CHAPTER 37

MAGNETIC PROPERTIES OF MATTER

37.1 MAGNETIZATION OF MATERIALS: INTENSITY OF MAGNETIZATION

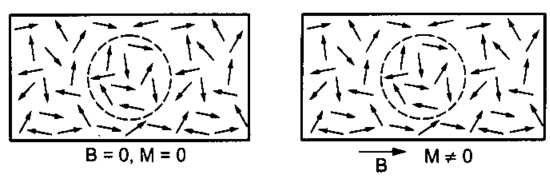
Matter is made of atoms and atoms are made of nuclei and electrons. The electrons in an atom move about the nucleus in closed paths and hence constitute electric current loops. As a current loop has a magnetic dipole moment, each electron in an atom has a magnetic moment due to its orbital motion. Besides this, each electron has a permanent angular momentum which is present even if it is at rest. This permanent angular momentum is called the *spin angular momentum* of the electron and can be understood only through quantum mechanics. Corresponding to its spin, each electron has a permanent magnetic moment. This magnetic moment has a fixed magnitude $\mu_s = 9{\cdot}285 \times 10^{-24}\ \mathrm{J\,T^{-1}}$. The magnetic moment due to the motion of the electron is over and above this. The nucleus may also have a magnetic moment but it is about several thousand times smaller than the magnetic moment of an electron. The resultant magnetic moment of an atom is the vector sum of all such magnetic moments.

The magnetic moments of the electrons of an atom have a tendency to cancel in pairs. Thus, the magnetic moments of the two electrons of a helium atom cancel each other. In a number of atoms and ions, the resultant magnetic moment is zero. But in some cases, the magnetic moment of an atom is not zero. Such an atom may be represented by a magnetic dipole having a permanent magnetic moment. We shall first discuss materials made of such atoms.

Any object of finite size contains a large number of atoms. In general, the magnetic moments of these atoms are randomly oriented and there is no net magnetic moment in any volume of the material that contains more than several thousand atoms (figure 37.1a). This volume is still quite small at macroscopic scale. However, when the material is kept in an external magnetic field, torques act on the atomic dipoles and these torques try to align them parallel to the field (figure 37.1b). The alignment is only partial, because, the thermal motion of the atoms frequently changes the orientation of the atoms and hence tries to randomize the magnetic moments. The degree of alignment increases if the strength of the applied field is increased and also if the temperature is decreased. With sufficiently strong fields, the alignment is near perfect. We then say that the material is magnetically *saturated.*

When the atomic dipoles are aligned, partially or fully, there is a net magnetic moment in the direction of the field in any small volume of the material. We define the *magnetization vector* $\vec{I}$ as the magnetic moment per unit volume. It is also called the *intensity of magnetization* or simply *magnetization.* Thus,

$$\vec{I} = \frac{\text{magnetic moment}}{\text{volume}} = \frac{\vec{M}}{V}. \quad \ldots \ (37.1)$$



(a) (b)

Figure 37.1

The unit of magnetic moment is ampere metre^2 so that from equation (37.1) the unit of I is ampere metre^{-1}.

Consider a bar magnet of pole strength m, length $2l$ and area of cross-section A. The magnetic moment of the bar magnet is $M = 2ml$. The intensity of magnetization is

$$I = \frac{M}{V} = \frac{2ml}{A(2l)} = \frac{m}{A}.$$

Thus, for a bar magnet, the intensity of magnetization may be defined as the *pole strength per unit face area.*

Example 37.1

A bar magnet made of steel has a magnetic moment of $2{\cdot}5\ \mathrm{A\,m^2}$ *and a mass of* $6{\cdot}6 \times 10^{-3}$ kg. *If the density of* *steel is* $7 \cdot 9 \times 10^{3}$ kg m^{-3}, *find the intensity of magnetization of the magnet.*

Solution : The volume of the bar magnet is

$$V = \frac{\text{mass}}{\text{density}} = \frac{6 \cdot 6 \times 10^{-3}\ \text{kg}}{7 \cdot 9 \times 10^{3}\ \text{kg m}^{-3}}$$

$$= 8 \cdot 3 \times 10^{-7}\ \text{m}^{3}.$$

The intensity of magnetization is

$$I = \frac{M}{V} = \frac{2 \cdot 5\ \text{A m}^{2}}{8 \cdot 3 \times 10^{-7}\ \text{m}^{3}} \approx 3 \cdot 0 \times 10^{6}\ \text{A m}^{-1}.$$

