MAGNETISM

Introduction

- The magnetic effects in magnetic materials are due to atomic magnetic dipoles in the materials. These dipoles result from effective current loops of electrons in atomic orbits, from effects of electron spin & atomic nuclei.
- The electric currents in an atom are caused by orbital and spin motions of electrons and those of its nucleus. Since all these motions of charged particles form closed electric currents, they are equivalent to "magnetic dipoles" which are oriented in different directions.

Definitions

Magnetic dipole

Each tiny dimension of a magnetic material (or) atoms in magnetic materials is called magnetic dipole. This magnetic dipole produces magnetic moment depending on the alignment with respect to the applied magnetic field H.

Intensity of Magnetization (M)

When a material is magnetized (Kept in applied Magnetic field H), it develops a net magnetic moment. The magnetic moment per unit volume is called Intensity of magnetization

Magnetization (M) = $\frac{\text{Magnetic moment}}{\text{Volume}}$

Units: Amp/m

Magnetic Induction (B)

The magnetic lines of force per unit area is called as Magnetic induction B.

i.e. B = $\frac{\Phi}{A}$ weber / m^2

$$B = B_o + B_I$$
$$B = \mu_o H + \mu_o M$$
$$B = \mu_o (H + M)$$

B_o = magnetic flux density due to magnetizing field
B_I = magnetic flux density due to magnetization of material

Magnetizing field strength (H)

When a medium is exposed to a magnetic field strength 'H', it causes an induction 'B' in that medium.

$$\text{i.e.}\quad B \propto H$$

$$B = \mu H$$

Where μ = absolute permeability of the medium.

If the medium is air or vacuum

$$B_o=\mu_0 H$$

μ_0 = permeability of free space i.e. air or vacuum

$\mu_0=4\pi \times 10^{-7}$ H/m

Permeability (μ)

It indicates, with which the material allows magnetic lines of force to pass through it.

Or

It is the ability of the medium to pass magnetic lines of forces through it.

There are three Permeabilities i.e. μ, μ_0, μ_r

$$\mu = \mu_0 \mu_r$$

Where μ = Absolute permeability of the medium

μ_0 = Permeability of free space i.e. air or vaccum

μ_r = Relative permeability of the medium

Magnetic moment

Magnetic moment μ_m= (current) × (area of circulating orbit)

$$\mu_m = (I) \times (\pi r^2)$$

Units: Amp-m^2

Magnetic susceptibility (χ)

It is defined as ratio of M the amount of magnetization of the material to H the applied magnetic field

$$\chi = \frac{M}{H}$$

χ = 0 in vacuum

χ = +ve for paramagnetic and Ferro magnetic materials

χ = -ve for diamagnetic materials

Units: It has no units.

Relation between relative permeability and susceptibility

We know that, $B = \mu_o(H + M)$ and B = μH

But $\mu = \mu_0 \mu_r$

Therefore, $B = \mu_0 \mu_r H$

$\Rightarrow \mu_o(H + M) = \mu_0 \mu_r H$

$\Rightarrow (H + M) = \mu_r H$

$\Rightarrow M = \mu_r H - H$

$\Rightarrow M = H(\mu_r - 1) \Rightarrow \frac{M}{H} = \mu_r - 1$

$\Rightarrow \chi = \mu_r - 1$

Origin of magnetic moment (Or) Sources of magnetic moment

In atoms, the permanent magnetic moment arises due to

a) Orbital motion of electrons and its magnetic moment is called orbit magnetic moment of electrons (μ_l)
b) The spin of electrons and its magnetic moment is called spin magnetic moment of electrons (μ_s)
c) The spin of nucleus (due to protons) and its magnetic moment is called spin magnetic moment of the nucleus. (μ_n).

