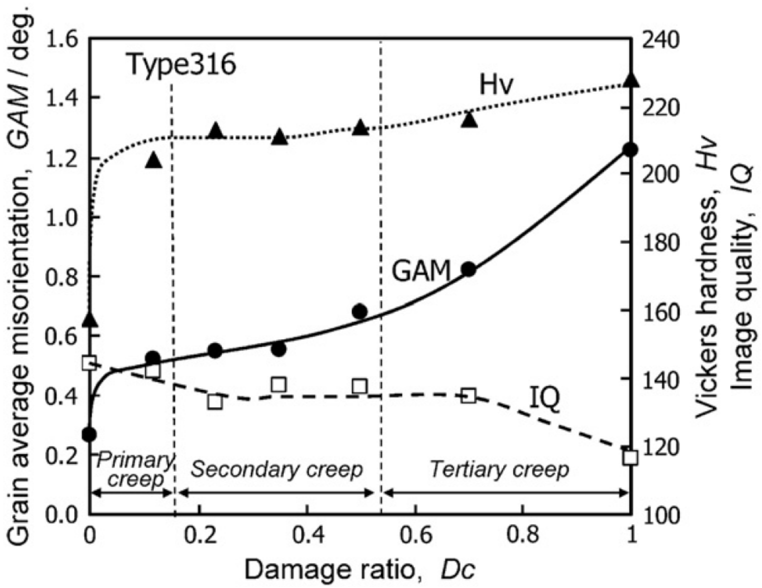


Matsumoto et al., Journal of Magnetism and Magnetic Materials, 2019

Example of results on creep-damaged high chromium steel

- When applying large stress at high temperature on steel materials results in a continuous strain variation (creep), leading eventually to the rupture
- Detection of creep damage is usually possible when entering the tertiary zone, where the strain evolves rapidly, and time to the rupture is becoming short
- Several attempts were published in order to use some indicators evolving also in secondary zone (e.g. hardness, grain mis-orientation etc.)

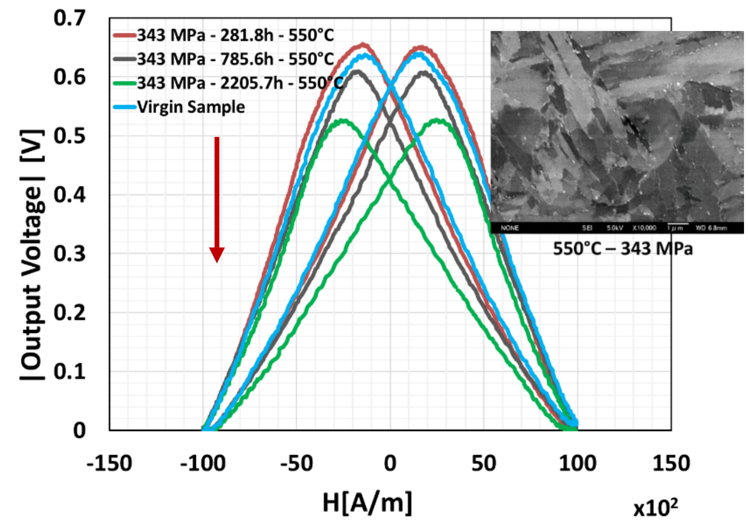


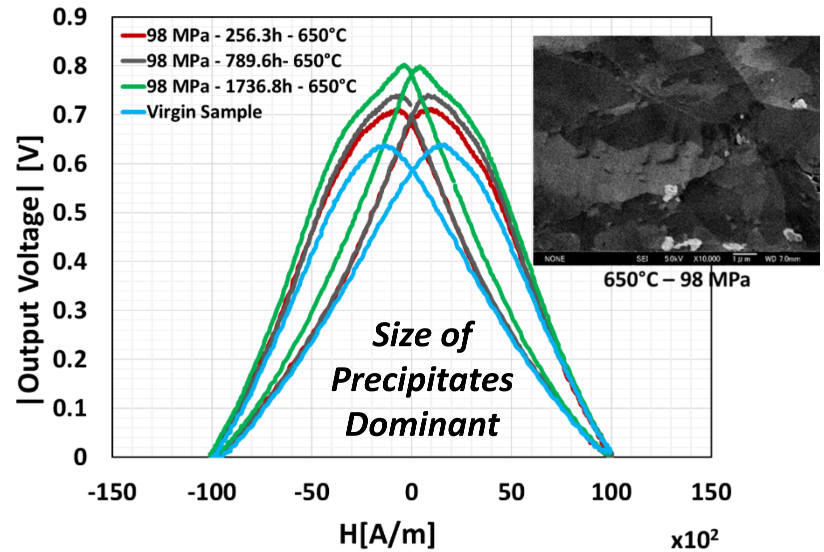


Yoda et al., *Materials Characterization*, **61**, 2010

Magnetic Incremental Permeability results for creep damage

- Sample were subjected to different stress and temperature heat treatments
- Magnetic Incremental Permeability was tested on samples at rest (i.e. no stress, room temperature) after the heat treatment,
- MIP signals (i.e. voltage of the measurement coil as a function of DC excitation H field) show a large dependence on the heat treatment
- The correlation between heat treatment and MIP signals shows some tendencies in terms of number of precipitates.



