Magnetism and Properties of Magnetic Materials

Molecular theory of Magnetism

i. The molecules of all the magnetic substance are complete magnet in themselves having North and south poles called elementary magnet or Tiny magnet.
ii. Inside the magnetic substances the molecules are arranged so as to form closed chains. Thus they neutralize the effect of each other.
iii. When a magnetic substance is magnetized, the molecules are regularly arranged with their North poles pointing in one direction and South poles pointing in opposite directions.

Domain Theory
Domain are basically the state of electron spin in its orbit.
Properties of magnetic lines of forces

i. They are closed and continuous curves. They never terminate.
ii. Outside the magnet the direction is from North to South and inside the magnet the direction is from South to North pole.
iii. The tangent drawn at any point on the curve gives the direction of resultant magnetic field at that point.
iv. They do not interest each other. If two lines of force intersect of a point, then there would be two tangents at that points hence the resultant force and field would have two directions which is not possible, therefore the lines of force do not intersect.
v. They are dense near the poles where magnetic field is strong and get separated where magnetic field is weak.
vi. They repel each other in the direction, perpendicular to it, therefore like poles repel each other.
vii. They experience tension along the lines of force therefore unlike poles attract each other.
viii. They behave just like a stretched elastic string.

Pole and Pole-Strength

Pole is that point in a magnet where attracting power of the magnet is max^{m}.
The pole of magnet directed towards north is n-pole and directed towards south is called south pole.

Pole strength of both poles is equal in magnitude and opposite in nature. Pole strength is vector quantity.
n $-$ pole $\rightarrow$ (+m)
s -pole$\rightarrow$ (-m)

Unit of Pole-Strength

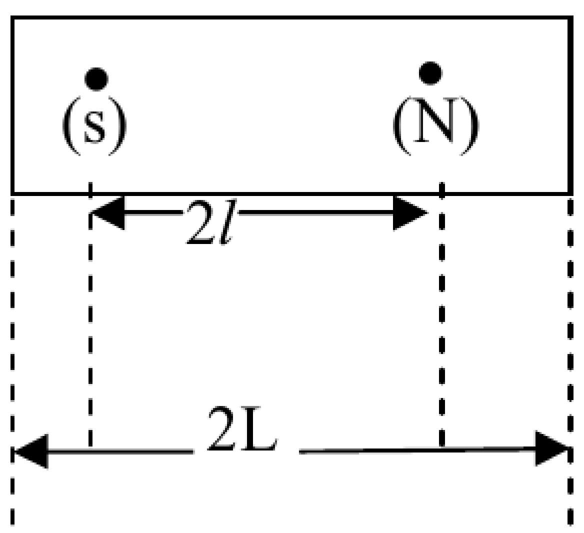
i. SI unit of pole -strength = Ampere meter (A.M)
ii. Electromagnetic c.g.s. unit of pole strength = Absolute ampere cm (ab Amp. Cm)

$$1 \text{ Amp. } = \frac{1}{10} \text{ ab Amp.}$$
$$1 \text{ Amp. Meter } = \frac{1}{10} \times 100 \text{ ab Amp. cm}$$
$$1 \text{ Amp. } = 10 \text{ ab Amp. cm}$$

Magnetic axis

It is defined as imaginary line passing though both pole of a magnet.

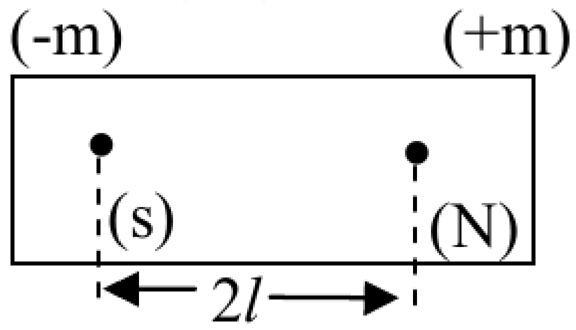
Magnetic Length and Geometrical length:



2l $\Rightarrow$ Magnetic length
2L $\Rightarrow$ Geometrical Length

$$\frac{\text{Magnetic length}}{\text{Geometrical length}} = 0.85$$

Magnetic Dipole moment ($\vec{M}$):-



$M = m \times 2l$
$M = 2ml$
$\rightarrow$ It direction is from South Pole to North Pole.

