Magnetic Properties of Materials
(Ch. 14-17, 재료과학 Ch. 20)

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11.6. Magnetic Anisotropy

- Different magnetic property for the different direction in X-tal

Magnetocrystalline anisotropy in a single iron crystal. $M$ vs. $H$ depends on the crystal on the crystal direction and is easiest along [100] and hardest along [111].
11.7. Soft Magnetic Materials (Electrical Steel)

- Area in hysteresis → amount of loss (heat generated)
- Especially, high frequency → eddy current → lot of heat !!

**Soft magnetic materials**
- To multiply the magnetic flux in the cores of electro-magnetic coils.
- Transformers, electromotors, generators, electromagnets
- In general: Ceramic magnetics
- High resistivity → less loss
  - AC → induction current (eddy current)
  → energy loss
# 11.7. Soft Magnetic Materials (Electrical Steel)


<table>
<thead>
<tr>
<th>Name</th>
<th>Composition (mass %)</th>
<th>Permeability, $\mu_{\text{max}}$ (unitless)</th>
<th>Coercivity, $H_c$ (Oe)</th>
<th>Saturation induction $B_s$ (kG)</th>
<th>Resistivity, $\rho(\mu\Omega \cdot \text{cm})$</th>
<th>Core loss at 1.5 T and 60 Hz (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low carbon steel</td>
<td>Fe–0.05% C</td>
<td>$5 \times 10^3$</td>
<td>1.0</td>
<td>21.5</td>
<td>10</td>
<td>2.8</td>
</tr>
<tr>
<td>Nonoriented silicon iron</td>
<td>Fe–3% Si, 0.005% C, 0.15% Mn</td>
<td>$7 \times 10^3$</td>
<td>0.5</td>
<td>19.7</td>
<td>60</td>
<td>0.9</td>
</tr>
<tr>
<td>Grain-oriented silicon iron</td>
<td>Fe–3% Si, 0.003% C, 0.07% Mn</td>
<td>$4 \times 10^4$</td>
<td>0.1</td>
<td>20</td>
<td>47</td>
<td>0.3</td>
</tr>
<tr>
<td>78 Permalloy</td>
<td>Ni–22% Fe</td>
<td>$10^5$</td>
<td>0.05</td>
<td>10.8</td>
<td>16</td>
<td>$\approx 2$</td>
</tr>
<tr>
<td>Mumetal</td>
<td>77% Ni; 16% Fe, 5% Cu, 2% Cr</td>
<td>$10^5$</td>
<td>0.05</td>
<td>6.5</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Supermalloy</td>
<td>79% Ni; 16% Fe, 5% Mo</td>
<td>$10^6$</td>
<td>0.002</td>
<td>7.9</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Supermendur</td>
<td>49% Fe, 49% Co, 2% V</td>
<td>$6 \times 10^4$</td>
<td>0.2</td>
<td>24</td>
<td>24</td>
<td>27</td>
</tr>
<tr>
<td>Metglas #2605 annealed</td>
<td>Fe$<em>{80}$B$</em>{20}$</td>
<td>$3 \times 10^5$</td>
<td>0.04</td>
<td>15</td>
<td>1.5</td>
<td>$\approx 200$</td>
</tr>
</tbody>
</table>

*Above $B$, the magnetization is constant and $dB/d(\mu_0H)$ is unity.*

- Permanent magnetization
  - No need of electric
  - Less heat
    - Hard magnetics are utilized after alignment of magnetic momentum.
    - Magnetics with remanent magnetization are utilized.
  - Motor application (electrical vehicle)
  - Cordless drill, Screw driver, small speaker, earphone…

Hard magnetic materials and \((BH)_{max}\):
Larger BH \(\rightarrow\) more difficult to magnetize
kJ/m3 (MGOe: \(10^6\) gauss-oersted)

Table 17.2. Properties of Materials Used for Permanent Magnets.