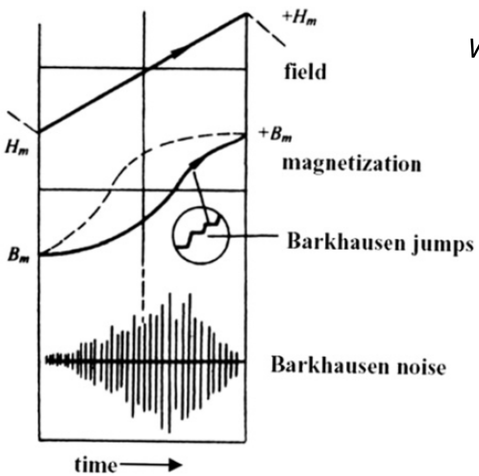


Gupta et al. NDT&E International, 2019

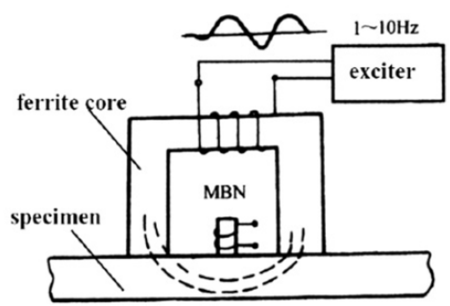
Barkhausen noise

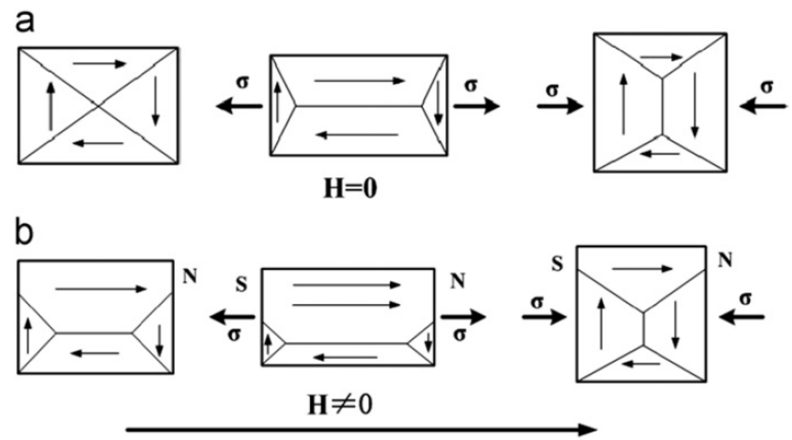
- Fundamental feature of ferromagnetic materials

The magnetization varies in a discontinuous process, resulting from avalanche phenomenon of the domain wall motion



Wang, Gu, Wang, JMMM (2010)

