Magnetic Materials

e-content for B.Sc Physics (Honours)

B.Sc Part-II

Paper-IV

Dr. Ayan Mukherjee,
Assistant Professor,
Department of Physics,
Ram Ratan Singh College, Mokama.
Patliputra University, Patna

MAGNETIC PROPERTIES

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 & from the magnetic moments of 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". When such dipoles are subjected to an external electric field, they experience a torque which tends to align their magnetic moments in the direction of the externally applied field.

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.

Magnetic flux (Φ)

It is defined as the amount of magnetic lines of forces passing perpendicularly through unit area of a given material. It is denoted by '**Φ**'

$$\Phi = AB$$

Where A= Area of cross section of the material in m^2

B = magnetic Induction in Wb/ m^2

Units: Weber (Wb)

Intensity of Magnetization (M)

When a material is magnetized, it develops a net magnetic moment. The magnetic moment per unit volume is called Intensity of magnetization

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

Units: Amp/m

Magnetic Induction (B)

Magnetic induction at a point is defined as the force experienced by a unit North Pole Placed at that point. It is denoted by 'B'

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

Magnetizing field strength (H)

When a medium is exposed to a magnetic field of intensity 'H', it causes an induction 'B' in the medium.

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

$$B = \mu H$$

Where μ = absolute permeability of the medium.

If the medium is air or vacuum

$$B=\mu_0 H$$

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

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

Units for H: Amp /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_1, 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

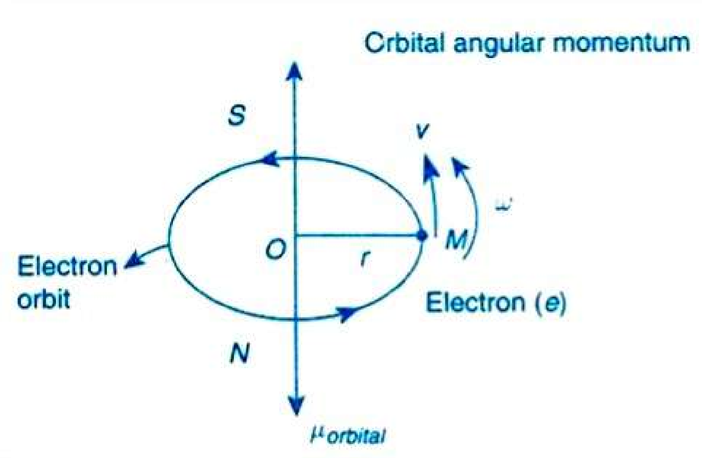


Fig. Revolving electron in an atom produces magnetic moment

When the magnetic dipoles (atoms consisting of charged particles like protons & neutrons) undergo orbital motion (or) spin motion produces a magnetic moment. Since motion of charged particles is considered as closed electric current loops which inturn produces a magnetic moment.

Relation between B, H, M

We know that

$$B = \mu H \quad \rightarrow (1)$$

But $\mu = \mu_0 \mu_r$

$$B = \mu_0 \mu_r H \quad \rightarrow (2)$$

Adding &subtracting with $\mu_0 H$ on right hand side of equation (2)

$$B = [\mu_0 \mu_r H] + \mu_0 H - \mu_0 H$$

$$= [\mu_0 \mu_r H - \mu_0 H] + \mu_0 H$$

$$= \mu_0 H [\mu_r - 1] + \mu_0 H$$

But $M = H[\mu_r - 1] \quad \rightarrow (3)$

Now eq(3) becomes $B = \mu_0 M + \mu_0 H$

$$B = \mu_0 [H + M] \quad \rightarrow (4)$$

Consider equation (3), $M = H[\mu_r - 1]$

$$\frac{M}{H} = \mu_r - 1 \quad \rightarrow (5)$$

But magnetic susceptibility $\chi = \frac{M}{H}$

From equations (5) and (6)

$$\chi = \frac{M}{H} = \mu_r - 1$$

$$\mu_r = 1 + \chi$$

Magnetic susceptibility (χ)

If H is the applied magnetizing field intensity and M is the amount of magnetization of the material, Then χ

$= \frac{M}{H}$

χ = 0 in vacuum

χ = +ve for paramagnetic and Ferro magnetic materials

χ = -ve for diamagnetic materials

Units:It has no units.

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 or μ_p).