37.2 PARAMAGNETISM, FERROMAGNETISM AND DIAMAGNETISM

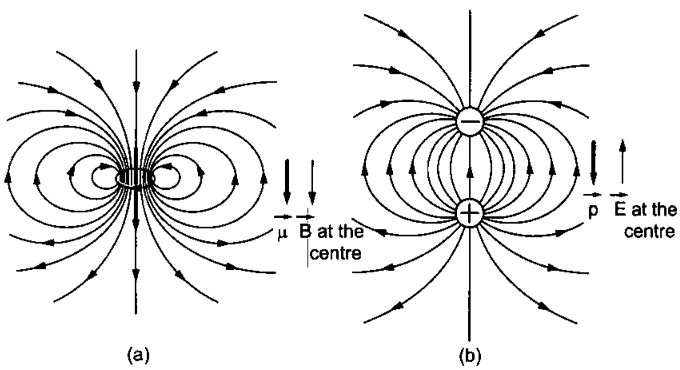


Figure 37.2

Figure (37.2a) shows a current loop and the magnetic field lines associated with it. The dipole moment $\vec{\mu} = i\vec{A}$ is also shown in the figure. The magnetic field at the centre of the dipole is in the direction of $\vec{\mu}$. This behaviour is opposite to that in the case of an electric dipole. The electric field at the centre of an electric dipole is opposite to the dipole moment (figure 37.2b).

Thus, when a magnetic field aligns the atomic dipoles in its direction, the magnetized material produces an extra magnetic field in the material in the direction of the applied field. The resultant magnetic field in the material is then greater than the applied field. The tendency to increase the magnetic field due to magnetization of material is called *paramagnetism* and materials which exhibit paramagnetism are called *paramagnetic materials.*

In some materials, the permanent atomic magnetic moments have strong tendency to align themselves even without any external field. These materials are called ferromagnetic materials and permanent magnets are made from them. The force between neighbouring atoms, responsible for their alignment, is called *exchange coupling* and it can only be explained by quantum mechanics. In normal unmagnetized state, the atoms form domains inside the material as suggested by figure (37.3). The atoms in any domain have magnetic moments in the same direction giving a net large magnetic moment to the domain. Different domains, however, have different directions of magnetic moment and hence, the material remains unmagnetized. Different domains have different sizes, the size may be as large as a millimetre in linear dimension. Remember, a volume of 1 mm^{3} contains about 10^{20} atoms !

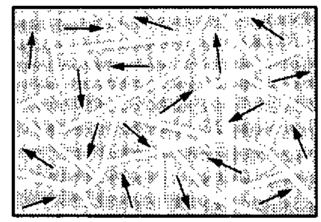


Figure 37.3

If a magnetic field is applied, the domains which are aligned along the direction of the field grow in size and those opposite to it get reduced. This happens because walls of the domains move across the sample. Also, domains may orient themselves in favour of the applied field. Figure (37.4) shows a qualitative description of the processes of domain-growing and domain-alignment.

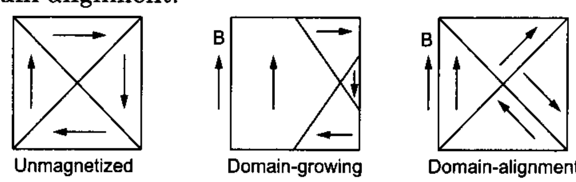


Figure 37.4

Because of the domain character of ferromagnetic materials, even if a small magnetic field is applied, it gives rise to large magnetization. The resultant field is much larger than the applied field in such a material.

Now suppose, the individual atoms of a material do not have a net magnetic dipole moment. When such a substance is placed in a magnetic field, dipole moments are induced in the atoms by the applied field. From Lenz's law, the magnetic field due to the induced magnetic moments opposes the original field. The resultant field in such materials is, therefore, smaller than the applied field. This phenomenon is called *diamagnetism* and such materials are called *diamagnetic* materials.

Magnetic moments are induced in all materials whenever a magnetic field is applied. Thus, all materials have the property of diamagnetism. However, if there is a permanent atomic magnetic moment, paramagnetism or ferromagnetism is much stronger than diamagnetism and the material does not show diamagnetic properties.

37.3 MAGNETIC INTENSITY H

When a magnetic field is applied to a material, the material gets magnetized. The actual magnetic field inside the material is the sum of the applied magnetic field and the magnetic field due to magnetization. It is convenient to define a new vector field

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{I} \qquad \text{... (37.2)}$$

where $\vec{B}$ is the resultant magnetic field and $\vec{I}$ is the intensity of magnetization. This quantity $\vec{H}$ is called *magnetic intensity* or *magnetizing field intensity*. The unit of H is the same as that of I, that is, ampere metre $^{-1}$. If no material is present (vacuum), $\vec{I} = 0$ and we have

$$\vec{H} = \frac{\vec{B}}{\mu_0}. \qquad \text{... (37.3)}$$

Thus, the magnetic intensity due to a current element $i\,d\vec{l}$ is, from Biot–Savart law,

$$d\vec{H} = \frac{1}{4\pi} \frac{i\,d\vec{l} \times \vec{r}}{r^3}. \qquad \text{... (37.4)}$$

The magnetic intensity due to a magnetic pole of pole strength m at a distance r from it is

$$H = \frac{m}{4\pi r^2}. \qquad \text{... (37.5)}$$

Whenever the end effects of a magnetized material can be neglected, the magnetic intensity due to magnetization is zero. This may be the case with a ring-shaped material or in the middle portion of a long rod. The magnetic intensity in a material is then determined by the external sources only, even if the material is magnetized.

