chapter thirty-eight

Magnetic Properties of Materials

THE magnetic properties of materials require investigation to decide whether they are suitable for permanent magnets such as loudspeaker magnets, for temporary magnets such as electromagnets, or for cores of electromagnetic induction machines such as transformers.

Induction or Flux Density in Magnetic Material

Consider a toroid of length L, wound with N turns each carrying a current I round a ring of magnetic material, Fig. 38.1.

The *total flux density B* in the material is partly due to the currents

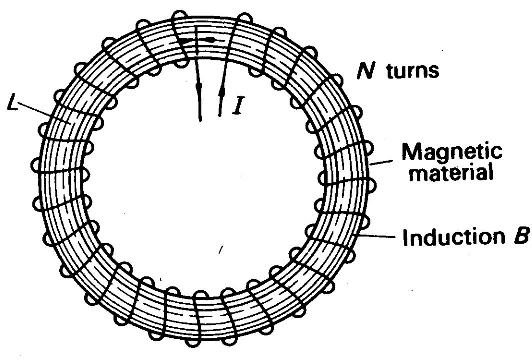

FIG. 38.1. Induction in magnetic material.

flowing in the wire and partly due to the magnetization of the material. We thus write

$$B = B_0 + B_M, \quad . \quad . \quad . \quad . \quad (1)$$

where B_0 is the flux density due directly to the current in the wire, and B_M is the flux density due to the magnetization of the material.

We now assume that the induction B_M is produced by many small circulating currents inside the magnetic material, due to the circulating and spinning electrons in the atoms. Fig. 38.2 shows that the effect of many small adjacent current loops may be thought of as one current loop. In the same way, the internal circulating and spinning currents can be replaced by a single current I_M flowing in the coil wound round the core. This theoretical surface or magnetization current is additional to the real or actual current I flowing in the coil.

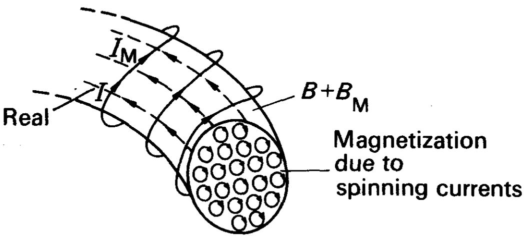

FIG. 38.2. Magnetizing surface current.

By itself, the real current I produces a flux-density B_0. If the toroid has n turns per unit length ($n = N/L$), then, from p. 938,

$$B_0 = \mu_0 nI.$$

The surface current I_M may be imagined to flow in n turns per metre of the solenoid, as the real current does. The flux density or induction B_M is then given by

$$B_M = \mu_0 nI_M.$$

This is the induction which would be produced by the current I_M if the material were not present in the toroid, that is, a current I_M in the coil would produce a flux density equal to that due to the magnetization in the material.

$$\therefore \text{ total induction } B = B_0 + B_M = \mu_0 n(I + I_M) \quad . \quad (2)$$

Intensity of Magnetization

It is possible to write B_M, the induction due to the magnetization of the material, in a different way. The magnetic moment of each turn due to this imaginary surface current $= A \times I_M$, where A is the area of each turn. See p. 885. The magnetic moment of the whole toroid is then $nLAI_M$, since nL is the total number of turns. Hence the *magnetic moment per unit volume*

$$= \frac{nLAI_M}{\text{volume}} = \frac{nLAI_M}{LA} = nI_M$$

The 'magnetic moment per unit volume' is called the *intensity of magnetization, M,* of the magnetic core in the toroid. Thus $B_M = \mu_0 nI_M = \mu_0 M$. Further, nI is the magnetic field intensity, H, in the toroid due to the current I.

Thus the *total induction or flux-density B* in the core when the coil carries a current is given by

$$B = B_0 + B_M = \mu_0 nI + \mu_0 nI_M$$

$$\therefore B = \mu_0(H + M) \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Equation (3) relates the total induction B to the magnetizing field intensity H due to the current and to the intensity of magnetization M of the material produced. Note that H and M have the same units from (3). *Thus the unit of M is ampere per metre* ($A\ m^{-1}$).

EXAMPLE

A solenoid 1 m long is wound with 10^4 turns of copper wire each carrying a current of 10 A. If the cross-sectional area of the coil is 10 cm^2, calculate (*a*) the magnetizing force or intensity in the solenoid, (*b*) the couple exerted on the solenoid when it is placed at right angles to an external field of induction 10^{-2} T.

If the solenoid is now filled with certain magnetic material, the induction in the material is 1·5 T. Calculate (*c*) the intensity of magnetization in the material, (*d*) the total couple exerted when the solenoid and material inside is placed at right angles to a field of induction 10^{-2} T.

(*a*) We have $H = nI$, where n is the number of turns per metre,

$$= 10^4 \times 10$$

$$= 10^5 \text{ ampere metre}^{-1}\ (\text{A m}^{-1}).$$

(*b*) Magnetic moment of each solenoid turn $= IA$.

$$\therefore \text{ magnetic moment of empty solenoid, } m, = NIA.$$

Since $N = 10^4$, $I = 10$ A, $A = 10\ \text{cm}^2 = 10 \times 10^{-4}\ \text{m}^2$,

$$\therefore m = 10^4 \times 10 \times 10 \times 10^{-4}$$

$$= 100\ \text{A m}^2.$$

Now couple $C = mB \sin\alpha$, where α is the angle between the solenoid axis and the external field B.

