Magnectic Properties of Matter

B.SC HONOURS (PHYSICS)

2ND SEM

CORE COURSE (C3T)

• Magnetisation vector **M**:

We have seen that the source of magnetic field is electric current. The circulating electrons in an atom, being tiny current loops, constitute a magnetic dipole with a magnetic moment whose direction depends on the direction in which the electron is moving. An atom as a whole, may or may not have a net magnetic moment depending on the way the moments due to different elecronic orbits add up.

In the absence of a magnetic field, the atomic moments in a material are randomly oriented and consequently the net magnetic moment of the material is zero. However, in the presence of a magnetic field, the substance may acquire a net magnetic moment either in the direction of the applied field or in a direction opposite to it. The former class of material is known as paramagnetic material while the latter is called diamagnetic.

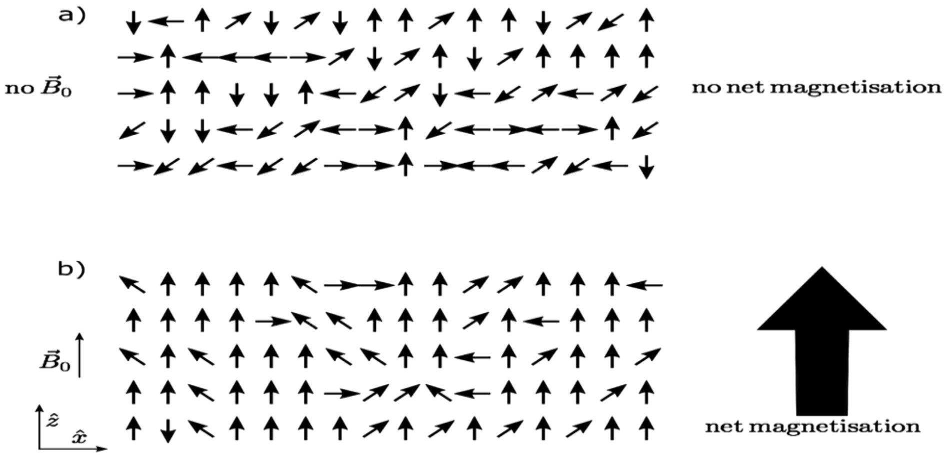


Fig.1

The magnetic dipole moment of an atom can be expressed as an integral over the electron orbits in the Bohr model: $m = \int_{atom} IA\hat{z}$

The current and magnetic moment of the i-th electron are:

$I=ev_i/2\pi r_i$, $m_i=(e/2m_e)L_i$

We define magnetization **M** of a sample as the net magnetic moment per unit volume. The unit of magnetization is Ampere/meter.

$$\boldsymbol{M} = \sum \boldsymbol{m}/V$$

Where V is volume.

Two mechanisms account for this magnetic polarization:

1. Paramagnetism: the dipoles associated with the spins of unpaired electrons experience a torque tending to line them up parallel to the field.
2. Diamagnetism: the orbital speed of the electrons is altered in such a way as to change the orbital dipole moment in the direction opposite to the field.

Bound Currents:

The magnetization current is called bound current because the electron is not free to move through the material as they would in a conductor, but are attached to a particular atom or molecule.

If, however, the magnetization is not uniform within the sample, the internal currents do not cancel and a magnetization current exists even in the bulk. It can be shown that the bound current density is given by

$$\vec{J}_b = \vec{\nabla}\times\vec{M}$$

Similarly the surface bound current is

$$\vec{K}_b = \vec{M}\times\hat{n}$$

Ampere's law and Magnetic intensity **H:**

$$\frac{1}{\mu_0}\vec{\nabla}\times\vec{B} = J = J_b + J_f = J_f = \vec{\nabla}\times\vec{M}$$

$$\Rightarrow \vec{\nabla}\times\left(\frac{1}{\mu}\vec{B}-\vec{M}\right) = J_f$$

$$\Rightarrow \vec{\nabla}\times\vec{H} = J_f$$

Where $\vec{H} = \frac{1}{\mu}\vec{B}-\vec{M}$ **, is called magnetic field intensity.**

Actually the magnetic field **B** generated by free current is calculated from Biot-Savart law or Ampere's Circuital law but when the generated field pass through materials which themselves contribute internal fields , ambiguities can arise about what part of the field comes from the external currents. In this case magnetic intensity H is important.

