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Module 4
Magnetic Materials

Magnetic materials, Diamagnetic materials, Paramagnetic materials, Ferromagnetic materials, Diamagnetism, Paramagnetism, Ferromagnetism, Antiferromagnetism, Ferrimagnetism, Soft & Hard Magnetic material and applications.

INTRODUCTION

- The materials which strongly attract a piece of iron are known as magnetic materials or magnets.
- The magnetic property of a material arises due to the **magnetic moment** or **magnetic dipole of materials**.
- Materials which are magnetised by the application of an external magnetic field are known as **magnetic materials**.
- Similarly, materials which are not magnetised due to the application of an external magnetic field are known as **nonmagnetic materials**.
- The magnetism of materials is responsible for magnetic moment of materials.
- When a current flows through a conductor, it produces a magnetic moment along the axis of the coil.
- The electrons revolving around the nucleus leads to an orbital magnetic moment.
- The spinmagnetic moment arises due to the spin ($\pm 1/2$) of electrons.
- Magnetic materials are more important in terms of potential practical applications like magnetic storage and biomedical uses.
- General classes of magnetic materials are diamagnetic, paramagnetic, ferromagnetic, anti-ferromagneitc and ferrimagnetic materials

MAGNETIC PARAMETERS

The magnetic property of materials depends on the degree of magnetisation. The parameters such as magnetisation, magnetic susceptibility and magnetic permeability are used to characterise magnetic materials.

(1) Magnetic Dipole The magnetic dipoles, generally known as north and south poles, commonly exist in magnetic materials. The magnetic dipoles are not separate poles unlike an electric dipole.

(2) Magnetic Field Strength(H) The magnetic field strength **H** at any point in a magnetic field is the force experienced by a unit north pole placed at that point. Its unit is A m^{-1}.

(3) Magnetic induction or Flux density(B) The magnetic induction or flux density **B** in any material is defined as the number of lines of force through a unit area of cross-section perpendicularly.

Therefore,

Magnetic induction $$B = \frac{\phi}{A}$$

where A is the area of cross-section and ϕ, the magnetic lines of force.

The unit for B is Wb m^{-2}.

(4) Magnetic Dipole Moment Consider that m is the magnetic pole strength and 2l, the length of magnet. The magnetic dipole moment is equal to the product m × 2l.

Magnetic dipole moment $\mu_m = m \times 2l$

The magnetic dipole moment is a vector quantity.

(5) Magnetisation or Intensity of Magnetisation(M) Magnetisation, or intensity of magnetisation is the measure of magnetism of magnetic materials and is defined as the **magnetic moment per unit volume**.

$$M = \frac{\mu_m}{V}$$

where V is the volume. The unit for M is A m^{-1}.

(6) Magnetic Susceptibility Magnetic susceptibility (χ) is used to explain the magnetisation of materials. It is defined as the ratio of **magnetisation** to the **magnetic field strength**.

$$\text{Magnetic susceptibility } \chi = \frac{M}{H}$$

(7) Magnetic Permeability The magnetic permeability μ is defined as the ratio of amount of magnetic density **B** to the applied magnetic field intensity H. It is used to measure the magnetic lines of forces penetrating through a material.

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

Rearranging the above equation, we get

$$\text{Magnetisation } \mathbf{B} = \mu_0 (\mathbf{M} + \mathbf{H})$$

where μ_0 is the permeability of free space and is equal to $4\pi \times 10^{-7}$ H m^{-1}.

Relation Between Magnetic Parameters

Relative permeability of a material is defined as the ratio of permeability of the medium to free space,

$$\text{Relative permeability } \boldsymbol{\mu_r = \frac{\mu}{\mu_o}}$$

Substituting the values of μ = B/H, we get

$$\boldsymbol{\mu_r = \frac{B}{\mu_o H}}$$

Substituting the value B from Eq. in the above equation, we get

$$\boldsymbol{\mu_r = \frac{\mu_o(M+H)}{\mu_o H}}$$

$$\boldsymbol{\mu_r = \frac{M}{H} + \frac{H}{H}}$$

Therefore, relative permeability $\boldsymbol{\mu_r = 1 + \chi}$

BOHR MAGNETON The magnetic moment of an atomic particle is represented by **Bohr magneton (β)**

1 Bohr magneton (β) = eh/4πm

$1\beta = 9.27 \times 10^{-24}$ A m^2

CLASSIFICATION OF MAGNETIC MATERIALS

Magnetic materials are classified into two categories based on existence of dipole moment and the response of the magnetic material to external magnetic fields.

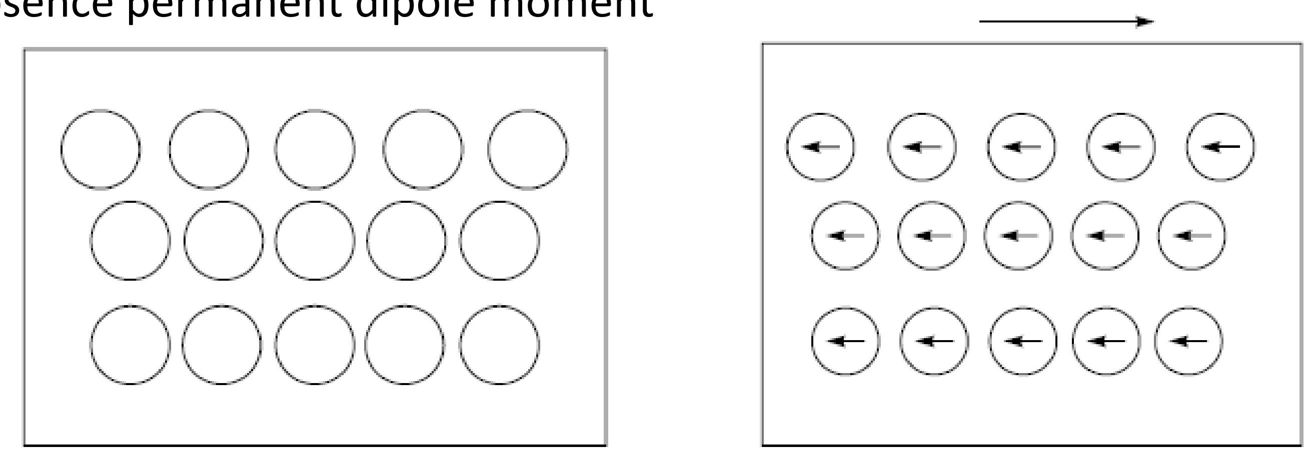
(1) Diamagnetic materials—no permanent magnetic moment.

(2) Paramagnetic, ferromagnetic, anti-ferromagnetic and ferrimagnetic materials—possess permanent magnetic moment.