$$\therefore C = mB \sin 90^\circ$$

$$= 100 \times 10^{-2}$$

$$= 1 \text{ newton metre (N m)}$$

(*c*) We have $B = \mu_0(H + M)$

$$\therefore M = \frac{B - \mu_0 H}{\mu_0}$$

$$= \frac{1{\cdot}5 - 4\pi \times 10^{-7} \times 10^5}{4\pi \times 10^{-7}}$$

$$= 10{\cdot}9 \times 10^5 \text{ ampere metre}^{-1}$$

(*d*) Total magnetic moment, m, of the specimen is given by,

$$m = MV$$

$$= 10{\cdot}9 \times 10^5 \times (1 \times 10^{-3})$$

$$= 10{\cdot}9 \times 10^2\ \text{A m}^2$$

$\therefore$ Total magnetic moment of the solenoid and the material inside

$$= 100 + 10{\cdot}9 \times 10^2$$

$$= 11{\cdot}9 \times 10^2\ \text{A m}^2$$

$$\therefore \text{Couple} = mB \sin \alpha \text{ newton metre}$$
$$= 11{\cdot}9 \times 10^2 \times 10^{-2} \times \sin 90°$$
$$= 11{\cdot}9 \text{ N m.}$$

Relative Permeability

The permeability of a material is defined by the relation $\mu = B/H$. Now, in general, $B = \mu_0(H+M)$

$$\therefore \mu H = \mu_0(H+M)$$

or

$$\frac{\mu}{\mu_0} = 1+\frac{M}{H}$$

The ratio μ/μ_0 is called the *relative permeability*, μ_r, of the material. The ratio M/H is called the *susceptibility*, χ, of the material. Hence, from above,

$$\mu_r = 1+\chi. \qquad (4)$$

It should be noted that μ_r and χ are dimensionless; each is the ratio of two quantities having the same dimensions. Permeability, μ, however, which is the ratio B/H, has dimensions; its unit is *henry per metre* ($H\ m^{-1}$). See p. 940.

We shall describe shortly how the variation of B with H may be measured. Here we shall anticipate the results. As a magnetic material, originally unmagnetized, is subjected to an increasing field, the intensity of magnetization M increases until it reaches a maximum value (Fig. 38.3 (*a*)). The material is then 'saturated'; that is, its magnetic

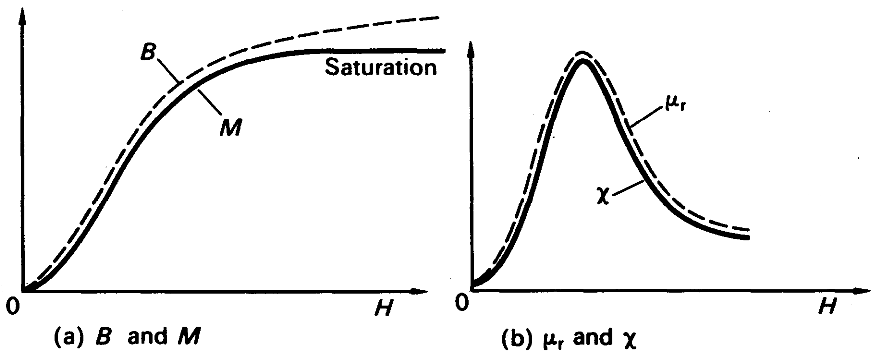

FIG. 38.3. Variation of B, M, μ_r, χ.

'domains' are completely aligned with the field H. B, however, continues to increase with H, since $B = \mu_0(H+M)$. Fig. 38.3 (*b*) also shows how the relative permeability μ_r and the susceptibility χ varies with H. It increases at first, and passes through a maximum value. As the material approaches saturation the domains cannot yield much further, and the susceptibility falls to a low value.

Variation of B with H

Ferromagnetic materials are those which have a high susceptibility. This is generally very much greater than 1, for example, 3000. Some materials are capable of retaining their magnetization and forming strong permanent magnets. Others form temporary magnets (p. 954).

The relationship between B, the flux density in a material, and the applied magnetizing field or force H, is best investigated experimentally by using a toroid shaped specimen. This eliminates the reduction in the field due to the effect of poles at the ends of a cylindrical rod. However, in the experiment described shortly, a specimen is placed inside a long current-carrying solenoid. This does not produce as large a value B as that obtained with a toroid, but the essential features of the variation of B with H are still observed.

One form of apparatus is shown in Fig. 38.4. The current I through the solenoid is measured on the ammeter A, and since $H = nI$, the current I is directly proportional to the magnetizing force H. C is a

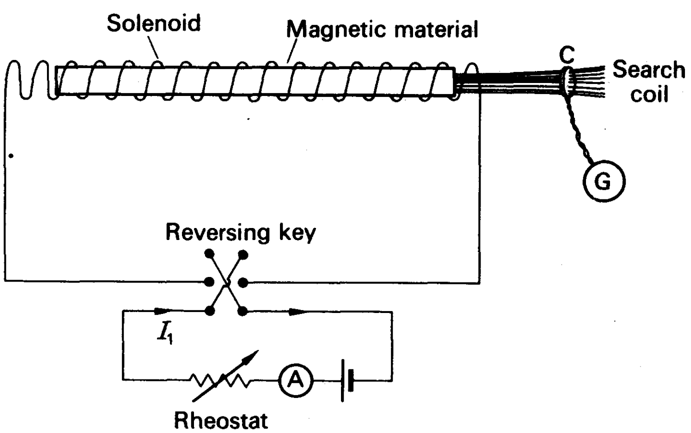

FIG. 38.4. Variation of B with H by experiment.

small search coil, which is placed in contact with the end of the specimen, and which is connected to a ballistic galvanometer G. When the coil is sharply removed from the vicinity of the specimen the throw on the galvanometer gives a measure of the flux change (see p. 920). Since the number of turns and area of the coil is constant, this throw will be proportional to the flux density B.