Magnetic Potential (V) :-

It is the work done in bringing unit n-pole from infinity to a point. It is scalar quantity.

$$\text{Magnetic potential } = \frac{\text{work done}}{\text{pole trength}}$$

$$\text{SI unit:- } \frac{\text{Joule}}{\text{A.m.}} = \frac{\text{weber}}{\text{meter}} = \text{wb}^{-1}$$

$$\text{Cgs unit } : \frac{\text{erg}}{\text{ab } Amp.\,cm} = \frac{\text{Maxwell}}{\text{cm}}$$

$$1\ \frac{\text{weber}}{m} = 10^6 \frac{\text{Maxwell}}{\text{cm}}$$

Magnetic field Induction $\vec{B}$

Magnetic field induction at a point in a magnetic field is defined as force experienced on unit n-pole placed at the point.

$$\vec{B} = \frac{\vec{F}}{m} \quad \vec{F} = \text{m}\vec{B}$$

$$\text{S.I. unit } : \frac{\text{Newtron}}{A, m} = \frac{\text{Newtron.m}}{A \cdot m^2} = \frac{\text{weber}}{m^2}$$

$$= \text{ Tesla (T)}$$

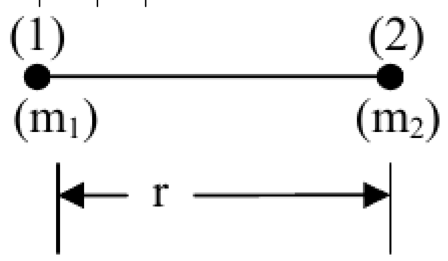
$$\text{CGS unit: } \frac{\text{Dyne}}{\text{ab Amp.cm}} = \frac{\text{Dyne.cm}}{\text{ab Amp.cm}}$$

$$= \frac{\text{erg}}{abAmp.\,cm^2} = \frac{\text{Maxwell}}{cm^2} = \text{ Gauss(G)}$$

$$1 \text{ Tesla } = 10^4 \text{ Gauss}$$

Coulomb's Law for magnetic forces

$\left|\overrightarrow{F_1}\right| = \left|\overrightarrow{F_2}\right| = F$



$\text{F} \propto \dfrac{m_1 m_2}{r^2}$

$\therefore \text{F} = \text{k}\dfrac{m_1 m_2}{r^2}$

Where k is constant, k = $\text{k} = \dfrac{\mu_0 \mu_{\text{r}}}{4\pi}$

μ_o = permeability of vaccum or air/absolute permeability
μ_r = Relative permeability of medium.

$\dfrac{\mu_0}{4\pi}$ = 10^{-7} Henry/meter

The relation between magnetic potential and magnetic field induction is given by

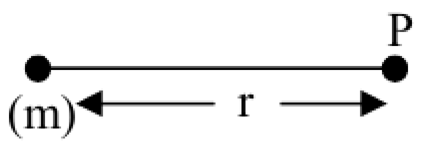
$$\vec{B} = -\frac{\mathrm{dV}}{\mathrm{dr}}$$