Diamagnetic Materials

- All materials exhibit diamagnetic properties.
- When an external magnetic field is applied, the individual dipoles are rotated and hence, produce an induced dipole moment.
- The induced dipole moment opposes the external magnetic field. As a result, the magnetic fields are repelled from the materials. This effect is known as **diamagnetism**.

Absence permanent dipole moment



$H = 0$ and $M = 0$

(*a*) *Absence of field*

$H = H_0$ and $M = -M_0$

(*b*) *Presence of field*

Diamagnetic properties

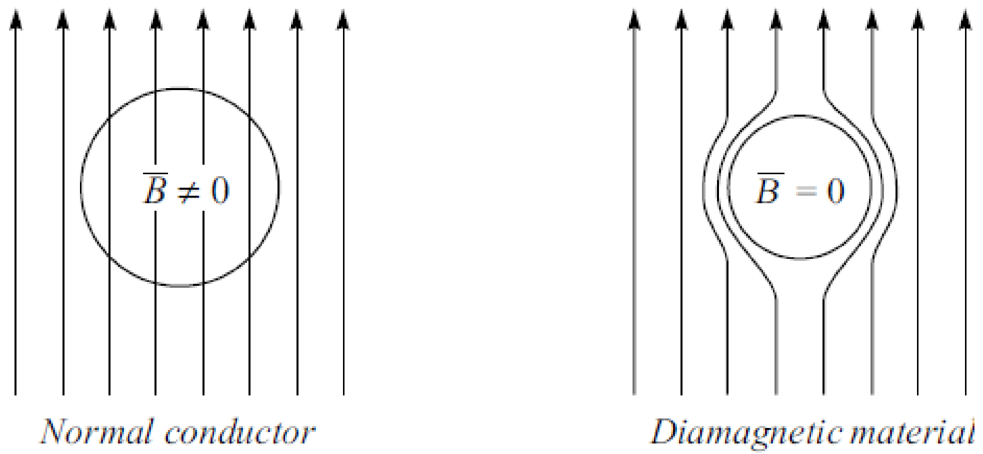
Properties

Following are the properties of diamagnetic materials:

(1) Diamagnetic materials do not have a permanent dipole moment.

(2) Magnetic effects are very weak.

(3) Diamagnetic materials repel the magnetic lines of force.



Diamagnetic material—Magnetic field

(4) The magnetisation becomes zero on removal of the external field.

(5) The susceptibility of a diamagnetic material is negative.

(6) The susceptibility is independent of temperature and external field.

Examples of diamagnetic materials are copper, gold, mercury, silver and zinc.

Paramagnetic Materials

- Paramagnetic materials possess a permanent magnetic moment.
- During the absence of an external magnetic field, the dipoles are randomly oriented.
- When an external magnetic field is applied, the magnetic moments of individual atoms align themselves in the direction of the field and hence, give nonzero magnetisation.

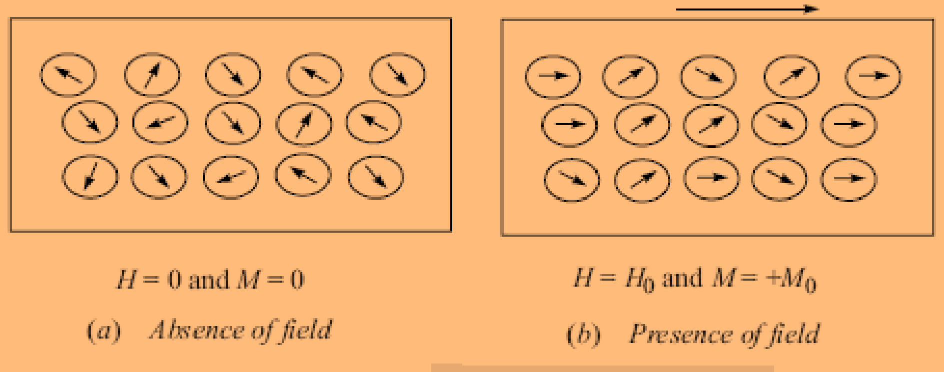
Properties

Following are the properties of paramagnetic materials:

(1) Paramagnetic materials possess a permanent dipole moment.

(2) The magnetic dipoles are aligned randomly.

(3) They attract the magnetic lines of force.



Paramagnetic properties

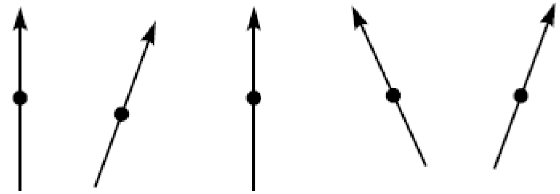
(4) The susceptibility is positive and depends on temperature: χ **=C/T**

where C is the Curie constant and T, the temperature.

Above Equation is known as the Curie law of paramagnetism.

(5) Paramagnetic susceptibility is inversely proportional to temperature.

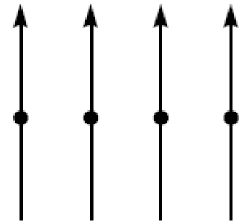
Eg: aluminum, chromium, sodium, titanium, zirconium, etc.



Paramagnetic material—spin arrangement

Ferromagnetic Materials

- Ferromagnetic materials possess permanent magnetic moment which is mainly due to the spin magnetic moment.
- The magnetic dipoles are aligned parallel to each other due to interaction between any two dipoles.
- The ferromagnetic materials exhibit spontaneous magnetisation, even in the absence of an external field. Due to the strong internal field which exists in materials, the alignment of magnetic moments results.
- On the other hand, when a small magnetic field is applied, it produces a large value of magnetisation due to the parallel alignment of dipoles.
- In a ferromagnetic material, the influences of internal and external fields make them different from other magnetic materials.



Ferromagnetic materials—dipoles arrangements

Properties

(1) The magnetic dipoles are arranged parallel to each other

(2) They possess permanent dipole moment.

(3) They attract the magnetic lines of force strongly.

(4) They have characteristic temperature, namely, ferromagnetic Curie temperature (θ_f). Materials below θ_f behave as ferromagnetic materials and obey hysteretic curve. A material behaves as a paramagnetic when it is above θ_f .

(5) During the absence of a magnetic field, it exhibits magnetisation which is due to the property of spontaneous magnetisation.

(6) The susceptibility of a ferromagnetic material is

$$\chi = \frac{C}{T-\theta}$$

where, C is Curie constant and θ, the paramagnetic Curie temperature

Examples of ferromagnetic materials are iron, cobalt and nickel.