Ths specimen is first demagnetized (see p. 958) and placed in the solenoid. The current I is now increased in steps from zero, and the corresponding deflections θ on the ballistic galvanometer are observed. The specimen is taken through a *magnetic cycle* of magnetization. This is done by increasing I until θ is nearly constant, when the specimen has become saturated, then reducing I to zero and reversing it until saturation is reached in the opposite direction, and finally reducing I to zero and increasing it once more in the opposite direction.

H can be calculated from the relation $H = nI$. If the search coil has N turns of area A, and the ballistic galvanometer is calibrated, then B can be found from:

$$\text{Charge} = \frac{\text{Change in flux}}{\text{Resistance of circuit, } R}$$

or

$$Q = \frac{BAN}{R}$$

If R and Q are measured, then B can be found.

Sometimes it is required to plot M against H rather than B against H. In this case M is calculated, using the relation (3) on p. 949, from

$$M = \frac{B - \mu_0 H}{\mu_0}.$$

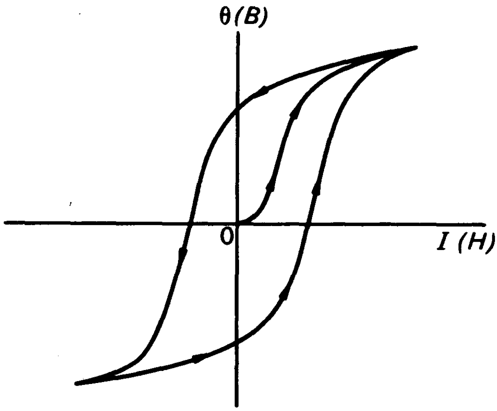

FIG. 38.5. *B-H* variation.

If only the general form of the $B-H$ curve is wanted, it is sufficient to plot θ against I. Fig. 38.5 illustrates a typical graph obtained; the arrows show the sequence in going round the magnetic cycle.

Hysteresis. Remanence. Coercive Force

Fig. 38.6 shows the variation of magnetic induction, B, with the applied field, H, when the specimen is taken through a complete cycle. After the specimen has become saturated, and the field is reduced to zero, the iron is still quite strongly magnetized, setting up a flux-density B_r. This flux-density is called the *remanence*; it is due to the tendency of groups of molecules, or domains, to stay put once they have been aligned.

When the field is reversed, the residual magnetism is opposed. Each increase of magnetizing field now causes a decrease of flux-density, as the domains are twisted farther out of alignment. Eventually, the flux-density is reduced to zero, when the opposing field H has the value

H_c. This value of H is called the *coercive force* of the iron; it is a measure of the difficulty of breaking up the alignment of the domains.

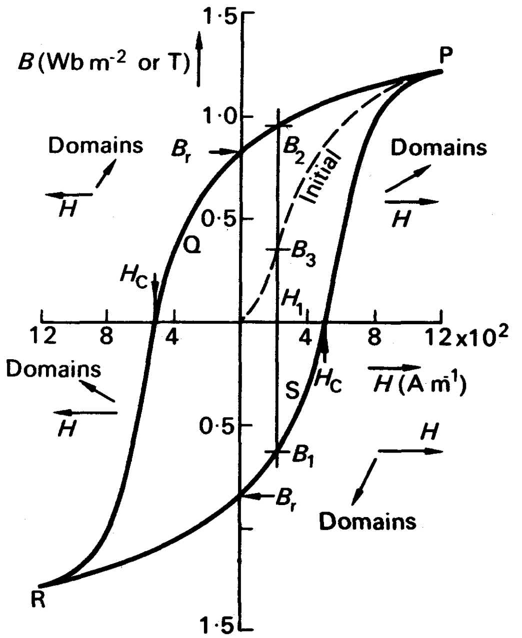

FIG. 38.6. Hysteresis loop.

We now see that, when once the iron has been magnetized, its magnetization curve never passes through the origin again. Instead, it forms the closed loop PQRS, which is called a *hysteresis loop.* Hysteresis, which comes from a Greek work meaning 'delayed', can be defined as *the lagging of the magnetic induction, B, behind the magnetizing field, H,* when the specimen is taken through a magnetic cycle.

Properties of Magnetic Materials

Fig 38.7 shows the hysteresis loops of iron and steel. Steel is more suitable for permanent magnets, because its high coercivity means that it is not easily demagnetized by shaking. The fact that the remanence of iron is a little greater than that of steel is completely outweighed by its much smaller coercivity, which makes it very easy to demagnetize. On the other hand, iron is much more suitable for electromagnets, which have to be switched on and off, as in relays. Iron is also more suitable for the cores of transformers and the armatures of machines. Both of these go through complete magnetizing cycles continuously: transformer cores because they are magnetized by alternating current, armatures because they are turning round and round in a constant field. In each cycle the iron passes through two parts of its hysteresis loop (near Q and S in Fig. 38.6), where the magnetizing field is having to demagnetize the iron. There the field is doing work against the internal

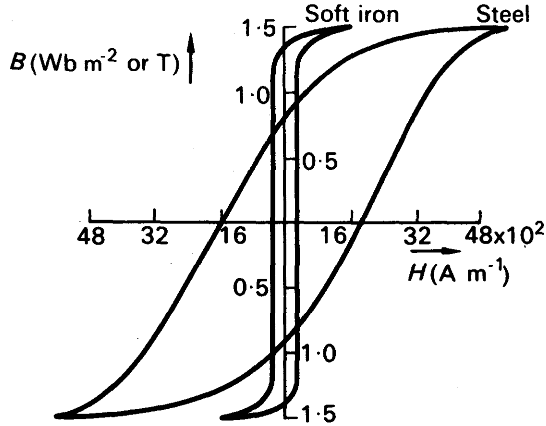

FIG. 38.7. Hysteresis curves for iron and steel.

friction of the domains. This work, like all work that is done against friction, is dissipated as heat. The energy dissipated in this way, per cycle, is less for iron than for steel, because iron is easier to demagnetize. It is called the *hysteresis loss*; we will show soon that it is proportional to the area of the *B-H* loop (p. 957).

