Lecture Five

Electrical and Magnetic Properties of Materials

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Classification of Magnetic Materials

- The material types can be divided into several main categories
  - Ferromagnetism
  - Ferrimagnetism
  - Diamagnetism
  - Paramagnetism
  - Antiferromagnetism
  - Hard magnet
Diamagnetism

- In **diamagnetic** materials, the electrons are oriented so their individual magnetic fields cancel each other out.
- Diamagnetism is a fundamental property of all matter, although it is usually very weak. It is due to the non-cooperative behavior of orbiting electrons when exposed to an applied magnetic field.
- Diamagnetic substances are composed of atoms which have no net magnetic moments (i.e., all the orbital shells are filled and there are no unpaired electrons). However, when exposed to a field, a negative magnetization is produced and thus the susceptibility is negative. If we plot $M$ vs $H$, we see:

  - People and frogs are diamagnetic.
  - Metals such as bismuth, copper, gold, silver and lead, as well as many nonmetals such as water and most organic compounds are diamagnetic.
This class of materials, some of the atoms or ions in the material have a net magnetic moment due to unpaired electrons in partially filled orbitals.

One of the most important atoms with unpaired electrons is iron. However, the individual magnetic moments do not interact magnetically, and like diamagnetism, the magnetization is zero when the field is removed.

In the presence of a field, there is now a partial alignment of the atomic magnetic moments in the direction of the field, resulting in a net positive magnetization and positive susceptibility.

When paramagnetic materials are placed in a magnetic field, the atoms align so that the material is weakly magnetic.
Paramagnetism

- **Paramagnetism** - When a paramagnetic material is placed near a magnet, it will be attracted to the region of greater magnetic field, like a ferromagnetic material. The difference is that the attraction is weak. It is exhibited by materials containing transition elements, rare earth elements and actinide elements. Liquid oxygen and aluminum are examples of paramagnetic materials.

- The paramagnetic materials at room temperature are Chromium, Tungsten, Aluminium, and Magnesium.
Ferromagnetism

- When a ferromagnetic material is placed near a magnet, it will be attracted toward the region of greater magnetic field. This is what we are most familiar with when our magnet picks up a bunch of paperclips.
- Iron, cobalt, nickel, gadolinium, dysprosium and alloys containing these elements exhibit ferromagnetism because of the way the electron spins within one atom interact with those of nearby atoms.
- They will align themselves, creating magnetic domains forming a permanent magnet.

- If a piece of iron is placed within a strong magnetic field, the domains in line with the field will grow in size as the domains perpendicular to the field will shrink in size.
- Unlike paramagnetic materials, the atomic moments in these materials exhibit very strong interactions. These interactions are produced by electronic exchange forces and result in a parallel or antiparallel alignment of atomic moments.
Magnetic field absent

In presence of magnetic field

Ferromagnetism
Types of Magnetism

Magnetic induction

\[ B = (1 + \chi) \mu_0 H \]

permeability of a vacuum: 
(1.26 x 10^{-6} \text{ Henries/m})

Magnetic induction

1. **diamagnetic** \((\chi \sim -10^{-5})\)
   - e.g., \(\text{Al}_2\text{O}_3, \text{Cu}, \text{Au}, \text{Si}, \text{Ag}, \text{Zn}\)

2. **paramagnetic** \((\chi \sim 10^{-4})\)
   - e.g., \(\text{Al}, \text{Cr}, \text{Mo}, \text{Na}, \text{Ti}, \text{Zr}\)

3. **ferromagnetic**
   - e.g. \(\text{Fe}_3\text{O}_4, \text{NiFe}_2\text{O}_4\)
   - \(\chi\) as large as \(10^6\)!

4. **ferrimagnetic**
   - e.g. ferrite(\(\alpha\)), Co, Ni, Gd
   - \(\chi\) as large as \(10^6\)!

Strength of applied magnetic field \((H)\)
(ampere-turns/m)

Plot adapted from Fig. 20.6, *Callister 7e*. Values and materials from Table 20.2 and discussion in Section 20.4, *Callister 7e*. 
Magnetic Responses for 4 Types

(1) diamagnetic
No Applied Magnetic Field (H = 0)

(2) paramagnetic
Applied Magnetic Field (H)

(3) ferromagnetic

(4) ferrimagnetic

Adapted from Fig. 20.5(a), Callister & Rethwisch 8e.

Adapted from Fig. 20.5(b), Callister & Rethwisch 8e.