Magnetic field Induction and potential

a. Due to single pole of a distance 'r' from it

$$\mathrm{B} = \frac{\mu_o}{4\pi}\frac{m}{r^2}$$

$$\mathrm{V} = \frac{\mu_o}{4\pi}\frac{m}{r}$$

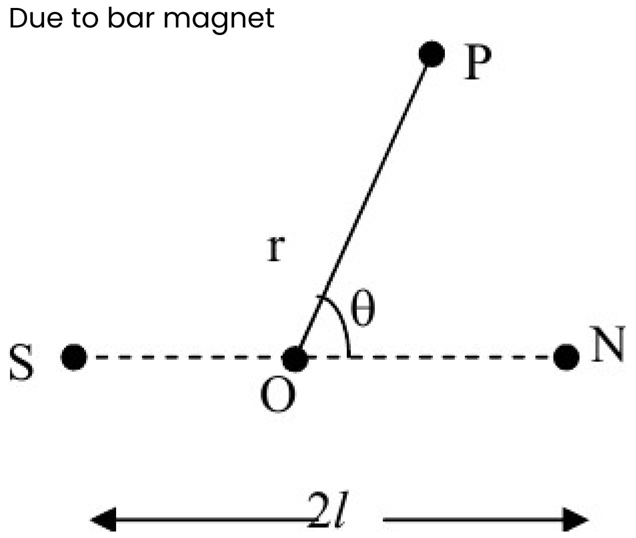


'B' at point 'p' is given by

$$\mathrm{B_P} = \frac{\mu_o}{4\pi}\frac{m}{r^2}$$

$$\mathrm{V_p} = \frac{\mu_o}{4\pi}\frac{\mathrm{m}}{r}$$

b. Due to bar magnet



At point P(r, θ)

Potential is given by $\mathrm{V_P} = \frac{\mu_o}{4\pi}\frac{\mathrm{M}\cos\theta}{\mathrm{r}^2}$

Field induction is given by,

$$\mathrm{B_p} = \frac{\mu_o}{4\pi}\frac{\mathrm{M}}{\mathrm{r}^3}\sqrt{1+3\cos^3\theta}$$

i. At end on position i, θ = 0^0

$$\mathrm{V} = \frac{\mu_o}{4\pi}\frac{\mathrm{M}}{\mathrm{r}^2}$$

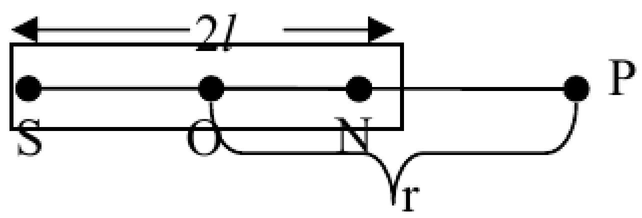
$$\mathrm{B} = \frac{\mu_o}{4\pi}\frac{2\mathrm{M}}{\mathrm{r}^3}$$

ii. Broad side on position, θ = 90^0

$$V = 0$$

$$B = \frac{\mu_o}{4\pi}\frac{2M}{r^3}$$

c. Due to long bar magnet



i. Magnetic potential at end on position is given by

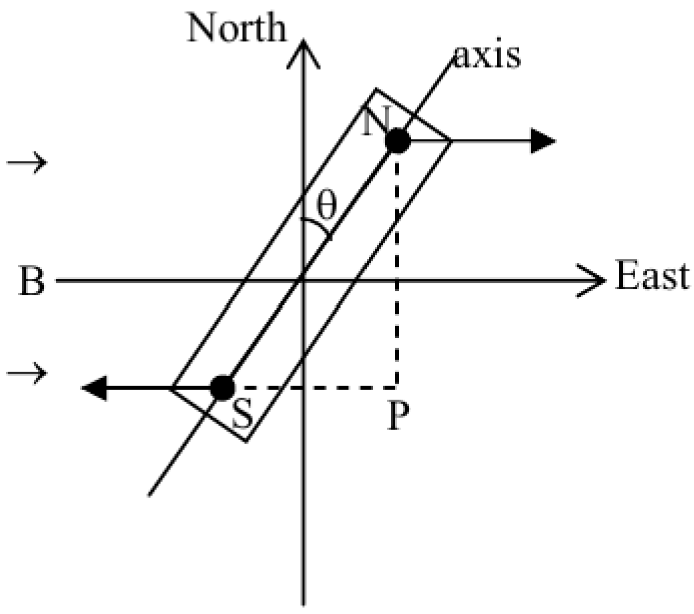
$$\mathrm{V} = \frac{\mu_o}{4\pi}\frac{\mathrm{M}}{(\mathrm{r}^2 - l^2)}$$