In a large transformer the hysteresis loss, together with the heat developed by the current in the resistance of the windings, liberates so much heat that the transformer must be artificially cooled. The cooling is done by circulating oil, which itself is cooled by the atmosphere: it passes through pipes which can be seen outside the transformer, running from top to bottom.

The table on p. 956 gives the properties of some typical magnetic materials; mumetal and ticonal are inventions of the last twenty years, the results of deliberate attempts to develop materials with extreme properties.

Hysteresis Loss; Area of Loop

To calculate the work done in carrying a piece of iron round a hysteresis loop, we adopt the method which we used to calculate the energy stored in the magnetic field of a coil: we consider the back-e.m.f. induced during a change of flux.

Fig 38.8 shows a ring of iron, wound with a uniform magnetizing coil of N turns, and mean length l. If the current through the coil is I, the magnetizing field is

$$H = \frac{NI}{l} \quad \text{(i)}$$

And if B is the flux density in the iron, and A its cross-sectional area, the flux through it $= AB$. The flux linkages with the magnetizing coil are therefore

$$\Phi = NAB.$$

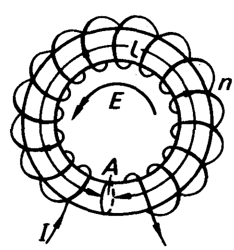

FIG. 38.8. Work done in magnetization of iron.

PROPERTIES OF MAGNETIC MATERIALS

Material	Relative Permeability μ_r	Saturation B_m 10^{-4} T	Remanence B_r 10^{-4} T	Coercivity H_c A m^{-1}	Hysteresis loss W J m^{-3} per cycle	Critical temp. t,* °C	Resistivity† ρ (approx.) 10^{-8} Ω-m	Applications
	SOFT MATERIALS (iron-like, used for electromagnets with varying currents)							
Iron (99·94%)	5500	21500	13000	81·0	500	770	10	
Nickel	600	6100	3600	272	30	360	7	
Cobalt	240	18000	5000	800	200	1120	10	
Silicon Iron (Stalloy) (Fe 96, Si 4)	6700	20000	12000	40	350	690	55	Armatures, relays, large transformer cores, telephone diaphragms
Mumetal (Ni 74, Fe 20, Cu 5, Mn 1)	80000	8500	6000	4	20	—	—	Small transformer cores, magnetic shields
	HARD MATERIALS (steel-like, used for permanent magnets)							
Carbon Steel	—	10000	8000	4800	20000	—	—	
Cobalt Steel	—	—	8000–10000	12000–19200	—	—	—	Moving-coil instruments, loudspeakers, microphones, telephone ear-piece magnets
Ticonal (Fe 51, Co 24, Ni 14, Al 8, Cu 3)	—	—	12500	44000	—	—	—	

* See page 963.

† The higher the resistivity of a magnetic material, the less the eddy-currents in it when the flux through it is changed; and therefore the less the energy lost as heat.

Now let us suppose that, in a brief time δt, we increase the current by a small amount, and so increase the flux and flux linkages. During the change a back-e.m.f. will be induced in the coil, of magnitude

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

Hence, from above,

$$E = NA\frac{dB}{dt}$$

To overcome this back-e.m.f., the source of the current I must supply energy to the coil at the rate

$$P = EI$$

Thus the total energy supplied to the coil, in increasing the flux through the iron, is

$$\begin{aligned} \delta W = P\delta t &= EI\delta t \\ &= INA\frac{dB}{dt}\delta t \\ &= INA\delta B \end{aligned}$$

where δB is the increase in flux-density.

Let us now substitute for the current I in terms of the magnetizing field H. From equation (i) we have

$$I = \frac{Hl}{N}$$

Hence

$$\begin{aligned} \delta W &= \frac{lHNA}{N}\delta B \\ &= VH\delta B \qquad \text{(ii)} \end{aligned}$$

where V, $= lA$, is the volume of the iron.

Equation (ii) shows that, in taking the flux from any value B_1 to any other B_2, the work done is

$$W = V\int_{B_1}^{B_2} HdB \qquad \text{(iii)}$$

On unit volume of the iron, the work is

$$\int_{B_1}^{B_2} HdB$$

The integral in this expression is the area between the B-H curve and the axis of B. Round the complete hysteresis loop, the work done per unit volume is

$$W = \oint HdB$$

Here the symbol $\oint$ denotes integration round the closed loop (PQRSP in Fig. 38.6); the integral is proportional to the area of the loop.

Subsidiary Hysteresis Loops

When a piece of iron is magnetized, first one way and then the other, it goes round a hysteresis loop even if it is not magnetized to saturation at any point (Fig. 38.9). The subsidiary loops, *ab* for example, may represent the magnetization of a transformer core by an alternating

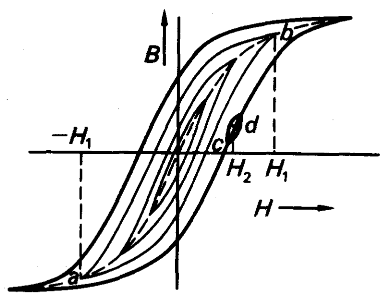

FIG. 38.9. Subsidiary hysteresis loops.

current in the primary winding: the amplitude H_1 of the magnetizing field is proportional to the amplitude of the current. A transformer core is designed so that it is never saturated under working conditions. For, if it were saturated, the flux through it would not follow the changes in primary current; and the e.m.f. induced in the secondary would be less than it should.

