where I is the current in the conductor, θ is the angle which the vector **r** makes with the direction of current and $\mu_o (= 4\pi \times 10^{-7}\ Wb.A^{-1}.m^{-1})$ is the permeability of free space. The magnitude of the magnetic field strength for the whole conductor is

$$B = \frac{\mu_o}{4\pi}\int I \frac{dl\sin\theta}{r^2} \qquad (5.3)$$

Eq. (5.2) or (5.3) is referred to as the *Biot - Savart Law.*

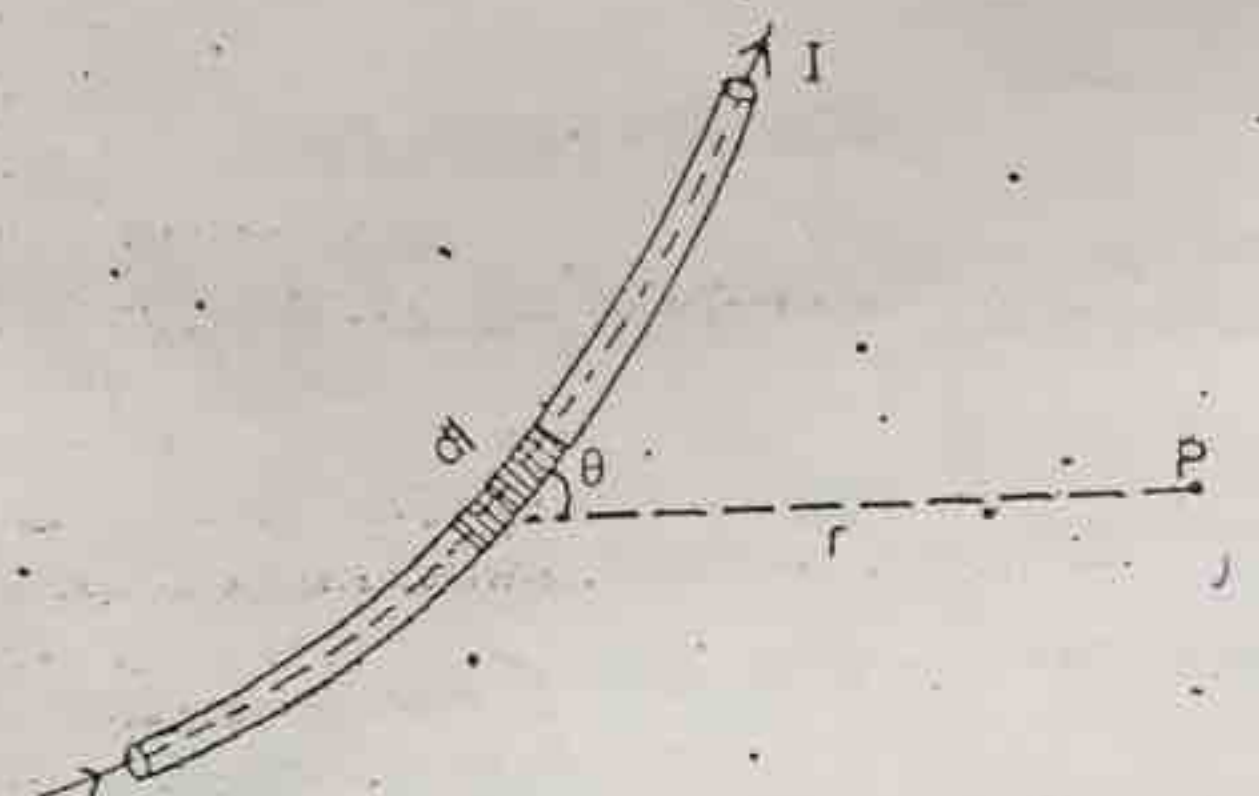


Fig. 5.3

The solution of Eq. (5.3) for specific conductor configurations yields:

(a) *At a distance r from an infinitely long straight wire* (Fig 5.4a)

$$B = \frac{\mu_o I}{2\pi r} \qquad (5.4)$$

To determine the direction of the magnetic field around a current-carrying wire, *the right palm is wrapped around the wire with the thumb pointing in the direction of current. The fingers point in the direction of the magnetic field.*