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 μ_l= I × A

μ_l = current area of circulating orbit

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

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

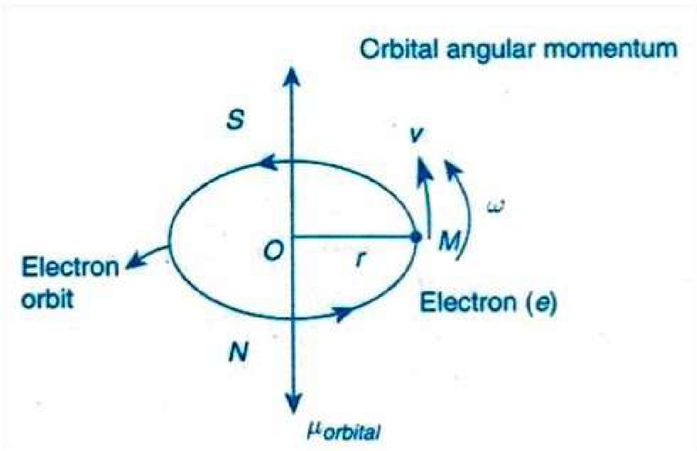


Fig. Orbital magnetic moment of electrons

We know that angular momentum of any particle, L = mωr^2

Substituting eq.(4) in eq.(3) we get

Orbital magnetic moment, $\mu_l = (-\frac{e}{2m}).L$ → (5)

[-ve sign indicates μ_l and are in opposite directions]

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

But from Bohr's atomic model

$$mvr = \frac{nh}{2\pi}$$

$$L = \frac{lh}{2\pi} \quad \text{Where } l = \text{orbital quantum number}$$

L = orbital angular momentum

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

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

$$\mu_l = -(\frac{eh}{4\pi m})\ l \qquad \rightarrow (6)$$

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

$$\mu_l = l\ \mu_B \qquad \rightarrow (7)$$

Bohr magneton is the fundamental unit of magnetic moment.

It is clear from eq (7) that electron can take only certain specified values of magnetic moment depending on the value of 'l'.

Bohr suggested that both magnitude and direction of 'l' are quantified. It is known as "Spatial quantization".

The spatial quantization introduces a new set of quantum numbers.

(a) Orbital magnetic quantum number (m_l)

(b) Spin magnetic quantum number (m_s)

For example: If electron is in'p' shell. Then n = 2, L= 0 to n-1, L = 0, 1,

If electron is placed in external magnetic field then eqn (6) can be written as

$$-(\frac{eh}{4\pi m})\ m_l \qquad \rightarrow (8)$$

Hence for'p' shell electron, m_l= 0 to ± L. The values are m_l = -1, 0, 1

Hence eqn (8) becomes

$$-(\frac{eh}{4\pi m}),\ 0,\ (\frac{eh}{4\pi m})$$

Therefore we have "Three" possible orientations for electron in d-shell which is shown in the figure 6.3.

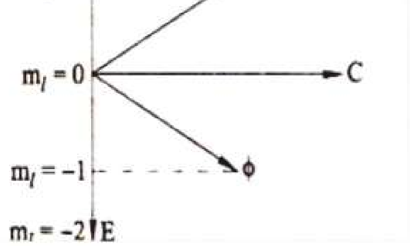


Fig. The three possible orientations of electron

'OC' represents the orientation of electron if $m_l = 0$
'OB' represents the orientation of electron if $m_l = +1$
'OD' represents the orientation of electron if $m_l = -1$

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

$$\text{Spin magnetic moment } \mu_s = -2\left(\frac{e}{2m}\right) S \qquad \rightarrow (9)$$

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.

