Magnetic properties

Magnetism

- Magnetism is a phenomenon by which a material exerts either attractive or repulsive force on another.
- Basic source of magnetic force is movement of electrically charged particles. Thus magnetic behavior of a material can be traced to the structure of atoms.
- Electrons in atoms have a planetary motion in that they go around the nucleus. This orbital motion and its own spin cause separate magnetic moments, which contribute to the magnetic behavior of materials. Thus every material can respond to a magnetic field.
- However, the manner in which a material responds depend much on its atomic structure, and determines whether a material will be strongly or weakly magnetic.

Bohr magneton

- Magnetic moment due to spin of an electron is known as Bohr magneton, M_B.

$$M_B = \frac{qh}{4\pi m_e} = 9.274 \times 10^{-24} A.m^2$$

- where q is the charge on the electron, h – Planck's constant, m_e – mass of electron.
- Bohr magneton is the most fundamental magnetic moment.

Why not all materials are magnets?

- As every material consists spinning electrons, each of them could be a magnet. Fortunately, not so!
- There are two reasons for it.
- *First*: according to Pauli exclusion rule, two electrons with same energy level must have opposite spins – thus so are their magnetic moments, which cancel out each other.
- *Second*: orbital moments of electrons also cancel out each other – thus no net magnetic moments if there is no unpaired electron(s).

- Some elements such as transition elements, lanthanides, and actinides have a net magnetic moment since some of their energy levels have an unpaired electron.

Magnetic dipoles

- Magnetic dipoles are found to exist in magnetic materials, analogous to electric dipoles.
- A magnetic dipole is a small magnet composed of north and south poles instead of positive and negative charges.
- Within a magnetic field, the force of field exerts a torque that tends to orient the dipoles with the filed.
- Magnetic forces are generated by moving electrically charged particles. These forces are in addition to any electrostatic forces that may already exist.
- It is convenient to think magnetic forces in terms of distributed field, which is represented by imaginary lines. These lines also indicate the direction of the force.

Magnetic field

- If a magnetic field is generated by passing current *I* through a coil of length *l* and number of turns *n*, then the magnetic field strength, H (units A/m), is given by

$$H = \frac{nI}{l}$$

Magnetic flux density (induction) is the measure of lines within a medium. It has units as weber (Wb) /m^2 *or* tesla and is defined as

$$B = \mu H$$

- where μ – permeability. It is a specific property of the medium, and has units as Wb/A.m or henry (H) /m.

- Relative magnetic permeability, is defined as

$$\mu_r = \frac{\mu}{\mu_0}$$

- μ_r is a measure of the degree to which the material can be magnetized.
- where μ_0 – magnetic permeability of vacuum.

If *M*- magnetization defined as *M*, is defined as $M = \chi_m H$ then

$$B = \mu_0 H + \mu_0 M = \mu_0 \mu_r H$$

- χ_m is called the magnetic susceptibility and is given as

$$\chi_m = \mu_r - 1$$

Types of Magnetism

- A material is magnetically characterized based on the way it can be magnetized.
- This depends on the material's magnetic susceptibility – its magnitude and sign.

- Three basic magnetisms are:
  - Dia-magnetism
  - Para-magnetism
  - Ferro-magnetism. Anti-ferro-magnetism and ferri-magnetisms are considered as subclasses of ferro-magnetism.

Dia-magnetism

- Very weak; exists ONLY in presence of an external field, non-permanent.
- Applied external field acts on atoms of a material, slightly unbalancing their orbiting electrons, and creates small magnetic dipoles within atoms which oppose the applied field. This action produces a negative magnetic effect known as diamagnetism.
- The induced magnetic moment is small, and the magnetization (M) direction is opposite to the direction of applied field (H).
- Thus the relative permeability is less than unity i.e. magnetic susceptibility is negative, and is in order of -10^{-5}.
- Materials such as Cu, Ag, Si, Ag and alumina are diamagnetic at room temperature.

Para-magnetism

- Slightly stronger; when an external field is applied dipoles line-up with the field, resulting in a positive magnetization. However, the dipoles do not interact.
- Materials which exhibit a small positive magnetic susceptibility in the presence of a magnetic field are called para-magnetic, and the effect is termed as *para-magnetism*.
- In the absence of an external field, the orientations of atomic magnetic moments are random leading to no net magnetization.
- When an external field is applied dipoles line-up with the field, resulting in a positive magnetization.
- However, because the dipoles do not interact, extremely large magnetic fields are required to align all of the dipoles.
- In addition, the effect is lost as soon as the magnetic field is removed.
- Since thermal agitation randomizes the directions of the magnetic dipoles, an increase in temperature decreases the paramagnetic effect.
- Para-magnetism is produced in many materials like aluminium, calcium, titanium, alloys of copper.