Explanation

a) Magnetic moment due to orbital motion of the electrons (μ_l)

Let us consider an electron of charge 'e' revolving around a nucleus in time

Period 'T' in a circular orbit of radius 'r'. Then a magnitude of circular current 'I'

is given by

$$I = \frac{Charge}{Time} = \frac{e}{T} \quad \rightarrow (1)$$

But $T = \frac{2\pi}{\omega}$

Where ω = angular velocity of electron

$$I = \frac{e\omega}{2\pi}$$

But magnetic moment of electron is $\mu_l = I \times A$

μ_l = current area of circulating orbit

$$\mu_l = \frac{e\omega}{2\pi}(\pi r^2)$$

$$\mu_l = \frac{e\omega r^2}{2} \qquad \rightarrow (2)$$

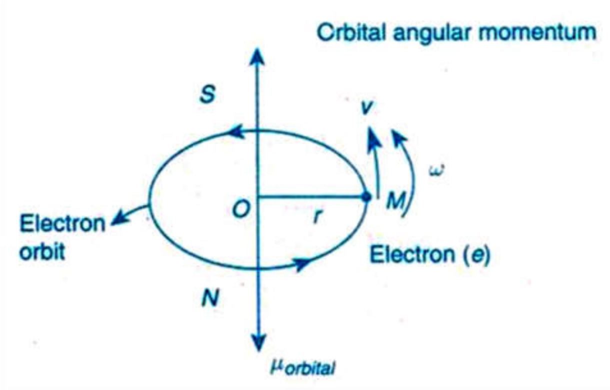


Fig. Orbital magnetic moment of electrons

We know that angular momentum of any particle, $L = m\omega r^2$

$$\Rightarrow \omega = \frac{L}{mr^2}$$

Substituting the value of ω in eqn(2) , We get

Eqn (2) $\rightarrow$ Orbital magnetic moment, $\mu_l = (-\frac{e}{2m}).L \qquad \rightarrow (3)$

[-ve sign indicates μ_l and L are Anti-parallel]

$$\mu_l = (-\frac{e}{2m})\,L$$

But from Bohr's atomic model, $L = \frac{lh}{2\pi}$ Where l = orbital quantum number

L = orbital angular momentum of electron

The values of l = 0, 1, 2---------- (n-1)

$$\text{Hence } \mu_l = (-\frac{e}{2m})(\frac{lh}{2\pi})$$

$$\mu_l = -(\frac{eh}{4\pi m})\,l$$

Where $\frac{eh}{4\pi m} = \mu_B$ is a constant called Bohr magneton and its value is 9.27×10^{-24} amp-m^2

Hence eq (6) becomes

$$\mu_l = \mu_B l$$

Bohr magneton is the fundamental unit of magnetic moment.

b) Magnetic moment of electrons due to spin of electrons (μ_s)

According to quantum theory; electrons should have intrinsic angular momemtum due to spin. Spin is also quantized both in magnitude and direction spin can take only one value i.e ½ or - ½.

The magnetic moment produced due to spin of electrons is called spin magnetic moment (μ_s).

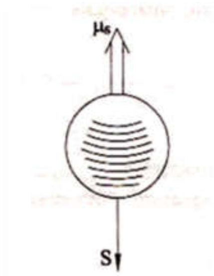
It is given by

$$\text{Spin magnetic moment } \mu_s = -2\left(\frac{e}{2m}\right) S$$

Where S=spin angular momentum, e = charge of electron, m = mass of electron

$$S = \frac{sh}{2\pi}$$

where S = spin quantum number; h = Planck's constant.