Example 37.2

Find the magnetic intensity H at the centre of a long solenoid having n turns per unit length and carrying a current i (a) when no material is kept in it and (b) when a long copper rod is inserted in the solenoid.

Solution : (a) When there is no rod, the magnetic field at the centre of the solenoid is given by

$$B = \mu_0 ni.$$

The magnetic intensity is

$$H = \frac{B}{\mu_0} = ni.$$

(b) As the solenoid and the rod are long and we are interested in the magnetic intensity at the centre, the end effects may be neglected. There is no effect of the rod on the magnetic intensity at the centre. Its value in both cases are the same. Thus $H = ni$.

37.4 MAGNETIC SUSCEPTIBILITY

For paramagnetic and diamagnetic substances, the intensity of magnetization of a material is directly proportional to the magnetic intensity. Thus,

$$\vec{I} = \chi \vec{H}. \qquad \text{... (37.6)}$$

The proportionality constant χ is called the *susceptibility* of the material. Table (37.1) gives susceptibility of some chosen materials. As I and H have the same dimensions, the susceptibility χ is a dimensionless constant. As there can be no magnetization in vacuum, $I = 0$ and hence $\chi = 0$. The materials with positive value of χ are paramagnetic and those with negative value of χ are diamagnetic.

Table 37.1 : *Susceptibilities of some materials*

Material	Temperature in °C	χ in 10^{-5}
Vacuum		Zero
Air	STP	0·04
Oxygen (gas)	STP	0·18
Magnesium	20	1·2
Aluminium	20	2·1
Tungsten	20	6·8
Titanium	20	7·06
Cerium	18	130
Ferric chloride	20	306
Oxygen (liquid)	– 219	490
Carbon dioxide (1 atm)	20	$-2{\cdot}3 \times 10^{-4}$
Nitrogen (1 atm)	20	$-5{\cdot}0 \times 10^{-4}$
Hydrogen (1 atm)	20	$-9{\cdot}9 \times 10^{-4}$
Sodium	20	– 0·24
Copper	18	– 0·96
Lead	18	– 1·6
Carbon (diamond)	20	– 2·2
Silver	20	– 2·6
Mercury	18	– 2·8
Gold	20	– 3·6
Carbon (graphite)	20	– 9·9
Bismuth	20	– 16·6

37.5 PERMEABILITY

The magnetic intensity is given by

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{I}$$

or,

$$\vec{B} = \mu_0(\vec{H} + \vec{I})$$
$$= \mu_0(\vec{H} + \chi\vec{H})$$
$$= \mu_0(1 + \chi)\vec{H}.$$

We can write,

$$\vec{B} = \mu\vec{H} \qquad \text{... (37.7)}$$

where $\mu = \mu_0(1+\chi)$ is a constant called the *permeability* of the material. The permeability of vacuum is μ_0 as $\chi = 0$ for vacuum. The constant

$$\mu_r = \frac{\mu}{\mu_0} = 1 + \chi \qquad \dots (37.8)$$

is called the *relative permeability* of the material.

The significance of relative permeability may be understood by the following simple description. Consider a long solenoid (or a toroid) having n turns per unit length and carrying a current i. The magnetic field B_0 inside the solenoid is

$$B_0 = \mu_0 ni$$

and the magnetic intensity is $H = ni$.

Now suppose, a material is inserted into the solenoid. The magnetic field now becomes

$$B = \mu H = \mu ni$$

or,
$$\frac{B}{B_0} = \frac{\mu}{\mu_0} = \mu_r.$$

Thus, μ_r is the factor by which the magnetic field B is increased when a material is brought in the field.

Example 37.3

Find the per cent increase in the magnetic field B when the space within a current-carrying toroid is filled with aluminium. The susceptibility of aluminium is $2{\cdot}1 \times 10^{-5}$.

