Electronics Engineering

Materials Science

Comprehensive Theory

with Solved Examples and Practice Questions

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CHAPTER 3

Magnetic Properties of Materials

The materials which can be magnetised are called magnetic materials. All materials show some magnetic effect. In many substances the effects are so weak that the materials are often considered to be non-magnetic. However, a vacuum is the only truly non-magnetic medium.

The response of a material at electronic, atomic, molecular and microscopic level to a magnetic field constitutes magnetic properties. Many characteristics of the magnetic materials are similar to the characteristics of the dielectric materials. Atoms and molecules give magnetic dipole moments similar to electric dipole moments. Some magnetic materials exhibit spontaneous magnetization just like spontaneous polarization in dielectrics. The study of magnetic materials can be done parallel to the study of dielectric materials. The difference is that individual electric charges of one sign do exist, whereas, magnetic monopole does not occur. While the electric field is due to fundamental charges, the magnetic field is always associated with an electric current flowing in a loop.

3.1 Parameters

There are three parameters to study the behaviour of magnetic materials:

- Permeability (μ)
- Magnetic dipole moment (p_m)
- Magnetic dipole
- Magnetization (M)

3.1.1 Permeability

Permeability is the ratio of magnetic flux density to the magnetic field intensity present at that material

$$\boxed{\mu = \frac{B}{H}} \qquad \text{...(3.1)}$$

Where, $\mu = \mu_0 \mu_r$

= Permeability

B = Magnetic flux density

H = Magnetic field intensity

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

= Permeability of non-magnetic medium (vacuum)

μ_r = Relative permeability

⇒ The factor μ is constant for some materials, but for some materials, the direction in space of vectors $\vec{B}$ and $\vec{H}$ are not the same, in that case μ becomes a tensor.

A quantity expressed as $\chi_m = \mu_r - 1$ is defined as magnetization per unit magnetic field intensity and is called **magnetic susceptibility (χ_m)**. This is a dimensionless quantity because magnetization and field intensity have the same units.

NOTE: As $\mu_r \overset{<}{\underset{>}{-}} 1$; so χ_m can have values negative or positive or equal to zero.

3.1.2 Magnetic Dipole

A current loop constitutes a magnetic dipole.

Origin of permanent magnetic dipole in materials

Whenever a charged particle has a angular momentum, particle will contribute to permanent magnetic dipole moment. In general there are three contribution to the angular momentum of an atom.

1. Orbital electron angular momentum → Due to orbital motion of electron.
2. Electron spin angular momentum → Due to self spin of electron.
3. Nucleus spin angular momentum → Due to nucleus spin.

NOTE: Magnetic properties of materials are affected only by electron spin angular momentum.

3.1.3 Magnetic Dipole Moment

The magnetic field produced by a small current loop is similar to the electric field produced from a small electric dipole. For this reason a small current loop is called magnetic dipole. Its dipole moment is defined as equal to the product of the area of the plane loop and the magnitude of circulating current. The vector direction of the dipole moment is perpendicular to the plane of the loop and is along the direction of a right hand screw when moved in the direction of current in the loop

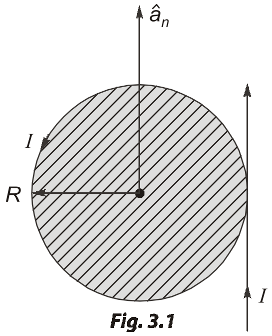


Fig. 3.1

$$\text{Area } \vec{A} = A\hat{a}_n$$

So, dipole moment,
$$\boxed{\vec{p}_m = IA\hat{a}_n} \quad \text{...(3.2)}$$

Unit of dipole moment is “Ampere/meter^2”.