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition (mass %)</th>
<th>Remanence $B_r$ (kG)</th>
<th>Coercivity $H_c$ (Oe)</th>
<th>Coercivity $H_c$ (A/m)</th>
<th>Maximum energy product $(BH)_{max}$ per Volume (MGOe)</th>
<th>$(kJ/m^3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>Fe–1% C</td>
<td>9</td>
<td>51</td>
<td>4 × 10³</td>
<td>0.2</td>
<td>1.6</td>
</tr>
<tr>
<td>36 Co steel</td>
<td>36 Co, 3.75 W, 5.75 Cr, 0.8 C</td>
<td>9.6</td>
<td>228</td>
<td>1.8 × 10⁴</td>
<td>0.93</td>
<td>7.4</td>
</tr>
<tr>
<td>Alnico 2</td>
<td>12 Al, 26 Ni, 3 Cu, 63 Fe</td>
<td>7</td>
<td>650</td>
<td>5.2 × 10⁴</td>
<td>1.7</td>
<td>13</td>
</tr>
<tr>
<td>Alnico 5</td>
<td>8 Al, 15 Ni, 24 Co, 3 Cu, 50 Fe</td>
<td>12</td>
<td>720</td>
<td>5.7 × 10⁴</td>
<td>5.0</td>
<td>40</td>
</tr>
<tr>
<td>Alnico 5 DG</td>
<td>same as above</td>
<td>13.1</td>
<td>700</td>
<td>5.6 × 10⁴</td>
<td>6.5</td>
<td>52</td>
</tr>
<tr>
<td>Ba-ferrite (Ceramic 5)</td>
<td>BaO · 6 Fe₂O₃</td>
<td>3.95</td>
<td>2,400</td>
<td>1.9 × 10⁵</td>
<td>3.5</td>
<td>28</td>
</tr>
<tr>
<td>PtCo</td>
<td>77 Pt, 24 Co</td>
<td>6.45</td>
<td>4,300</td>
<td>3.4 × 10⁵</td>
<td>9.5</td>
<td>76</td>
</tr>
<tr>
<td>Remalloy</td>
<td>12 Co, 17 Mo, 71 Fe</td>
<td>10</td>
<td>230</td>
<td>1.8 × 10⁴</td>
<td>1.1</td>
<td>8.7</td>
</tr>
<tr>
<td>Vicalloy 2</td>
<td>13 V, 52 Co, 35 Fe</td>
<td>10</td>
<td>450</td>
<td>3.6 × 10⁴</td>
<td>3.0</td>
<td>24</td>
</tr>
<tr>
<td>Cobalt–Samarium</td>
<td>Co₅Sm</td>
<td>9</td>
<td>8,700</td>
<td>6.9 × 10⁵</td>
<td>20</td>
<td>159</td>
</tr>
<tr>
<td>Iron–Neodymium–Boron</td>
<td>Fe₁₄Nd₂B₁</td>
<td>13</td>
<td>14,000</td>
<td>1.1 × 10⁶</td>
<td>40</td>
<td>318</td>
</tr>
</tbody>
</table>
A superconductor such as lead evinces a transition to zero resistivity at a critical temperature $T_c$ (7.2 K for Pb) whereas a normal conductor such as silver does not, and exhibits residual resistivity at the lowest temperatures.

Photograph of a magnet levitating above a superconductor immersed in liquid nitrogen (77 K). This is the Meissner effect. (SOURCE: Photo courtesy of Professor Paul C.W. Chu.)
The Meissner effect. (due to perfect diamagnetism)
A superconductor cooled below its critical temperature expels all magnetic field lines from the bulk by setting up a surface current. A perfect conductor ($\sigma = \infty$) shows no Meissner effect.
Characteristics of Type I and Type II superconductors. \( B = \mu_0 H \) is the applied field and \( M \) is the overall magnetization of the sample. Field inside the sample, \( B_{\text{inside}} = \mu_0 H + \mu_0 M \), which is zero only for \( B < B_c \) (Type I) and \( B < B_{c1} \) (Type II).
The critical surface (Temp, current density, magnetic field) for a niobium-tin alloy which is a Type II superconductor.
In 1986 J. George Bednorz (right) and K. Alex Müller, at IBM Research Laboratories in Zurich, discovered that a copper oxide based ceramic-type compound (La-Ba-Cu-O) which normally has high resistivity becomes superconducting when cooled below 35 K. This Nobel prize winning discovery opened a new era of high-temperature superconductivity research; now there are various ceramic compounds that are superconducting above the liquid nitrogen (an inexpensive cryogen) temperature (77 K). 

|SOURCE: IBM Zürich Research Laboratories.|
These high temperature superconductor (HTS) flat tapes are based on \((\text{Bi}_{2-x}\text{Pb}_x)\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10-d}(\text{Bi-2223})\). The tape has an outer surrounding protective metallic sheath.

Right: HTS tapes having ac power loss below 10 mW/m have a major advantage over equivalent-sized metal conductors, in being able to transmit considerably higher power loads. Coils made from HTS tape can be used to create more compact and efficient motors, generators, magnets, transformers and energy storage devices.

| SOURCE: Courtesy of Australian Superconductors. |
11.10. Applications

Principle of the spin valve (a) No applied field. (b) Applied field has fully oriented the free layer magnetization. (c) **Resistance change vs. applied field magnetic field** (schematic) for a FeNi/Cu/FeNi spin valve.
The principle of longitudinal magnetic recording on a flexible medium, e.g. magnetic tape in an audio cassette.
The principle of the hard disk drive magnetic recording. The **write inductive head** and the **GMR read sensor** have been integrated into a single tiny read/write head.

Above: Giant magnetoresistance (GMR) hard disk heads on a U.S. quarter. Left: A small hard disk drive next to a quarter coin—a microdrive.

SOURCE: Courtesy of IBM.
11. 11. Magnetics in the circuits

- Transformer
- Inductor
- EMI filter
- ...