Solution : In absence of aluminium, the magnetic field is

$$B_0 = \mu_0 H.$$

As the space inside the toroid is filled with aluminium, the field becomes

$$B = \mu H = \mu_0(1+\chi)H.$$

The increase in the field is

$$B - B_0 = \mu_0 \chi H.$$

The per cent increase is

$$\frac{B - B_0}{B_0} \times 100 = \frac{\mu_0 \chi H}{\mu_0 H} \times 100$$
$$= \chi \times 100$$
$$= 2{\cdot}1 \times 10^{-3}.$$

37.6 CURIE'S LAW

As the temperature is increased, the randomization of individual atomic magnetic moments increases, decreasing the magnetization I for a given magnetic intensity H. The resultant magnetic field B decreases, which means χ decreases as T increases. *Curie's law* states that far away from saturation, the susceptibility of a paramagnetic substance is inversely proportional to the absolute temperature:

$$\chi = \frac{c}{T} \qquad \dots (37.9)$$

where c is a constant called the *Curie constant*. When a ferromagnetic material is heated, it becomes paramagnetic at a certain temperature. This temperature is called *Curie point* or *Curie temperature*. After this, the susceptibility varies with temperature as

$$\chi = \frac{c'}{T - T_c} \qquad \dots (37.10)$$

where T_c is the Curie point and c' is a constant. The Curie point of iron is 1043 K.

Table 37.2 : *Curie temperatures for some ferromagnetic substances*

Substance	T_c (K)
Iron	1043
Cobalt	1394
Nickel	631
Gadolinium	317
Fe_2O_3	893

37.7 PROPERTIES OF DIA-, PARA- AND FERROMAGNETIC SUBSTANCES

Suppose a material is placed in an external magnetic field. If the material is paramagnetic, a small magnetization occurs in the direction of the field. If it is ferromagnetic, a large magnetization occurs in the direction of the field and if the material is diamagnetic, a small magnetization occurs opposite to the field. The lines of magnetic field $\vec{B}$, thus, become more dense in a paramagnetic or ferrormagnetic material but become less dense in a diamagnetic material.

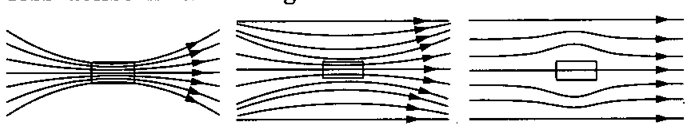


Figure 37.5

The magnetic susceptibility is a small but positive quantity ($\approx 10^{-3}$ to 10^{-5}) for paramagnetic substances; of the order of several thousands (positive) for ferromagnetic substances and small but negative for diamagnetic substances. The relative permeability $\mu_r = 1 + \chi$ is slightly more than 1 for paramagnetic, of the order of thousands for ferromagnetic and slightly less than 1 for diamagnetic substances.

Paramagnetism or diamagnetism may be found in solids, liquids or gases but ferromagnetism is normally found only in solids.

A paramagnetic substance is weakly attracted by a magnet, a ferromagnetic substance is strongly attracted by a magnet and a diamagnetic substance is weakly repelled by a magnet. Thus, when a rod is suspended in a magnetic field (figure 37.6), the rod becomes perpendicular to the field if it is diamagnetic and parallel to the field if it is paramagnetic or ferromagnetic.

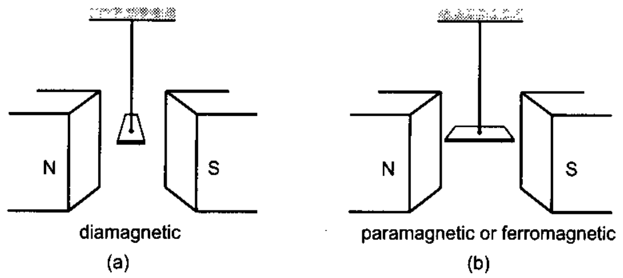


Figure 37.6

The susceptibility is inversely proportional to the absolute temperature for paramagnetic substances but it varies in a complicated way for ferromagnetic substances. For diamagnetic substances, the variation of χ with temperature is very small.

One can make permanent magnets from ferromagnetic substances only. Hysteresis (explained below) is also shown by ferromagnetic substances only.

37.8 HYSTERESIS

The magnetization in a ferromagnetic material not only depends on the magnetic intensity H but also on the previous history of the specimen. Suppose a ferromagnetic material is formed in the shape of a ring and is placed inside a toroid having n turns per unit length. A current i can be passed through the toroid to produce a magnetic intensity H in it. The magnetic field produced by the current is

$$B_0 = \mu_0 n i$$

and hence $$H = \frac{B_0}{\mu_0} = ni. \quad \ldots \text{ (i)}$$

Note that B_0 is the field produced by the toroid-current only. The ring gets magnetized and produces an extra field due to magnetization. The total field in the ring is

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

or, $$I = \frac{B}{\mu_0} - H$$

$$= \frac{B}{\mu_0} - ni. \quad \ldots \text{ (ii)}$$

One can measure the total field B inside the ring by using an apparatus known as Rowland's ring. The intensity of magnetization I can then be obtained from equation (ii). Thus, from (i) and (ii) one can obtain H and I for any current.