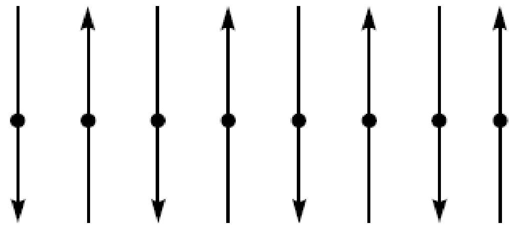
Anti-ferromagnetic Materials

- In ferromagnetic materials, the magnetic dipoles are parallel to each other.
- The magnitudes of all dipoles are equal and hence, resultant magnetic moment and magnetisation is zero.
- The anti-parallel alignment exists in materials below a critical temperature known as Neel temperature.

Properties

1. When the temperature increases, susceptibility increases and reaches a maximum at a temperature known as Neel temperature, beyond which it decreases.

(2) The value of susceptibility is positive and is very small when T is greater than the Neel temperature, T_N.



Anti-ferromagnetic materials—dipole arrangements

$$\chi = \frac{C}{T+\theta}$$

(3) Anti-parallel alignment of dipole is due to exchange interactions.

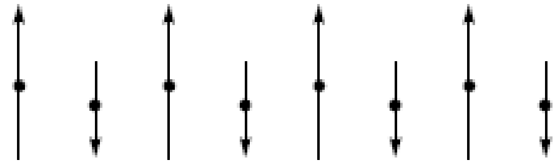
Examples of anti-ferromagnetic materials are ferrous oxide, manganese oxide, manganese sulphite, chromium oxide, etc.

Ferrimagnetic Materials

- Ferrimagnetic materials are a special case of anti-ferromagnetic materials.
- The magnetic dipoles are anti-parallel, similar to an anti-ferromagnetic material.
- Ferrimagnetic materials magnitudes are not equal due to the magnetic interactions existing between dipoles.
- Ferrimagnetic materials possess net magnetic moments due to the anti-parallel dipoles with different magnitudes.
- Ferrimagnetic materials produce a large magnatisation even for a small applied external field.

Properties

(1) Ferrimagnetic materials, the dipoles are not equal in magnitude.
(2) Net magnetisation is larger even for a small external field.



Ferrimagnetic materials—dipole arrangements

(3) The susceptibility is positive and very large when the temperature is higher than T_N

$$\chi = \frac{C}{T \pm \theta}$$

(4) They behave as paramagnetic and ferromagnetic materials, respectively, above and below Curie temperature.
(5) Ferrimagnetic domains are used as magnetic bubbles in memory elements.

DIAMAGNETISM

- Diamagnetic materials possess a weak induced magnetic field when an external magnetic field is applied due to electromagnetic induction.
- Lenz's law states that the magnetisation (M) will oppose the applied magnetic field (H).
- The susceptibility of a diamagnetic material is very small and negative. It is usually less than 10^{-5}.
- Diamagnetism is very weak and it is present in most materials. Eg: Cu, Au, Ge etc

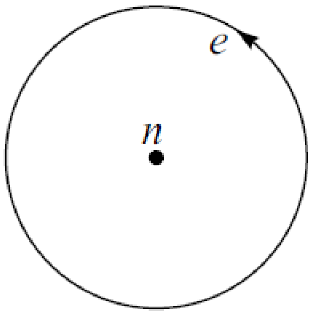
Langevin' s Theory of Diamagnetism

- The permanent magnetic moment arises if there is any unfilled electronic state in the atoms of an element. When all states are completely filled, then there is no permanent dipole moment.
- Inert gases such as He, Ne and Ar have completely filled electronic states. However, they possess a small value of induced magnetic moment, when there is an applied magnetic field.
- This property is known as **diamagnetic property**. This small value of induced magnetic moment is produced in all elements.
- Therefore, all elements possess diamagnetic property. The diamagnetic property arises due to Lenz's law operating in atomic scale.

In order to derive an expression for susceptibility of a diamagnetic material, consider an electron revolving around a nucleus. It acts like a current loop. The current produced by the revolving electron is proportional to ***ef***, where e is the charge of an electron and f, its frequency.

Let ω be the angular frequency of an electron, then $\omega = 2\pi f$.

Therefore, the current produced by the revolving electron is,



Atomic view—electron revolving around the nucleus

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

The magnetic moment induced by the revolving electron is, $\mu_m = IA$, where A is the area of crosssection. Substituting, the value of I and A ($= \pi r^2$), we get

$$\mu_m = -\frac{1}{2}\frac{e\omega}{\pi}\pi r^2 = -\frac{1}{2}e\omega r^2 \qquad \text{..........} (1)$$

The electron revolving around a nucleus looks like a current carrying coil of wire. Hence, it induces a magnetic field. Consider that the magnetic field is increased from zero to B. According to Lenz's law, the magnetic field associated with this current opposes the increase in flux. Hence, Lenz's law is given as

$$\int \overline{E}.d\overline{l} = -\frac{d\phi}{dt}$$

For an electron revolving in a circular orbit, $dl = 2\pi r$ and hence

$$E = -\frac{1}{2\pi r}\frac{d\phi}{dt}$$

We know that, the magnetic flux density $B = \dfrac{\phi}{\pi r^2}$ => $\Phi = B\,\pi r^2$

Substituting the value of $d\phi$ in $E = -\dfrac{1}{2\pi r}\dfrac{d\phi}{dt}$

we get $E = -\dfrac{r}{2}\dfrac{dB}{dt}$

The force experienced by an electron due to this electric field is F = -eE

$$F = \frac{er}{2}\frac{dB}{dt} \qquad \text{........(2)}$$

The force can be written as the rate of change of momentum

$$F = \frac{dp}{dt} = \frac{d}{dt}(mv) = \frac{d}{dt}(mr\omega) \qquad F = mr\frac{d\omega}{dt} \qquad \text{........(3)}$$

where v is linear velocity

From (2) and (3)

$$\frac{er}{2}\frac{dB}{dt} = mr\frac{d\omega}{dt}$$

$$d\omega = \frac{e}{2m}dB$$

Integrating the above equation with limitation ω_0 and ω , we get $\int_{\omega_0}^{\omega} d\omega = \dfrac{e}{2m}\int dB$

$$\omega - \omega_0 = \frac{e}{2m}B \;\Rightarrow\; \omega = \omega_0 + \frac{e}{2m}B$$

where ω_0 is the angular frequency of an electron when B = 0.

When the field is applied, the angular velocity is given by

$$\omega = \omega_0 + \frac{e}{2m} B = \omega_0 + \omega_L$$

where ω_L is called Larmor angular frequency and is equal to eB/2m.

