西安交通大学航天航空学院
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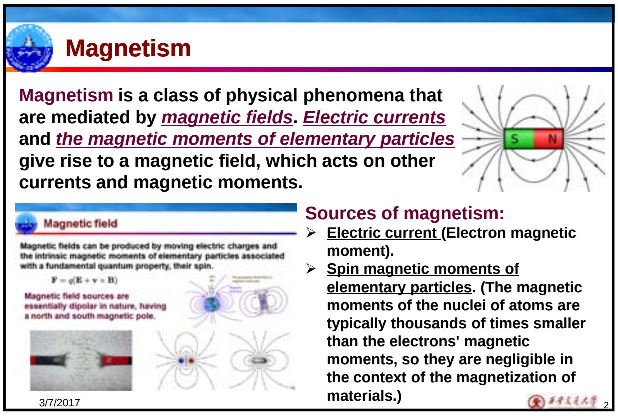
Advanced Electromagnetic Nondestructive Testing and Evaluation (NDT&E) ---MFL

- **Yong Li**



Magnetism

Magnetism is a class of physical phenomena that are mediated by ***magnetic fields***. ***Electric currents*** and ***the magnetic moments of elementary particles*** give rise to a magnetic field, which acts on other currents and magnetic moments.

Magnetic field

Magnetic fields can be produced by moving electric charges and the intrinsic magnetic moments of elementary particles associated with a fundamental quantum property, their spin.

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Magnetic field sources are essentially dipolar in nature, having a north and south magnetic pole.

Sources of magnetism:

- Electric current (Electron magnetic moment).
- Spin magnetic moments of elementary particles. (The magnetic moments of the nuclei of atoms are typically thousands of times smaller than the electrons' magnetic moments, so they are negligible in the context of the magnetization of materials.)

H-field and B-field

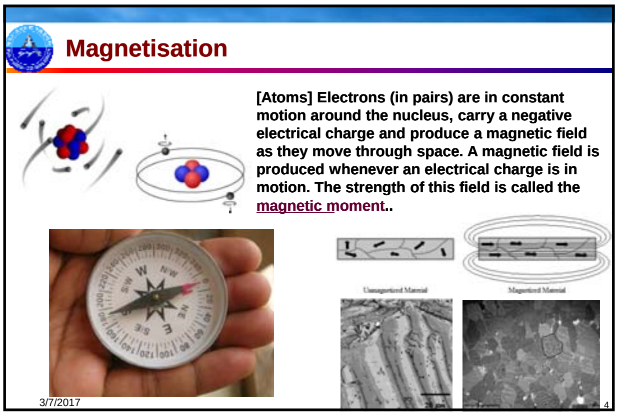
The magnetic field can be defined in several equivalent ways based on the effects it has on its environment.

B-field: the magnetic field is defined by the force it exerts on a moving charged particle.

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

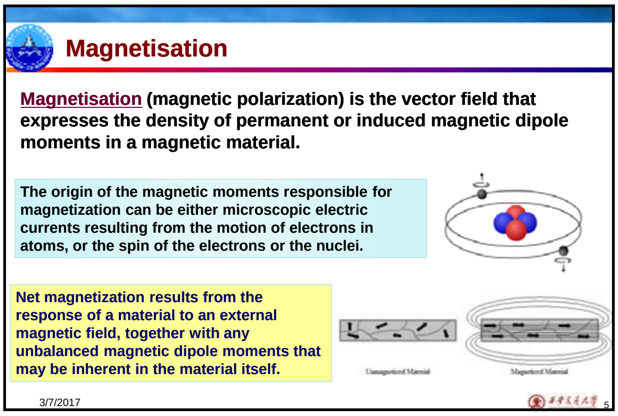
H-field: there is a quantity *H*, which is also sometimes called the magnetic field. In a vacuum, *B* and *H* are proportional to each other, with the multiplicative constant depending on the physical units. Inside a material they are different (*H and B → inside and outside of magnetic materials*).

$$\overline{B} = \mu_0(\overline{H} + \overline{M})$$



Magnetisation

[Atoms] Electrons (in pairs) are in constant motion around the nucleus, carry a negative electrical charge and produce a magnetic field as they move through space. A magnetic field is produced whenever an electrical charge is in motion. The strength of this field is called the magnetic moment..

