Magnetic properties of material

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Magnetic moment (μ):-

Magnetic moment is the product of current flowing in a coil and the area of that coil. i.e.

$$\mu = I \times A$$

The unit of magnetic moment is Am^2.

Intensity of magnetization (I)

Intensity of magnetization is the magnetic moment produced per unit volume of the material i.e.

$$I = \frac{\mu}{V}$$

The unit of intensity of magnetization is A/m.

T.U. Magnetic susceptibility (χ)

Magnetic susceptibility is the ratio of intensity of magnetization produced to the magnetizing field applied. i.e.

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

Magnetic susceptibility is the unitless quantity.

T.U. Relative permeability (μ_r)

Relative permeability is the ratio of permeability of a medium to the permeability of free space. i.e.

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

The relative permeability has no unit.

T.U.

Relation between relative permeability and susceptibility ($\mu_r = 1 + \chi$)

When a current is allowed to flow through a coil, the free space inside it gets magnetized. The magnetic field induced in this free space is given by,

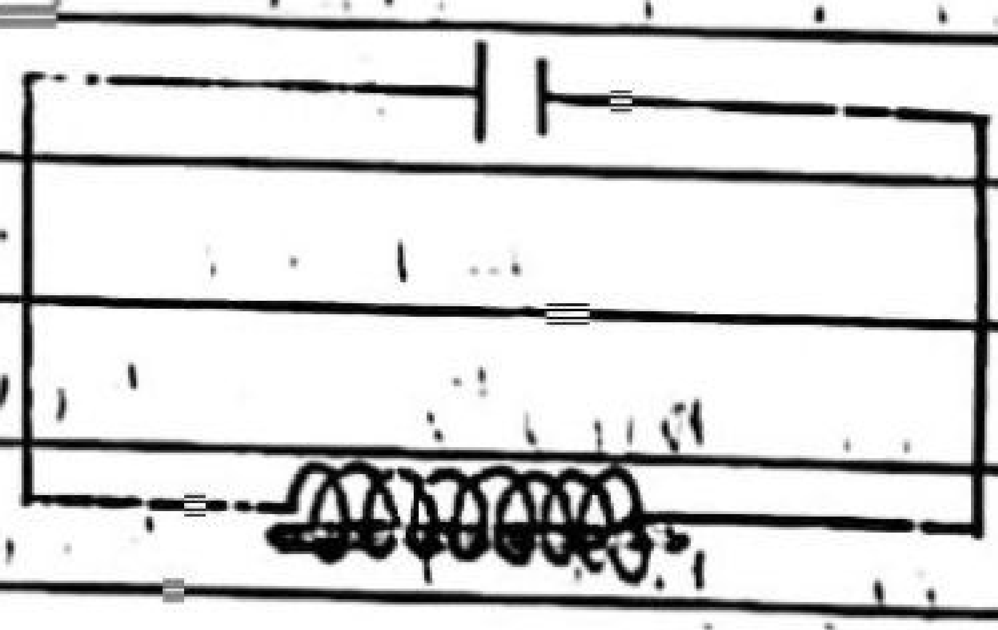
$$B_0 = \mu_0 H$$

If a metallic rod is inserted within this coil, the rod also gets magnetized and produces its own field B_m given by

$$B_m = \mu_0 I$$

In this case, the total magnetic field within the coil becomes

$$B = B_0 + B_m$$



or, $\mu H = \mu_0 H + \mu_0 I$

or, $\mu H = \mu_0 (H + I)$

or, $\dfrac{\mu}{\mu_0} = \left(\dfrac{H + I}{H}\right)$

or, $\mu_r = 1 + \dfrac{I}{H}$

or, $\boxed{\mu_r = 1 + \chi}$ $\left[\because \chi = \dfrac{I}{H}\right]$

This is the required relation between magnetic susceptibility and relative permeability.

Diamagnetic material ③

Diamagnetic material are the materials which are weakly magnetized opposite to the field direction. Such materials are weakly repelled by magnets. Some examples are:- Copper, silver, gold, water etc.

T.U.

