

Electromagnetic Field Theory

Week 12

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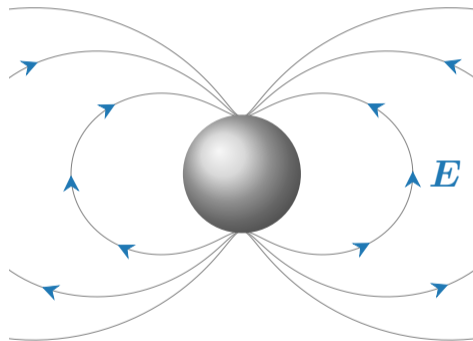
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1. Magnetic Materials





Magnetic Materials

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

$$\mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \chi_m \mathbf{H} = \mu_0 (1 + \chi_m) \mathbf{H} = \mu_0 \mu_r = \mu \mathbf{H}$$

Classification	Magnetic Moments	B Values	Comments
Diamagnetic	$ \mathbf{m}_o + \mathbf{m}_s = 0$	$B_{\text{int}} < B_0$	Nonmagnetic matrix
Paramagnetic	$ \mathbf{m}_o + \mathbf{m}_s \rightarrow 0$	$B_{\text{int}} > B_0$	Low magnetic response
Ferromagnetic	$ \mathbf{m}_s \gg \mathbf{m}_o $	$B_{\text{int}} \gg B_0$	Domains
Antiferromagnetic	$ \mathbf{m}_s \gg \mathbf{m}_o $	$B_{\text{int}} = B_0$	Adjacent moments oppose
Ferrimagnetic	$ \mathbf{m}_s \gg \mathbf{m}_o $	$B_{\text{int}} > B_0$	Unequal adjacent moments oppose
Superparamagnetic	$ \mathbf{m}_s \gg \mathbf{m}_o $	$B_{\text{int}} > B_0$	Nonmagnetic matrix

Classification of magnetic materials (the table is adopted from Hyat & Buck), \mathbf{m}_o stands for an orbital moment, \mathbf{m}_s for a spin moment, B_{int} stands for the magnitude of magnetic field inside the material, and B_0 stands for the magnitude of external magnetic field.



Diamagnetic Materials

- ▶ $\chi_m \approx -10^{-5}$, $\mu_r < 1$.
- ▶ Weakly repelled by a magnetic field.
- ▶ No permanent magnetic moment in the absence of a magnetic field.



Paramagnetic Materials

- ▶ $\chi_m > 0, \mu_r > 1$.
- ▶ Weakly attracted to a magnetic field.
- ▶ Magnetic moments align with the external field but only in its presence; the alignment is random when the field is removed.

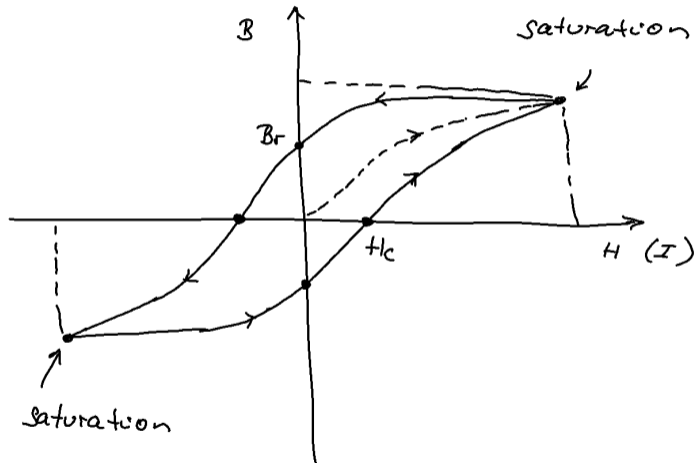


Ferromagnetic Materials

- ▶ $\chi_m \approx 10^3-10^5$
- ▶ Strongly attracted to a magnetic field.
- ▶ Highly nonlinear materials.
- ▶ Exhibit hysteresis in their magnetization curve.

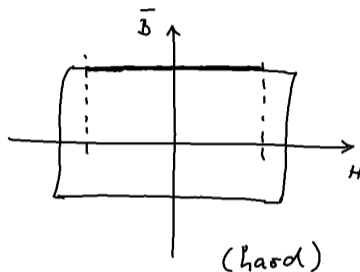
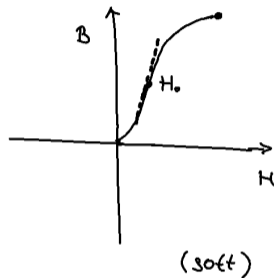


Hysteresis



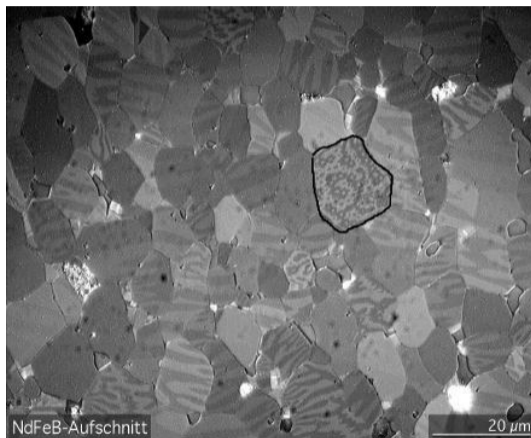


Soft and Hard Materials



Soft materials are usually used around a point where the permeability can be linearized. Hard materials (permanent magnets) are used with magnetic field intensity so they are never de-magnetized.

Soft and Hard Materials



Microcrystalline grains within a piece of $\text{Nd}_2\text{Fe}_{14}\text{B}$ (neodymium magnet). The domains are the light and dark stripes visible within each grain. The outlined grain has an almost vertical magnetocrystalline axis, so the domains are seen end-on. Credits: Wikipedia.



Boundary Conditions in Magnetic Field

$$\mu_1 H_{1,\text{norm}} = \mu_2 H_{2,\text{norm}}$$

$$\frac{B_{1,\text{tan}}}{\mu_1} = \frac{B_{2,\text{tan}}}{\mu_2}$$

$$H_{1,\text{tan}} - H_{2,\text{tan}} = \frac{NI}{dl} = nI$$



Magnetic Circuits

Electric circuit	Magnetic circuit
electromotive voltage U	magnetomotive voltage NI
electric current I	magnetic flux Φ
resistance R	reluctance R_m
conductance G	permeance P_m
conductivity σ	permeability μ

Analogies between electric and magnetic circuits.

Hopkinson's law

$$U_m = \Phi R_m$$

Questions?

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