Find induction at end on position is given by

$$\mathrm{B} = \frac{\mu_o}{4\pi}\frac{2rM}{(\mathrm{r}^2 - l^2)^2}$$

ii. Magnetic potential in broad side-on position is given by
V = 0
Magnetic field indention in Broad side on position is given by
$$B = \frac{\mu_o}{4\pi} \frac{M}{(r^2 + l^2)^{3/2}}$$

Torque on a Bar magnet in a magnetic field



Force on N-pole = mB along $\vec{B}$
Force on S-pole = mB opposite to $\vec{B}$
Torque acting on the dipole
$$\begin{aligned} T &= \text{Force} \times \perp^r \text{ distance} \\ &= mB \times 2l \sin\theta \end{aligned}$$
$$\therefore T = MB \sin\theta$$
$$\vec{T} = \overline{M} \times \vec{B}$$
$$\text{If } \theta = 0^0 \text{ or } 180^\circ; T_{\min} = 0$$
$$\text{If } \theta = 90^\circ; T_{\max} = MB$$

$\rightarrow$ Work done in rotating a magnet in a magnetic field through an angle 'θ' from equilibrium condition is
W = MB (1 -cosθ)

$\rightarrow$ Work done in rotating the dipole from an angle θ_1 to θ_2
W = MB (Cos θ_1 -cos θ_2)

$\rightarrow$ A loop of current acts as dipole of magnetic moment
M = IA; when 'I' is the current through loop
'A' is the area enclosed by loop

Magnetic moment of electron revolving in an orbit

$M = iA = \frac{\omega e}{2\pi} \times \pi r^2 = \frac{1}{2} e\omega r^2$---(i)
According to Bohr's theory
$\text{mvr} = \frac{nh}{2\pi}$----(ii)
Where $\mu_B = \frac{eh}{4\pi m}$ is called Boh'r Magnetron
$\Rightarrow$ Potential energy of a magnet in magnetic field at an angle 'θ' from stable equilibrium condition
U = MB cosθ

Neutral Points

Neutral point is a point in a magnetic field where resultant of applied magnetic field by a magnet $(\vec{B})$ and horizontal component of earth field $(\overrightarrow{B_H})$ is zero.
i.e.
$$\begin{aligned} & \vec{B} + \vec{B}_H = 0 \\ \therefore \quad & \vec{B} - \vec{B}_H \\ \therefore \quad & |\vec{B}| = \left|\vec{B}_H\right| \end{aligned}$$

Neutral points in different cases

1. When magnet is in magnetic meridian
   a. When N-pole of magnet is toward north:-
   In this case neutral points are found perpendicular bisector

$$\mathrm{B}=\frac{\mu_{\mathrm{o}}}{4\pi}\frac{M}{\left(r^{2}+l^{2}\right)^{3/2}}=\mathrm{B}_{\mathrm{H}}$$

b. When magnet is towards east -west direction
In this case:

$$\mathrm{B}=\frac{\mu_{0}}{4\pi}\frac{M}{r^{3}}\sqrt{1+3\cos^{2}\theta}=\mathrm{B}_{\mathrm{H}}$$

TERRESTRIAL MAGNETISM

Earth behaves like a big magnet. The behaves like a big magnet. The behavior of earth is such that, along hypothetical bar magnet lies insides earth surface passing through centre of earth having n-pole towards south and S-pole towards north. The following reasons are given for earth magnetism :-

a. Due to presence of magnetic substance inside earth surface.
b. Due to steller cosmic rays coming in earth's atmosphere.

Geographical Meridian :-
A hypothetical vertical plane passing through geographical north and south is called geographical meridian.

Magnetic Meridian
A hypothetical vertical plane passing through magnetic north and south is called magnetic meridian.

Latitude
A line joining a place on earth surface and centre of earth makes some angle with equilibrium plane.

Magnetic elements of earth

1. Angle of Declination (θ)
   It is an angle between magnetic meridian and geographical meridian at a place.
   $\rightarrow$ The value of declination at equator is 17^{0}
   $\rightarrow$ Declination varies from place to place.

Agonic Lines
The lines joining the places having zero value of declination are called Agonic lines

Iso-Gonic Lines
The lines joining the places having same value of declination are called isogonic lines.

