Magnetisation of a Material:

We define Magnetisation M of a sample to be equal to net magnetic moment per unit volume. i.e.

$M = m_{net} / V$

Again, the magnetic field inside a long solenoid of n turns per unit length and carrying a current I is given as,

$B_0 = \mu_0 nI$

And in terms of magnetic intensity H, we can write,

$B_0 = \mu_0 H$

If, now we introduce a material inside the solenoid which have magnetisation M, then we have total magnetic field as,

$B = \mu_0 H + \mu_0 M$

$B = \mu_0 (H + M)$

Again, magnetisation can also be defined as,

$M = \chi H$

Where, χ is called as magnetic susceptipility and is a measure of how a magnetic material responds to an external magnetic field.

Therefore,

$$\begin{aligned} B &= \mu_0 (1 + \chi)H \\ &= \mu_0 \mu_r H \\ &= \mu H \end{aligned}$$

Where, $\mu_r = 1 + \chi$ is a dimensionless quantity called the relative magnetic permeability of the substance.

Classification of Magnetic Materials:

Different magnetic materials can be mainly classified into 3 types namely-

1) Diamagnetic materials
2) Paramagnetic materials
3) Ferromagnetic materials

1) Diamagnetic materials:

The materials which are repelled by a magnetic field or feebly magnetized in the direction opposite to that of the applied magnetic field are known as diamagnetic materials. Some characteristics of diamagnetic materials are-

a) These are non permanent magnets and exists only in presence of an external magnetic field.
b) The induced magnetic moment is small, and the magnetisation(M) direction is opposite to the direction of applied field(H).
c) The value of magnetic susceptibility(χ) is small and negative and as a result, the relative permeability is less than unity.
d) Some examples of diamagnetic materials are- Cu, Ag, Si, Alumina etc.

2) Paramagnetic materials:

The materials which get weakly magnetized in the direction of the applied field are known as paramagnetic materials. Some of their important characteristics are-

a) Slightly stronger magnets; when an external field is applied, their dipoles line-up with the field resulting in a positive magnetization. However, the dipoles do not interact.
b) In the absence of an external field, the orientations of atomic magnetic moments are random leading to no net magnetization and hence these are non permanent magnets.

c) Since, thermal agitation randomizes the directions of the magnetic dipoles, an increase in temperature decreases the paramagnetic effect.
Experimentally, it is found that the magnetisation of a paramagnetic material is inversely proportional to the absolute temperature T.
Mathematically, $M = C\,B_0/T$
Or, $\chi = C\,\mu_0/T$
This is known as Curie's law and C is called Curie's constant.
d) Magnetic susceptibility of these materials is slightly positive an lies in the range of $+10^{-5}$ to $+10^{-2}$.
e) Some paramagnetic materials are- Al, Na, Ca, alloys of Cu etc.

3) Ferromagnetic materials:

The materials which get strongly magnetized in the direction of external magnetic field or strongly attracted by the applied field are known as ferromagnetic materials. Some characteristics of ferromagnetic materials are-

a) The atoms of ferromagnetic materials posses dipole moment and unlike paramagnetic materials, they interact with each other in such a way that they spontaneously align themselves in a common direction over a macroscopic volume called domains.
b) Even in the absence of external magnetic field, they posses a net magnetic moment in a particular direction and hence are called as permanent magnets.
c) The ferromagnetic property depends on temperature. The domain structure disintegrates with the increase in temperature. The temperature of transition from ferromagnetic to paramagnetism is called Curie temperature (T_C). The susceptibility above the Curie temperature, i.e. in the paramagnetic phase is described by,

$$\chi = C/(T - T_C) \qquad (T > T_C)$$

Soft Magnets:

The ferromagnetic materials whose magnetisation disappears upon removal of the external magnetic field are known as Soft magnets.

Soft magnets are characterized by low coercive forces and high magnetic permeabilities and they generally exhibit small hysteresis losses. They are used in cores for electromagnets, electric motors, transformers, generators and other electrical equipments.

Some examples of soft magnets are- ingot iron, low- carbon steel, silicon iron, permalloy, supermalloy etc.

Hard Magnets:

The ferromagnetic materials whose magnetisation persists even after removal of external magnetic field are known as Hard magnets. These are also called as permanent magnets.

Hard magnets are characterized by high retentivity and high coercivities. These magnets are useful in many applications including fractional horse- power motors, automobiles, audio and video recorders, earphones, computer peripherels and clocks etc.

Some examples of hard magnets are- steel, alnico, rare earth alloys like $SmCo_5$, Sm_2Co_{17}, NdFeB etc.

Domain Theory:

Domain in a substance is a small local region in which all the magnetic dipoles align parallel to each other giving rise to certain magnetisation within the domain. However, the direction of magnetisation within a domain is different from that in the neighbouring domain, as a result the net magnetisation of the specimen as a whole is almost zero. The boundary between two domains in a magnetic materialmarked by a layer wherein the direction of magnetization is assumed to change gradually from one domain to the other is called as Domain wall or Bloch wall.

When a magnetic field is imposed on the material, domains that are nearly lined up with the field grow at the expense of unaligned domains. When the domain growth is completed, a further increase in the magnetic field causes the domains to rotate and align parallel to the applied field. As the process continues, there comes an instant when almost all the domain gets aligned parallel to the external field and saturation is said to be achieved after which no further increase will take place even on increasing the strength of the external field.