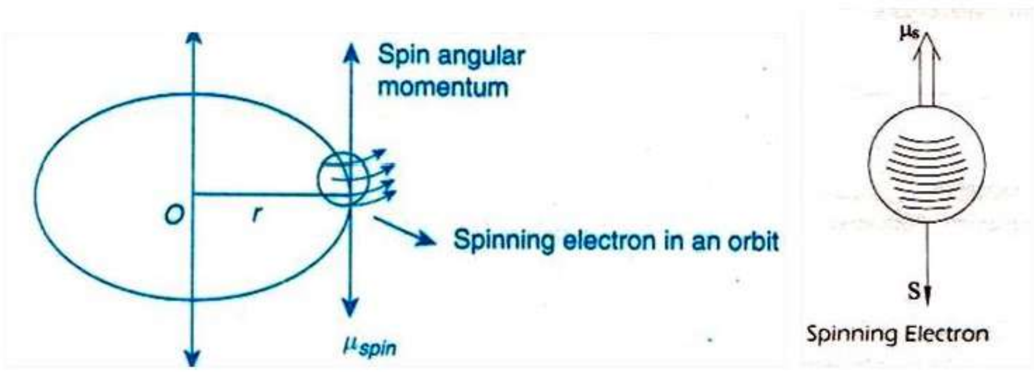


Fig. Spin magnetic moment of electrons

From equation (9), $\mu_s = -2\left(\frac{e}{2m}\right) S$

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

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

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

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

$$\mu_s = +\mu_B, -\mu_B$$

Hence spin magnetic moment of electron is equal to μ_B. That is one Bohr magneton
Hence there are two possible orientations of electron.
Conclusion: Para magnetism, Ferro magnetism is due to spin magnetic moment.
Diamagnetism is due to orbital magnetic moment.

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

The magnetic moment of the nucleus is given by $\mu_n = \frac{eh}{4\pi m_p}$ $\rightarrow$ (10)

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

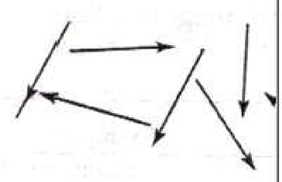
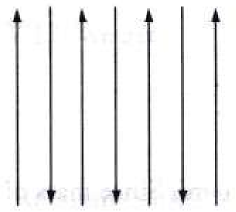
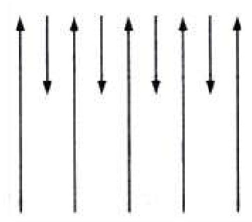
This is small when compared to Bohr magneton.

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

amagnetic materials	**ramagnetic materials**	**rromagnetic materials**	**ıti ferro magnetic materials**	**rri magnetic materials ·)ferrites**
Diamagnetism: It is the property of the material which has repulsive nature (or) opposing magnetization	*Paramagnetism:* It is the property of the material which has weak attractive force.	*Ferromagnetism* is property of the material which has strong attractive force.	*Anti Ferro magnetism:* is the property of the material which has weak attractive force.	*Ferrimagnetism:* It is the 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	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 	3. Spin is anti parallel. 	3. Spin is anti parallel but of different magnitudes. 
4. These materials are lack of magnetic dipoles	4.These materials have permanent dipoles	4.They have permanent magnetic dipoles	4.They have permanent magnetic dipoles	4. They have permanent magnetic dipoles.
5. They do not possess permanent dipole magnetic moment (it is zero). Hence spontaneous magnetization is zero.	5. They possess permanent magnetic dipole moment. But there is no spontaneous magnetization in the absence of external field. Due to random spin.	5. They possess permanent magnetic dipole moment. Also in the absence of field they have spontaneous magnetization even in the absence of external field due to parallel	5. They do not possess permanent magnetic dipole moment. Since in the absence of field they have no spontaneous magnetization due to anti parallel spin	5. They possess permanent magnetic diploement. Also in the absence of field they have spontaneous magnetization. Since spin is anti parallel but of different magnitudes.
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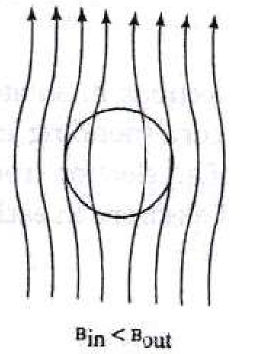
<td>
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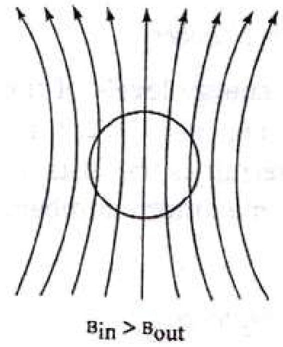
<td>
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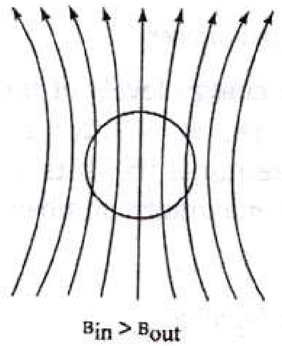
<td>
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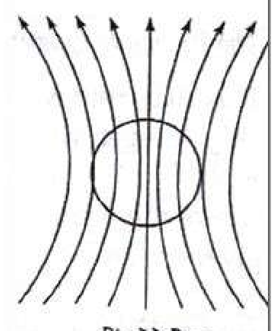
<td>
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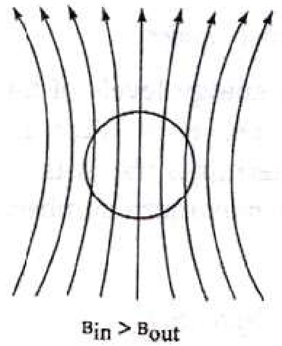
<td>
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<td>7.The relative permeability $\mu_r<1$</td>
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<td>7.The relative permeability $\mu_r>1$</td>
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<td>8.Susceptibility χ is small and negative</td>
<td>8. Susceptibility is small but positive</td>
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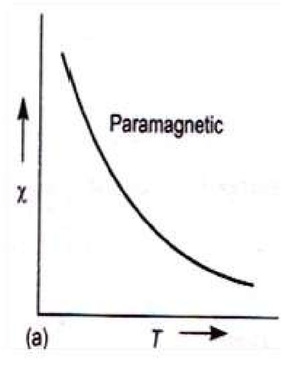
<td>9. χ does not depend on temperature. No particular is graph is drawn.</td>
<td>9. χ depends on temperature