Langevin theory of diamagnetism

Diamagnetism is the result of orbital motion of electron in its orbit. For an electron to revolve round the orbit, the centripetal force is needed in such case,

$$F = m\omega^2 r$$

If external magnetic field is applied, the orbital motion of electron is disturbed due to presence of extra Lorentz force Bev. Let $d\omega$ be the change in angular velocity due to application of magnetic field. Then

$$F + Bev = m(\omega + d\omega)^2 r$$

or, $m\omega^2 r + Bev = m(\omega^2 + 2\omega d\omega + d\omega^2)r$

or, $m\omega^2 r + Bev = m\omega^2 r + 2m\omega d\omega r$

or, $Be\omega r = 2m\omega d\omega r$

or, $Be = 2md\omega$

or, $d\omega = \frac{Be}{2m}$

This gives the value of change in angular velocity due to application of magnetic field.

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We have,

$$\omega = 2\pi f$$

or, $d\omega = 2\pi df$

or, $df = \frac{d\omega}{2\pi}$

or, $df = \frac{Be}{4\pi m}$

The change in current arised due to this frequency change is then given by,

$$I = \frac{q}{t} = \frac{-e}{t} = -edf$$

or, $I = -e \cdot \frac{Be}{4\pi m}$

or, $I = -\frac{Be^2}{4\pi m}$

So, magnetic moment (μ) becomes

$$\mu = I \times A = -\frac{Be^2}{4\pi m} \times \pi r^2$$

or, $\mu = -\frac{Be^2 r^2}{4m}$

So, for an atom, total magnetic moment becomes,

$$\mu = -\frac{Be^2 \sum r_i^2}{4m}$$

If N be the no. of atoms per unit volume, then intensity of magnetization (M) becomes

$$M = N\mu$$

or, $$M = -\frac{NBe^2\sum r_i^2}{4m}$$

or, $$M = -\frac{N\mu_0 He^2\sum r_i^2}{4m} \quad [\because B = \mu_0 H]$$

or, $$\frac{M}{H} = -\frac{N\mu_0 e^2\sum r_i^2}{4m}$$

or, $$\boxed{\chi = -\frac{N\mu_0 e^2\sum r_i^2}{4m}} \quad \left[\because \chi = \frac{M}{H}\right]$$

This is the required expression for susceptibility of diamagnetic material. Here, the negative sign means that the material is oppositely magnetized by external field.

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T.U Langevin theory of paramagnetism

According to Langevin, every atom has its own permanent magnetic moment m. When such atom is placed in external magnetic field 'B', the magnetic moment tend to align along the field direction. The P.E. stored in such case is given by,

$$U = -\vec{m}\cdot\vec{B} = -mB\cos\theta$$

or, $$dU = mB\sin\theta\, d\theta$$

According to Maxwell's distribution law, the no. of atoms (per unit volume) present within energy range U and U+dU is given by,

$$dn = Ae^{-\frac{U}{K_BT}} \, d\omega$$

or, $$dn = Ae^{\frac{mB\cos\theta}{K_BT}} \, mB\sin\theta \, d\theta$$

or, $$n = \int dn = \int_0^{\pi} e^{\frac{mB\cos\theta}{K_BT}} \, mB\sin\theta \, d\theta$$

or, $$n = A\int_0^{\pi} e^{x\cos\theta} \, mB\sin\theta \, d\theta \quad \left[\because \text{Let } x = \frac{mB}{K_BT}\right]$$

or, $$A = \frac{n}{\int_0^{\pi} e^{x\cos\theta} \, mB\sin\theta \, d\theta} \quad \text{--- (1)}$$

Here, the value of magnetic moment along the field direction is $m\cos\theta$ for single atom. So, for dn atoms, total magnetic moment becomes $dn \, m\cos\theta$.