Now $\mathbf{H}=\mathbf{B}/\mu_0-\mathbf{M}$ or $\mathbf{B}=\mu_0(\mathbf{H}+\mathbf{M})$ →Relation among **B, H, M.**

Magnetic Susceptibility & Relative Permeability:

The magnetization vector is proportional to the external magnetic field strength **H**: $\mathbf{M}=\chi_m H$ where χ_m is the magnetic susceptibility of the material

**Note - some books use $\chi_B=\mu_0 M/B$ instead of $\mathbf{M}=\chi_m H$

Then linear relationship between B, H and M gives
$\mathbf{B}=\mu_0(1+\chi_m)\mathbf{H}$, but in material medium $B=\mu H$

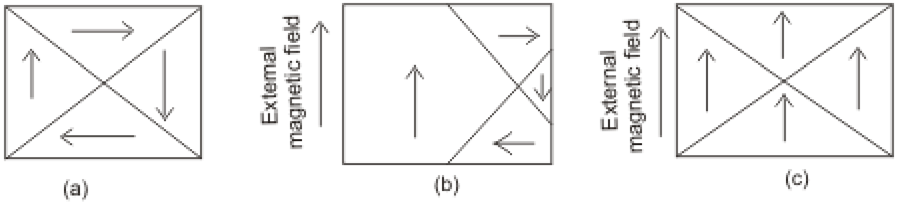
So we can write $\mu=\mu_0(1+\chi_m)$ **or** $\mu_r=\mu/\mu_0=1+\chi_m$ is called relative permeability.

General advice - wherever μ_0 appears in electromagnetism, it should be replaced by $\mu_r\mu_0$ for magnetic materials

concept of ferromagnetism

- Ferromagnetism is the existence of the spontaneous magnetization ,even in the absence of an external magnetic field.
- Internal magnetic field in ferromagnetism may be hundred or thousand times greater than that of diamagnetic and paramagnetic material.
- Relation between I and H magnetization intensity and magnetic field is not linear. M and H are no longer have direct proportionality in case of ferromagnetic materials .hence magnetic susceptibility is very large but no longer constant.
- Even in the absence of external field some ferromagnetic material exhibits large magnetization and can become permanent magnetized.
- Some of the elements exhibiting ferromagnetic properties at room temperature are iron ,nickel,cobalt and gadolinium.
- Because of complicated relation ship between I and H in case of ferromagnetic material, it is not possible to express M as a function of H
- So when a piece of unmagnetized iron is brought near a magnet or is subjected to the magnetic field of an electric current, the magnetization induced in iron by the field is described by a magnetization curve obtained by plotting the intensity of magnetization M against the field strength H
- Ferromagnetism can occur only in paramagnetic material i.e molecule and atoms of a ferromagnetic material also has unpaired electrons and hence non -zero permanent magnetic moment.
- All ferromagnetic materials are composed of many small magnets or domains ,each of which consists of many atoms within a domain. Size of a domain is usually microscopic

•Within the domain, all magnetic moments are aligned ,but the alignment of magnetic moments varies from domain to domain which result in zero net magnetic moment of the macroscopic piece of material as a whole shown below in fig 2(a)



(a) (b) (c)

Figure 2

when the substance is placed in an external field ,magnetism of substance can increase in two different ways

(i) By the displacement of the boundaries of the domain where domains oriented favourably with respect to the external field increase in and those oriented opposite to the external field are reduced in size as shown in fig 2(b)

(ii) By the rotation of domain that is the domain rotate until their magnetic moments are aligned more or less in the direction of the externally applied magnetic field

In presence of week magnetic field material is magnetized mostly by the displacement of the domains and in presence of strong fields magnetization takes place mostly by the rotation of the domains.

In case of ferromagnetic materials on removal of the external magnetic field ,material is not completely demagnetized and some residual magnetization remains in it

Every ferromagnetic material has a critical temperature known as curie temperature (T_c) above which material becomes paramagnetic and this transition of material from ferromagnetic to paramagnetic is a phase change or phase transition analogous to those between solid, liquid and gaseous phases of the matter.

Hysteresis

We have already mentioned that in case of ferromagnetic materials ,the relation between M or I and H is not linear. This relation can even depend on the history of the sample i.e whether it has been previously magnetized or not.

when we place a ferromagnetic material in the magnetic field it gets magnetized by induction. If the field strength is first increased from a zero to high value and then decreased again, it is observed that the original curve is not retraced, the induction lags behind and follows a characteristics curve. This phenomenon is known as Hysteresis and characteristics curve is known as hysteresis loop as shown below in the curve.