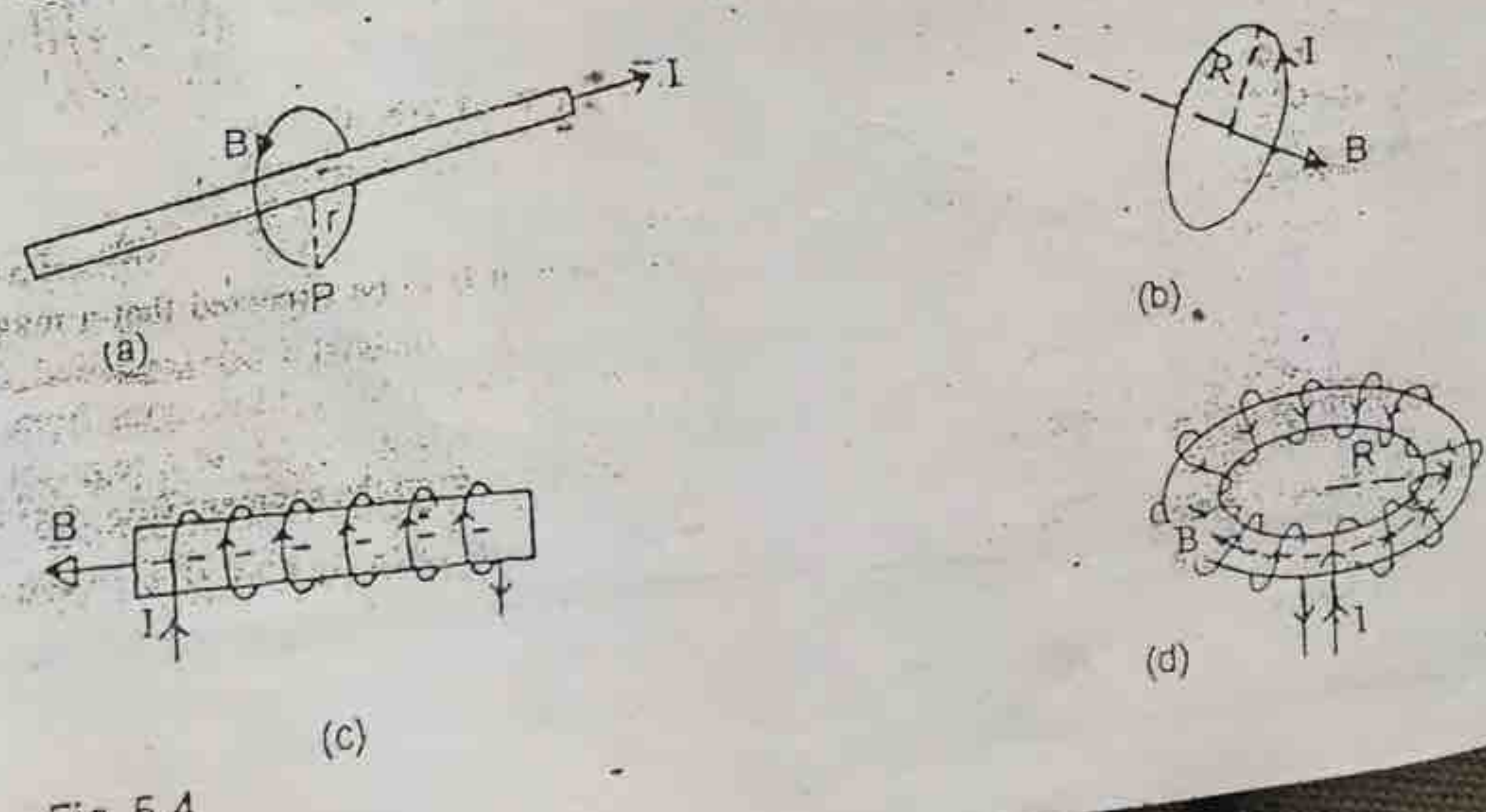


Fig. 5.4

(b) *At the centre of a circular loop of radius R* (Fig. 5.4b)