So from definition, the intensity of magnetization becomes,

$$M = \int_0^{\pi} dn \, m\cos\theta$$

or, $$M = \int_0^{\pi} Ae^{\frac{mB\cos\theta}{K_BT}} \, mB\sin\theta \, d\theta \, m\cos\theta$$

(using the value of dn)

or, $$M = A\int_0^{\pi} e^{x\cos\theta} \, m^2B\sin\theta\cos\theta \, d\theta$$

or, $$M = n \frac{\int_0^{\pi} e^{x\cos\theta} \, m^2B\sin\theta\cos\theta \, d\theta}{\int_0^{\pi} e^{x\cos\theta} \, mB\sin\theta \, d\theta} \quad \text{[using eqn (1)]}$$

$$\text{or, } M = nm \frac{\int_0^{\pi} e^{x\cos\theta} \sin\theta \cos\theta \, d\theta}{\int_0^{\pi} e^{x\cos\theta} \sin\theta \, d\theta}$$

$$\text{or, } M = nm \cdot \frac{x}{3} \left[\because \frac{\int_0^{\pi} e^{x\cos\theta} \sin\theta \cos\theta \, d\theta}{\int_0^{\pi} e^{x\cos\theta} \sin\theta . d\theta} = \frac{x}{3} \right]$$

$$\text{or, } M = \frac{nm . mB}{3K_BT} \quad \text{(Using the value of } x\text{)}$$

$$\text{or, } M = \frac{nm^2 B}{3K_BT}$$

$$\text{or, } M = \frac{nm^2 \mu H}{3K_BT}$$

$$\text{or, } \frac{M}{H} = \frac{nm^2 \mu}{3K_BT}$$

$$\therefore \chi = \frac{nm^2 \mu}{3K_BT} \left\{ \because \chi = \frac{M}{H} \right\}$$