- Magnetic susceptibility of these materials is slightly positive, and lies in the range $+10^{-5}$ to $+10^{-2}$.

Ferro-magnetism

- Both dia- and para- magnetic materials are considered as non-magnetic because they exhibit magnetization only in presence of an external field.
- Certain materials possess permanent magnetic moments even in the absence of an external field.
- This is result of permanent unpaired dipoles formed from unfilled energy levels.
- These dipoles can easily line-up with the imposed magnetic field due to the exchange interaction or mutual reinforcement of the dipoles. These are chrematistics of *ferro-magnetism*.
- Materials with ferro-magnetism (Examples: Fe, Co, Ni, Gd) possess magnetic susceptibilities approaching 10^6.
- Above the Curie temperature, ferro-magnetic materials behave as para-magnetic materials and their susceptibility is given by the Curie-Weiss law, defined as

$$\chi_m = \frac{C}{T - T_c}$$

- where C – material constant, T – temperature, T_c – Curie temperature.

- Ferro Magnets are very strong; dipoles line-up permanently upon application of external field. Has two sub-classes:-
    - **Anti-ferro-magnetism:**
    - **Ferri-magnetism:**

Anti-ferro-magnetism

- Dipoles line-up, but in opposite directions, resulting in zero magnetization.
- Eg: Mn, Cr, MnO, NiO, CoO, $MnCl_2$
- Exchange interaction which is responsible for parallel alignment of spins is extremely sensitive to inter-atomic spacing and to the atomic positions. This sensitivity causes anti-parallel alignment of spins.
- When the strength of anti-parallel spin magnetic moments is equal, no net spin moment exists, and resulting susceptibilities are quite small.
- One noticeable characteristic of anti-ferro-magnets is they attain maximum susceptibility at a critical temperature called *Neel temperature*. At temperatures above this, anti-ferro-magnets become para-magnetic.

Ferri-magnetism

- Some ceramic materials exhibit net magnetization.

- Eg: Fe_3O_4, $NiFe_2O_4$, $(Mn.Mg)Fe_2O_4$, $PbFe_{12}O_{19}$, Ba $Fe_{12}O_{19}$, YIG – yttrium iron garnet $Y3Fe_5O_{12}$.
- In a magnetic field, the dipoles of a cation may line up with the field, while dipoles of other cation may not. These ceramics are called ferrites, and the effect is known as *ferri-magnetism*.
- Ferri-magnetism is similar to anti-ferro-magnetism in that the spins of different atoms or ions line up anti-parallel. However, the spins do not cancel each other out, and a net spin moment exists.
- Below the Neel temperature, therefore, ferromagnetic materials behave very much like ferromagnetic materials and are paramagnetic above the Neel temperature.
- These materials exhibit a large but field dependent magnetic susceptibility similar to ferro-magnets.
- They also show Curie-Weiss behavior. As these ceramics are good insulators, electrical losses are minimal, and hence ferrites have lot of applications in devices such as high frequency transformers.

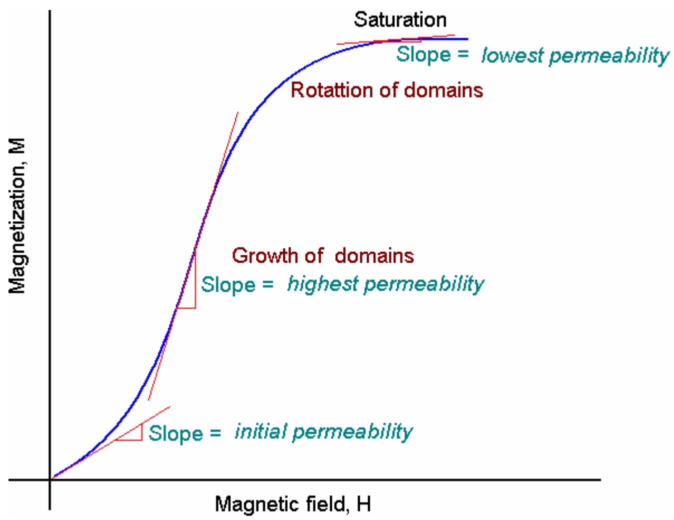
Magnetism	Magnetic susceptibility		Examples
	sign	magnitude	
Dia	-	Small, Constant	Organic materials, superconducting materials, metals like Bi
Para	+	Small, Constant	Alkali and transition metals, rare earth elements
Ferro	+	Large, Function of H	Transition metals (Fe, Ni, Co), rare earth elements (Gd)
Anti-Ferro	+	Small, Constant	Salts of transition elements (MnO)
Ferri	+	Large, Function of H	Ferrites ($MnFe_2O_4$, $ZnFe2O_4$) and chromites