Spinning Electron

From equation (9),

$$\mu_s = -2\left(\frac{e}{2m}\right) S \qquad \text{and Since } S = \frac{sh}{2\pi}$$

$$\mu_s = -2\left(\frac{e}{2m}\right)\left(\frac{sh}{2\pi}\right)$$

$$s = \pm\frac{1}{2}, \quad \mu_s = \pm\frac{eh}{4\pi m}$$

$$\mu_s = \frac{eh}{4\pi m}, -\frac{eh}{4\pi m}$$

$$\mu_s = +\boldsymbol{\mu_B}, -\boldsymbol{\mu_B}$$

Hence spin magnetic moment of electron is equal to μ_B. That is one Bohr magneton

Hence there are two possible orientations of electron

c) Magnetic moment due to Nuclear spin or spin of all protons (μ_n)

The magnetic moment of the nucleus is given by $\mu_n = \frac{eh}{4\pi mp}$

Where m_p= mass of proton

The constant $\frac{eh}{4\pi mp}$ is called nuclear magneton.

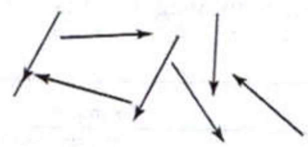
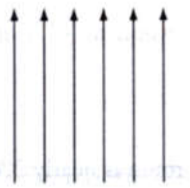
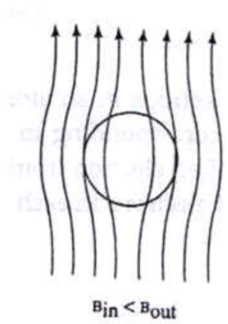
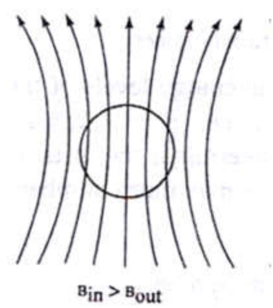
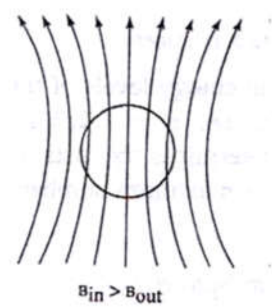
The value of nuclear magneton $\frac{eh}{4\pi mp}$=5x10^{-27}A-m^2 ; This is small when compared to Bohr magneton.

Classification of Magnetic Materials

Magnetic materials are classified as follows:

a) Diamagnetic
b) Paramagnetic
c) Ferro magnetic
d) Anti Ferro magnetic
e) Ferric magnetic or ferrites

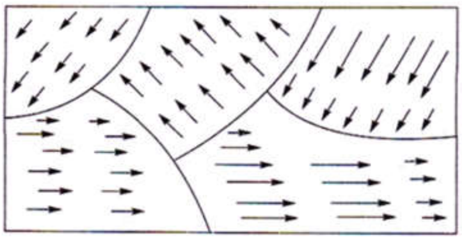
Diamagnetic materials	**Paramagnetic materials**	**Ferromagnetic materials**
1.Diamagnetism: It is the property of the material which has repulsive nature (or) opposing magnetization	*1.Paramagnetism:* It is the property of the material which has weak attractive force.	*1.Ferromagnetism* It is property of the material which has strong attractive force.
2.The property is due to orbital motion of electrons	2.The property is due to spin of electrons	2.The property is due to spin of electrons

3.There is no spin	3.Spin is random 	3.Spin is parallel 
4. These materials are lack of magnetic dipoles	4.These materials have permanent dipoles	4.They have permanent magnetic dipoles
5. They do not possess permanent dipole magnetic moment (it is zero).	5. They possess permanent magnetic dipole moment.	5. They possess permanent magnetic dipole moment.
6. 	6. 	6. 
7.The relative permeability μ_r<1	7. The relative permeability μ_r>1.	7.The relative permeability μ_r>>1
8.Susceptibility χ is small and negative	8. Susceptibility is small but positive	8. Susceptibility is large and positive

9. χ does not depend on temperature.	9. χ depends on temperature	9. χ depends on temperature
11.Examples Cu, Au, Zn, H_20, Bi etc. organic materials.	11.Examples: Al, Pt, Mn,CuCl2 etc. Alkali & transition metals.	11.Examples: Fe, Ni, Co, MnO, $Fe_2\,0_3$, Zn ferrite, Ni ferrite, Mn ferrite

Domain theory (or) Weiss theory of Ferromagnetism

- According to Weiss, Ferromagnetic material consists of a number of regions called "Domains" [$\sim10^{-6}$m] which are spontaneously magnetized.