Figure (37.7) shows a typical magnetization curve when the current is changed. In the beginning, the current is zero and the sample has no magnetization.

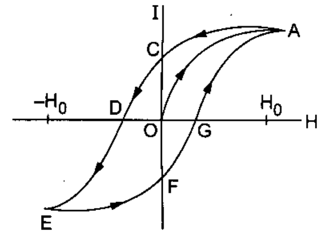


Figure 37.7

Thus, $H = 0$ and $I = 0$. This corresponds to the point O. As the current is increased, H increases and the magnetization increases. As the current is increased to a maximum, H becomes H_0 and the magnetization I becomes nearly saturated. In the whole process, the magnetization varies along the path OA. Now suppose, the current is gradually decreased. The magnetization decreases but the path OA is not retraced. As the current reduces to zero, H also becomes zero. But, there is still some magnetization left in the ring. The domains, that were aligned at the time of increasing H, are not completely randomized as the magnetic intensity H is reduced to zero. The remaining value of I at the point C is called the *retentivity* of the material. To reduce I to zero, a current must be passed in the opposite direction so as to disalign the domains forcibly. The value of H needed to make $I = 0$ is called *coercive force*. In figure (37.7), the coercive force is represented by the magnitude of H corresponding to OD. As the current is increased further in the opposite direction, the material gets magnetized in the opposite direction. The magnetization I follows the path DE as the magnetic intensity becomes $-H_0$. If the current is now reduced to zero, the magnetization I follows the path EF. Finally, if the current is increased in the original direction, the point A is reached via FGA. If we repeat the current cycle so that H changes from H_0 to $-H_0$ to H_0, the curve $ACDEFGA$ is retraced.

As H is increased and then decreased to its original value, the magnetization I, in general, does not return to its original value. This fact is called *hysteresis*. The curve $ACDEFGA$ is called the *hysteresis loop*. The area of the hysteresis loop is proportional to the thermal energy developed per unit volume of the material as it goes through the hysteresis cycle.

37.9 SOFT IRON AND STEEL

Figure (37.8) shows hysteresis loops for soft iron and steel. The retentivity and the coercive force are larger for steel than for soft iron. The area of the hysteresis loop is also larger for steel than for soft iron. Soft iron is, therefore, easily magnetized by a magnetizing field but only a small magnetization is retained when the field is removed. Also, the loss of energy, as the material is taken through periodic variations in magnetizing fields, is small. Materials

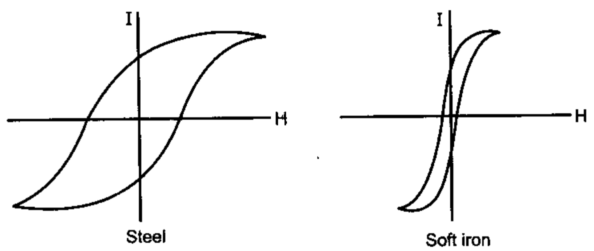


Figure 37.8

like soft iron are suitable for making electromagnets and cores inside current-carrying coils to increase the magnetic field. In transformers, moving-coil galvanometers, etc., soft-iron core is used in the coils.

On the other hand, steel and similar materials are suitable for making permanent magnets. Large magnetizing fields are needed to appreciably magnetize the material. But once magnetized, the magnetization is retained to a large extent even when the magnetizing field is removed (retentivity is large). The magnetization is not easily destroyed even if the material is exposed to stray reverse fields (coercive force is large).

Worked Out Examples

1. *A tightly-wound, long solenoid having* 50 turns cm^{-1}, *carries a current of* 4·00 A. *Find the magnetic intensity H and the magnetic field B at the centre of the solenoid. What will be the values of these quantities if an iron core is inserted in the solenoid and the magnetization I in the core is* $4{\cdot}00\times 10^{6}\ A\ m^{-1}$?

Solution : The magnetic intensity H at the centre of a long solenoid is

$$H = ni$$
$$= 50\times 10^{2}\ m^{-1}\times 4\ A = 2\times 10^{4}\ A\ m^{-1}.$$

The magnetic field $B=\mu_0 H$

$$= 4\pi\times 10^{-7}\ Tm\ A^{-1}\times 2\times 10^{4}\ A\ m^{-1}$$
$$= 8\pi\times 10^{-3}\ T\approx 25\ mT.$$

The value of H does not change as the iron core is inserted and remains $2\times 10^{4}\ A\ m^{-1}$. The magnetic field B becomes

$$B=\mu_0(H+I)$$
$$=(4\pi\times 10^{-7}\ Tm\ A^{-1})\,(2\times 10^{4}+4\times 10^{6})\ A\ m^{-1}=5{\cdot}05\ T.$$

It should be noted that the magnetic intensity H is very small as compared to the magnetization I in presence of the iron core.