3.1.4 Magnetization

In the presence of magnetic field all materials acquire magnetic dipole moments. The magnitude of dipole moment per unit volume, is called the **magnetization** of the medium (material) and is described by a vector $\vec{M}$ A/m. When a magnetic field is applied to a material, the magnetic induction (flux density) is the sum of the effect on vacuum and that on the material, so that,

$$\vec{B} = \mu_0\vec{H} + \mu_0\vec{M} \quad \text{...(3.3)}$$
$$= \mu_r\vec{H}$$

Then,
$$\vec{M} = (\mu_r - 1)\vec{H}$$
$$= \chi_m\vec{H} \quad \text{...(3.4)}$$

where, χ_m is the magnetic susceptibility, a dimensionless quantity.

The magnetization $\vec{M}$ of a material may be expressed in terms of its elementary magnetic dipole moments, $\vec{p}_m$ by

$$\boxed{\vec{M} = N\vec{p}_m} \qquad \text{...(3.5)}$$

where N is the number of magnetic dipoles per unit volume.

Equation (3.4) gives the definition of **magnetic susceptibility**, $\chi_m (= \mu_r - 1)$ of the medium as the magnetization per unit magnetic field, and is a pure number.

Media are generally classified by the sign and magnitude of their susceptibility, such that:

⇒ χ_m is negative and typically in the range of -10^{-5} if the material is **diamagnetic.**

⇒ χ_m is small and positive, typically ~ 10^{-3} at room temperature if the material is **paramagnetic.**

⇒ **Ferromagnetic** materials have large positive values of χ_m.

3.2 Magnetic Dipole Moment

In any magnetic material three types of magnetic dipole moments are always found even in the absence of external magnetic field.

- Orbital magnetic dipole moment.
- Electron spin dipole moment.
- Nucleus spin dipole moment.

3.2.1 Orbital Magnetic Dipole Moment

Let us consider how an atomic model behaves as an elementary magnet.

Let us consider the Bohr model of an atom in which an electron describes a circular orbit of radius r, with a stationary nucleus at the centre. The model is represented in figure (3.2). Let us assume that the electron rotates in the orbit with an angular velocity ω_0 radians/second, in the direction indicated in figure (3.2).

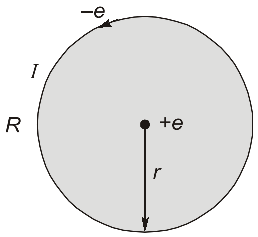


Fig. 3.2 : *Elementary magnet (Bohr Atom)*

Due to the rotation of the electron, atom behaves like a current carrying loop with zero resistance. Such an electron may be said to behave as an elementary magnet. The current associated with the electron will be ef, where, $f = \dfrac{\omega_0}{2\pi}$, is the frequency of rotation. Thus the magnetic dipole moment of the orbit is

$$\left|p_{m_{\text{orb}}}\right| = \text{Current} \times \text{Area enclosed by the current}$$

$$= ef\pi r^2$$

$$= \frac{1}{2} e\omega_0 r^2 \qquad \text{...(3.6)}$$

This dipole moment is called the orbital dipole moment of the atom.

Orbital magnetic dipole moment in vector form can be given as below:

$$\boxed{\vec{p}_{m_{\text{orb}}} = -\frac{1}{2} e\omega_0 r^2 \, \hat{a}_n} \qquad \text{...(3.7)}$$

Bohr Magneton

Angular momentum, $\vec{M}_a = mr \times \vec{v}$

$$\Rightarrow \qquad \boxed{\vec{M}_a = m\,r^2\,\omega_0 \hat{a}_n} \qquad \text{...(3.8)}$$

So, $\vec{p}_m = -\frac{1}{2}\frac{e}{m}\vec{M}_a$

Now applying Bohr's postulate,

$$1\,\beta = \left|\vec{p}_{\text{morb}}\right|$$

$$\Rightarrow \qquad 1\,\beta = \frac{1}{2}\frac{e}{m}\cdot\frac{h}{2\pi} \qquad \left(\because \vec{M}_a = \frac{h}{2\pi}\right) \text{ Put, } n = 1$$

$$\Rightarrow \qquad \boxed{1\beta = 9.27 \times 10^{-24}\ \text{Am}^2} \qquad \text{...(3.9)}$$

