L13 Ferromagnetism

Lecture outline:
- The mechanism of ferromagnetism
- Domains.
- Antiferromagnetism.
- Ampere's law in a magnetic material.
- Electromagnets
- Magnetic recording

L13.1 Ferromagnetism

The Mechanism of Ferromagnetism
Iron crystals are made of domains, in which the magnetic dipoles are aligned.

4 domains:
(1) Dipoles cancel, not magnetized
(2) Domains grow
(3) Some domains disappear,
(4) All dipoles aligned, saturation
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Magnetic domains as seen in a polarizing microscope

There is a critical temperature, the Curie temperature, above which the thermal motion randomizes the domains and destroys the magnetization.

\[ T_c \]

Fe  1043 K
Co  1388 K
Ni  627 K

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Anti-ferromagnetism: interaction between neighbouring dipoles has opposite sign: adjacent moments tend to align antiparallel (paramagnetic), eg Cr, Mn.

\[ \uparrow \downarrow \uparrow \downarrow \]

Ferrimagnetism:
If there are 2 unequal kinds of moments, there is a net magnetization even under complete antiparallel ordering:

Such materials are ferrites, eg lodestone, FeOFe₂O₃.
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Consider a little loop: dipole moment \( \mathbf{m} \)

Magnetization \( \mathbf{M} = \frac{\mathbf{m}}{\text{volume}} = \frac{\mathbf{m}}{ad} \)

\[ m = Mad = Ia \quad \text{so} \quad I = Md \]

and \( \frac{I}{d} = \text{“surface current density”} \quad (\text{Am}^{-1}) = M = J_{\text{surface}} \)

(compare result relating polarization to surface charge density)

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Ampere’s law:

\[ \oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \oint (\mathbf{H} + \mathbf{M}) \cdot d\mathbf{s} = \mu_0 i = \mu_0 (i_{\text{free}} + i_{\text{surface}}) \]

Here \( i_{\text{surface}} = i_{\text{bound}} \) (due to internal dipoles)

\( i_{\text{free}} = \) current applied from outside

\[ \overrightarrow{\mathbf{M}} = 0 \quad \text{But} \quad \mu_0 \oint \mathbf{M} \cdot d\mathbf{s} = \mu_0 I = \mu_0 i_{\text{surface}} \]

This is Ampere’s law in a magnetic material.
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Put a magnetized sphere in a magnetic field:

\[ \mathbf{M} \text{ in sphere is uniform. } \mathbf{B} \text{ is continuous (can’t start or stop).} \]

But \( \mathbf{H} \) may not be continuous:

\[ \oint \mathbf{H} \cdot d\mathbf{s} = 0 \]

so \( \mathbf{H} \) may reverse in the material.

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Magnetic shielding: put a hole in a ferromagnet. The field gets trapped in the magnet, with zero field inside hole.

(compare electrical shielding).
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Use Ampere’s law in an iron toroid:
\[ \oint H \cdot ds = i_{free} = NI = HL \]
so \( H = \frac{NI}{L} \) and \( B = \frac{NI}{\mu L} \) inside.

Example: \( N = 1000 \), \( L = 1 \text{ m} \),
so \( H = 1000 \text{ Am}^{-1} \).
From the chart, \( B = 1.15 \text{ T} \),
so \( \mu = B/H = 1.15 \times 10^{-3} \),
and \( \mu_r = \mu/\mu_0 = 1.15 \times 10^{-3}/(4\pi \times 10^{-7}) = 900. \)

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Electromagnet with a gap. For a small gap, \( B \) is continuous, so \( B \) is nearly the same in the iron and the gap.

Now \( H \) in the iron is \( H_1 = \frac{B}{\mu} = \frac{B}{\mu_r \mu_0} \)
and \( H \) in the gap is \( H_2 = \frac{B}{\mu_0} \)
so \( \oint H \cdot ds = H_1L + H_2l = \frac{BL}{\mu_r \mu_0} + \frac{Bl}{\mu_0} = NI \)
\( \therefore B = \frac{\mu_0 NI}{L/\mu_r + l} \approx \frac{\mu_0 NI}{l} \) because \( \mu_r \) is very big.

Example: \( L = 1 \text{ m}, l = 1 \text{ cm}, N = 1000 \), then \( B = 4\pi \times 10^{-7} \times 1000/0.01 = 0.13 \text{T} \)

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For a permanent magnet, $i = 0$, so

$$H_1L + H_2l = 0 \Rightarrow H_{iron} = -\frac{H_{gap}}{L} = -\frac{Bl}{\mu_0 L}$$

(note the minus sign)

Example: $L = 1m$, $l = 1cm$, $B = 0.1T$,

$$H_{gap} = \frac{B}{\mu_0} = \frac{0.1}{4\pi \times 10^{-7}} \approx 80000 \text{ Am}^{-1} \quad \text{and} \quad H_{iron} = -800 \text{ Am}^{-1}$$

L13.11 Ferromagnetism

Magnetic recording:

There are 3 heads: erase, write and read. The tape with magnetic coating moves over the heads. At the gap in the electromagnet, there is a fringing magnetic field that extends over the tape.

In writing, the time variation in the field is translated to a space varying magnetization in the moving tape.
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Audio tape uses needle-like particles of Fe₂O₃ or CrO₂ (~ 1µm), on a substrate of mylar (a polyester).

The spatial frequency translates to an audio frequency (analogue).
Video tape is similar.
In reading, the changing field in the tape induces a signal in the coil.

Computer disks store information digitally, as bits. Domains are magnetized in up or down direction.

Field of view 30µm.