$$B = \frac{\mu_o I}{2R} \tag{5.5}$$

For N such closely spaced loops all of radius R,

$$B = \frac{\mu_o NI}{2R} \tag{5.5a}$$

(c) *Along the axis of a solenoid of length L containing N turns* (Fig 5.4c)

$$B = \frac{\mu_o NI}{L} \tag{5.6}$$

(d) *Inside a toroidal winding containing N turns at distance R from the centre* (Fig. 5.4d)

$$B = \frac{\mu_o NI}{2\pi R} \tag{5.7}$$

5.5 Magnetic Properties of Matter

are valid

The equations derived for magnetic field in a solenoid or toroid {Eqs. (5.6) and (5.7)} if the core of the winding is air or vacuum. For other substances the magnetic permeability μ is generally different from μ_o. If such substances are made the core of the solenoid or toroid, Eqs. (5.6) and (5.7) are modified to give :

$$\text{For a solenoid : } B = \frac{\mu NI}{L} \tag{5.6a}$$

$$\text{and for a toroid : } B = \frac{\mu NI}{2\pi R} \tag{5.7a}$$

The ratio μ/μ_o is called the *relative permeability* (K_m) of the substance, i.e.

$$K_m = \mu/\mu_o \tag{5.8}$$

Thus $K_m = 1$ for air or vacuum. diamagnetic (e.g. bismuth, lead, copper).

If K_m is less than 1, the substance is said to be *diamagnetic* (e.g. aluminium, platinum,

If K_m is slightly greater than 1, the substance is *paramagnetic* (e.g. iron, cobalt, nickel).

sodium). If K_m is much greater than 1, the substance is *ferromagnetic*

The *magnetic intensity* or *magnetic field strength* H is defined such that

$$B = \mu H \tag{5.9}$$

with units of [Am^{-1}].

5.6 Magnetic Hysteresis

The permeability μ in Eq. (5.9) is generally not constant for a given material. The relationship between B and H is illustrated in Fig. 5.5 for a ferromagnetic material. As the magnetizing field strength H is increased the magnetic flux density B in the material increases (non - linearly) until a saturation value of B is reached at point S. If H is now decreased, a new path SA is followed such that the magnetic flux density is OA when H is reduced to zero. OA is called the ***retentivity*** or ***remanence*** of the sample.