Substituting ω in eq (1), we get the magnetic moment

$$\mu_m = \frac{1}{2} e r^2 (\omega_0 + \omega_L) \qquad (\because \mu_m = \frac{1}{2} e r^2 \omega)$$

$$= -\frac{1}{2} e r^2 \omega_0 - \frac{e^2 r^2}{4m} B \qquad \text{........(4)}$$

where the term $-\frac{1}{2} e r^2 \omega$, is the **magnetic moment** of an electron before the application of the field, and the second term, $-\frac{e^2 r^2}{4m} B$ represents the **induced magnetic moment** produced due to the application of field. The negative sign shows that the magnetic moment opposes the applied field.

The induced magnetic moment from Eq. (4) can be written as

$$\mu_m(ind) = -\frac{e^2 r^2}{4m} B \qquad \text{........(5)}$$

Substituting, B = μH, and for an element with N number of dipoles, Eq. (5) can be written as

$$N\, \mu_m(ind) = -\frac{N e^2 r^2}{4m} \mu H \qquad \text{........(6)}$$

The term, N μ_m(ind) gives the magnetisation induced and hence, Eq. (6) can be written as

$$\chi = \frac{M}{H} = -\frac{Ne^2r^2}{4m}\mu$$

We know that $\mu = \mu_o\mu_r$, hence, the above equation can be written as

$$\chi = -\frac{Ne^2r^2}{4m}\mu_o\mu_r \quad \text{.........}(7)$$

Equation (7) represents the susceptibility of a diamagnetic material. This equation is derived based on the assumption that an electron is revolving around a circular path. Generally, in atoms all orbits are not circular. Therefore, for a spherical symmetrical atom, let r_x, r_y and r_z be the average radii of all electronic orbits, then

$$r_0^2 = \overline{r_x^2} + \overline{r_y^2} + \overline{r_z^2} \quad \text{and} \quad \overline{r_x^2} = \overline{r_y^2} = \overline{r_z^2} = \frac{\overline{r_0^2}}{3}$$

Let r be the radius of an atom. The average radius of an atom can be written as,

$$\overline{r^2} = \overline{r_x^2} + \overline{r_y^2} = \frac{2}{3}\overline{r_0^2}$$

Substituting the value of r^2 in Eq. (7), we get

$$\chi = -\frac{Ne^2\,\mu_0\mu_r r_o^2}{6m}$$

PARAMAGNETISM

- In paramagnetic materials, permanent dipole moment exists even in the absence of an external magnetic field. The dipoles try to align themselves on application of an external magnetic field.
- However, the thermal agitation present in the material disturbs the alignment of dipoles. Therefore, the resultant magnetisation is based on the intensity of applied magnetic field and thermal energy responsible for agitation.
- The classical theory of Langevin is used to explain the above mechanism, and it gives the necessary expression for susceptibility of paramagnetic materials

Langevin Theory of Paramagnetism

$$\chi_p = \frac{C}{T}$$

where C is the known as Curie constant and is equal to $\mathbf{N\mu_m^2/3k}$. The above results support the Curie experimental results on materials like Nd, $CuSO_4.K_2SO_4.6H_2O$ and O_2.

Limitations of Langevin's Theory

a. It fails to explain the relationship between para and ferromagnetism.

b. It fails to explain the deviation exhibited in many substances like compounds and cooled gases, solid salts and crystals.

Weiss Theory of Paramagnetism

- Langevin's theory failed to explain the complicated temperature dependence of susceptibility of paramagnetic materials.
- In order to explain the same, the internal or molecular field concept of Weiss theory is used. According to this theory, in a real gas, the internal or molecular field seen by a gaseous dipole is equal to the sum of **applied field** and **the field due to the contribution from neighbouring gaseous dipoles**.

The resultant magnetic field (***H****i*) is

$$\boldsymbol{H_i = H_a + \gamma M} \quad \dots\dots\dots..(1)$$

where H_a is the applied field; γ, the internal field constant and M, the intensity of magnetisation. From Langevin's theory, the magnetisation experienced by a paramagnetic material is obtained from susceptibility value,

$$\chi_p = \frac{N\mu_m^2}{3kT} \qquad \text{or} \qquad \frac{M}{H} = \frac{N\mu_m^2}{3kT}$$

Therefore, the magnetisation $$M = \frac{N\mu_m^2 \mu_o H_i}{3kT} \quad \dots\dots(2)$$ **($\because H=\mu_o H_i$)**

Substituting the value of H_i from Eq. (1) in Eq. (2), we get

$$M = \frac{N\mu_m^2 \mu_o (H_a + \gamma M)}{3kT}$$

$$M = \frac{N\mu_m^2\mu_o}{3kT} H_a + \frac{N\mu_m^2\mu_o}{3kT}\gamma M$$

$$M = \frac{\frac{N\mu_m^2\mu_o}{3kT} H_a}{(1 - \frac{N\mu_m^2\mu_o\gamma}{3kT})}$$

Substituting, $\frac{N\mu_m^2\mu_o\gamma}{3k} = \theta$ and $C = \frac{N\mu_m^2\mu_o}{3k}$ in Eq.

we get $$\chi = \frac{M}{H_a}$$

$$\chi = \frac{C}{T - \theta} \quad \text{..........(3)}$$

where C is known as Curie constant and θ, the paramagnetic Curie temperature

Equation (3) is known as **Curie–Weiss law**. This equation shows that the susceptibility is negative below Curie temperature (when T < θ). However, in most of paramagnetic materials, the Curie temperature is very low and hence, the occurrence of a situation such as T < θ is rare.

FERROMAGNETIC MATERIALS

- Materials like Fe, Co, Ni and certain alloys exhibit a high degree of magnetisation.
- When the magnetic field is absent, these materials exhibit finite value of magnetisation known as **ferromagnetism**. These materials are known as **ferromagnetic materials**.
- Ferromagnetic materials exhibit two different properties as a function of temperature. Above a particular temperature known as **ferromagnetic Curie temperature** (θ_f), they behave as paramagnetic materials.
- Below the ferromagnetic Curie temperature, the materials behave as ferromagnetic materials and show the hysteresis curve.

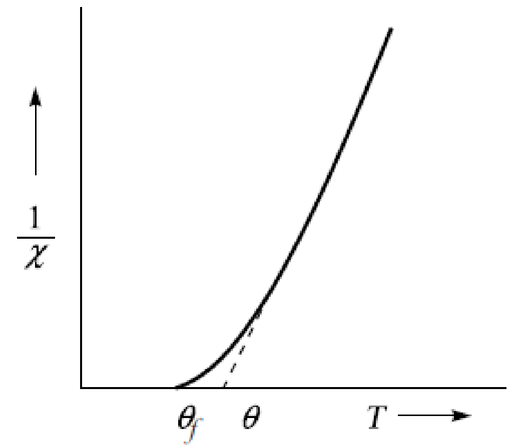
Case 1 ($T > \theta_f$)

- When the temperature is greater than θ_f, a ferromagnetic material behaves as a paramagnetic material.
- The material shows similar properties as that of paramagnetic materials and a unique relationship between magnetisation and applied field.
- In this region, susceptibility depends on the Curie–Weiss law,

$$\chi = \frac{C}{T - \theta_f} \quad (\text{for } T \gg \theta_f)$$

where C is the Curie constant and θ_f, the paramagnetic Curie temperature.