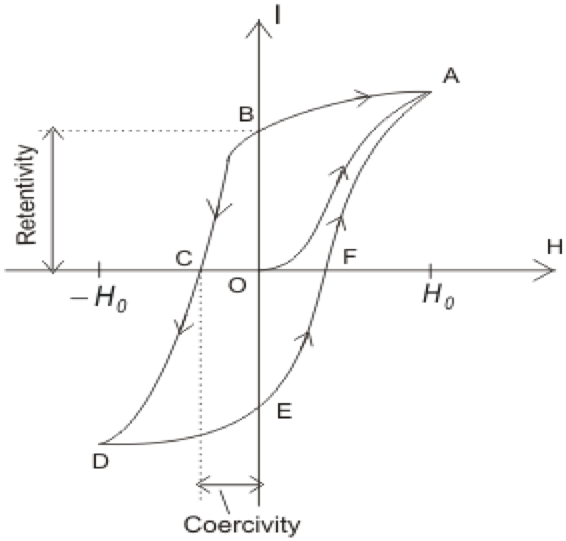


Figure 3:- Variation of I with H

Figure 3 shows the variation of I and H. In the beginning I= 0 and H=0 as represented by the point O in the figure. At this instant the sample is in unmagnetized state.

As value of H is increased, I also increases non uniformly. If we increase H indefinitely the intensity of magnetization of ferromagnetic material approaches finite limit known as saturation.

Thus at $H=H_0$,the magnetization becomes nearly saturated and magnetization and magnetization varies along path OA.

Now if we begin to decrease the value of magnetic field ,the magnetization I of the substance also begin to decrease but this time not following the path AO but following a new path AB.

when H becomes equal to zero, I still have value equal to OB,This magnetization remaining in substance when magnetizing field becomes equal to zero is called the residual magnetism and the remaining value of I at point B is known as retentively of the material.

To reduce I to zero, we will increase field H in reverse direction and the magnetization I decreases following curve BC where at point C,I becomes equal to zero where H=OC.

The value OC of the magnetizing field is called coercivity of the substance.

the coercivity of the substance is a measure of the reverse magnetizing field required to bring magnetization I equal to zero, if we further increase H beyond OC the sample begins to get magnetized in reverse direction ,again getting saturated at D at $H=-H_0$

while taking back H from its negative value through zero to its original maximum positive value H_0,we symmetrical curve DEFA.

Thus we see that if the field strength is first increased from zero to saturated and then decreased again, it is observed that original curve is not retraced, the induction lags behind the field and follows a characteristic curve. This phenomenon is known as hysteresis and the characteristic curve (Here ABCDEFA) is known as Hysteresis loop.

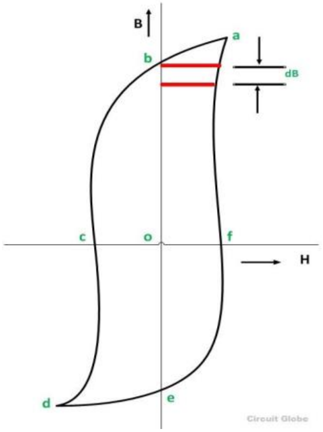
Hysteresis Loss

Definition: The work done by the magnetising force against the internal friction of the molecules of the magnet, produces heat. This energy which is wasted in the form of heat due to hysteresis is called **Hysteresis Loss.**

When in the magnetic material, magnetisation force is applied, the molecules of the magnetic material are aligned in one particular direction. And when this magnetic force is reversed in the opposite direction, the internal friction of the molecular magnets opposes the reversal of magnetism resulting in Magnetic Hysteresis.

Magnitude of Hysteresis Loss

The figure below shows one cycle of magnetisation of the magnetic material.



Consider a strip of small thickness dB on the hysteresis loop as shown in the above
For any value of current I, the corresponding value of flux is,

$$\varphi = B \times A \qquad weber$$

For the small charge dφ that are dB x A, the work done will be given as
dW = (ampere-turn) x (change of flux)

$$\mathrm{dW = NI \times (dB \times A) \quad Joules}$$

$$\mathrm{dW = N\left(Hl/_n\right)(dB \times A)\ \ Joules\ (as\ H = {}^{NI}/_{l})}$$

$$\mathrm{dW = H\,(Al)\,dB \quad Joules\ldots\ldots\ldots(1)}$$

The total work done during a complete cycle of magnetisation is obtained by integrating both the side of the above equation 1

$$\mathrm{W = \int H\,(Al)\,dB = Al\int H\,dB\ \ Joules}$$

Where ∫ HdB is the area of the hysteresis loop
Therefore, W=Al x (area of the hysteresis loop) or
Work done /unit volume (W/m^3) = area of the hysteresis loop in Joules.
Now if f is the number of cycles of magnetisation made per second, then Hysteresis loss/m^3 = (area of one hysteresis loop) x (f joules/second or Watts).