Adapted from Fig. 20.7, Callister & Rethwisch 8e.
## Comparison of Magnetic Properties

<table>
<thead>
<tr>
<th>TYPE</th>
<th>SUSCEPTIBILITY $\chi_m$</th>
<th>TEMPERATURE DEPENDENT, $T$</th>
<th>EXAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamagnet</td>
<td>a) small &amp; negative</td>
<td>a) $\chi_m \propto T$</td>
<td>Organic materials, light elements and alkali metals</td>
</tr>
<tr>
<td></td>
<td>b) medium &amp; negative</td>
<td>b) $\chi_m \propto T$ and $H$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c) large &amp; negative</td>
<td>c) Exist below critical temp. $T_c$</td>
<td></td>
</tr>
<tr>
<td>Paramagnet</td>
<td>a) small &amp; positive</td>
<td>a) $\chi_m$ not $\propto T$</td>
<td>Alkali metals, transition metals, rare earth metals</td>
</tr>
<tr>
<td></td>
<td>b) large &amp; positive</td>
<td>b) $\chi_m \propto 1/T$</td>
<td></td>
</tr>
<tr>
<td>Ferromagnet</td>
<td>Very large and positive</td>
<td>$T&gt;0$, $\chi_m = 1/(T-\theta)$</td>
<td>Transition metals and rare earth metals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T&lt;0$, $\chi_m$ is complex</td>
<td></td>
</tr>
<tr>
<td>Antiferromagnet</td>
<td>Small and positive</td>
<td>$T&gt;T_N$, $\chi_m = 1/(T+\theta)$</td>
<td>Salts and transition metals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T&lt;T_N$, $\chi_m \propto T$</td>
<td></td>
</tr>
<tr>
<td>Ferrimagnet</td>
<td>Very large and positive</td>
<td>$T&gt;T_N$, $\chi_m \propto 1/(T\pm\theta)$</td>
<td>Ferrites, ferrous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T&lt;T_N$, $\chi_m$ complex</td>
<td></td>
</tr>
</tbody>
</table>

$T_N$: Neel temperature; $\theta$: Curie temperature
Making a Magnet from a Ferromagnetic Material

- domains in which the magnetic fields of individual atoms align
- orientation of the magnetic fields of the domains is random
- no net magnetic field.

- when an external magnetic field is applied, the magnetic fields of the individual domains line up in the direction of the external field
- this causes the external magnetic field to be enhanced
A small group of metals have very strong magnetic properties, including iron, nickel, and cobalt.

These metals are the best known examples of ferromagnetic materials.

Atoms with similar magnetic orientations line up with neighboring atoms in groups called magnetic domains.
Magnetic Domains

One domain
Domain wall
Another domain

Domain wall
Magnetic Properties of Materials

- Magnetic domains in a ferromagnetic material will always orient themselves to attract a permanent magnet.
  - If a north pole approaches, domains grow that have south poles facing out.
  - If a south pole approaches, domains grow that have north poles facing out.
• As the applied field \((H)\) increases, the magnetic domains change shape and size by movement of domain boundaries.

- “Domains” with aligned magnetic moment grow at expense of poorly aligned ones!

Adapted from Fig. 20.13, Callister & Rethwisch 8e. (Fig. 20.13 adapted from O.H. Wyatt and D. Dew-Hughes, Metals, Ceramics, and Polymers, Cambridge University Press, 1974.)
Hysteresis and Permanent Magnetization

The striking property of Ferro Magnetic materials is the relation between Magnetization and the strength of Magnetic field. This property is called Hysteresis.

- The magnetic hysteresis phenomenon

Stage 1. Initial (unmagnetized state)

Stage 2. Apply $H$, align domains

Stage 3. Remove $H$, alignment remains! => permanent magnet!

Stage 4. Coercivity, $H_c$. Negative $H$ needed to demagnetize!

Stage 5. Apply $-H$, align domains

Stage 6. Close the hysteresis loop

Adapted from Fig. 20.14, Callister & Rethwisch 8e.
Hard and Soft Magnetic Materials

Hard magnetic materials:
-- large coercivities
-- used for permanent magnets
-- have small values of permeability and susceptibility.
-- add particles/voids to inhibit domain wall motion
-- example: tungsten steel
-- $H_c = 5900 \text{ amp-turn/m}$

Soft magnetic materials:
-- small coercivities and retentivity, hence these materials can be easily magnetized and demagnetized.
-- have low hysteresis loss due to small hysteresis loop area.
-- have large values of permeability and susceptibility
-- used for electric motors
-- example: commercial iron 99.95 Fe, Iron silicon alloys, Ferrous nickel alloy

Adapted from Fig. 20.19, Callister & Rethwisch 8e. (Fig. 20.19 from K.M. Ralls, T.H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*, John Wiley and Sons, Inc., 1976.)
Influence of Temperature on Magnetic Behavior

- With increasing temperature, the saturation magnetization diminishes gradually and then abruptly drops to zero at Curie Temperature, $T_c$. 