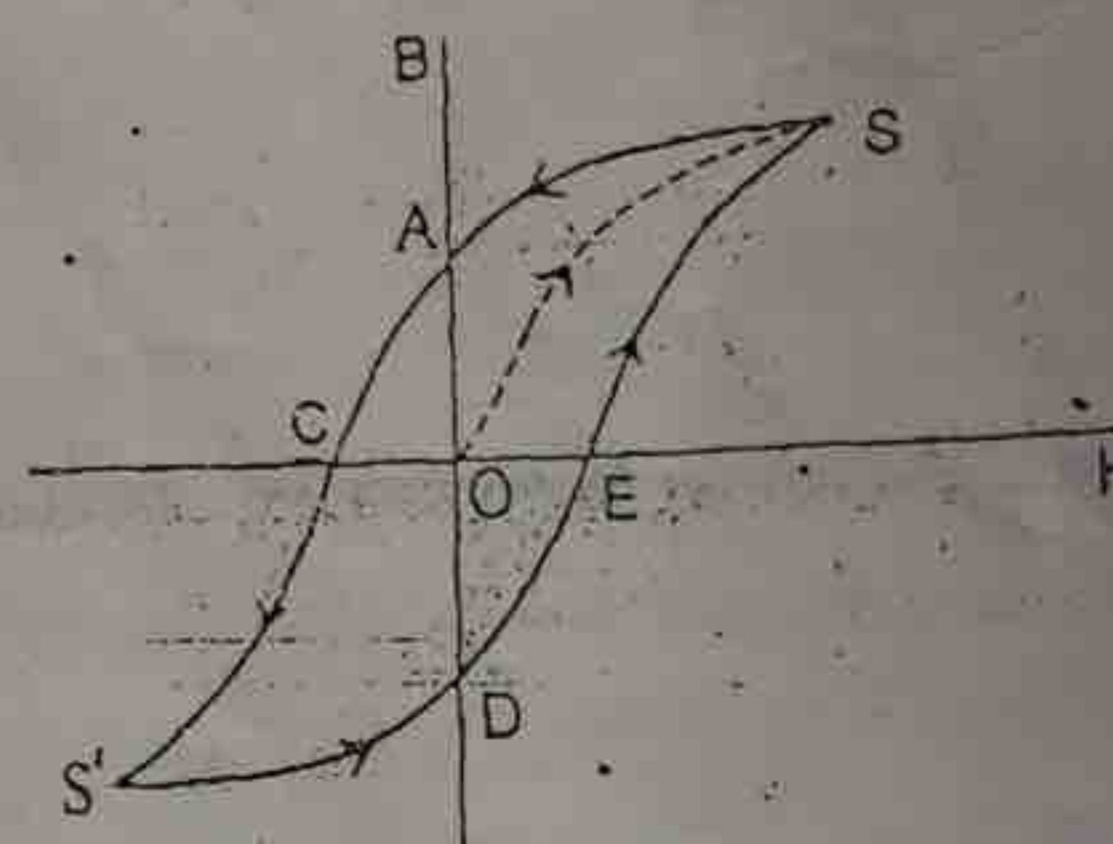
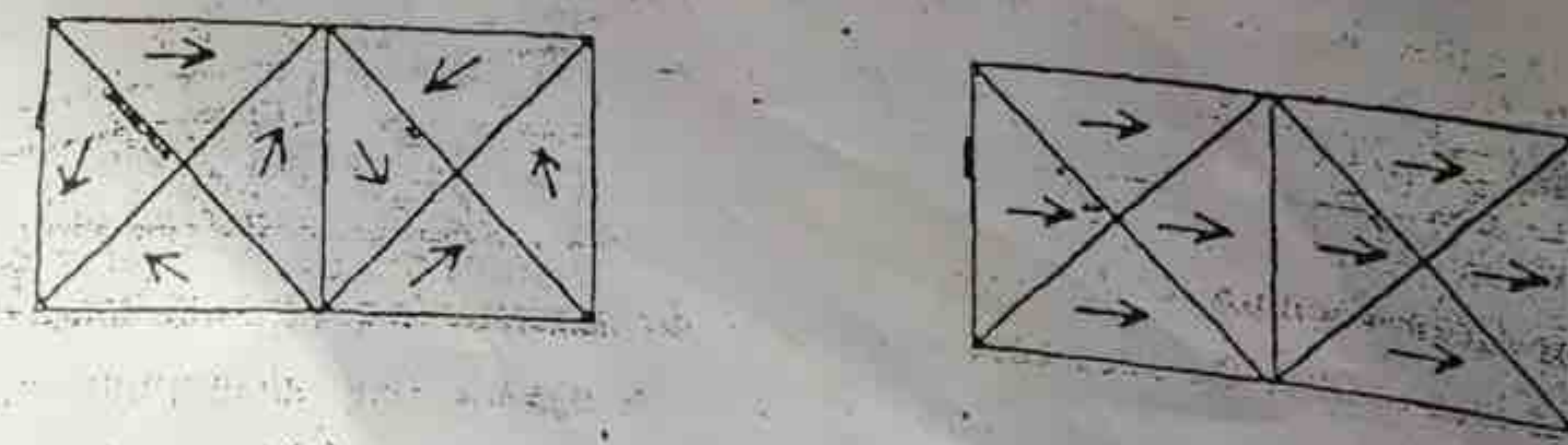


Fig. 5.5

The existence of some residual magnetism while the magnetic field is reduced to zero is termed ***hysteresis***. To reduce the value of B to zero i.e. to demagnetize the material completely, the direction of H must be reversed until a point C is reached. The value of H required to completely demagnetize the material, i.e. OC, is called the ***coercive force***. If H is increased beyond this value in the negative direction, a negative saturation point S' is again reached. Increasing the value of H in the positive direction beyond this point results in the curve S'DES, which completes the B-H loop (SACS'DES).

The area enclosed by the B-H loop is a measure of the work done per unit volume per cycle on the ferromagnetic material. It is usually converted into heat energy within the material, resulting in increase in temperature. Materials for permanent magnets should have a high retentivity and a large coercive force to avoid easy demagnetization.



(a)

(b)

Fig. 5.6