Angle of Inclination (DIP) (δ)
It is the angle which the direction of total intensity of earth's magnetic field makes with a horizontal line in magnetic meridian
$\rightarrow$ It varies from 0^{0} to 90^{0}
At equator, δ = 0, At pole ; δ = 90^{o}
At other place 0 $<\delta<$ 90^{0}
$\rightarrow$ Instrument used to measure dip at a place is called dip circle.
$\rightarrow$ A dip circle shows an apparent dip at δ_{1} at a place where true dip is δ. If the dip circle is rotated through 90^{0} the apparent dip is δ_{2} then true dip is
Cot^{2} δ_{1} + cot^{2} δ_{2}= cot$^{2}\delta$
True dip means it is measured in magnetic meridian.
$\rightarrow$ The line joining the points on a earth's surface where the angle of inclination or dip is zero is known as magnetic equator.

Actinic Lines
The lines joining the zero dip.

Iso-clinic lines
The lines joining the places of same value of dip.

Relation between Dip and Latitude of a lace.
Tanδ = 2tanλ

Horizontal Component of earth's field (B$_{H}$):-

At a place earth's magnetic field $(\overrightarrow{B_{E}})$ makes some angle with horizontal.

The horizontal component of $\overrightarrow{B_{E}}$ is called $\overrightarrow{B_{H}}$ and the vertival component of $\overrightarrow{B_{E}}$ is called $\overrightarrow{B_{V}}$.
B$_{H}$ = B$_{E}$ cosδ

$$\mathrm{B}_{\mathrm{H}}=\mathrm{B}_{\mathrm{E}}\cos\delta$$

$$\mathrm{B}_{\mathrm{v}}=\mathrm{B}_{\mathrm{E}}\sin\delta$$

$$\mathrm{Tan}\delta=\frac{B_{v}}{B_{H}}$$

$$\mathrm{B}_{\mathrm{E}}=\sqrt{\mathrm{B}_{\mathrm{H}}^{2}+\mathrm{B}_{\mathrm{V}}^{2}}$$

Adynamic Lines
The lines joining the places of zero value of horizontal components of earth's magnetic field.

Iso-Dynamic Lines
The lines joining the places of same value of horizontal component of earth's magnetic field.
$\Rightarrow$ The variation of angle of dip at a place near about area indicates the presence of iron cares etc.
In a vertical plane at an angle θ to magnetic meridian

$$\cos\theta = \frac{\tan\delta}{\tan\delta_1}$$

Here δ_1 = value of apparent dip along a vertical plane which is at an angle θ with magnetic meridian.

Tangent Law:-
According to tangent law, when a magnet is suspended under the combined action of two uniform magnetic fields of intensities F and H action at 90^0 to each other, the magent comes to rest making an angle θ with the direction of H; such that
F = H tanθ

Where,
F = B= Magnetic field
H = B_H = Horizontal component of the earth's magnetic field.

Deflection Magnetometer
It is an appartus which is used for compassing magnetic moments of two magnets.
It is based on tangent law.

1. Gauss tanA position or End on position
   As, F = H tanθ ie, B = B_H tanθ
   B_H tanθ =
   For two magnets
   $$\frac{M_1}{M_2} = \frac{\tan\theta_1}{\tan\theta_2}$$
   In the null method,
   $\frac{M_1}{M_2} = \frac{r_1^3}{r_2^3}$; when magnets are shat.

2. Gauss tanB position or Broad side on position:-
   F = H tanθ; ie; B = B_H tanθ
   $$\mathrm{B_H}\tan\theta = \frac{\mu_o}{4\pi}\frac{M}{r^3}$$
   For two magnets;
   $$\frac{M_1}{M_2} = \frac{\tan\theta_1}{\tan\theta_2}$$
   In the null methods
   $$\frac{M_1}{M_2} = \frac{\left(r_1^2 + l_1^2\right)^{3/2}}{\left(r_2^2 + l_2^2\right)^{3/2}} = \frac{r_1^3}{r_2^3}$$
   (when magnets are short)