![Graph showing the influence of temperature on magnetic behavior.](image)
Superconductivity

Found in 26 metals and hundreds of alloys & compounds

- $T_C = \text{critical temperature}$
  - = temperature below which material is superconductive

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![Graph showing superconductivity transition](image)

- Copper (normal)
- Mercury

Fig. 20.26, Callister & Rethwisch 8e.
Meissner Effect

- Superconductors expel magnetic fields

This is why a superconductor will float above a magnet

Fig. 20.28, Callister & Rethwisch 8e.
<table>
<thead>
<tr>
<th><strong>TABLE 19-2</strong></th>
<th>Units, conversions, and values for magnetic materials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gaussian</strong></td>
<td><strong>SI Units</strong></td>
</tr>
<tr>
<td>and cgs emu</td>
<td></td>
</tr>
<tr>
<td>(Electromagnetic Units)</td>
<td></td>
</tr>
<tr>
<td><strong>Inductance</strong></td>
<td><strong>Gauss (G)</strong></td>
</tr>
<tr>
<td><strong>Magnetic flux</strong></td>
<td><strong>Maxwell (Mx), G-cm²</strong></td>
</tr>
<tr>
<td><strong>Magnetic potential difference</strong></td>
<td><strong>Gilbert (Gb)</strong></td>
</tr>
<tr>
<td>or magnetic electromotive force (U, F)</td>
<td><strong>Gilbert (Gb)/cm</strong></td>
</tr>
<tr>
<td><strong>Magnetic field strength,</strong></td>
<td><strong>Oersted (Oe), Gilbert (Gb)/cm</strong></td>
</tr>
<tr>
<td><strong>magnetizing force</strong> (H)</td>
<td><strong>emu/cm³</strong></td>
</tr>
<tr>
<td><strong>(Volume) magnetization</strong> (M)</td>
<td><strong>emu/cm³</strong></td>
</tr>
<tr>
<td><strong>(Volume) magnetization</strong> ($4\pi M$)</td>
<td><strong>emu/cm³</strong></td>
</tr>
<tr>
<td><strong>Magnetic polarization or intensity of magnetization</strong> ($J$ or $I$)</td>
<td><strong>emu/g</strong></td>
</tr>
<tr>
<td><strong>(Mass) magnetization</strong> ($\sigma, M$)</td>
<td><strong>emu/g</strong></td>
</tr>
<tr>
<td><strong>Magnetic moment</strong> ($m$)</td>
<td><strong>emu, erg/G</strong></td>
</tr>
<tr>
<td><strong>Magnetic dipole moment</strong> ($j$)</td>
<td><strong>emu, erg/G</strong></td>
</tr>
<tr>
<td><strong>Magnetic permeability</strong> ($\mu$)</td>
<td><strong>Dimensionless</strong></td>
</tr>
<tr>
<td><strong>Magnetic permeability of free space</strong> ($\mu_0$)</td>
<td><strong>1 gauss/oersted</strong></td>
</tr>
<tr>
<td><strong>Relative permeability</strong> ($\mu_r$)</td>
<td><strong>Not defined</strong></td>
</tr>
<tr>
<td><strong>(Volume) energy density,</strong></td>
<td><strong>erg/cm³</strong></td>
</tr>
<tr>
<td><strong>energy product</strong> ($W$)</td>
<td></td>
</tr>
</tbody>
</table>
The Curie Temperature

- Curie temperature - The temperature above ($T_c$) which ferromagnetic or ferrimagnetic materials become paramagnetic.

<table>
<thead>
<tr>
<th>Material</th>
<th>Curie Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gadolinium</td>
<td>16</td>
</tr>
<tr>
<td>Nd$<em>2$Fe$</em>{12}$B</td>
<td>312</td>
</tr>
<tr>
<td>Nickel</td>
<td>358</td>
</tr>
<tr>
<td>BaO · 6Fe$_2$O$_3$</td>
<td>469</td>
</tr>
<tr>
<td>Co$_5$Sm</td>
<td>747</td>
</tr>
<tr>
<td>Iron</td>
<td>771</td>
</tr>
<tr>
<td>Alnico 1</td>
<td>780</td>
</tr>
<tr>
<td>Cunico</td>
<td>855</td>
</tr>
<tr>
<td>Alnico 5</td>
<td>900</td>
</tr>
<tr>
<td>Cobalt</td>
<td>1117</td>
</tr>
</tbody>
</table>
Applications of Magnetic Materials

- **Soft Magnetic Materials** - Ferromagnetic materials are often used to enhance the magnetic flux density ($B$) produced when an electric current is passed through the material. Applications include cores for electromagnets, electric motors, transformers, generators, and other electrical equipment.