Different possible orientations of domains

- When an external field is applied there are two possible ways of alignment of domains. They are
  1. By motion of domain walls
  2. By rotation of domain

a) The domains which are parallel to the direction of applied magnetic field will grow in size than other domains. This is called "Motion of domain walls". Also other domains which are opposite to the field direction are reduced. This is shown in the figure.

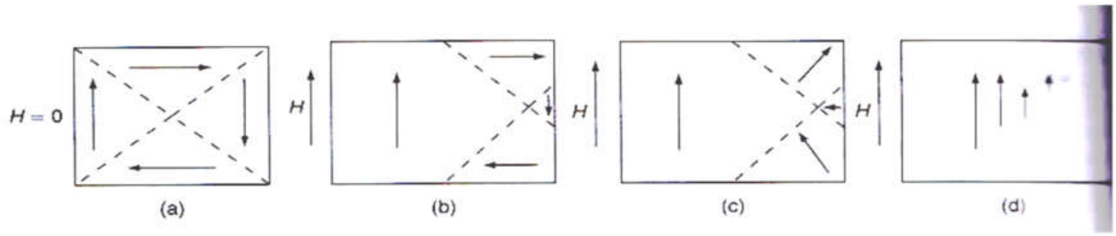


Fig. (a) Domain orientation in the absence of the magnetic field (b) Domain enhancement shrinkage due to weak fields (c) Domain ratation due to strong fields (d) Saturation due to very high fields

b) As the magnetic field is strong, the magnetic moments of the domains can rotate in the applied field direction. This is called "rotation of domain".

B-H curve (or) Hysteresis curve of a Ferromagnetic material

Definition: Hysteresis means the lagging of magnetization "M" behind the applied magnetizing field "H". The energy supplied to the specimen during magnetization is not fully utilized. The balance of energy left in the material is produced as heat i.e. loss of energy called" Hysteresis Loss".

- This phenomenon of magnetic hysteresis is an "Irreversible" process and characteristic of a ferromagnetic material. The loop (or) area refers to the hysteresis loop. Hysteresis occurs in ferromagnetic materials below Curie temperature.

The complete cycle of operation is discussed as follows:

- When a pristine ferromagnetic material is placed in a magnetic field H, it is gradually magnetized and takes the path OABP.
- In figure, from point O to A motion of domain walls takes place. When the Magnetic field is suddenly off, the domains again go back to original position O. This is a reversible process. Afterwards from point A to P the process is irreversible.
- For higher magnetic fields H, the magnetization reaches to a maximum limit P i.e saturation magnetization denoted by (M_s) due to rotation of domain.
- When the magnetic field is OFF, the curve does not go back to 'O' but traces a new path PR [as shown in fig] to a point called Remanence Magnetization M_r. The process is called retentivity.
- To reduce the remanence magnetization to zero, a magnetic field 'H_c' has to be applied in opposite direction. When the sufficient opposite field is applied, the Remanence magnetization becomes zero and this field is known as "negative coercive field" ($-H_c$). The process is called coercively.
- Further again if the opposite magnetic field is increased, then magnetization increases in negative direction and reaches to maximum limit (S) known as negative saturation magnetization ($-M_s$).

- If the opposite field is decreased back to zero the negative saturation of magnetization will trace a new path (ST) and reaches a point called negative remanence magnetism '$-M_r$'.
- To make the negative remanence magnetism to zero some magnetic field has to be applied in positive direction. The amount of magnetic field required to bring remanence magnetization to zero is known as positive coercive field (H_c).
- Further increase of positive magnetic field, the magnetization reaches again to positive saturation (M_s) and **THIS IS A CYCLIC PROCESS**.