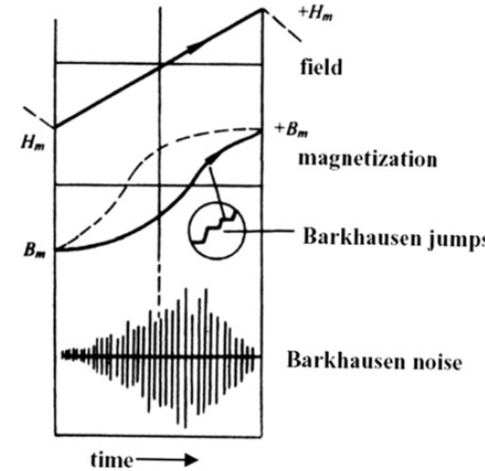




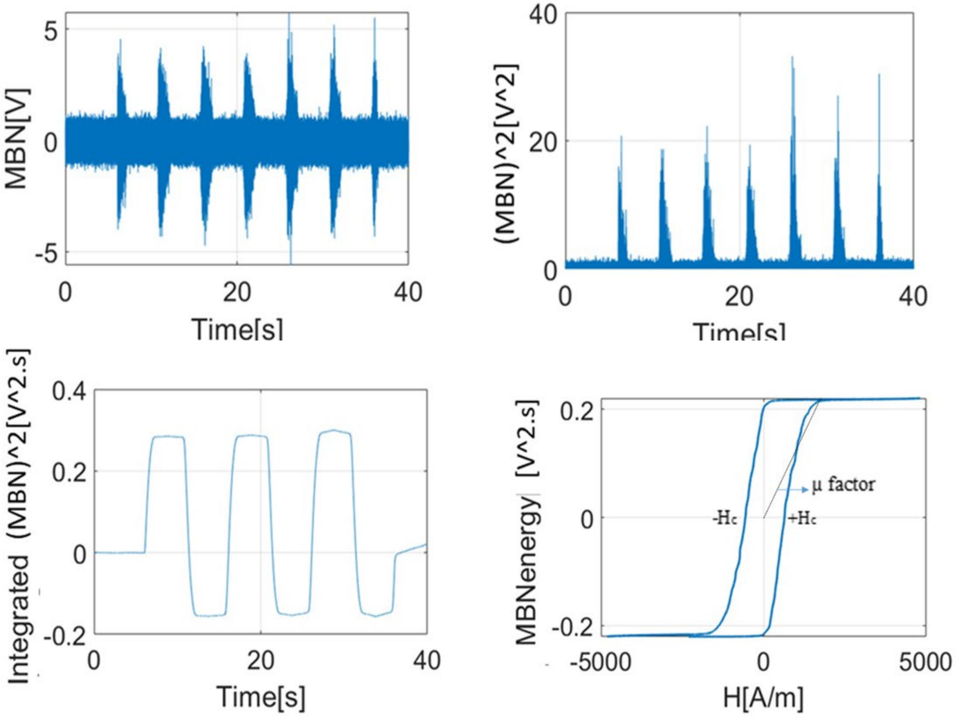
- The noise properties is correlated with several defects, such as residual stress, plastic deformation.

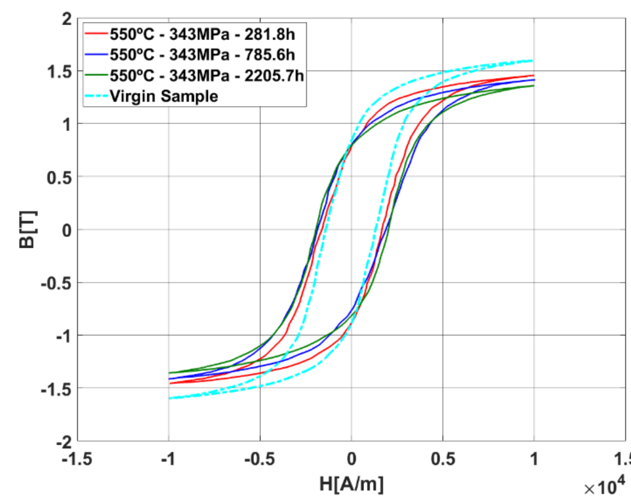
Barkhausen noise and magnetic hysteresis

- Barkhausen noise relates only the avalanche phenomena of magnetic domains
- It does not contain information about the continuous deformation or growth of domains, or on the magnetic permeability
- In a sense it is a raw signal, free of strong “phenomenon averaging”, leading to information easier to interpret



Gupta et al., Journal of Magnetism and Magnetic Materials, 2020

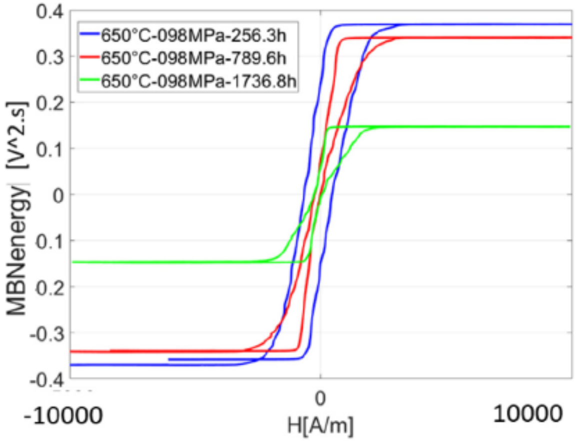


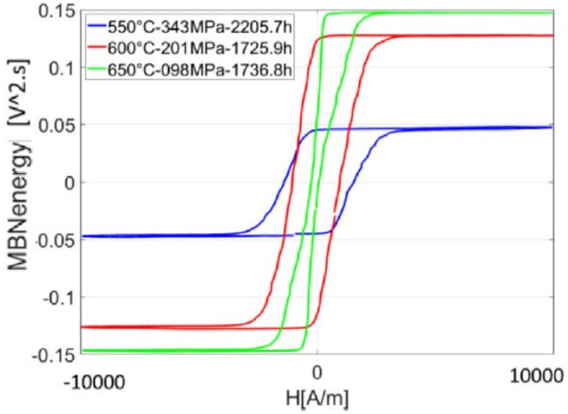


Utilization of Barkhausen noise in NDT

- Creep damage: ruptured samples at different temperatures show very different behaviors