2. *A long, cylindrical iron core of cross-sectional area* $5{\cdot}00\ cm^{2}$ *is inserted into a long solenoid having* 2000 turns m^{-1} *and carrying a current* 2·00 A. *The magnetic field inside the core is found to be* 1·57 T. *Neglecting the end effects, find the magnetization I of the core and the pole strength developed.*

Solution : The magnetic intensity H inside the solenoid is

$$H = ni = 2000\ m^{-1}\times 2\ A = 4000\ A\ m^{-1}.$$

Also $B=\mu_0(H+I)$

or, $$I=\frac{B}{\mu_0}-H$$

$$=\frac{1{\cdot}57\ T}{4\pi\times 10^{-7}\ Tm\ A^{-1}}-4000\ A\ m^{-1}$$
$$=(1{\cdot}25\times 10^{6}-4000)\ A\ m^{-1}\approx 1{\cdot}25\times 10^{6}\ A\ m^{-1}.$$

Note again that the magnetization $I >> H$ for iron core. The pole strength developed at the ends is

$$m = IA$$
$$=(1{\cdot}25\times 10^{6}\ A\ m^{-1})\times(5\times 10^{-4}\ m^{2})=625\ A\ m.$$

3. *An ideal solenoid having* 40 turns cm^{-1} *has an aluminium core and carries a current of* 2·0 A. *Calculate the magnetization I developed in the core and the magnetic field B at the centre. The susceptibility* χ *of aluminium* $= 2{\cdot}3\times 10^{-5}$.

Solution : The magnetic intensity H at the centre of the solenoid is

$$H = ni = 4000\ \text{turns}\ m^{-1}\times 2{\cdot}0\ A$$
$$= 8000\ A\ m^{-1}.$$

The magnetization is $I=\chi H$

$$=2{\cdot}3\times 10^{-5}\times 8000\ A\ m^{-1}=0{\cdot}18\ A\ m^{-1}.$$

The magnetic field is $B=\mu_0(H+I)$

$$=(4\pi\times 10^{-7}\ Tm\ A^{-1})\,[800+0{\cdot}18]\ A\ m^{-1}\approx 3{\cdot}2\pi\times 10^{-4}\ T.$$

Note that $H >> I$ in case of a paramagnetic core.

4. *Find (a) the magnetization I, (b) the magnetic intensity H and (c) the magnetic field B at the centre of a bar magnet having pole strength* 3·6 A m, *magnetic length* 12 cm *and cross-sectional area* $0{\cdot}90\ cm^{2}$.

Solution : (a) Magnetization $I=\dfrac{m}{A}=\dfrac{3{\cdot}6\ A\ m^{-1}}{0{\cdot}90\times 10^{-4}\ m^{2}}$

$$=4\times 10^{4}\ A\ m^{-1}.$$

The direction will be from the south pole to the north pole at the centre of the magnet.

(b) Magnetic intensity H_n due to the north pole is

$$H_n=\frac{1}{4\pi}\frac{m}{d^{2}}=\frac{3{\cdot}6\ A\ m^{-1}}{4\pi\times(6\times 10^{-2}\ m)^{2}}=79{\cdot}6\ A\ m^{-1}.$$

The direction will be towards the south pole. The magnetic intensity H_s at this point due to the south pole is also $79.6\ A\ m^{-1}$ in the same direction. The resultant magnetic intensity is

$$H = H_n + H_s$$

$$= 159{\cdot}2\ \mathrm{A\ m^{-1}}$$ towards the south pole.

(c) The magnetic field $\vec{B}$ at the centre is

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

or, $$B = (4\pi \times 10^{-7}\ \mathrm{Tm\ A^{-1}})\,(4 \times 10^{4} - 159{\cdot}2)\ \mathrm{A\ m^{-1}}$$

$$= 5{\cdot}0 \times 10^{-2}\ \mathrm{T}.$$

The field is towards the north pole.

5. *The maximum value of the permeability of* μ*-metal* (77% *Ni*, 16% *Fe*, 5% *Cu*, 2% *Cr*) *is* $0{\cdot}126\ \mathrm{Tm\ A^{-1}}$. *Find the maximum relative permeability and susceptibility.*

Solution : Relative permeability is

$$\mu_r = \frac{\mu}{\mu_0} = \frac{0{\cdot}126\ \mathrm{Tm\ A^{-1}}}{4\pi \times 10^{-7}\ \mathrm{Tm\ A^{-1}}}$$

$$= 1{\cdot}00 \times 10^{5}.$$

Susceptibility $\chi = \mu_r - 1 \approx 1{\cdot}00 \times 10^{5}$.