![Magnetics components](image_url)
Inductance (L)

- Inductance
  - 자기유도 (self induction): Current change (Δi) → magnetic flux change (Δϕ) → induce the voltage (V)
  - Dimension: L (Henry)

\[
V = \left( \frac{\mu N^2 A}{l} \right) \frac{di}{dt} = L \frac{di}{dt}
\]

\[
L \equiv \frac{\mu N^2 A}{l}
\]
Impedance

• Inductor
  − DC: $R = 0$ (just coil)
  − AC

\[
V = L \frac{di}{dt} = L \frac{d_i}{dt} \sin \omega t = L i_m \omega \cos \omega t = L i_m \omega \sin(\omega t + 90^\circ)
\]

• $90^\circ$ phase difference bw current and voltage
• Impedance $= jX_L \rightarrow$ magnitude of Impedance due to inductor $= \omega L$
• high frequency $\rightarrow$ larger impedance, low frequency $\rightarrow$ smaller impedance
Serial connection

전류가 같으므로 전체 전압은

\[ v = \sum_{i=1}^{n} v_i = \sum_{i=1}^{n} L_i \frac{di}{dt} = \left( \sum_{i=1}^{n} L_i \right) \frac{di}{dt} = L \frac{di}{dt} \]

\[ L \equiv \sum_{i=1}^{n} L_i \]
Parallel connection

- As the voltages are same

\[ L_1 \frac{di_1}{dt} = L_2 \frac{di_2}{dt} = \cdots = L_n \frac{di_n}{dt} = v \quad i_i = \frac{1}{L_i} \int_{-\infty}^{t} v(\tau) d\tau \quad i = 1, \ldots, n \]

\[ i = \sum_{i=1}^{n} i_i = \sum_{i=1}^{n} \left( \frac{1}{L_i} \int_{-\infty}^{t} v(\tau) d\tau \right) = \left( \sum_{i=1}^{n} \frac{1}{L_i} \right) \int_{-\infty}^{t} v(\tau) d\tau \]

\[ \frac{1}{L} \equiv \sum_{i=1}^{n} \frac{1}{L_i} \]
### Energy storage of R, C, L

#### Dissipated Energy (Heat) : $i^2RT$

<table>
<thead>
<tr>
<th>Classification</th>
<th>Energy</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic</td>
<td>$W_M = \frac{1}{2}Mu^2$</td>
<td>$M$ mass, $u$ velocity</td>
</tr>
<tr>
<td>Elastic</td>
<td>$W_K = \frac{1}{2}Kx^2$</td>
<td>$K$ spring constant, $x$ displacement [m]</td>
</tr>
<tr>
<td>Capacitor</td>
<td>$W_C = \frac{1}{2}Cv^2$</td>
<td>$C$, $v$ voltage</td>
</tr>
<tr>
<td>Inductor</td>
<td>$W_L = \frac{1}{2}Li^2$</td>
<td>$L$, $i$ current</td>
</tr>
</tbody>
</table>

- **No storage**
- **Heat dissipation**
- **Storage as electric field**
- **Storage as magnetic field**
<table>
<thead>
<tr>
<th>Circuit</th>
<th>Impedance</th>
<th>Admittance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real</td>
<td>Imaginary</td>
</tr>
<tr>
<td>R</td>
<td>$R$</td>
<td>0</td>
</tr>
<tr>
<td>L</td>
<td>0</td>
<td>$wL$</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>$1/wC$</td>
</tr>
</tbody>
</table>

복수(complex) 평면에서 표현하면,

Why complex number?
• AC에서 $L$, $C$는 위상차가 발생하며, 전체 Impedance를 계산할 때, 복소수함수를 이용하면 편리함.
1. Ch. 14: Problems 1, 2, 3, 4
2. Ch. 17. Problems 1, 2, 4

3. 총길이가 0.25m이며 400회 감긴 코일 도선에 15A의 전류가 흐르고 있다. (a) 자기장세기 H는 얼마인가? (b) 코일이 진공 내에 있을 경우, 자속 밀도 B를 계산하시오.

4. A coil produces a self-induced voltage of 42mV when current (i) varies at the rate of 19 mA/ms. How much is L?

5. Calculate the energy in joules stored in the magnetic field of a 60-mH L with a 90-mA I.

6. (잘 모르면 1학년 물리책 참고) : (a) A transformer delivers 400 W out with 500 W in. Calculate the efficiency in percent. (b) A transformer with 80% efficiency delivers 400W total secondary power. Calculate the primary power.

7. 어떤 금속 합금의 막대 내부의 자화는 200 A/m의 H자기장에서 1.2 x 10^6 A/m이다. 다음을 계산하시오. (a) 자화율 (b) 투자율 (c) 이 재료내의 자속 밀도 (d) 어떤 종류의 자성이 이 재료에서 나타나는가? 그 이유는 무엇인가?
Why

- Why TV case is black?