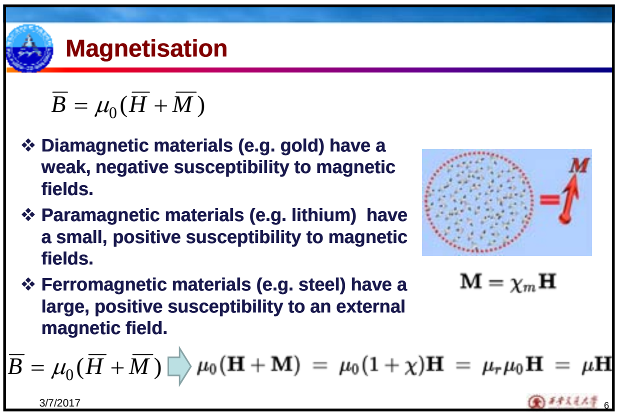


Magnetisation

Magnetisation (magnetic polarization) is the vector field that expresses the density of permanent or induced magnetic dipole moments in a magnetic material.

The origin of the magnetic moments responsible for magnetization can be either microscopic electric currents resulting from the motion of electrons in atoms, or the spin of the electrons or the nuclei.

Net magnetization results from the response of a material to an external magnetic field, together with any unbalanced magnetic dipole moments that may be inherent in the material itself.



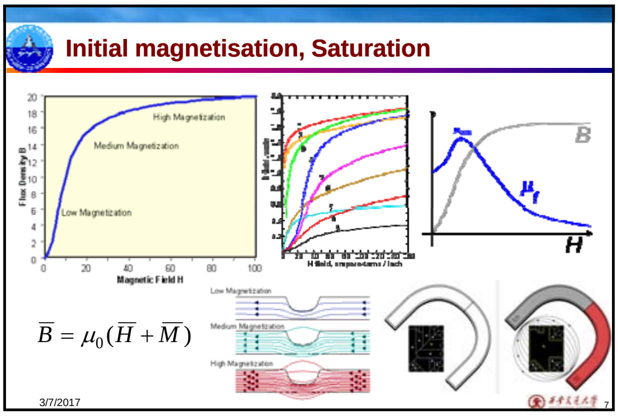
Magnetisation

$$\overline{B} = \mu_0(\overline{H} + \overline{M})$$

- Diamagnetic materials (e.g. gold) have a weak, negative susceptibility to magnetic fields.
- Paramagnetic materials (e.g. lithium) have a small, positive susceptibility to magnetic fields.
- Ferromagnetic materials (e.g. steel) have a large, positive susceptibility to an external magnetic field.

$$\mathbf{M} = \chi_m \mathbf{H}$$

$$\overline{B} = \mu_0(\overline{H} + \overline{M}) \Rightarrow \mu_0(\mathbf{H} + \mathbf{M}) = \mu_0(1 + \chi)\mathbf{H} = \mu_r \mu_0 \mathbf{H} = \mu \mathbf{H}$$



Initial magnetisation, Saturation

$$\overline{B} = \mu_0(\overline{H} + \overline{M})$$

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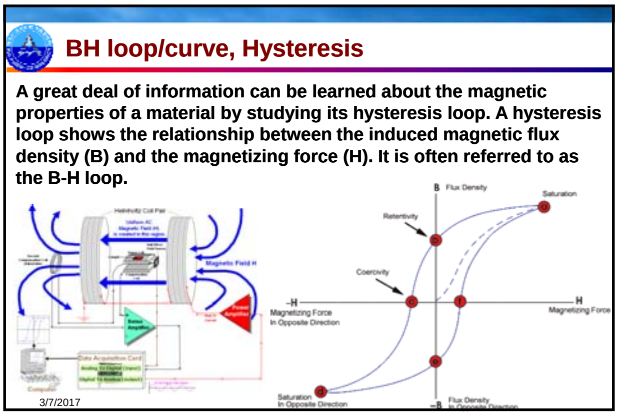