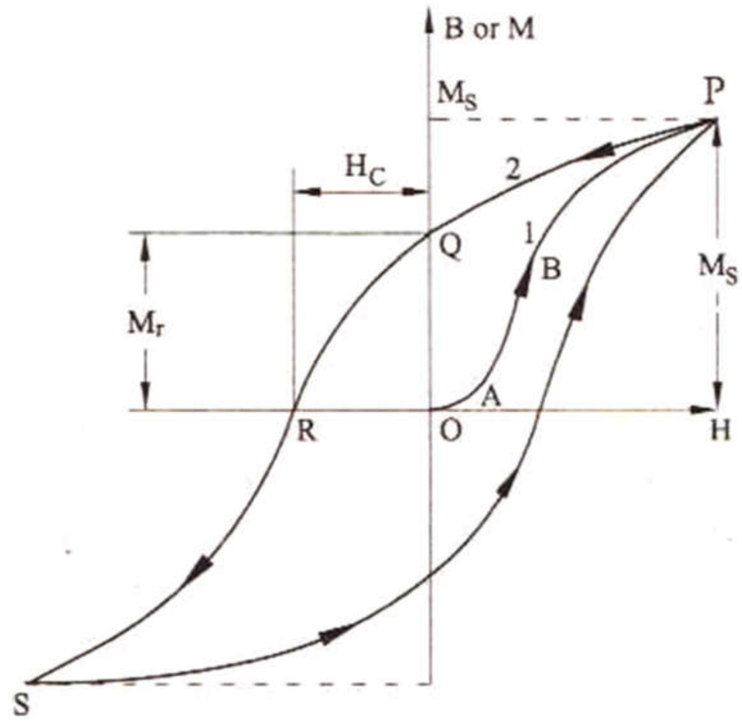


Fig. Magnetic Hysteresis curve (or) B – H curves of a Ferro magnetic material

Remanence magnetization (M_r): *The residual magnetization in the ferromagnetic material even if the applied magnetic field H is made zero*.

Coercive field (H_c): *The amount of magnetic field applied in opposite direction to bring Remanence magnetization to zero.*

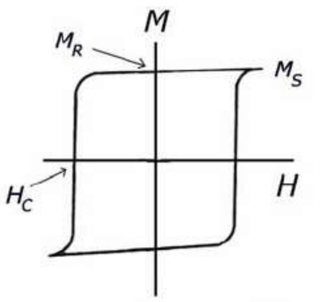
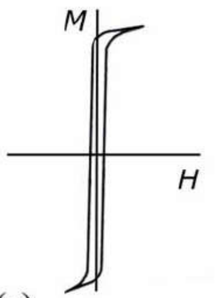
Soft and Hard magnetic materials

Soft magnetic materials

The magnetic materials that are easy to magnetize and demagnetize are called as soft magnetic materials.

Hard magnetic materials

The magnetic materials that are difficult to magnetize and demagnetize are called as hard magnetic materials.

Hard magnetic materials	**Soft magnetic materials**
Difficult to magnetize and demagnetize	Easy to magnetize and demagnetize
large hysteresis loop area hence more heat loss	small hysteresis loop area hence less heat loss
Have large hysteresis loss	Have very low hysteresis loss
 (b)	 (a)
The coercively($-H_c$) and retentively (M_r) are large. The value of permeability and susceptibility are large.	The coercively ($-H_c$)and retentively (M_r) are small. The values of permeability and susceptibility are small.
Used to make permanent magnets Examples- *Iron-nickel-aluminium alloys (alnicol)* *Copper nickel iron (cunife)*	Used to make electromagnets in motors Examples- *Fe-Si , Ferrous nickel alloys ,Ferrites, Garnets*
Applications: magnetic detectors, microphones flux meters, voltage regulators, life heavy vessels etc.	**Applications:** magnetic inductors, cores, storage of data, switching circuits, audio frequency applications, magnetic amplifier etc as electro magnets.