6. *A toroid has a mean radius R equal to* $20/\pi$ cm, *and a total of* 400 *turns of wire carrying a current of* 2·0 A. *An aluminium ring at temperature* 280 K *inside the toroid provides the core. (a) If the magnetization I is* $4{\cdot}8 \times 10^{-2}\ \mathrm{A\ m^{-1}}$, *find the susceptibility of aluminium at* 280 K. *(b) If the temperature of the aluminium ring is raised to* 320 K, *what will be the magnetization* ?

Solution : (a) The number of turns per unit length of the toroid is

$$n = \frac{400}{2\pi R}.$$

The magnetic intensity H in the core is

$$H = ni$$

$$= \frac{400 \times 2{\cdot}0\ \mathrm{A}}{2\pi \times \frac{20}{\pi} \times 10^{-2}\ \mathrm{m}} = 2000\ \mathrm{A\ m^{-1}}.$$

The susceptibility is

$$\chi = I/H$$

$$= \frac{4{\cdot}8 \times 10^{-2}\ \mathrm{A\ m^{-1}}}{2000\ \mathrm{A\ m^{-1}}} = 2{\cdot}4 \times 10^{-5}.$$

(b) The susceptibility χ of a paramagnetic substance varies with absolute temperature as $\chi = c/T$.

Thus, $\chi_2/\chi_1 = T_1/T_2$.

The susceptibility of aluminium at temperature 320 K is, therefore,

$$\chi = \frac{280}{320} \times 2{\cdot}4 \times 10^{-5} = 2{\cdot}1 \times 10^{-5}.$$

Thus, the magnetization at 320 K is

$$I = \chi H$$

$$= 2{\cdot}1 \times 10^{-5} \times 2000\ \mathrm{A\ m^{-1}}.$$

$$= 4{\cdot}2 \times 10^{-2}\ \mathrm{A\ m^{-1}}.$$

□

QUESTIONS FOR SHORT ANSWER

1. When a dielectric is placed in an electric field, it gets polarized. The electric field in a polarized material is less than the applied field. When a paramagnetic substance is kept in a magnetic field, the field in the substance is more than the applied field. Explain the reason of this opposite behaviour.
2. The property of diamagnetism is said to be present in all materials. Then, why are some materials paramagnetic or ferromagnetic ?
3. Do permeability and relative permeability have the same dimensions ?
4. A rod when suspended in a magnetic field stays in east–west direction. Can we be sure that the field is in the east–west direction ? Can it be in the north–south direction ?
5. Why cannot we make permanent magnets from paramagnetic materials ?
6. Can we have magnetic hysteresis in paramagnetic or diamagnetic substances ?
7. When a ferromagnetic material goes through a hysteresis loop, its thermal energy is increased. Where does this energy come from ?
8. What are the advantages of using soft iron as a core, instead of steel, in the coils of galvanometers ?
9. To keep valuable instruments away from the earth's magnetic field, they are enclosed in iron boxes. Explain.

OBJECTIVE I

1. A paramagnetic material is placed in a magnetic field. Consider the following statements:

(A) If the magnetic field is increased, the magnetization is increased.

(B) If the temperature is increased, the magnetization is increased.
(a) Both A and B are true.
(b) A is true but B is false.
(c) B is true but A is false.
(d) Both A and B are false.

2. A paramagnetic material is kept in a magnetic field. The field is increased till the magnetization becomes constant. If the temperature is now decreased, the magnetization
(a) will increase (b) decrease
(c) remain constant (d) may increase or decrease.

3. A ferromagnetic material is placed in an external magnetic field. The magnetic domains
(a) increase in size (b) decrease in size
(c) may increase or decrease in size
(d) have no relation with the field.

4. A long, straight wire carries a current i. The magnetizing field intensity H is measured at a point P close to the wire. A long, cylindrical iron rod is brought close to the wire so that the point P is at the centre of the rod. The value of H at P will
(a) increase many times (b) decrease many times
(c) remain almost constant (d) become zero.

5. The magnetic susceptibility is negative for
(a) paramagnetic materials only
(b) diamagnetic materials only
(c) ferromagnetic materials only
(d) paramagnetic and ferromagnetic materials.

6. The desirable properties for making permanent magnets are
(a) high retentivity and high coercive force
(b) high retentivity and low coercive force
(c) low retentivity and high coercive force
(d) low retentivity and low coercive force.

7. Electromagnets are made of soft iron because soft iron has
(a) high retentivity and high coercive force
(b) high retentivity and low coercive force
(c) low retentivity and high coercive force
(d) low retentivity and low coercive force.