The energy dissipated as heat in going round a subsidiary hysteresis loop is proportional to the area of the loop, just as in going round the main one.

Another kind of subsidiary loop is shown at *cd* in the figure. The iron goes round such a loop when the field is varied above and below the value H_2. This happens in a transformer when the primary carries a fluctuating direct current.

Demagnetization

The only satisfactory way to demagnetize a piece of iron or steel is to carry it round a series of hysteresis loops, shrinking gradually to the origin. If the iron is the core of a toroid, we can do this by connecting the winding to an a.c. supply via a potential divider, as in Fig. 38.10, and reducing the current to zero. Since the iron goes through fifty loops per second, we do not have to reduce the current very slowly.

To demagnetize a loose piece of iron or steel, such as a watch, we merely put it into, and take it out of, a coil of many turns connected to an a.c. supply. As we draw the watch out, it moves into an ever-weakening field, and is demagnetized.

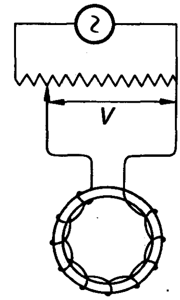

FIG. 38.10. Demagnetization.

Electromagnets and Magnetic Circuits

Consider the electromagnet shown in Fig. 38.11. The magnetic material, which is almost a complete toroid, is wound with N turns

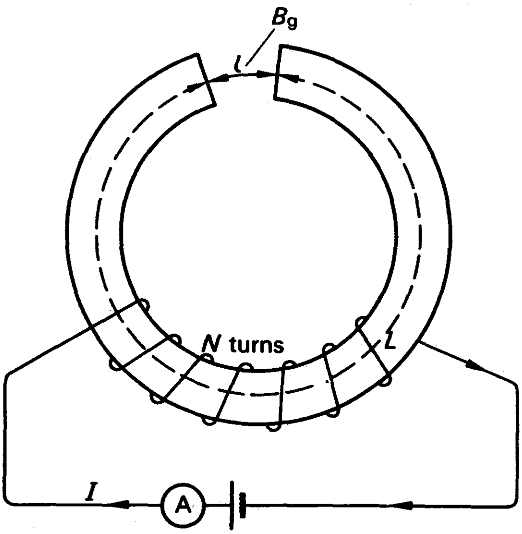

FIG. 38.11. Magnetic circuit.

each carrying a current I. The length of the magnetic material is L and of the small air gap l. We now calculate the induction B_g in the gap between the faces of magnetic material. From $B = \mu H$,

$$B_g = \mu_0 H_g \quad . \quad . \quad . \quad . \quad (1)$$

and

$$B_m = \mu H_m, \quad . \quad . \quad . \quad . \quad (2)$$

where H_g is the value of the magnetizing force in the gap, and H_m and B_m are respectively the magnetizing force and flux density inside the material. μ is the permeability of the material.

Taking the closed loop indicated in Fig. 38.11, by Ampere's theorem,

$$H_g l + H_m L = NI.$$

Thus from (1) and (2):

$$\frac{B_g l}{\mu_0} + \frac{B_m L}{\mu} = NI.$$

The total flux Φ round the magnetic circuit is constant. Since the area of cross-section of the air gap is the same as that of the material, it follows that

$$B_g = B_m.$$

$$\therefore B_g \left(\frac{l}{\mu_0} + \frac{L}{\mu} \right) = NI$$

or $$B_g = \frac{NI}{(l/\mu_0 + L/\mu)} \quad . \quad . \quad . \quad (3)$$

$$\therefore \Phi = B_g A = \frac{NI}{(l/\mu_0 A + L/\mu A)}$$

In general, the value of μ depends on the current flowing in the electromagnet coil.

EXAMPLE

A toroid made from an iron bar of length 6 cm and of cross-sectional area 4 cm^2, has an air gap of length 1 cm. If it is wound with 500 turns of wire carrying a current of 20 A, find the flux density in the gap. The material may be assumed to have a permeability of 3000 times that of free space under these conditions (that is $\mu_r = 3000$). If there were no air gap, what would be the induction or flux density in the iron?

We have $N = 500$, $I = 20$ A, $l = 1$ cm $= 0{\cdot}01$ m, $\mu = \mu_r\mu_0 = 3000 \times 4\pi \times 10^{-7}$. From (3) above,

$$\therefore B_g = \frac{500 \times 20}{1/\mu_0(l + L/3000)} = \frac{500 \times 20 \times 4\pi \times 10^{-7}}{(0{\cdot}01 + 0{\cdot}0002)}$$

$$= 1{\cdot}3 \text{ Wb m}^{-2} \text{ (approx.)}.$$

If $l = 0$, so that there is no air gap, and assuming the value of μ does not alter, then the flux density in the iron is now given by

$$B = \frac{NI}{L/\mu} = \frac{500 \times 20 \times 3000 \times 4\pi \times 10^{-7}}{0{\cdot}6}$$

$$= 53 \text{ Wb m}^{-2}.$$

Note that even a small air gap considerably reduces the value of the flux density obtained.

Magnetomotive Force. Reluctance.

In equation (3), NI is called the *magnetomotive force*, M.M.F., in the magnetic circuit comprising the iron and air gap. It is analogous to the e.m.f. in an electric circuit. The flux Φ through a cross-section of the circuit, which is given by BA, is analogous to the current.