3.2.2 Electron Spin Dipole Moment

The dipole moment resulting from spin of electrons is known as electron spin magnetic dipole moment. The magnitude of electron spin dipole moment is always greater than the orbital magnetic dipole moment i.e.

$$\left|\vec{p}_{m_{\text{spin}}}\right| > \left|\vec{p}_{m_{\text{orb}}}\right|$$

In terms of Bohr magnetron electron spin dipole moment is given as

$$\boxed{e^- \text{ spin dipole moment} = m\beta} \qquad \text{...(3.10)}$$

where m is the number of unpaired electrons present in the atom.

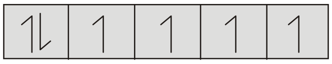
For example consider the electronic configuration of following atoms:

Ca –20 → $1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 4s^2$

Number of unpaired electrons = 0

∴ Electron spin dipole moment = 0.β

Fe – 26 → $1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 4s^2, 3d^6$



Number of unpaired electrons = 4

∴ Electron spin dipole moment = 4β

3.2.3 Nucleus Spin Dipole Moment

Dipole moment due to spin of the nucleus results in nucleus spin dipole moment and it has least effect in the overall dipole moment of the atom.

A force acting on a particle during a period dt, changes its momentum and can be written as

$$f\,dt = d(mv) = m\,dv \qquad \text{...(3.11)}$$

where v is the velocity of the particle. At any instant t let $\omega(t)$ be the angular frequency of the electron, then.

The force acting on the electron = $\frac{er}{2}\frac{dB}{dt}$

By using equation (3.11), $\frac{er}{2}\frac{dB}{dt}dt = m\,r\,d\omega$

$$\text{or} \qquad d\omega = \frac{e}{2m}dB \qquad \text{...(3.12)}$$

when $B = 0$, we have $\omega = \omega_0$.

Integrating equation (3.12), the angular velocity for any value of B becomes

$$\boxed{\omega = \omega_0 + \frac{e}{2m}B} \qquad \text{...(3.13)}$$

In equation (3.13), $\frac{e}{2m}B$ is the change in the angular frequency of the electron due to flux density and is called **Larmor angular frequency.** When $B = 0$, the dipole moment was

$$p_{mi} = -\frac{1}{2}e\omega_0 r^2$$

and after the field is applied, it becomes

$$p_{mf} = -\frac{1}{2}e\,\omega_0 r^2 - \frac{e^2}{4m}r^2 B$$

The magnetic dipole moment induced by the field is

$$\boxed{p_{m_{ind}} = p_{mf} - p_{mi} = -\frac{e^2}{4m}r^2\,B} \qquad \text{...(3.14)}$$

Note that induced dipole moment has a direction opposite to the applied magnetic field and is independent of the initial angular velocity, ω_0 of the electron.

3.3 Classification of Magnetic Materials

A material possesses magnetic properties on account of

1. motion of charges and
2. permanent magnetic dipoles or moments of the atom or electrons.

Hence those materials which lack permanent magnetic dipoles are called **diamagnetic.**

Those atoms which possess permanent magnetic dipoles may be **paramagnetic, ferromagnetic, antiferromagnetic or ferrimagnetic** depending on the interaction between individual dipoles.

Paramagnetic

In this material, the interaction between adjacent dipole moments of atoms is negligible or zero.

Ferromagnetic

The dipole moment of neighbouring atoms are aligned in a particular direction (parallel) to each other and there is a strong magnetic field.

Antiferromagnetic

The permanent dipole moment of neighbouring atoms are aligned opposite to each other (antiparallel) so that there is no magnetization.

Ferrimagnetic

The dipole moments of neighbouring atoms are aligned antiparallel like antiferromagnetic. But these magnitudes are unequal so that there is large net magnetization like ferromagnetic materials. Figure (3.3) indicates dipole arrangements for different magnetic behaviours. Table 3.1 summarizes features of different magnetic behaviour of materials.