Vibration Magnetometer:-
It is an instrument used for comparing earth's horizontal magnetic field at two places and magnetic moments of two magnets
Time period of vibration magnet is given by

$$\mathrm{T} = 2\pi\sqrt{\frac{I}{MB_H}}$$

Where,
I = Moment of inertia of magnet
M = Magnetic moment of the magnet
B_H = Horizontal component of earth's field.
For rectangular magnet;
$\mathrm{I} = \mathrm{m}\left(\mathrm{l}^2 + \mathrm{b}^2\right)$; l = length; b = width
For cylindrical magnet;
$\mathrm{I} = \mathrm{m}\left(\frac{R^2}{4} + \frac{l^2}{12}\right)$; R = radius; l = length
For this magnet; $\mathrm{I} = \frac{\mathrm{m}l^2}{12}$
$\Rightarrow$ If magnet is cut into length wise them,

$$\mathrm{I}' = \frac{1}{12}\left(\frac{m}{2}\right) \times \left(\frac{l}{2}\right)^2 = \frac{1}{12}Ml^2 \times \frac{1}{8} = \frac{I}{8}$$

$$\mathrm{M}' = \mathrm{m} \times (1/2) = \frac{M}{2}$$

1. Substitution method
   Comparision of magnetic moment of magnets of the same size.

$$\left(\frac{\mathrm{T}_1}{\mathrm{T}_2}\right)^2 = \frac{M_2}{M_1}$$

Comparision of earth's magnetic field at two different places.

$$\left(\frac{T_1}{T_2}\right)^2 = \frac{B_{H_2}}{B_{H_1}}$$

2. Sum and difference method

$$\frac{M_1}{M_2} = \frac{T_2^2 + T_1^2}{T_2^2 - T_1^2}$$

Sum and different method is applicable only when these is a large difference of magnetic moments of two magnets

Properties of Magnetic Materials

Flux Density

It is defined as total flux (ϕ) passing through unit area placed perpendicularly. It is also called magnetic field induction $\vec{B}$

$$\vec{B} = \phi/\mathrm{A} \quad [\phi = \vec{B}, \vec{A}]$$

Magnetic field intensity of magnetizing field (H)
The applied magnetic field is called magnetic field.

$$\vec{H} = \vec{B}/\mu$$

Unit of $\vec{H}$; Amper/meter (SI)
Ab amp/cm (cgs)

Intensity of Magnetization (I) :
It shows the degree of magnetization. It is given by ratio of magnetic moment and volume of magnet.

$$\vec{I} = \frac{\vec{M}}{V}$$

$$I = \frac{m \times 2l}{A \times 2l}$$

$$= \frac{m}{A} = \frac{\text{pole strength}}{\text{Area}}$$

$$\text{Unit} = \text{A/meter}$$

Permeability
It is that physical quantity which tells us how easily magnetic lines of force can pass through a medium. It is given by,

$$\mu = \frac{B}{H}$$

Unit = Henry/meter = Weber .A^{-1}m^{-1}

Susceptibility (χ_m) :-
It is defined as the ratio of intensity of magnetization to that of magnetic field intensity

$$\chi_{\mathrm{m}} = \frac{I}{H}$$

It is that physical quantity which tells us how easily a substance is magnetized

i. χ_m is a number, therefore it is unitless and dimensionless
ii. For vaccum χ_m = 0
iii. If I and H it are parallel then χ_m is (+) ve and if I and H are antiparallel then χ_m is (-) ve.
iv. The dependence of X$_m$ with temperature is given by scientist curie us

$$\chi_{\mathrm{m}} \propto \frac{I}{T}; \quad \chi_{\mathrm{m}} = \frac{C}{T}$$

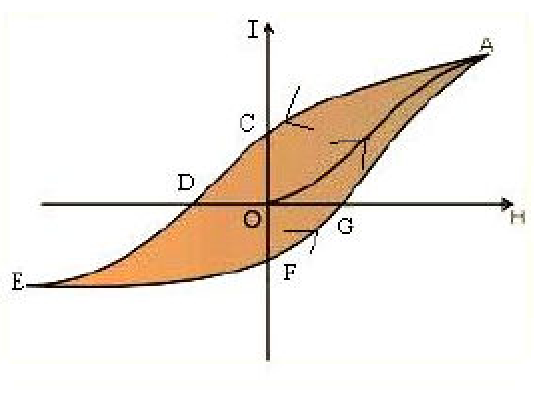
T = Absolute temperature of material
C = curie's constant. It is different for different material.