BH loop/curve, Hysteresis

A great deal of information can be learned about the magnetic properties of a material by studying its hysteresis loop. A hysteresis loop shows the relationship between the induced magnetic flux density (B) and the magnetizing force (H). It is often referred to as the B-H loop.

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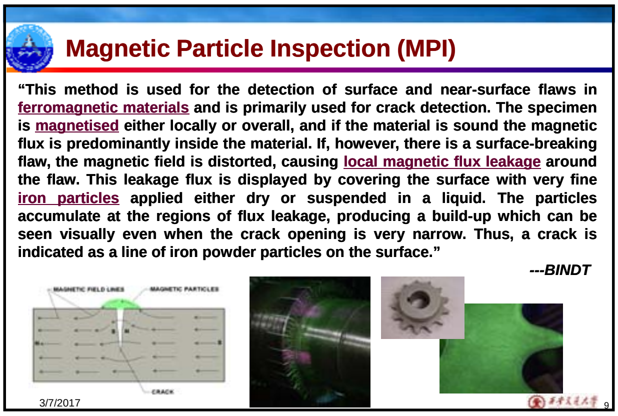

Magnetic Particle Inspection (MPI)

"This method is used for the detection of surface and near-surface flaws in ferromagnetic materials and is primarily used for crack detection. The specimen is magnetised either locally or overall, and if the material is sound the magnetic flux is predominantly inside the material. If, however, there is a surface-breaking flaw, the magnetic field is distorted, causing local magnetic flux leakage around the flaw. This leakage flux is displayed by covering the surface with very fine iron particles applied either dry or suspended in a liquid. The particles accumulate at the regions of flux leakage, producing a build-up which can be seen visually even when the crack opening is very narrow. Thus, a crack is indicated as a line of iron powder particles on the surface."

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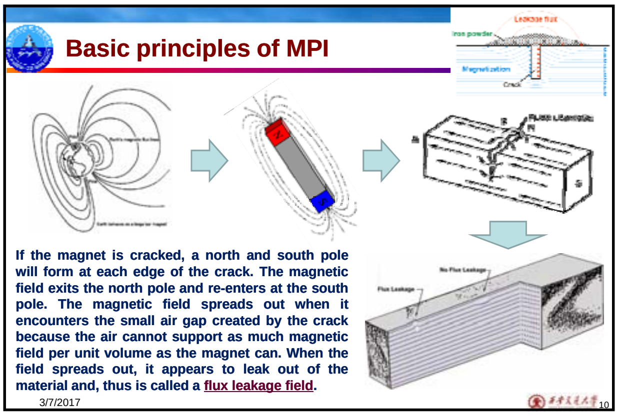
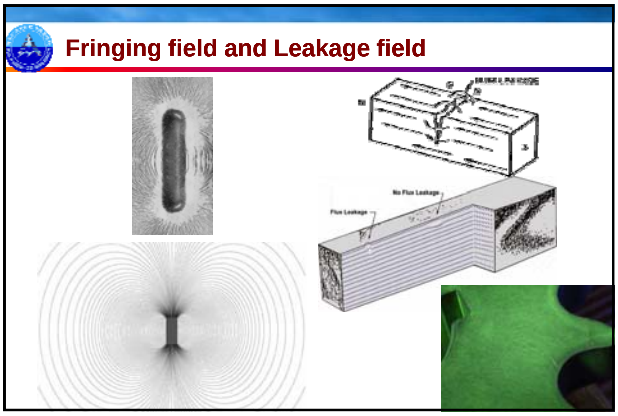
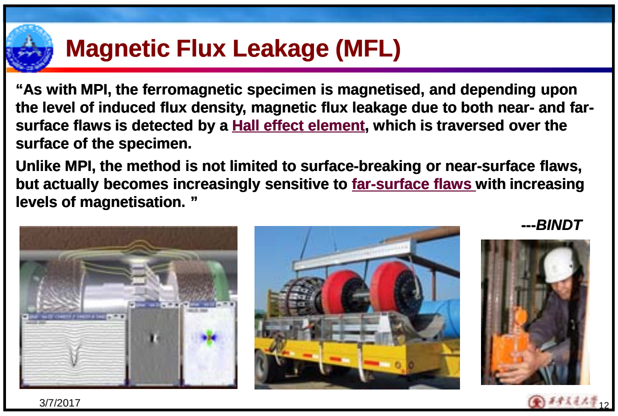