- **Data Storage Materials** - Magnetic materials are used for data storage.

- **Permanent Magnets** - Magnetic materials are used to make strong permanent magnets.

- **Power** - The strength of a permanent magnet as expressed by the maximum product of the inductance and magnetic field.
Application of Magnetic property

In real world there many operation of magnetic property. This property is use as two form as Electromagnetic field and magnetic field.

Electronic Motor and Generator
An electric motor that uses electromagnets in the spinning stator to turn. There is an electrical 'slip-ring' on the stator that directs the power to a different magnet section of the stator to achieve rotation. Quick & dirty, but there are books written on the subject.
Magnetic storage and magnetic recording are terms from engineering referring to the storage of data on a magnetized medium. Magnetic storage uses different patterns of magnetization in a magnetizable material to store data and is a form of non-volatile memory. The information is accessed using one or more read/write heads.
Magnetic bearing

A magnetic bearing is a bearing which supports a load using magnetic levitation. Magnetic bearings support moving machinery without physical contact, for example, they can levitate a rotating shaft and permit relative motion with very low friction and no mechanical wear.
Magnetic separator and Holding Device

Magnetic separator for particle size less than 3mm magnetite, pyrrhotite, ilmenite and other materials, wet magnetic separation, but also for coal, non-metallic minerals, building materials and other materials in addition to iron work. Available downstream, semi-reflux, reflux-type and other forms of magnetic separator, cylinder surface magnetic field strength can be produced according to the actual use of the special.
Magnetic property in Medical

The Attraction of Magnet Therapy

Some magnets are multipolar, with both the north and south poles facing the patient/desired body part, often with manufacturers touting that their circular or checkerboard or triangular pattern is in some way superior. But this also further limits how far the magnetic field reaches. Any effect inside the body must be limited to a few millimeters, only skin deep.
Magnetic Resonance Angiogram (MRA)

A magnetic resonance angiogram (MRA) is a type of magnetic resonance imaging (MRI) scan that uses a magnetic field and pulses of radio wave energy to provide pictures of blood vessels inside the body. In many cases MRA can provide information that can't be obtained from an X-ray, ultrasound, or computed tomography (CT) scan.
Summary

• A magnetic field is produced when a current flows through a wire coil.

• Magnetic induction ($B$):
  -- an internal magnetic field is induced in a material that is situated within an external magnetic field ($H$).
  -- magnetic moments result from electron interactions with the applied magnetic field

• Types of material responses to magnetic fields are:
  -- ferrimagnetic and ferromagnetic (large magnetic susceptibilities)
  -- paramagnetic (small and positive magnetic susceptibilities)
  -- diamagnetic (small and negative magnetic susceptibilities)

• Types of ferrimagnetic and ferromagnetic materials:
  -- Hard: large coercivities
  -- Soft: small coercivities

• Magnetic storage media:
  -- particulate barium-ferrite in polymeric film (tape)
  -- thin film Co-Cr alloy (hard drive)
1. What is a magnetic field?
2. What is the source of a magnetic field?
3. What is magnetic flux?
4. What is permeability?
5. What is relative permeability?
6. What is the origin of magnetic moments in materials?
7. What are the different kinds of magnetism?
8. How is electron configuration related to magnetism?
9. What is ferrimagnetism? How is it different from ferromagnetism?
10. Explain the origin of ferrimagnetism taking the example of Fe$_3$O$_4$
11. What is antiferromagnetism?
12. What is a magnetic domain?
13. What is magnetic susceptibility?
14. Why do ferromagnets reach saturation on application of a magnetic field of sufficient strength?
15. Why does a residual magnetism remains even at $H = 0$ during magnetic reversal in ferromagnets?
16. What is Coercivity?
17. What is meant by hard and soft magnets?
18. Which parameter decides the magnetic hardness?
19. Give examples of soft and hard magnets.
20. What is initial permeability? How is it related to magnetization?
21. Why should soft magnets for transformer core application be free of defects and impurities?
22. Why the magnetism is lost when ferromagnets are heated above a certain temperature?
23. What is magnetic anisotropy? What are hard and soft axis of magnetization?
Thank you