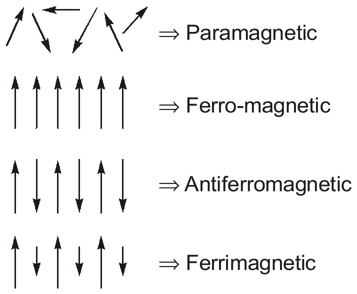


***Fig. 3.3 :** Different magnetic behaviour of materials (arrangement of dipole moments of spins)*

Table-3.1

Type	Susceptibility x_m	x_m Vs T relation	Examples
1. Diamagnetic	$\sim -10^{-6}$ (negative)	Independent	Atoms of solids having closed shells and some metal Au, Ge, etc.
2. Paramagnetic	$\sim -10^{-5}$ (positive)	$x_m = \frac{C}{T}$ Curie-law or $x_m = \frac{C}{T-\theta}$ Curie-Weiss law	Atoms possessing odd number of electrons, ionic crystals, etc. $MnSO_4$, Fe_2O_3 Cr_2O_3, $FeCl_2$ etc.
3. Ferromagnetic	Very large and positive	$(x_m \to \infty)$	Iron, cobalt, nickel, godolinium
4. Antiferromagnetic	Small and positive	x_m decreases with temperature	Salts and oxides of transition metals, e.g. NiO, MnF_2
5. Ferrimagnetic	Large and positive	$x_m \to \infty$	Ferrites, e.g. FeO_4

3.3.1 Diamagnetic Material

⇒ Permanent dipole moment is absent in the absence of external field

$$\vec{p}_m = \vec{p}_{m_{\text{spin}}} + \vec{p}_{m_{\text{orb}}} = 0$$

$$\vec{p}_{m_{\text{spin}}} = -\vec{p}_{m_{\text{orb}}}$$

⇒ The magnetic susceptibility of diamagnetic material is negative and of the order of 10^{-5} i.e.

$$\chi_m = -10^{-5} \text{ to } -10^{-6}$$

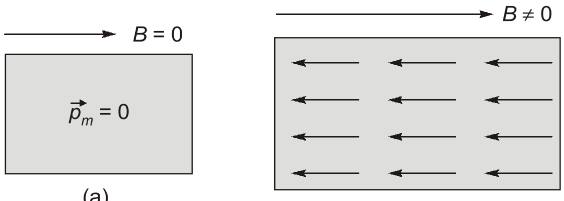
⇒ For perfect diamagnetic material

$$\boxed{\chi_m = -1}$$

⇒ In diamagnetic materials magnetization is achieved in the opposite direction of applied magnetic field

$$\vec{M} = \chi_m \vec{H}$$

⇒ $$\vec{M} = (-ve)\vec{H}$$



(a)

Fig. 3.4 (b)

⇒ Field inside the material

$$B_{\text{int}} = \mu H$$

or $$B_{\text{int}} = \mu_0 \mu_r H$$

and $$\mu_r = 1 + \chi_m$$

For diamagnetic material χ_m is negative.

∴ $$\mu_r < 1$$

so, $$B_{\text{int}} < \mu_0 H$$

or $$B_{\text{int}} < B_{\text{ext}}$$

Field outside the material, $$B_{\text{ext}} = \mu_0 H$$

Hence when an external field is applied to a diamagnetic material, it expose the magnetic lines as shown in figure 3.5 (a). Figure 3.5 (b) gives B-H curve for a diamagnetic substance.