OBJECTIVE II

1. Pick the correct options.
(a) All electrons have magnetic moment.
(b) All protons have magnetic moment.
(c) All nuclei have magnetic moment.
(d) All atoms have magnetic moment.

2. The permanent magnetic moment of the atoms of a material is not zero. The material
(a) must be paramagnetic (b) must be diamagnetic
(c) must be ferromagnetic (d) may be paramagnetic.

3. The permanent magnetic moment of the atoms of a material is zero. The material
(a) must be paramagnetic (b) must be diamagnetic
(c) must be ferromagnetic (d) may be paramagnetic.

4. Which of the following pairs has quantities of the same dimensions ?
(a) Magnetic field B and magnetizing field intensity H
(b) Magnetic field B and intensity of magnetization I
(c) Magnetizing field intensity H and intensity of magnetization I
(d) Longitudinal strain and magnetic susceptibility.

5. When a ferromagnetic material goes through a hysteresis loop, the magnetic susceptibility
(a) has a fixed value (b) may be zero
(c) may be infinity (d) may be negative.

6. Mark out the correct options.
(a) Diamagnetism occurs in all materials.
(b) Diamagnetism results from the partial alignment of permanent magnetic moment.
(c) The magnetizing field intensity H is always zero in free space.
(d) The magnetic field of induced magnetic moment is opposite to the applied field.

EXERCISES

1. The magnetic intensity H at the centre of a long solenoid carrying a current of 2·0 A, is found to be 1500 A m^{-1}. Find the number of turns per centimetre of the solenoid.

2. A rod is inserted as the core in the current-carrying solenoid of the previous problem. (a) What is the magnetic intensity H at the centre? (b) If the magnetization I of the core is found to be 0·12 A m^{-1}, find the susceptibility of the material of the rod. (c) Is the material paramagnetic, diamagnetic or ferromagnetic ?

3. The magnetic field inside a long solenoid having 50 turns cm^{-1} is increased from $2·5 \times 10^{-3}$ T to 2·5 T when an iron core of cross-sectional area 4 cm^2 is inserted into it. Find (a) the current in the solenoid, (b) the magnetization I of the core and (c) the pole strength developed in the core.

4. A bar magnet of length 1 cm and cross-sectional area 1·0 cm^2 produces a magnetic field of $1·5 \times 10^{-4}$ T at a point in end-on position at a distance 15 cm away from the centre. (a) Find the magnetic moment M of the magnet. (b) Find the magnetization I of the magnet. (c) Find the magnetic field B at the centre of the magnet.

5. The susceptibility of annealed iron at saturation is 5500. Find the permeability of annealed iron at saturation.

6. The magnetic field B and the magnetic intensity H in a material are found to be 1·6 T and 1000 A m^{-1}

respectively. Calculate the relative permeability μ_r and the susceptibility χ of the material.

7. The susceptibility of magnesium at 300 K is $1{\cdot}2 \times 10^{-5}$. At what temperature will the susceptibility increase to $1{\cdot}8 \times 10^{-5}$?

8. Assume that each iron atom has a permanent magnetic moment equal to 2 Bohr magnetons (1 Bohr magneton equals $9{\cdot}27 \times 10^{-24}$ A m^2). The density of atoms in iron is $8{\cdot}52 \times 10^{28}$ atoms m^{-3}. (a) Find the maximum magnetization I in a long cylinder of iron. (b) Find the maximum magnetic field B on the axis inside the cylinder.

9. The coercive force for a certain permanent magnet is $4{\cdot}0 \times 10^4$ A m^{-1}. This magnet is placed inside a long solenoid of 40 turns/cm and a current is passed in the solenoid to demagnetize it completely. Find the current.

□

ANSWERS

OBJECTIVE I

1. (b) 2. (c) 3. (c) 4. (c) 5. (b) 6. (a) 7. (d)

OBJECTIVE II

1. (a), (b) 2. (d) 3. (b) 4. (c), (d) 5. (b), (c), (d) 6. (a), (d)

EXERCISES

1. 7·5
2. (a) 1500 A m^{-1} (b) $8{\cdot}0 \times 10^{-5}$ (c) paramagnetic
3. (a) 0·4 A (b) $2{\cdot}0 \times 10^6$ A m^{-1} (c) 800 A m
4. (a) 2·5 A m^2 (b) $2{\cdot}5 \times 10^6$ A m^{-1} (c) 1·2 T
5. $6{\cdot}9 \times 10^{-3}$
6. $1{\cdot}3 \times 10^3$ each
7. 200 K
8. (a) $1{\cdot}58 \times 10^6$ A m^{-1} (b) 2·0 T
9. 10 A

□