Basic principles of MPI

If the magnet is cracked, a north and south pole will form at each edge of the crack. The magnetic field exits the north pole and re-enters at the south pole. The magnetic field spreads out when it encounters the small air gap created by the crack because the air cannot support as much magnetic field per unit volume as the magnet can. When the field spreads out, it appears to leak out of the material and, thus is called a flux leakage field.



Fringing field and Leakage field



Magnetic Flux Leakage (MFL)

"As with MPI, the ferromagnetic specimen is magnetised, and depending upon the level of induced flux density, magnetic flux leakage due to both near- and far-surface flaws is detected by a Hall effect element, which is traversed over the surface of the specimen.

Unlike MPI, the method is not limited to surface-breaking or near-surface flaws, but actually becomes increasingly sensitive to far-surface flaws with increasing levels of magnetisation. "

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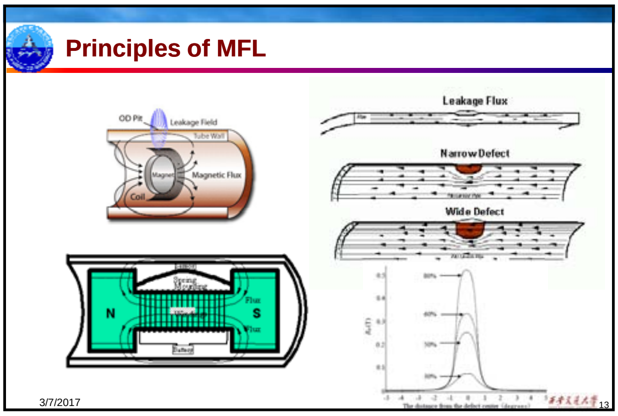

Principles of MFL

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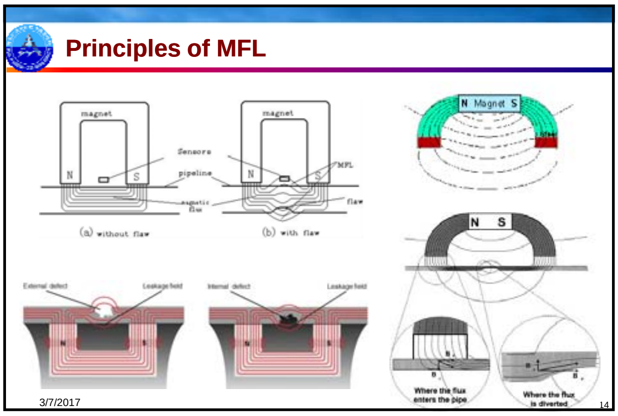