This is required expression for susceptibility of paramagnetic material. Its positive value means that, the paramagnetic materials are magnetized along the field direction.

From the above relation,

$$\chi \propto \frac{1}{T}$$

This relation explains the curie law.

Paramagnetic materials:-

The materials which are weakly magnetized along the field direction are called paramagnetic materials. Such materials are weakly attracted by magnets. For example:- Aluminium, oxygen, mercury etc.

Domain theory of ferromagnetism

Domains are the very small elementary regions within ferromagnetic materials inside which the alignment of all atomic magnetic moments are parallel. But the alignment is random with respect to different domains. Due to such random alignment for different domains, the net magnetic moment of total sample is zero.

When external magnetic field is applied, all the atomic magnetic moments tend to align along the field direction. So their magnitude & added with each other and hence the material becomes magnetized.

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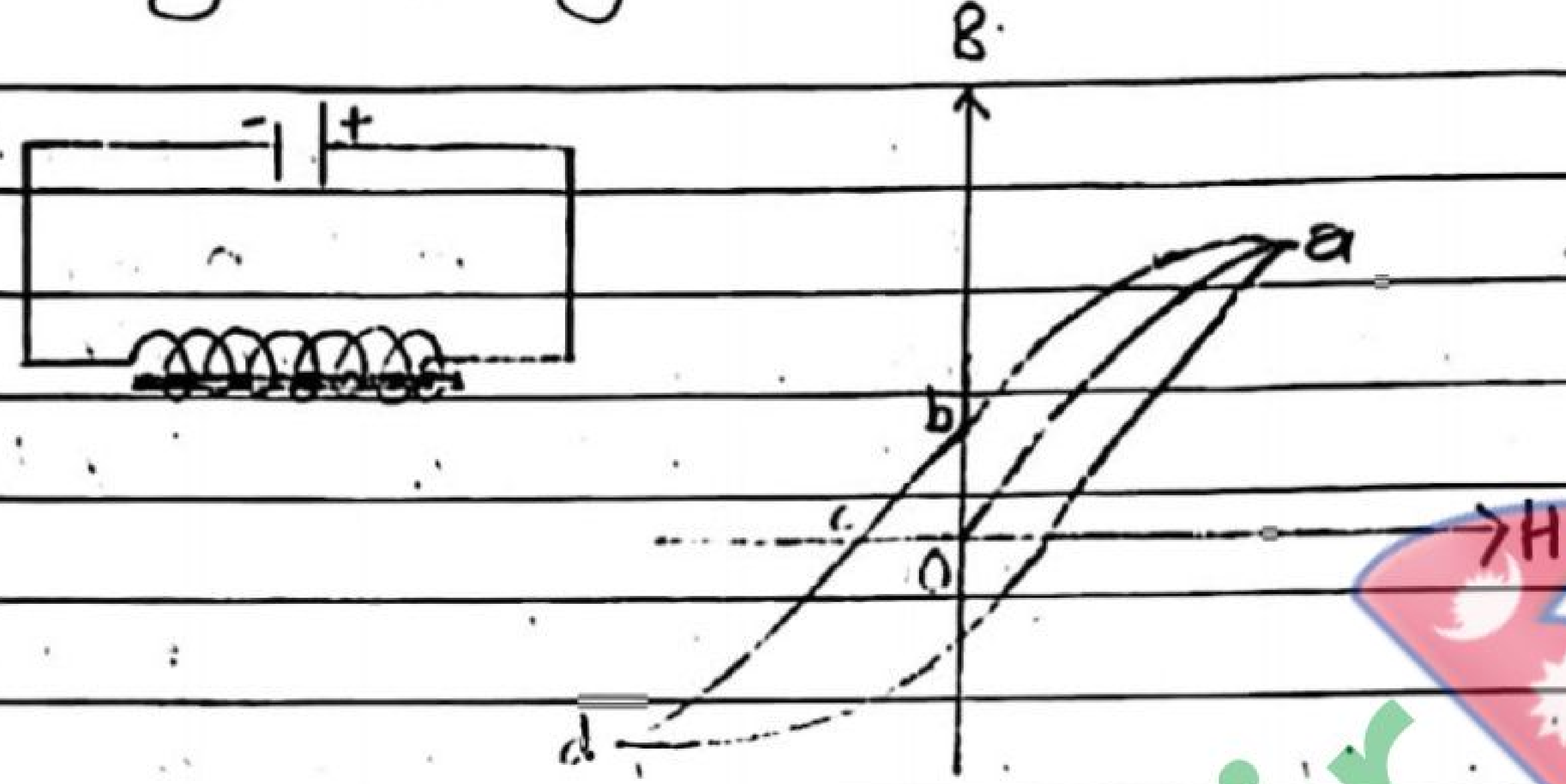
Ferromagnetic hysteresis