Solution: 5

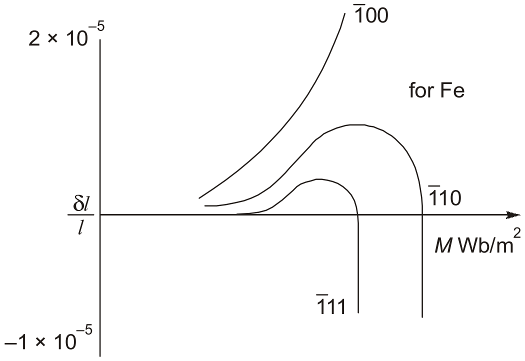
Magnetostriction means the change in length along the direction of magnetization of a multidomain solid. The humming sound of a transformer core magnetic material is due to Magnetostriction phenomenon. The iron lamina undergoes alterations in their dimensions at 50 cycles per second of the AC voltage and current which causes magnetization and magnetostriction to produce vibration and sound effects.

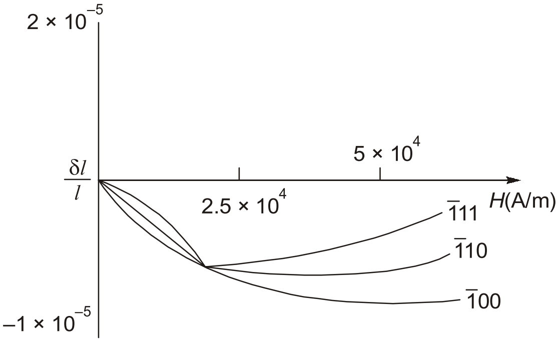
Atomic theory: When the magnetic electron-spin dipole moments of the atoms in a solid are rotated into alignment, the length of the bonds between the atoms, changes. The fields of these dipoles affect the atomic spacing as they may attract or repel each other. Therefore the shape and volume of ferromagnetic material undergo changes as it is magnetised. The principal change called Magnetostriction is a reversible strain along the axis of magnetization. Depending on the solid the magnetic material, may expand or contract. The magnetostriction is non-isotropic because the elastic properties are anisotropic.

For any given crystal direction, the magnetostriction approaches a final constant value at high H-field. Magnetostriction and magnetisation usually saturate at the same time.

The graph shows magnetostriction versus applied *H*-field curves for Ni and Fe single crystals at <100>, <110> and <111> field orientations.

The strain $\frac{\delta l}{l}$ along *H*-axis is plotted as a function of H-intensity.





Student's Assignments 2

Q.1 A bar magnet made of steel has a magnetic moment of 2.5 A-m^2 and a mass of 6.6×10^3 kg. If the density of steel is 7.9×10^3 kg/m^3, the intensity of magnetization is

(a) 8.3 A/m (b) 3 A/m

(c) 6.3 A/m (d) 9.2 A/m

Q.2 According to Curie law for paramagnetic materials, how is the susceptibility χ is related to absolute temperature T?

(a) $\chi \propto T$ (b) $\chi \propto 1/T$

(c) $\chi \propto T^2$ (d) $\chi \propto 1/T^2$

Q.3 Match **List-I** with **List-II** and select the correct answer using the codes given below the lists:

	List-I		**List-II**
A.	Larmor frequency	**1.**	$\chi = C/(T - \theta)$
B.	Bohr magnetron	**2.**	$B = \mu_0(H + M)$
C.	Magnetic induction	**3.**	$eh/4\pi m$
D.	Curie-Weiss law	**4.**	$eB/2m$

Codes:

	A	B	C	D
(a)	2	1	4	3
(b)	2	3	4	1
(c)	4	1	2	3
(d)	4	3	2	1

Q.4 Find the magnitude of the magnetic flux density in a material for which the magnetisation is 2.8 A/m and susceptibility is 0.0025

(a) 1.41×10^{-3} Wb/m^2
(b) 2.52×10^{-3} Wb/m^2
(c) 2.93×10^{-3} Wb/m^2
(d) 3.49×10^{-3} Wb/m^2

Q.5 Consider the following statements regarding diamagnetic material

1. χ_m is positive and small.
2. χ_m is independent of temperature.
3. Diamond is a diamagnetic material.
4. It posses induced dipoles.

Which of the above statements is/are correct?

(a) 2 only (b) 2 and 3
(c) 2, 3 and 4 (d) 1 and 4

Q.6 What happens when a paramagnetic material is heated above Curie temperature?