Principles of MFL

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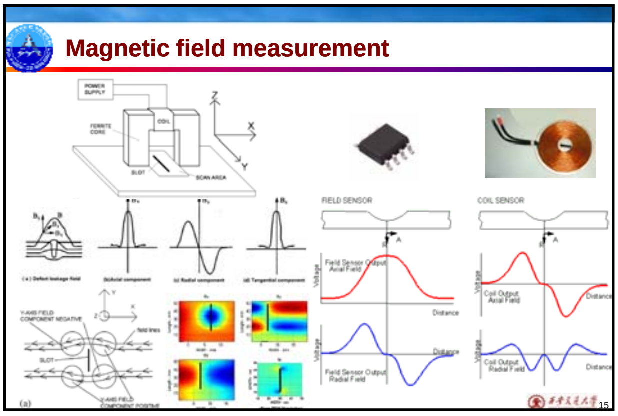
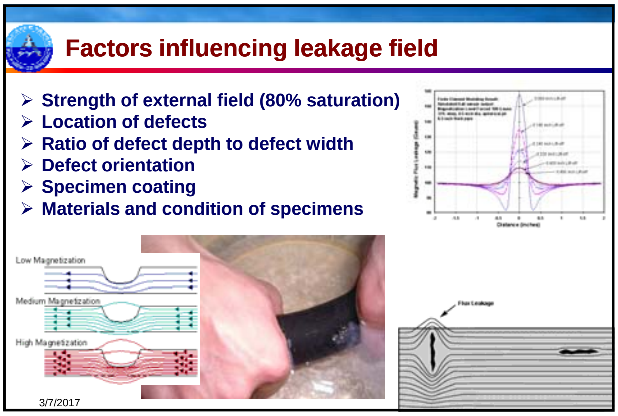


Magnetic field measurement



Factors influencing leakage field

- ➢ Strength of external field (80% saturation)
- ➢ Location of defects
- ➢ Ratio of defect depth to defect width
- ➢ Defect orientation
- ➢ Specimen coating
- ➢ Materials and condition of specimens

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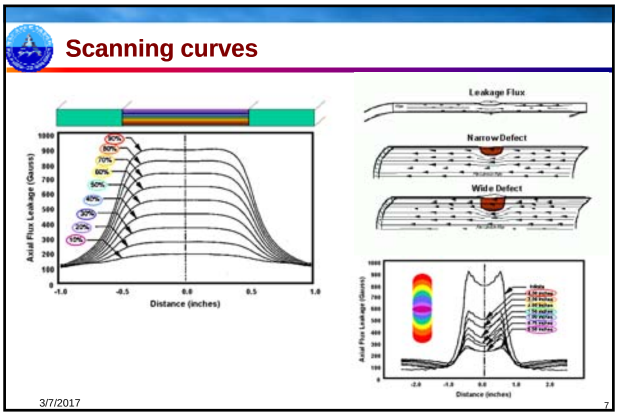

Scanning curves

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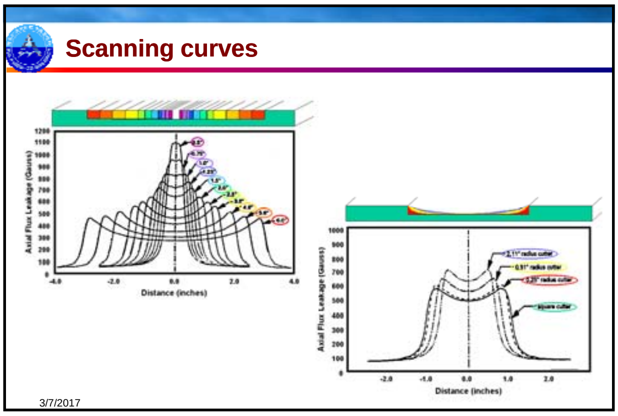