The linear portion of the curve is identified and extrapolated to determine the **paramagnetic Curie temperature, θ**. The **intercept made on the x-axis** gives the value of θ. Generally, the paramagnetic Curie temperature θ is greater than the ferromagnetic Curie temperature θ_f.



Reciprocal of susceptibility as a function of temperature—ferromagnetic material

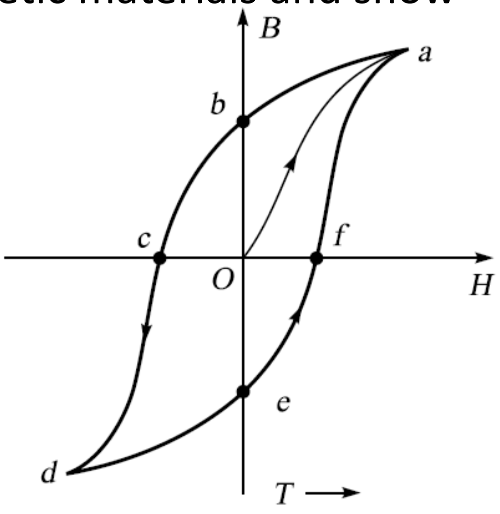
Table. Ferromagnetic and Paramagnetic Curie Temperatures of Few Ferromagnetic Materials

Sr. No.	*Material*	*θ (K)*	*θ_f (K)*
1.	Fe	1093	1043
2.	Co	1428	1393
3.	Ni	650	631

Case 2 ($T < \theta_f$)

When the temperature is less than θ_f, materials behave as ferromagnetic materials and show the wellknown hysteresis curve.

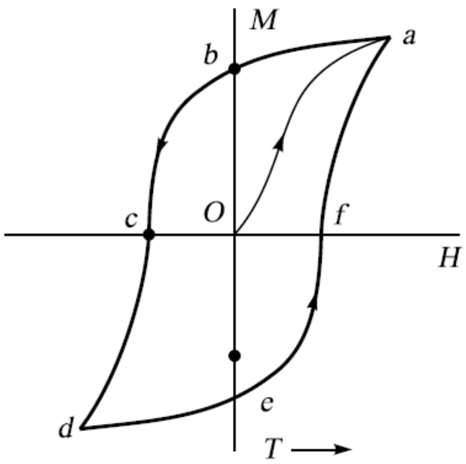
- The magnetic flux density B increases with increase in applied field (H) and it reaches saturation at a level known as $\mathbf{B_{sat}}$ beyond which it remains constant even for a further increase in applied field.
- when the field is decreased, the magnetic flux density decreases through a new path ab instead of oa.
- When the field reaches zero value, the magnetic flux exists in the material and is known as **remanent flux density $\mathbf{B_r}$**.
- When a negative field is applied, the magnetic flux density decreases and it **reaches zero** value at a field strength of $\mathbf{-H_C}$ by taking the path bc.



(a) Magnetic flux density as a function of applied field

- The field required to bring the magnetic flux density to zero value, i.e., $-H_C$ is known **as coercive field**.
- When the field is increased in the negative direction, it results in magnetic flux saturation (**$-\mathbf{B_{sat}}$**), by taking the path cd, beyond which the flux density remains constant for a further increase in field.
- When the field is increased in the positive direction, the flux density takes the path de and ef, and finally reaches the point a.
- The path turned by the B-H curve forms a loop known as **hysteresis loop.**

- The curve is obtained by taking the magnetisation M and the applied field H is known as M-H curve.
- The zero magnetic field (H = 0), the magnetisation exists in materials known as **remanent magnetisation (M_r)**.
- The field required to bring M_r to zero value is known as **coercive field or coercivity**.
- The existence of remanent magnetisation at H = 0, is known as **spontaneous magnetisation**.



(b) Magnetisation as a function of applied field

Table Saturation Values of Flux Density and Magnetisation of Ferromagnetic Materials

Sr. No.	*Materials*	*Bohr magneton per atom*	$B_{sat} = \mu_0 M_{sat}$ T	$\mu_{sat} \times 10^{-6}$ A m^{-1}
1.	Fe	2.22	2.2	1.75
2.	Co	1.72	1.82	1.45
3.	Ni	0.60	0.64	0.50

Weiss Theory of Ferromagnetism

In order to explain the ferromagnetic properties, Weiss proposed two postulates namely, **internal field** and **domain concept**.

- Based on the Weiss theory, internal field is the field employed between two interacting atoms in ferromagnetic materials.

Therefore, internal field or molecular field produced in a material is

$$\mathbf{H_i = \gamma M} \quad \text{...............(1)}$$

where γ is the internal field constant or Weiss molecular field constant and M, the magnetisation

The internal-field concept is used to explain most of the properties such as **spontaneous magnetisation, Curie law** and behaviours of ferromagnetic materials.

However, **the internal-field concept fails** to explain the following points

1) Based on Weiss theory, the Curie temperature for ferromagnetic and paramagnetic states is the same. However, the experimental values show that ferromagnetic and paramagnetic Curie temperatures, i.e., θ_f and θ are different.

(2) The classical theory fails to explain the **magnetic interaction** and **interaction energy** in a ferromagnetic material.

Therefore, the concept of wave nature based on quantum theory has been introduced. Hence, **the magnetic interaction** and **interaction energy** are explained in terms **of exchange force in wave mechanics**.