v. The relation among $\vec{B}, \vec{H}$ and $\vec{I}$

$$\mathrm{B} = \mu_0(\mathrm{I} + \mathrm{H})$$

$$\text{Also,} \quad \mu_{\mathrm{r}} = 1 + \chi_{\mathrm{m}}$$

(I-H) Curve



An unmagnetised bar is kept gradually increasing field. Initially it is observed that intensity of magnetization increases slowly. But latter in it increases rapidly acquiring the path OA. At it becomes constant, i.e., on further increasing H, these will be no increase in I. If H is gradually decreased and further applied in reverse direction.

a. Retentivity
If $\vec{H}$ is decreased gradually then it is observed that $\vec{I}$ also decreases. But $\vec{I}$ does not repeat its path and decreases obeying the path AC. This shows that when the value of $\vec{H}$ is zero the intensity of magnetization (or magnetic induction $\vec{B}$) is not zero, but has value OC. This value is called residual magnetism or retentivity ofsubstance.

b. Coercivity
To destroy the residual magnetism we reverse the direction of magnetizing field H. It is observed that for H= OD, the intensity of magnetization is zero. The value of H required to destroy theresidual magnetism is called coercivity.

c. Hysteresis
If H is further increased in reverse direction then I-attains another saturation point at E. Again H is increased in intial direction then curve ACDEFGA is obtained, called hysteresis loop. From the hysteresis loop it is clear that I always lags behind H. The phenomenon of lagging of I, behind H is called hysteresis.

Hysteresis loss
The energy used in magnetizing a bar is not completely obtained by demagnetization. This loss of energy is called hysteresis loss. It is generally used in heating the bar.

Diagmagnetic Materials

- Substance having no magnetic moment.
- Eg:-Bi, Sb, Hg, Zn, Cu, P, H_2O, H_2 etc.
- $\mu r<1$ and χ_m is constant and negative
- μ and χ_m are independed of T and H
- It does not exhibit hysteresis

Paramagnetic Materials
Substances having small value of magnetic moment.
eg. Platinum, Al, Cr, Mn, Pd, Os, $FeCl_3$ (solution), Oxygen, $CuCl_2$ etc.

- $\mu r<1$, and χ_m has small position value.
- Obey curies law.
- Para magnetism on the basis of electron theory
- Magnetic lines of induction crowd through such substance.

Ferromagnetic materials:-
Substances having high value of magnetic moment
Eg. Fe, Co, Ni, Steel, Fe_2O_3, Fe_3O_4

- Permanent magnets :-Cobalt steel, Alnico tinconal
- Temporary magnets :-These are used to move electromagnets.

They Exhibit Hysteresis
$\rightarrow$ When ferromagnetic material is placed in magnetic field it acquires a magnetic dipole moment M in the direction of magnetic field. Silicon iron or stalloy or mumetal with 4% silicon and Nickel called "transformer Steel" or permalloy is used for making the cores of the transformer and chokes, Armature of dynamos and meter.
$\Rightarrow$ If a ferromagnetic substance is heated, it is converted into a paramagnetic substance above a temperature, called curie temp. for iron curie temp. is 750^0C.

Electromagnet
An electromagnet is made of soft iron because

i. Soft iron has high value of intensity of magnetization for a week field.
ii. Soft iron has high susceptibility.
iii. It has small hysteresis loop i.e. low value of hysteresis loss.

Permanent Magnet
A permanent magnet is made of steel because.

i. It has high retentivity
ii. It has capacity of sustaining temperature variation and rough handling.
iii. It has large hysteresis loop, i.e. high value of hysteresis loss.