Scanning curves

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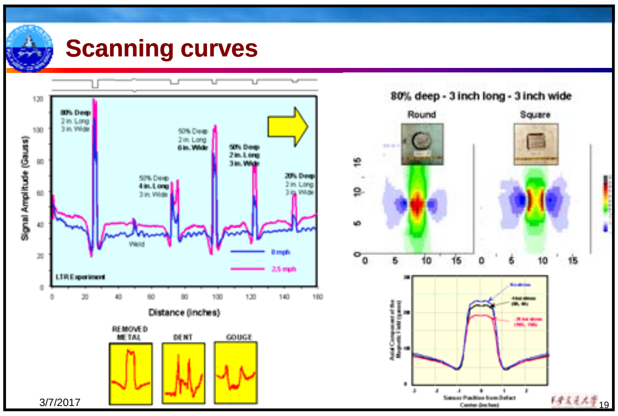

Scanning curves

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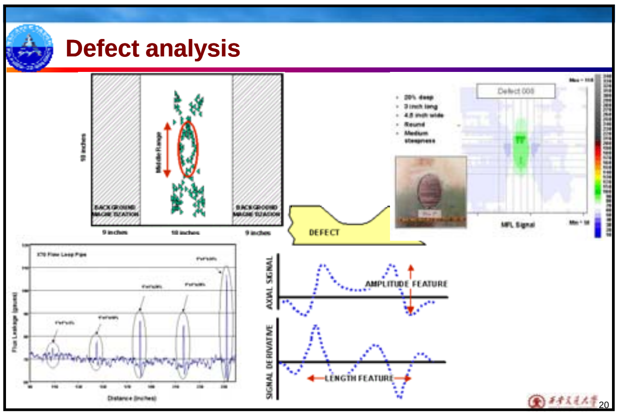

Defect analysis

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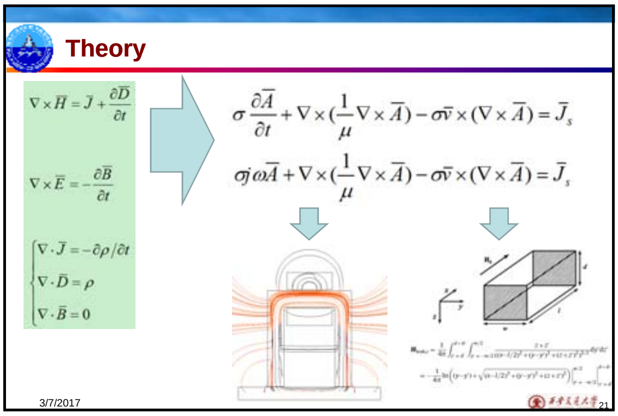

Theory

$$\nabla \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t}$$

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t}$$

$$\begin{cases} \nabla \cdot \bar{J} = -\partial \rho / \partial t \\ \nabla \cdot \bar{D} = \rho \\ \nabla \cdot \bar{B} = 0 \end{cases}$$

$$\sigma \frac{\partial \bar{A}}{\partial t} + \nabla \times \left(\frac{1}{\mu} \nabla \times \bar{A}\right) - \sigma \bar{v} \times (\nabla \times \bar{A}) = \bar{J}_s$$

$$\sigma j \omega \bar{A} + \nabla \times \left(\frac{1}{\mu} \nabla \times \bar{A}\right) - \sigma \bar{v} \times (\nabla \times \bar{A}) = \bar{J}_s$$