According to Weiss, **the internal field** expressed by dipoles is the sum of applied field and the field experienced by the contribution from neighbouring dipoles.

$$\mathbf{H_{ef} = H + \gamma M} \quad \text{..........(2)}$$

Case (i): High Temperature (T > θ_f) A ferromagnetic material behaves as a paramagnetic material when the temperature is greater than the Curie temperature.
In order to explain this property, consider the equation for magnetisation as given

$$M = N\,\mu_m\,\tanh\left[\frac{\mu_0\mu_m H}{kT}\right]$$

where μ_m represents the permanent magnetic moment of a dipole. Taking μ_m = 1 β (one Bohr magneton), the above equation can be written as

$$M = N\beta\tanh\left[\frac{\mu_0\beta H}{kT}\right]$$

Replacing H by H + γ M in above Eq., we get

$$M = N\beta\tanh\left[\frac{\mu_0\beta(H+\gamma M)}{kT}\right]$$

When T is very high, the value within the square bracket in above Eq. will become small. For smaller value of x, tan hx is = x. Therefore, above Eq. can be written as

$$M = \left[\frac{N\beta^2\mu_0(H+\gamma M)}{kT}\right]$$

Rearranging above Eq. , we get

$$M - \frac{N\beta^2\mu_0\gamma M}{kT} = \frac{N\beta^2\mu_0 H}{kT}$$

$$M - \frac{N\beta^2\mu_0\gamma M}{kT} = \frac{N\beta^2\mu_0 H}{kT}$$

The value of susceptibility can be written as

$$\chi = \frac{M}{H} = \frac{\frac{N\beta^2\mu_0}{kT}}{1 - \frac{N\beta^2\mu_0\gamma}{kT}}$$

$$\chi = \frac{C}{T - \gamma C} \quad \text{or} \quad \chi = \frac{C}{T-\theta} \quad \text{..........(3)}$$

$$Where\ C = \frac{N\beta^2\mu_0}{k}\ and\ \theta = \gamma C$$

Equation (3) gives the susceptibility of a ferromagnetic material, when the temperature is very high. Equation (3) is similar to the susceptibility of a paramagnetic material.

- This shows that ferromagnetic materials behave as paramagnetic materials above a certain temperature known as Curie temperature.
- The **internal field constant** for a ferromagnetic material is equal to **103**. The internal field is due to the wave nature of electrons. According to wave mechanics, the above fields are known as exchange force.

Case (ii): Ferromagnetic Curie Temperature According to the Curie–Weiss law, susceptibility becomes infinite, when T = θ_f .

This shows the existence of a nonvanishing value of M, even though H = 0. The existence of magnetisation even in the absence of a magnetic field is known as **spontaneous magnetisation**.

The spontaneous magnetisation is obtained by substituting, H = 0 in below Eq.

$$M = N\beta \tanh\left[\frac{\mu_0 \beta (H + \gamma M)}{KT}\right] \ldots \ldots . . (4)$$

Therefore, H=0 so that we get $$M = N\beta \tanh\left[\frac{\mu_0 \beta \gamma M}{kT}\right] \ldots\ldots\ldots (5)$$

Let $\boldsymbol{x = \frac{\mu_0 \gamma \beta M}{kT}}$ ....(6)

Substituting the value of x in the above equation, we get

$$M = N\beta \; \tan \mathrm{h}\, x \ldots\ldots . (7)$$

where **Nβ** represents the total magnetisation produced by all dipoles and it is known as **saturation magnetisation, M_s**. Therefore, above Eq. can be written as

$$\frac{M}{N\beta} = \frac{M}{M_s} = \tan h\, x \; \ldots \ldots \ldots \ldots . (8)$$ (Since $N\beta = M_S$)

From Eq. (6), we get $$M = \frac{kT}{\mu_0 \gamma B} x \; \ldots\ldots\ldots\ldots (9)$$

Substituting the value of M from Eq. (9) in Eq. (8), we get

$$\boldsymbol{\frac{M}{M_s} = \frac{kT}{N\mu_0\gamma\beta^2} x} \text{ ....(10)}$$

where $M_s = N\beta$

Therefore, $\frac{M}{M_s} = \frac{T}{\theta} x \ldots\ldots\ldots\ldots\ldots.(11)$

where $\theta = \gamma C = \frac{N\beta^2\gamma}{k}$

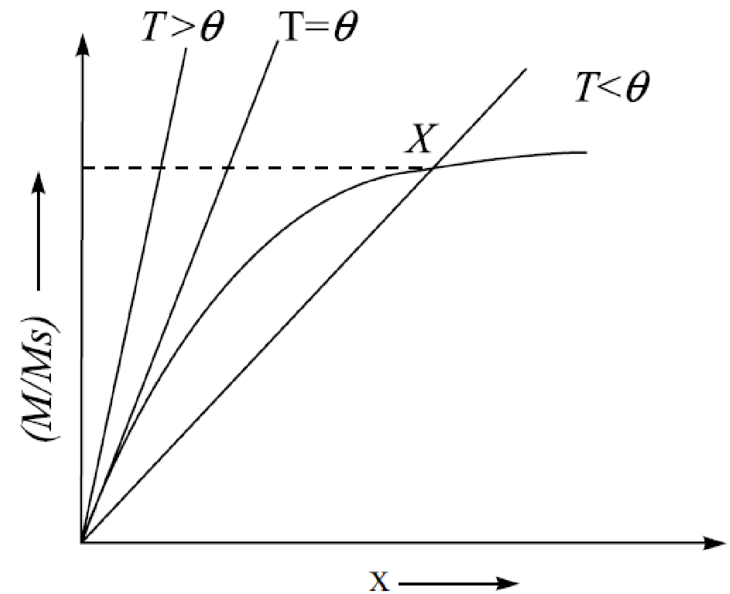


Fig. M/M_s as a function of x

A graphical solution for Eq. (11) is obtained by drawing ***tan hx*** curve between, M/M_s and x as shown in Fig. From Eqs. (8) and Eq. (11), we infer that the value of M/M_s should satisfy these two equations.

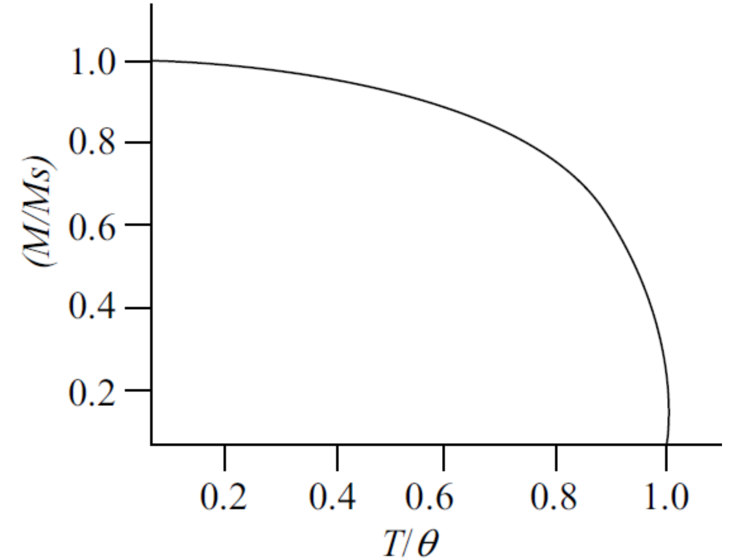
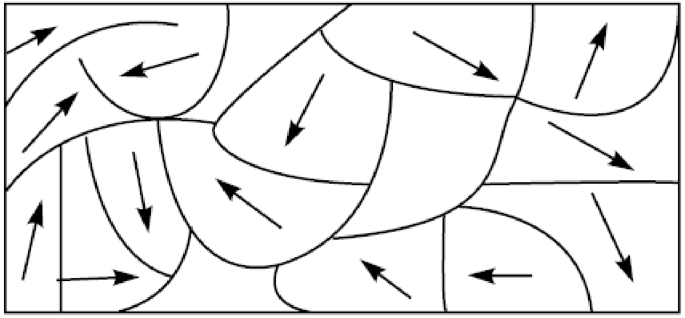