The quantity $(l/A\mu_0 + L/A\mu)$ in the denominator in (3) is called the *reluctance* of the magnetic circuit. It is analogous to electrical resistance R, since $R = \rho l/A$ (p. 788). Each term in the expression for the reluctance is due to a separate part of the magnetic circuit. Thus $l/\mu_0 A$ is the reluctance of the air gap and $L/\mu A$ is that of the iron. In the above example, the reluctance of the air gap was $0{\cdot}01/(4\pi \times 10^{-7} \times A)$ whilst that of the iron was $0{\cdot}6/(3000 \times 4\pi \times 10^{-7} \times A)$. Thus the reluctance of the air gap is fifty times greater than that of the iron. This accounts for the considerable reduction in the value of B when the air gap is introduced. It should be noted that the reluctances are in series in Fig. 38.11. They are added together, as are series resistances in electric circuits.

Permanent Magnets

A permanent magnet is shown in Fig. 38.12 (i). We apply Ampère's theorem to the circuit shown by the dotted line. Here there are no external currents flowing so that, using the same notation as in the last section,

$$H_m L + H_g L = 0$$

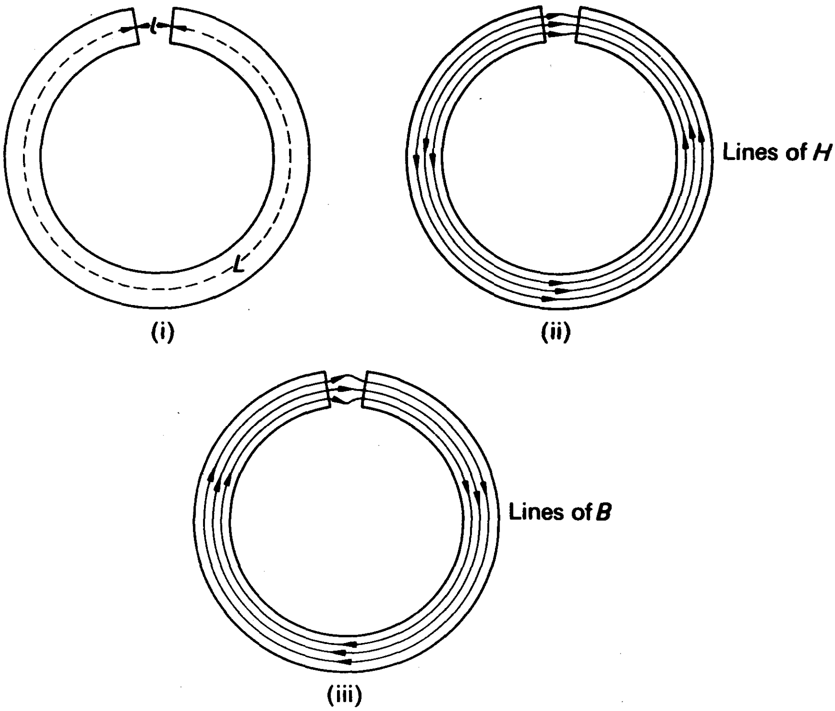

FIG. 38.12. Permanent magnet. B and H.

Also,

$$B_g = \mu H_g \qquad \text{and} \qquad B_g = B_m,$$

for the same reasons as in the case of electromagnets.
Combining these equations,

$$\therefore \frac{B_m}{H_m} = -\mu_0 \frac{L}{l} \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

This result expresses the fact that B *and* H *are oppositely directed inside the medium.* The lines of B and H are shown in Fig. 38.12 (ii) and (iii) respectively. Since $B = \mu H$, the value of μ in the case of this permanent magnet is $-\mu_0 L/l$. Fig. 38.13 shows the points, A or C, representing the magnetic state of the material of a permanent magnet.

The relationship between B and H is provided by the hysteresis loop. Also, B and H inside the material satisfy equation (1), which is represented by the line AOC. The only two points which satisfy both these conditions are A and C, the points of intersection of the line with the curve. At A or C, H is oppositely directed to B and hence μ is negative. For any given shape of toroidal magnet, one can predict, using (1), the greatest possible induction in the air gap.

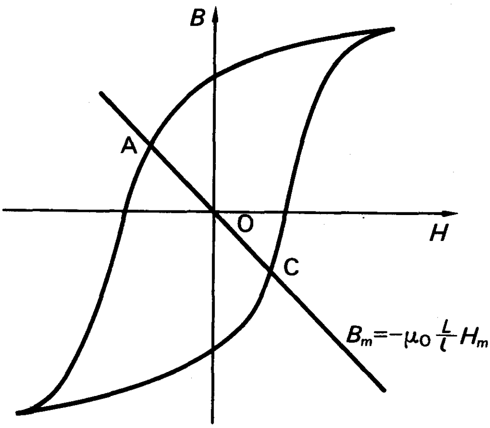

FIG. 38.13. Permanent magnet.

Diamagnetism, Paramagnetism, Ferromagnetism

We have already mentioned that the magnetic properties of materials are due to circulating and spinning electrons within the atoms.

Diamagnetism

If a magnetic field is produced in the neighbourhood of a magnetic material, a changing flux occurs in the current loops within the atoms. An e.m.f. or electric field will then be set up which causes the electrons to alter their motions, so that an extra or induced current is produced. By Lenz's law, this current gives rise to a magnetic field which *opposes* the applied magnetic field H. Thus the induced magnetization will be in the opposite direction to H, that is, M/H is negative. Hence the susceptibility χ is negative. This phenomenon is called *diamagnetism.* For a diamagnetic material, χ is generally very small, about $-0{\cdot}000015$ for bismuth, for example. The relative permeability, μ, which is given by $\mu_r = 1+\chi$, is thus generally slightly less than 1. All substances have a diamagnetic contribution to their susceptibility, since the induced currents always oppose the applied field. In many substances, the diamagnetism is completely masked by another magnetic phenomenon (p. 953).