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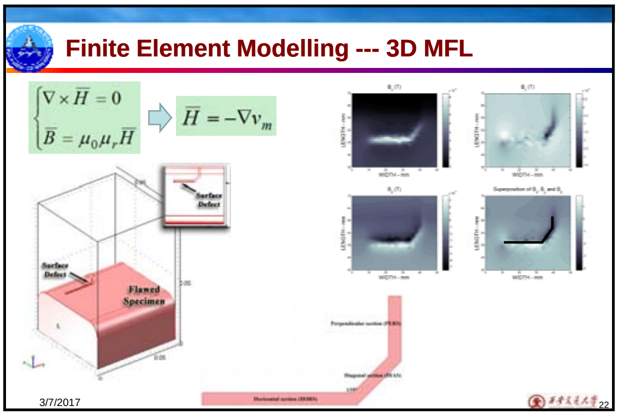
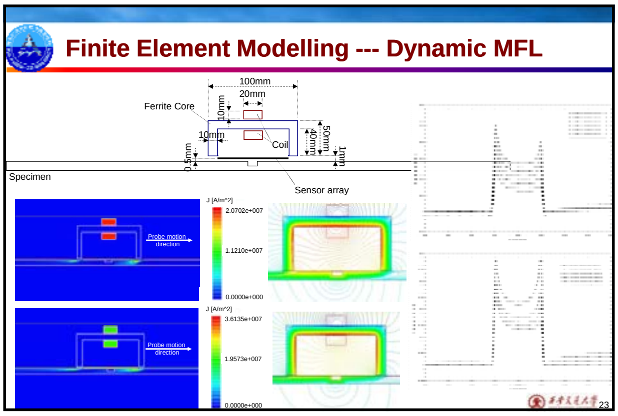
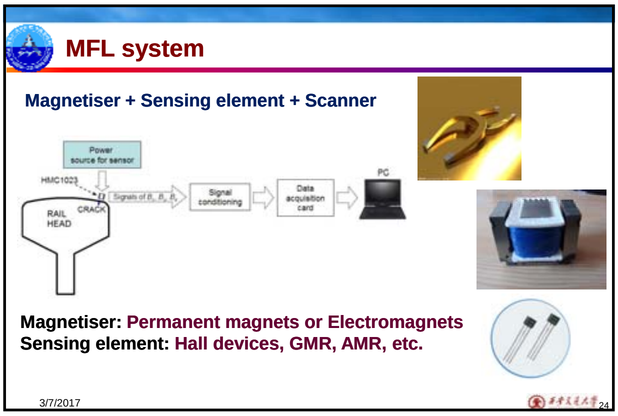


Finite Element Modelling --- 3D MFL

$$\begin{cases}\nabla \times \overline{H} = 0 \\ \overline{B} = \mu_0 \mu_r \overline{H}\end{cases} \Rightarrow \overline{H} = -\nabla v_m$$



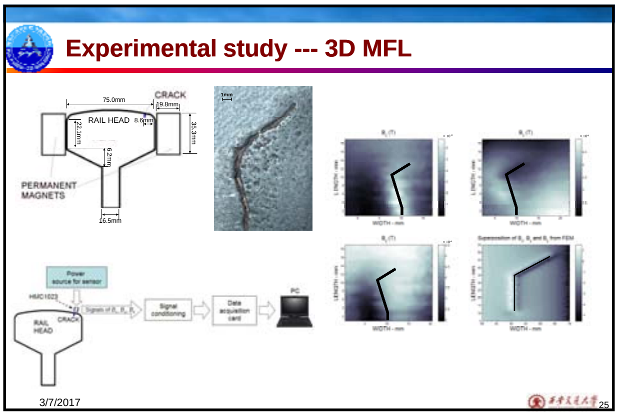
Finite Element Modelling --- Dynamic MFL



MFL system

Magnetiser + Sensing element + Scanner

Magnetiser: Permanent magnets or Electromagnets
Sensing element: Hall devices, GMR, AMR, etc.



Experimental study --- 3D MFL

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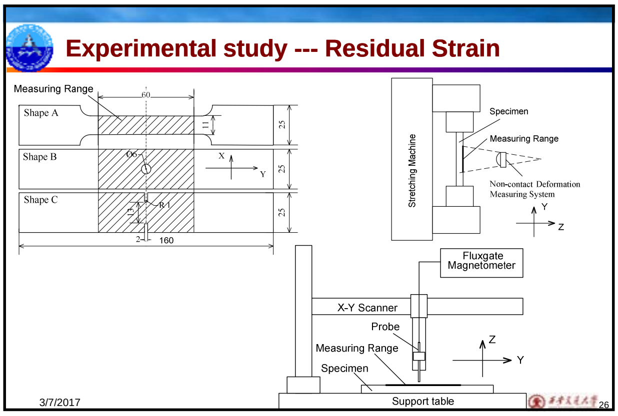