Fig. M/M_s as a function of T/θ

Domain Theory of Ferromagnetism

- The magnetic properties of ferromagnetic materials are explained based on the Weiss domain concept. Hence, this theory is known as domain theory of ferromagnetism.
- The small region within which all spin magnetic moments are aligned in a specific direction is known **as magnetic domain**.
- The smallest region in which there is an alignment of spin in one direction is known as **ferromagnetic domain**.
- The ferromagnetic material consists of a number of domains. Generally, the size of the domain will be of the order of 10^{-6}m or larger.
- Each domain acts as a single magnetic dipole and is oriented in random direction. Therefore, the net magnetisation is zero, in the absence of a magnetic field.



Net magnetisation = 0

(a) Iron—absence of field

- Each domain is separated from other domains by a wall known as **bloch** or **domain wall**.
- When an external magnetic field is applied, the domains which are parallel or nearly parallel to the applied field, **grow in size at the expense of other domains**.
- The domains which are not parallel to the applied field have **a decrease in size**.
- During the **absence of a magnetic field**, even though the magnetic **domains are ordered**, the net magnetisation force in a cubic ferromagnetic crystal is zero.
- When the material is placed in an external magnetic field, the central domain grows at the expense of other domains.

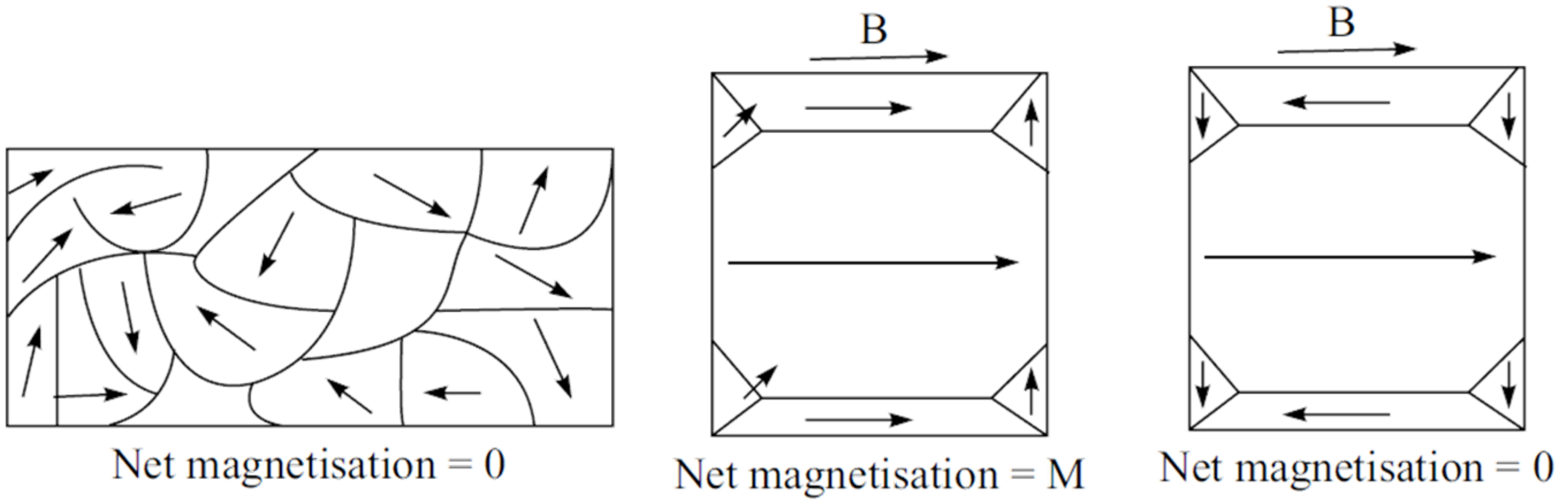


Fig. Ferromagnetic domains

HARD AND SOFT MAGNETIC MATERIALS

Ferromagnetic materials are classified into two types namely, **soft and hard magnetic materials**, based on the characteristic parameters such as **hystersis and magnetisation**.

Soft Magnetic Materials

- Soft magnetic materials are easy to **magnetise and demagnetise**.
- When a small amount of magnetic field is applied, it results in large magnetisation due to easy movements of magnetic domains.
- The degrees of magnetisation and demagnetisation of these materials are very high even for a small applied field.
- In order to prepare soft magnetic materials, the pure material is first heated to the required high temperature. When the temperature is high, the atoms can move freely in the molten state and are allowed to settle in an ordered lattice during slow cooling. The resultant material is a soft magnetic material.
- The potential applications of soft magnetic materials are based on their characteristic properties.

Examples

(1) Iron–nickel–aluminum alloys with a small dopant cobalt known as FeAlNiCo alloy

(2) Iron–silicon alloys

(3) Iron–cobalt–mangann alloys

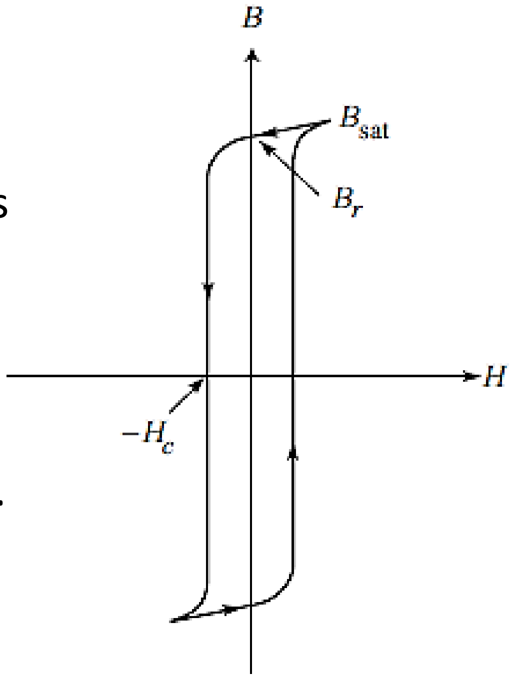
(4) Copper–nickel–iron alloys

Properties

(1) It is easy to magnetise and demagnetise.
(2) Its hysteresis loop is very thin and long
(3) The hysteresis loop area is very less and hence, the hysteresis loss is very small.
(4) The coercive field is very low while the saturation magnetisation is very high.
(5) The susceptibility and permeability values are very high.
(6) Its resistivity is very high and hence, eddy-current loss is very low.
(7) The magnetostatic energy is very small since such materials are free from irregularities like strain.