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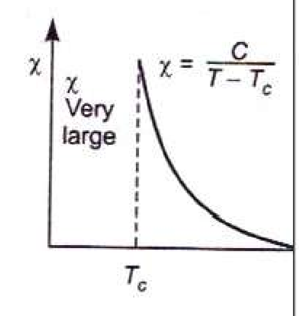
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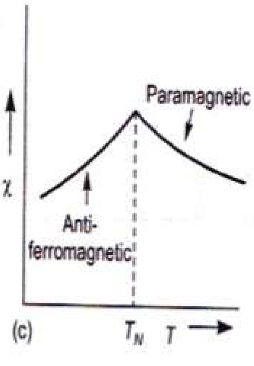
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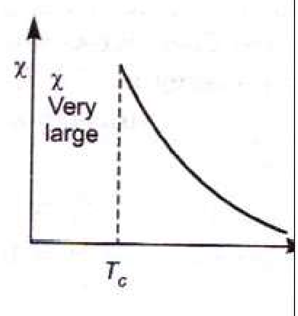
<td>9. χ depend on temperature

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<td>10. χ does not depend on temperature</td>
<td>10. χ = c/T (curie law)
C=curie constant
T = absolute temperature</td>
<td>10. χ = c/T-θ
curie-Weiss law
θ = curie temperature</td>
<td>10. χ = C/T+θ
= C/T+T_N
T_N = Neel temperature</td>
<td>10. χ = C/T±T_N
T = absolute temperature</td>
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Cu, Au, Zn, H_20, Bi etc. organic materials.	Al, Pt, Mn,CuCl2 etc. Alkali & transition metals.	Fe, Ni, Co, MnO, Fe_2 0_3, Zn ferrite, Ni ferrite, Mn ferrite	FeO,MnO,Cr_20_5 etc.	$ZnFe_20_4$, Ni ferrite, Cu ferrite, Mn ferrite, Ferrous Ferrite

Domain theory (or) Weiss theory of Ferromagnetism

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

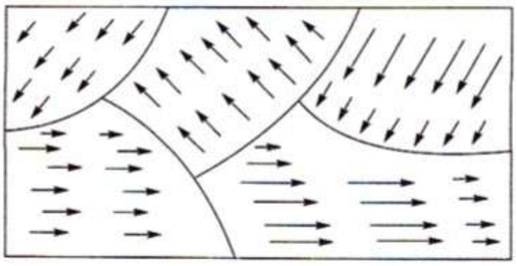

Fig. : Different possible orientations of domains

- Spontaneous magnetization is due to parallel alignment of all magnetic dipoles (in each domain) even when no external field is applied.
- Different domains possess different orientations hence net magnetization is zero.
- 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 walls
- Domains arise to minimize the energy of the material. The total internal energy is minimum. The alignment of domains, parallel to field is discussed as follows:

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 6.6.