(a) It becomes diamagnetic.
(b) It becomes non-magnetic.
(c) It becomes ferromagnetic.
(d) It becomes anti-ferromagnetic.

Q.7 Temperature below which certain materials are anti-ferromagnetic is called

(a) Curie temperature (b) Neel temperature
(c) Wein temperature (d) Debye temperature

Q.8 For a permanent magnetic material

(a) the residual induction and the coercive field should be large
(b) the residual induction and the coercive field should be small
(c) the area of hysteresis loop should be small
(d) the initial relative permeability should be large

Q.9 Match **List-I** (Magnetic materials) with **List-II** (Dipole arrangement in external field) and select the correct answer using the codes given below:

List-I

A. Paramagnetic
B. Ferromagnetic
C. Antiferromagnetic
D. Ferrimagnetic

List-II

1. All dipoles are aligned in one preferred direction and have equal magnitudes
2. Half of the dipoles are aligned in opposite direction and have equal magnitudes
3. Half of the dipoles (with equal magnitudes) are aligned in opposite direction to other half having equal but lower magnitudes
4. All dipoles have equal magnitudes but are randomly oriented

Codes:

	A	B	C	D
(a)	4	3	2	1
(b)	4	1	2	3
(c)	2	1	4	3
(d)	2	3	4	1

Q.10 Consider the following statements:

In a transformer, the core material should have low

1. coercivity
2. retentivity
3. permeability

Which of these statements are correct?

(a) 1 and 2 (b) 2 and 3
(c) 1 and 3 (d) 1, 2 and 3

Q.11 Which of the following are the properties of ferromagnetic domains?

(a) Permanent magnetisation
(b) Atomic moments in individual domains are all aligned neither parallel to nor perpendicular to one another below Curie point temperature
(c) Each domain is magnetically saturated
(d) Above Curie temperature, domains disrupt

Q.12 The material which has the property of becoming electrically polarized in response to an applied mechanical stress is termed as

(a) Ferroelectric (b) Piezoelectric
(c) Optoelectronic (d) Superconducting

4. (a)

$$B = \mu_0 (H + M)$$

$$= \mu_0\left(\frac{M}{\chi_m} + M\right) = \mu_0 M\left(\frac{1}{\chi_m} + 1\right)$$

$$= 4\pi \times 10^{-7} \times 2.8 \times \left(\frac{1}{0.0025} + 1\right)$$

$$= 1.41 \times 10^{-3}\ \text{Wb/m}^2$$

5. (c)

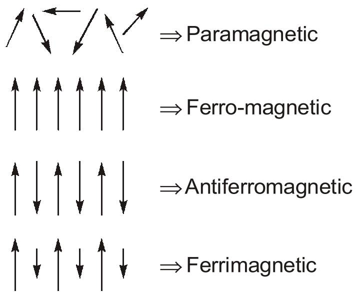
For diamagnetic materials, χ_m is negative.

8. (a)

Permanent magnetic materials are those which retain a considerable amount of their magnetic energy after the magnetizing force has been removed, i.e. the materials which are difficult to demagnetize. Therefore for a permanent magnetic material, the residual induction and coercive field should be large.

9. (b)

The arrangement of dipole moments in different magnetic materials is shown below:



10. (a)

In a transformer, the core material should have low coercivity, retentivity and high permeability.

11. (c)

In ferromagnetic material, all domains are aligned parallel to each other below Curie temperature.

13. (d)

Resistivity of ferrites is very much higher than that of ferromagnetic materials.

15. (c)

Above Curie temperature, the ferroelectric material becomes paraelectric.

17. (b)

It should have high $B_{\text{saturation}}$ and low coercive field H_C.

18. (b)

4% Si - Fe is a soft magnetic material having coercive field $H_C = 40$ amp-m^{-1}.

19. (d)

Magnetic cores should have low hysteresis and eddy current losses.