Applications

a. They are used in transformer cores, motors, relays and sensors.
b. Iron–silicon alloy magnets are used in electrical equipment.
c. Silicon steel magnets are used in alternators and highfrequency rotating materials.
d. Soft magnetic materials are used in storage components and microwave isolators



Hysteresis loop—soft ferrities

Hard Magnetic Materials

- Hard magnetic materials are those which are **difficult to magnetise and demagnetise**.
- These materials require high magnetic field for both magnetisation and demagnetisation.
- It is difficult to rotate the magnetic domains due to the impurities and crystal defects existing in such materials.
- In order to make the materials hard magnetic, the molten mixture which is at a high temperature is rapidly quenched in cold liquid.
- In addition, impurities are added to the base materials to make them hard. The hard magnetic materials are used where a permanent and high magnetic field is required.

Properties

(1) They are hard to magnetise and demagnetise.

(2) The hysteresis loop is very large and hence, hysteresis loss is heavy due to **larger hysteresis area**.

(3) It is very difficult to rotate the domain walls due to impurities and crystal imperfections.

(4) The susceptibility and permeability values are low.

(5) The values of coercivity and resistivity are larger.

(6) The value of eddy current loss is very high.

(7) The mechanical strain is more due to the presence of impurities and crystal imperfections.

Therefore, the magnetostatic energy **is very large**.

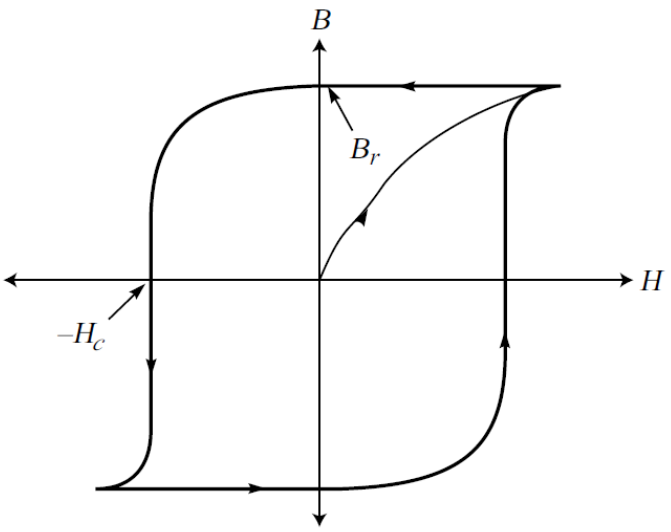


Fig. Hysteresis loop—hard ferities

Examples

AlNiCo, rare earth metal alloys with Mn, Fe, Co, Ni, carbon steels and tungsten steels.

Applications

a. They are used for production of permanent magnetism.
b. The magnetism in toys, compass needles, meters, etc., are made from carbon steel.
c. The magnets in DC motors and measuring devices are made from tungsten steel.
d. Neodymium magnets are used in microphones instead of conventional magnets mainly to reduce the microphone size.
e. Cast AlNiCo magnets are used in speed meters, and sensors in automobiles, motors, etc

Applications of magentic materials :

- **Ferromagnetic** materials are used in magnetic recording devices, such as for cassette tapes, floppy discs for computers, and the magnetic stripe on the back of credit cards.
- **Diamagnetic** materials are used for magnetic levitation, where an object will be made to float in are above a strong magnet.
- **Magnetic soft materials** are used in making electromagnets and these electromagnets are used in telephone receiver, bells, loud speakers etc.
- **Magnetic hard materials** are used in making permanent magnets.

Soft Magnetic Materials Soft magnetic materials are used in a wide variety of electrical machines in daily use, such as power transformers, output transformers, motors, generators, electromagnets etc.

I. **Low Carbon Steel** Pure iron has a higher permeability but its higher electrical conductivity causes more eddy current losses. Low carbon steel (Fe-0.05% C) has a relatively small permeability and a higher resistivity. It is the least expensive core material and is used where low cost is more important than other factors.

II. **Iron-silicon alloys** The addition of about 3-4% silicon to iron produces iron-silicon alloys with improved characteristics. Silicon increases the electrical resistivity of low carbon steel and thus reduces the eddy current losses. It increases the magnetic permeability and lowers hysteresis losses.

III. **Nickel-iron alloys**

- 36% nickel, 50% nickel and 77% nickel. 36% nickel alloys have high resistivity and low permeabilities. They are used for high frequency devices such as high-speed relays, wideband transformers and inductors.
- The 50% nickel alloy have moderate permeability (μ_{max} = 25,000) and high saturation induction (B_{sat} = 1.6T).They are used where low loss and small size are required, such as in relays, small motors and synchros, etc.
- The 79% nickel ally has high permeability ($\mu_{max} = 10^6$) but lower saturation induction (B_{sat} = 0.8 T). They are used in recording heads, pulse transformers, sensitive relays etc.

iv. **Mumetal** Mumetal having a composition of 77% nickel, 16% iron, 5% copper and 2% chromium can be rolled into thin sheets and is used to shield electronic equipment from stray magnetic fields.

v. **Soft ferrites** Some of the most important uses of soft ferrites are for low signal memory core, audiovisual and recording head applications and high frequencies, without the eddy current losses.

vi. **Magnetic Storage Materials** Magnetic materials are widely used for storage of information. The entertainment electronics and computer industries heavily rely on magnetic tapes for the storage and reproduction of audio, video and digital sequences.

Eg. γ-Fe_2O_3, cobalt-doped γ-Fe_2O_3,

Hard Magnetic Materials Hard magnetic materials have a high resistance to demagnetization. A high remanence, high permeability, a high coercive field and a large hysteresis loop characterize the hard magnetic materials.

- **Alnico alloys** Alnico alloys are mechanically hard and brittle. Their magnetic properties are highly stable against variations in temperature.
- **Hard Ferrites** Hard ferrites are used in making permanent magnets. The most important hard ferrites are the barium ferrite ($BaFe_2O_3$) and strontium ferrite ($SrFe_2O_3$). They are widely used in generators, relays, loud speakers, telephone ringers, toys etc. Hard ferrite powders are often mixed with plastic materials to form flexible magnets for door closer and other holding devices.

Thank you