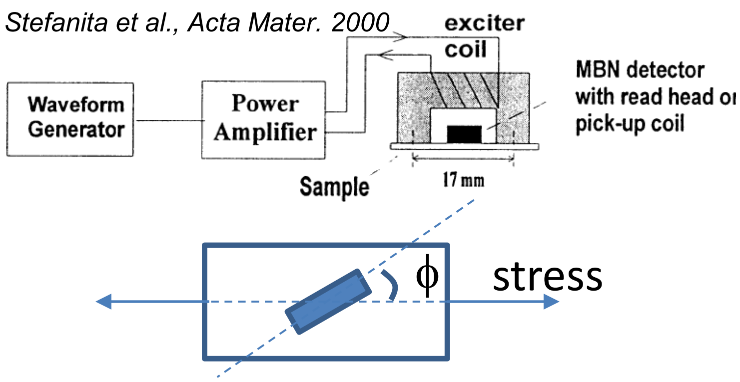
Gupta et al., Journal of Magnetism and Magnetic Materials, 2020

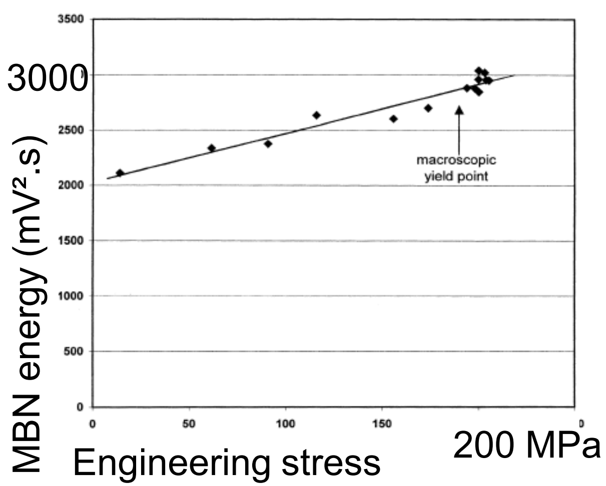


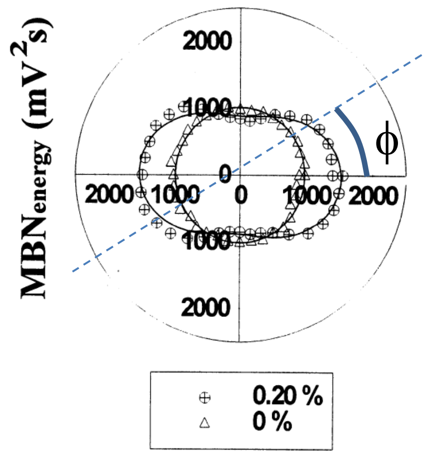


- Effect of uniaxial stress on Barkhausen noise
- Magnetic signals are recorded for static stress level, at different angles

Stefanita et al., Acta Mater. 2000







Industrial applications of Barkhausen noise

- There exist roughly three categories of practical applications of Barkhausen noise testing, mostly for process verification:
  - Evaluation of residual stresses: for example, cold working processes used to generate compressive residual stress distributions, like shot peening (this helps further resistance to rupture)
  - Evaluation of hardness: for example, Barkhausen noise increases in soft materials and decreases in hard ones
  - Testing surface defects: grinding burn (thermal damage) inducing local discolorations on the surface

https://www.stresstech.com/en/products/

https://www.ndt.com.au/what-is-barkhausen-noise-analysis/

Combining all magnetic techniques to get more information

- Electromagnetic based methods are still developed and tested separately
- Depending on the case studies, sensitivity to a given point of interest depends on each technique
- When facing complex phenomenon (like microstructure changes), the interpretation of the signals of a single NDT technique is difficult,
- Some recent developments now addresses integrated multi electro-magnetic systems

- Example: 3MA system combines 4 electromagnetic methods
  - Harmonic analysis in the time signal of the tangential magnetic field strength
  - Magnetic Barkhausen noise analysis
  - Incremental permeability analysis
  - Eddy current impedance analysis

https://www.izfp.fraunhofer.de/content/dam/izfp/en/documents/2017/3ma-3max8-bemi-en.pdf

Summary

- General overview on Non Destructive Techniques and underlying physical mechanisms
  - Dozens of techniques exist, based on material properties and how their estimation can give knowledge about defects
  - Although only limited by scientists imagination, practical implementation, and validation (certification) is a very long run process
  - Current efforts concerns polymer composite materials (i.e. almost non-conductive) and additive manufactured parts (highly complex geometries and nature of defects is different from molding for example)

- Focus on ET and other electromagnetic methods
  - From well-established Eddy Current testing, magnetic based techniques offer new possibilities
  - Detection of geometrical defects is well implemented (such as cracks)
  - Correlation with material microstructure is at a much lower TRL level

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