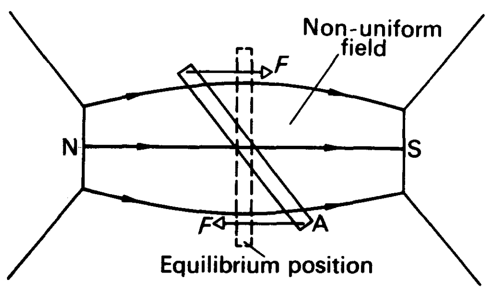

FIG. 38.14. Rod of diamagnetic material in strong field.

If a rod of diamagnetic material is placed in a non-uniform magnetic field, it will settle at right angles to the field. Fig. 38.14 shows the specimen slightly displaced from this position. The magnetization will oppose the applied field so that the end A will now effectively be a weak S pole. It will then experience a force as shown by the arrow, so that a restoring couple turns the specimen back to its position at right angles to the field.

It should be noted that diamagnetism is a natural 'reaction' to an applied magnetic field and that it is independent of temperature.

Paramagnetism

In contrast to bismuth, a rod of a material such as platinum will settle along the same direction as the applied magnetic field. Further, the induced magnetism will be in the same direction as the field. Fig. 38.15. Platinum is an example of a *paramagnetic* material. The susceptibility, χ, of a paramagnetic substance is very small and positive, $+0{\cdot}0001$ for example, so that its relative permeability μ_r is very slightly greater than 1 from $\mu_r = 1+\chi$.

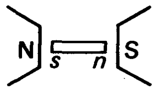

FIG. 38.15. Rod of paramagnetic material in strong field.

As we have already mentioned, atoms contain circulating and spinning electrons. Each electron possesses a resultant magnetic moment on account of its orbital motion and its spin motion. In a diamagnetic atom, all these contributions to the magnetic moment cancel. In a paramagnetic atom, however, there is a resultant magnetic moment. Generally, the thermal motions of the atoms will cause these magnetic moments to be oriented purely at random and there will be no resultant magnetization. If, however, a field is applied, each atomic moment will try to set in the direction of the field but the thermal motions will prevent complete alignment. In this case there will be overall weak magnetization in the direction of the applied field. This accounts for the phenomenon of paramagnetization.

It is clear that paramagnetism is temperature dependent. At low temperatures, the thermal motions will be less successful at preventing the alignment of the atomic moments and so the susceptibility will be larger. At higher temperatures thermal motion will make alignment difficult. At very high temperatures, the material may become diamagnetic, for the diamagnetic contribution to χ is not affected by temperature whilst the paramagnetic contribution falls.

Ferromagnetism. Magnetic Domain Theory

A ferromagnetic material has a very high value of susceptibility, χ, and hence of relative permeability, μ_r. The value of μ_r can be several thousands. Like a paramagnetic material, the magnetization is in the direction of the applied field and a rod of a ferromagnetic material will align itself along the field.

In a paramagnetic substance which is not subjected to a magnetic field, the magnetic moments are oriented purely at random due to the thermal vibrations. In a ferromagnetic material, however, strong 'interactions' are present between the moments, the nature of which requires quantum theory to understand it and is outside the scope of this work. These cause neighbouring moments to align, even in the absence of an applied field, with the result that tiny regions of very strong magnetism are obtained inside the unmagnetized material called *magnetic domains*. Above a critical temperature called the *Curie point*, ferromagnetics become paramagnetics (see Table, p. 956).

Domain Formation

A crystal of ferromagnetic material is shown in Fig. 38.16 (i). If all the domains were aligned completely, the material would behave like one enormous domain and the energy in the magnetic field outside is then considerable, as represented by the flux shown. Now all physical systems settle in equilibrium when their energy is a minimum. Fig. 38.16(ii) is therefore more stable than Fig. 38.16(i)

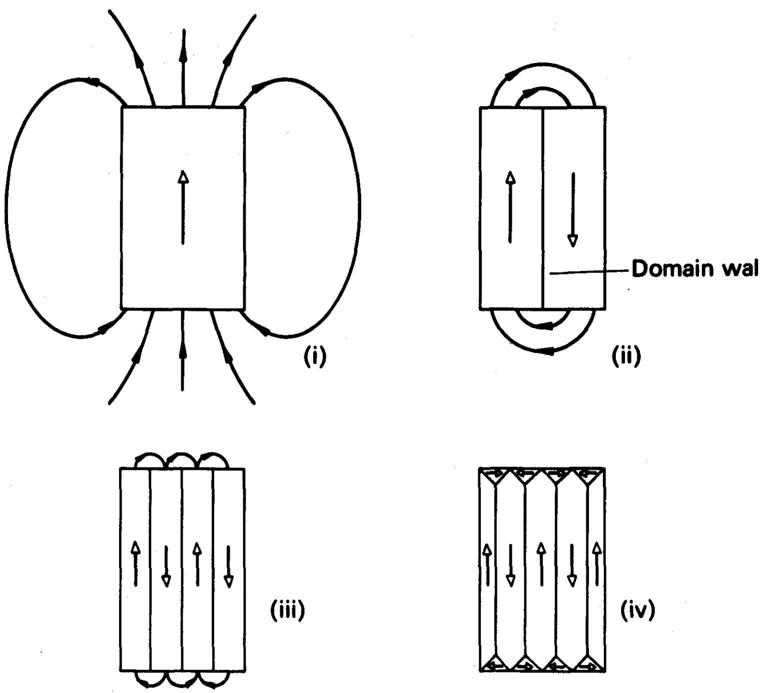

FIG. 38.16. Magnetic domains.

because the external magnetic field energy is less. Thus the domains grow in the material, as shown in Fig. 38.16 (iii) and (iv). The region between two domains, where the magnetization changes direction, is called a *domain wall* and also contains energy. When the formation of a new domain wall requires more energy than is gained by the reduction in the external magnetic field, no more domains are formed. Thus there is a limit to the number of domains formed. This occurs when the volume of the domains is of the order 10^{-4} cm^3 or less.