Temperature effect

- Temperature does have a definite effect on a materials' magnetic behavior.
- With rising temperature, magnitude of the atom thermal vibrations increases. This may lead to more randomization of atomic magnetic moments as they are free to rotate.
- Usually, atomic thermal vibrations counteract forces between the adjacent atomic dipole moments, resulting in dipole misalignment up to some extent both in presence and absence of external field.
- As a consequence of it, saturation magnetization initially decreases gradually, then suddenly drops to zero at a temperature called Curie temperature, *Tc*.
- The magnitude of the Curie temperatue is dependent on the material. For example: for cobalt – 1120 ˚C, for nickel – 335 ˚C, for iron – 768 ˚C, and for Fe_3O_4 – 585 ˚C.

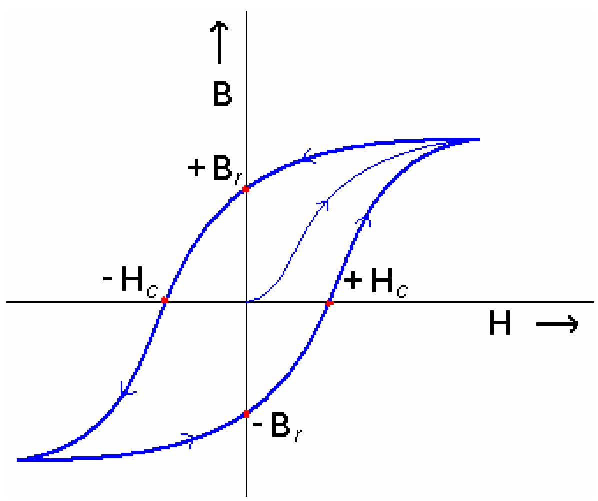
Magnetic domains

- In addition to susceptibility differences, the different types of magnetism can be distinguished by the structure of the magnetic dipoles in regions called domains.
- Each domain consists of magnetic moments that are aligned, giving rise to a permanent net magnetic moment per domain.
- Each of these domains is separated from the rest by domain boundaries / domain walls. Boundaries, also called *Bolch walls*, are narrow zones in which the direction of the magnetic moment gradually and continuously changes from that of one domain to that of the next.
- The domains are typically very small about 50 µm or less, while the Bloch walls are about 100 nm thick. For a polycrystalline specimen, each grain may have more than one microscopic sized domain.
- Domains exist even in absence of external field.
- In a material that has never been exposed to a magnetic field, the individual domains have a random orientation. This type of arrangement represents the lowest free energy.
- When the bulk material is un-magnetized, the net magnetization of these domains is zero, because adjacent domains may be orientated randomly in any number of directions, effectively canceling each other out.
- The average magnetic induction of a ferro-magnetic material is intimately related to the domain structure.
- When a magnetic field is imposed on the material, domains that are nearly lined up with the field grow at the expense of unaligned domains. This process continues until only the most favorably oriented domains remain.
- In order for the domains to grow, the Bloch walls must move, the external field provides the force required for this moment.
- When the domain growth is completed, a further increase in the magnetic field causes the domains to rotate and align parallel to the applied field. At this instant material reaches saturation magnetization and no further increase will take place on increasing the strength of the external field.
- Under these conditions the permeability of these materials becomes quite small.



Magnetic hysteresis

1. Once magnetic saturation has been achieved, a decrease in the applied field back to zero results in a macroscopically permanent or residual magnetization, known as *remanance*, *Mr*. The corresponding induction, *Br*, is called *retentivity* or *remanent induction* of the magnetic material. This effect of retardation by material is called *hysteresis*.
2. The magnetic field strength needed to bring the induced magnetization to zero is termed as *coercivity*, *Hc*. This must be applied anti-parallel to the original field.
3. A further increase in the field in the opposite direction results in a maximum induction in the opposite direction. The field can once again be reversed, and the field-magnetization loop can be closed, this loop is known as *hysteresis loop* or *B-H plot* or *M- H plot*.