Experimental study --- Residual Strain

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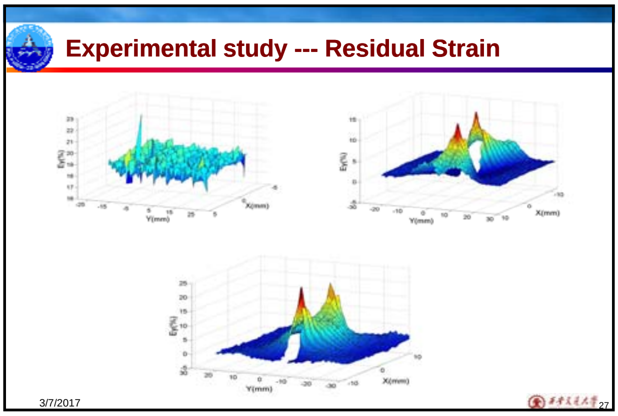

Experimental study --- Residual Strain

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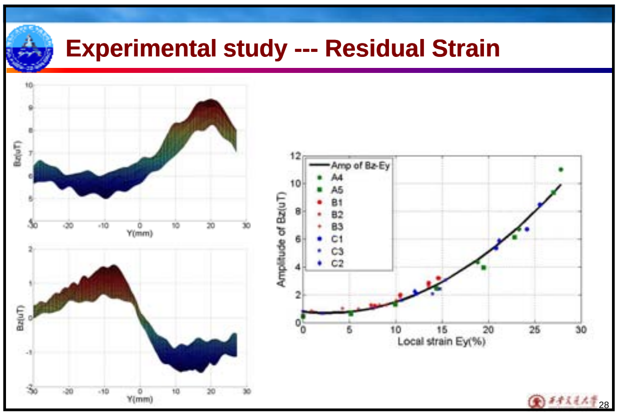

Experimental study --- Residual Strain

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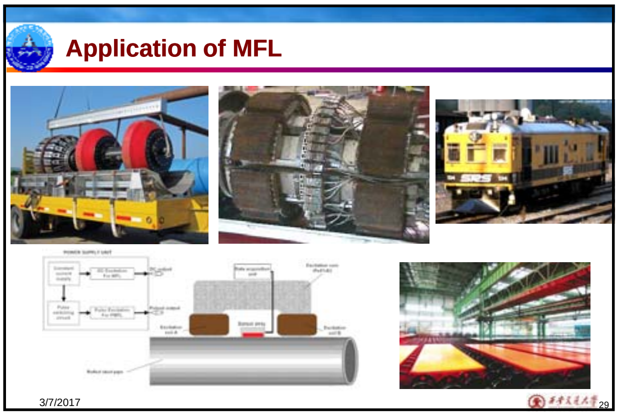

Application of MFL

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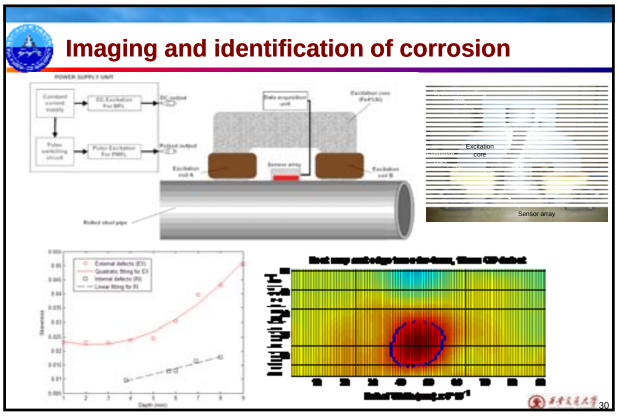

Imaging and identification of corrosion

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Thank you!

and Any Questions?

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