Domains and Magnetization

Some of the phenomena in magnetization of ferromagnetic material can now be explained. In an unmagnetized specimen, the domains are oriented in different directions. The net magnetization is then zero. If a small magnetic field H is applied, there is some small rotation of the magnetization within the domains, which produces an overall component of magnetization in the direction of H. This occurs in the region AB of the magnetization-field (M-H) curve shown in Fig. 38.17.

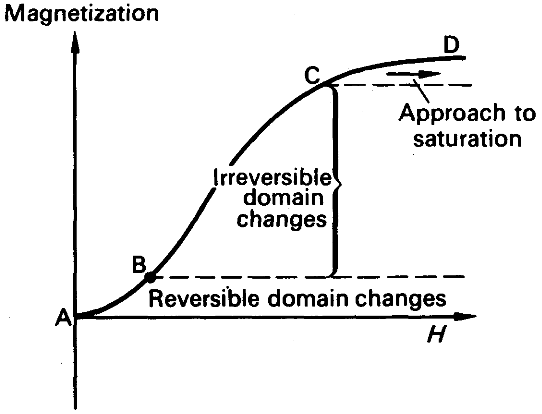

FIG. 38.17. Domain movement in magnetization.

If the field H is removed, the domain magnetization returns to its original direction. Thus the magnetization returns to zero. The changes in the part AB of the curve are hence reversible. If the field H is increased beyond B in the region BC, the magnetization becomes greater. On removal of the field the magnetization does not return to zero, and so remanence occurs. Along BC, then, irreversible changes take place; the domains grow in the direction of the field, by movement of domain walls, at the expense of those whose magnetization is in the opposite direction. At very high applied fields H there is complete alignment of the domains and so the magnetization M approaches 'saturation' along CD.

EXERCISES 38

1. Define *intensity of magnetization*, *susceptibility* and *permeability*. Two substances, A and B, have relative permeabilities slightly greater and slightly less than unity respectively. What does this signify about their magnetic properties? To what group of magnetic substances fo A and B each belong?

A soft iron ring of cross-sectional diameter 8 cm and mean circumference 200 cm has 400 turns of wire wound uniformly on it. Calculate the current necessary to produce magnetic flux to the value of 5×10^{-4} Wb if the relative permeability of the iron in the condition stated is 1800. Why is it not possible to say from this information what the flux would be if the current were reduced to 1/10 of its calculated value? (*L.*)

2. Define *permeability* (*relative permeability*) of a magnetic substance.

Indicate the orders of magnetide of the relative permeabilities of ferromagnetic, paramagnetic and diamagnetic substances respectively. Discuss in relation to its (relative) permeability one aspect of the behaviour of a specimen of each of these substances when placed in turn in the same magnetic field.

An iron ring of mean circumference 30 cm and of area of cross-section 1·5 cm^2 has 240 turns of wire uniformly wound on it, through which passes a current of 2 A. If the flux in the iron is found to be $7{\cdot}5 \times 10^{-4}$ Wb, find the relative permeability of the iron. (*L.*)

3. Give diagrams to illustrate the distribution of the lines of induction when a sphere of (*a*) soft iron, (*b*) bismuth (which is diamagnetic) is placed in a magnetic field, initially uniform. Compare and contrast the magnetic properties of these materials.

The magnetic induction (flux density) in a uniformly magnetized specimen of cast iron is 0·3 Wb m^{-2} when the strength of the magnetizing field is 1000 A m^{-1}. Find (i) the intensity of magnetization, (ii) the relative permeability, (iii) the magnetic susceptibility of the specimen. (*L.*)

4. What is meant by *intensity of magnetization* and *hysteresis*? Describe an experiment from the observations of which a graph of intensity of magnetization (M) against magnetizing field strength (H) over a complete hysteresis cycle may be plotted for a ferromagnetic material. What information may be obtained from the graph by measuring (*a*) the area enclosed by the loop, (*b*) the intercept on the M axis, (*c*) the intercept on the H axis, (*d*) the slope of a line joining a point on the graph to the origin? (*L.*)

5. Define *intensity of magnetization M* and *magnetic susceptibility* χ_m, and with the aid of a diagram explain what is meant by *hysteresis*.

Sketch a graph showing how M varies with the applied magnetizing field as the field applied to a specimen of soft iron, initially unmagnetized, is slowly increased from zero. On the same diagram sketch the corresponding graph for steel.

By reference to your earlier account state, with reasons, desirable magnetic properties of materials to be used as (*a*) the core of an electromagnet, (*b*) the core of a transformer, (*c*) a permanent magnet. (*L.*)

6. Define *magnetic moment* and explain why this concept is useful in the study of magnetism.

A bar of magnetic material is magnetized in the uniform field inside a solenoid. How would you study experimentally the changes in its magnetic moment when the magnetizing current is varied in magnitude and direction?

How would you represent the results of your measurements graphically? Give freehand sketches of the graphs you would expect to obtain for (i) material suitable for the core of a transformer, (ii) material suitable for a permanent magnet. Point out in each case the features of the graph which indicate that the material is suitable for its purpose. (*O. & C.*)

7. Define *susceptibility*, *permeability*, and state the relation between them.

Describe briefly how you would test if a small rod is diamagnetic, paramagnetic, or ferromagnetic. Draw intensity of magnetization graphs for each type of material and comment on their special features. (*N.*)

8. Explain what is meant by a *ferromagnetic material*. Give a general account of the wide range of magnetic properties exhibited by different ferromagnetic materials and indicate the practical applications of these properties. (*N.*)