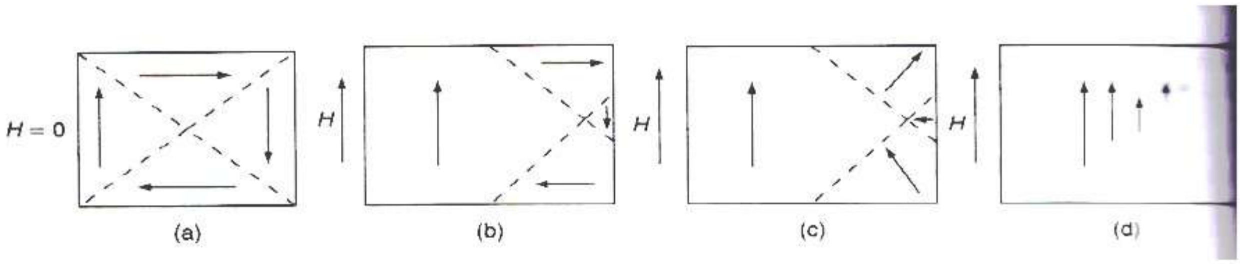

Fig. 6.6 (a) Domain orientation in the absence of the magnetic field (b) Domain enhancement shrinkage due to weak fields (c) Domain ratation due to strong fields (d) Saturation due to very high fields

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 walls".

Domain theory of ferromagnetism based on the basis of B-H curve

(or) Hysteresis curve

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

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

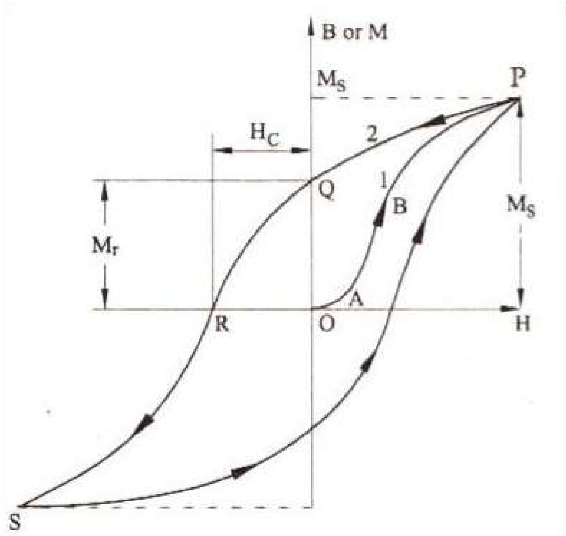

Fig. : Magnetic Hysteresis curve (or) B – H curves of a Ferro magnetic material

The complete cycle of operation is discussed as follows:

- When the magnetic field is applied on a ferromagnetic material the magnetization increases slowly and reaches a constant M_s called saturation magnetization
- In fig (6.7) from point O to A, the displacement of domain walls takes place. When the field is suddenly off, the domains again go for original position.
- From point A to B, as the field is further increased, the magnetization also increases. Here when the field is made off the domain displacement does not return back to original condition.
- For higher fields the magnetization reaches maximum ie saturation magnetization M_s due to rotation of domain walls.
- In this case at the region B to P, if the field is suddenly made off, the domains does not return back to original direction. But there is some magnetic field remained inside the specimen.
- The point M_s is called saturation of magnetization. When the field is off, the curve does not go back to 'O'[as shown in fig] but creates a new path to a point M_r called "retentivity" (or) residual (or) remanence Magnetization
- To reduce the residual magnetism to zero, a negative field 'Hc' has to be applied. When the sufficient negative field is applied, the residual; magnetization becomes zero and this field is known as "negative coercive field" ($-H_c$) or coercively. Further again if the negative field is applied then magnetization increases but in negative direction. This is known as negative saturation magnetization ($-M_s$).

- If the negative field is decreased back to zero the negative saturation of magnetization will not reach the initial path at '0' but creates a new path and reaches a point called negative residual magnetism '-M_r' know as negative receptivity.
- To decrease the negative residual magnetism to zero some positive field is applied. The amount of magnetic field required to bring residual magnetization to zero is known as positive coercive field (H_c).
- Further the increase of positive magnetic field the magnetization reaches again to positive saturation (M_s) and this is a cyclic process.
- The final conclusion is that when the magnetization vector is started from origin 'O' will not reach back to that point. "The magnetization lags behind H". This is called magnetic hysteresis loss measured in the area of the loop (or) curve. If the loop area of a ferromagnetic material is large, more energy is wasted. This is also called as "dielectric loss" for one complete cyclic operation.