Magnetic hysteresis is the phenomenon of lagging behind of magnetic field induction (B) when there is change in the value of magnetising field (H) on the ferromagnetic materials.

When the value of H is gradually increased from zero, the value of B also increases and becomes saturate at certain value. On reducing the value of H the value of B also reduces but at the slower rate. So when H reduces to zero, there remains certain value of B left. This value of B left is called retentive magnetic field (B_r). If H is then increased in opposite direction, the value of B decreases and becomes zero at certain negative value of H called coercive magnetic field (H_c). The complete cycle of magnetization & demagnetization forms a loop in B-H graph called hysteresis loop.

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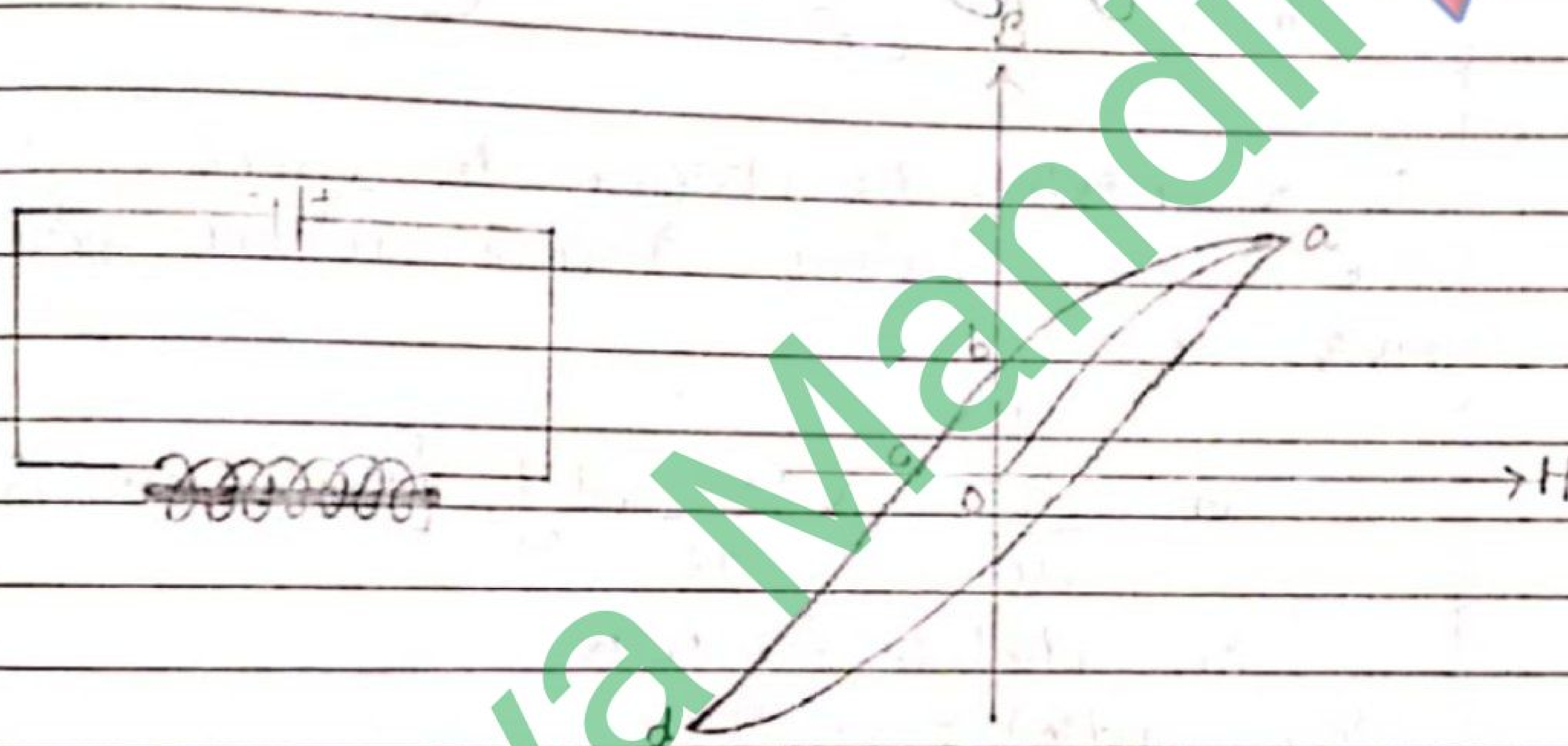
Ferromagnetic materials

The materials which are strongly magnetized along the field direction are called ferromagnetic materials. Such materials are strongly attracted by magnets. For example: iron, steel etc.

Heat loss per unit volume during hysteresis



Suppose a coil of length l and no. of turns N is carrying current I. If a ferromagnetic material is inserted within turns of the coil, the magnetic field induced is given by

$$B = \mu n I$$

or, $\mu H = \mu \frac{N}{l} I$ $\quad \left[\because B = \mu H \text{ \& } n = \frac{N}{l}\right]$

or, $I = \frac{Hl}{N}$ ——— (1)

When there is change in current through the coil, the magnetic flux linked with coil changes and hence back emf is induced in it. The value of emf induced is given by

$$E = \frac{d\phi}{dt}$$

or, $E = \frac{d(NBA)}{dt}$

or, $E = NA\frac{dB}{dt}$ ——— (iii)

To maintain the change in current through the coil, the battery should deliver certain power given by,

$$P = E \cdot I$$

or, $\frac{dW}{dt} = NA\frac{dB}{dt} \cdot \frac{Hl}{N}$ [using eqn (i) & (iv)]

or, $dW = AlHdB$

So, $\int dW = \int AlHdB$

or, $W = Al\int HdB$

or, $W = V\int HdB$ [$\because V = A \times l$]

or, $\frac{W}{V} = \int HdB$

This work done appears in the form of heat. So,

$$\frac{\text{heat produced}}{\text{Volume}} = \int HdB$$

Since $\int xdy$ gives the area below x-y curve, the quantity must give area of B-H curve.

So heat produced per unit volume is equal to area of B-H curve.

Note:-

⟨I⟩ The hysteresis loop of soft iron is smaller so, there is small value of dissipation of heat during the process of magnetization and demagnetization of iron. That is why, iron is used in core of the transformer.

⟨II⟩ Steel has higher value of both coercivity and retentivity. It means that the magnetic field of steel magnet is stronger and it is harder to demagnetize it. That is why, the steel is used in making permanent magnets.