Semi-hard magnets

- The area within the hysteresis loop represents the energy loss per unit volume of material for one cycle.
- The coercivity of the material is a micro-structure sensitive property. This dependence is known as *magnetic shape anisotropy*.
- The coercivity of recording materials needs to be smaller than that for others since data written onto a data storage medium should be erasable. On the other hand, the coercivity values should be higher since the data need to be retained. Thus such materials are called magnetically semi-hard.
- Ex.: Hard ferrites based on Ba, CrO_2, γ-Fe_2O_3; alloys based on Co-Pt-Ta-Cr, Fe-Pt and Fe-Pd, etc.

Soft magnets

1. *Soft magnets* are characterized by low coercive forces and high magnetic permeabilities; and are easily magnetized and de-magnetized.
2. They generally exhibit small hysteresis losses.
3. Application of soft magnets include: cores for electro-magnets, electric motors, transformers, generators, and other electrical equipment.
4. Ex.: ingot iron, low-carbon steel, Silicon iron, superalloy (80% Ni-5% Mo-Fe), 45 Permalloy (55%Fe-45%Ni), 2-79 Permalloy (79% Ni-4% Mo-Fe), MnZn ferrite / Ferroxcube A (48% $MnFe_2O_4$-52%$ZnFe_2O_4$), NiZn ferrite / Ferroxcube B (36% $NiFe_2O_4$-64% $ZnFe_2O_4$), etc.

Hard magnets

- *Hard magnets* are characterized by high remanent inductions and high coercivities.
- These are also called *permanent magnets* or *hard magnets*.
- These are found useful in many applications including fractional horse-power motors, automobiles, audio- and video- recorders, earphones, computer peripherals, and clocks.
- They generally exhibit large hysteresis losses.
- Ex.: Co-steel, Tungsten steel, $SmCo_5$, $Nd_2Fe_{14}B$, ferrite Bao.6Fe_2O_3, Cunife (60% Cu 20% Ni-20% Fe), Alnico (alloy of Al, Ni, Co and Fe), etc.

Multiple Choice Questions' Bank:

1. Basic source of magnetism_______________.

(a) Charged particles alone (b) Movement of charged particles
(c) Magnetic dipoles (d) Magnetic domains

2. Units for magnetic flux density

(a) Wb / m^2 (b) Wb / A.m (c) A / m (d) Tesla / m

3. Magnetic permeability has units as

(a) Wb / m^2 (b) Wb / A.m (c) A / m (d) Tesla / m

4. Magnetic permeability has units as

(a) Tesla (b) Henry (c) Tesla / m (d) Henry / m

5. Magnetic field strength's units are

(a) Wb / m^2 (b) Wb / A.m (c) A / m (d) Tesla / m

6. Example for dia-magnetic materials

(a) super conductors (b) alkali metals (c) transition metals (d) Ferrites

7. Example for para-magnetic materials

(a) super conductors (b) alkali metals (c) transition metals (d) Ferrites

8. Example for ferro-magnetic materials

(a) super conductors (b) alkali metals (c) transition metals (d) Ferrites

9. Example for anti-ferro-magnetic materials

(a) salts of transition elements (b) rare earth elements (c) transition metals (d) Ferrites

10. Example for ferri-magnetic materials

(a) salts of transition elements (b) rare earth elements (c) transition metals (d) Ferrites

11. Magnetic susceptibility para-magnetic materials is

(a) $+10^{-5}$ (b) -10^{-5} (c) 10^{5} (d) 10^{-5} to 10^{-2}

12. Magnetic susceptibility dia--magnetic materials is

(a) $+10^{-5}$ (b) -10^{-5} (c) 10^{5} (d) 10^{-5} to 10^{-2}

13. Magnetic susceptibility ferro-magnetic materials is

(a) $+10^{-5}$ (b) -10^{-5} (c) 10^{5} (d) 10^{-5} to 10^{-2}

14. Typical size of magnetic domains_______(mm).

(a) 1-10 (b) 0.1-1 (c) 0.05 (d) 0.001

15. Typical thickness of Bloch walls_______(nm).

(a) 0.1-1 (b) 1-10 (c) 10-50 (d) 100

16. Example for soft magnet

(a) 45 Permalloy (b) CrO_2 (c) Fe-Pd (d) Alnico

17. Example for hard magnet

(a) 45 Permalloy (b) CrO_2 (c) Fe-Pd (d) Alnico

18. Example for magnetic material used in data storage devices

(a) 45 Permalloy (b) CrO_2 (c) Cunife (d) Alnico

Answers:

1. b
2. a
3. b
4. d

5. c
6. a
7. b
8. c
9. a
10. d
11. d
12. b
13. c
14. c
15. d
16. a
17. d
18. b