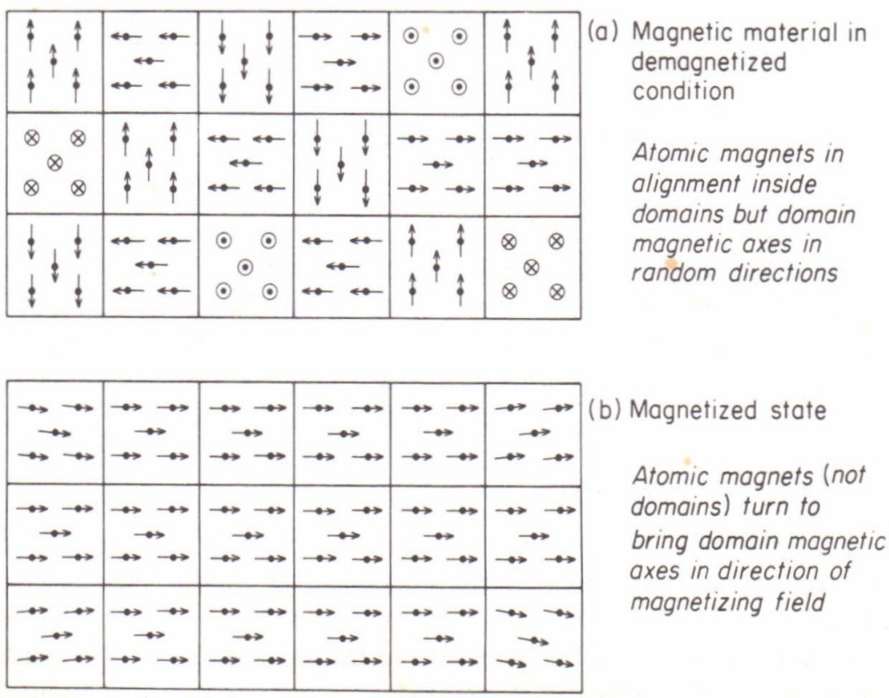


Fig 1.1: Domain structures in unmagnetised and magnetised ferromagnets

Hysteresis in Ferromagnetic Materials:

Let us consider an unmagnetised specimen of a ferromagnetic substance. Initially when no magnetic field(H) is applied, the magnetic induction(B) on the specimen is zero.

If, magnetic intensity is now monotonically increased from zero, B will increase along curve 1 as shown in figure. This curve is known as the magnetisation curve of the material. With an increase in H from zero, the magnetisation M increases from zero to a saturated value M_s and accordingly, B increases following the relationship, $B = \mu_0 (H + M)$. When M saturates at high values of H, B will slowly increase due to $\mu_0 H$ term. This accounts for the non linear nature of the curve in the figure.

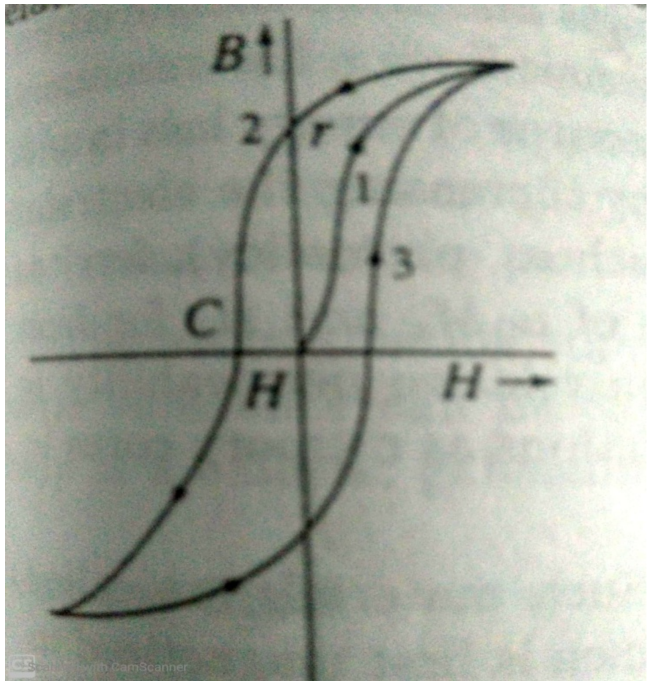


Fig 2.1: B – H curve or Hysteresis loop

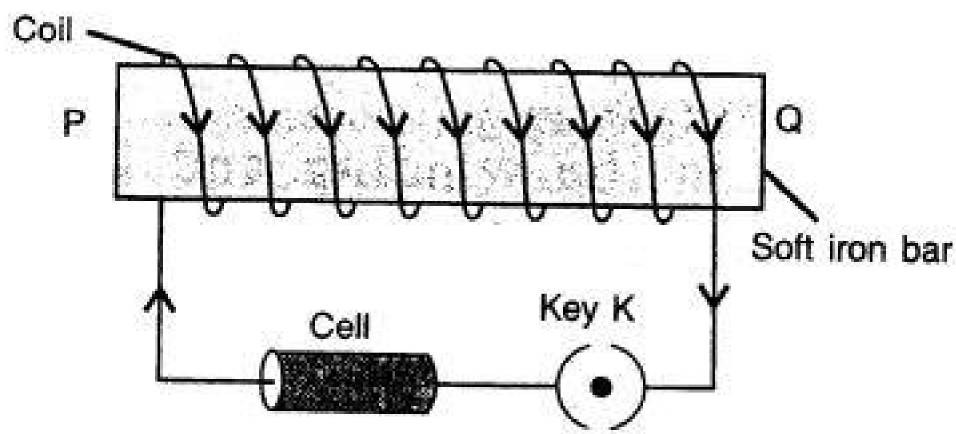
After reaching the saturation magnetisation, the value of H is gradually decreased. The B-H relationship does not follow back down the curve 1 of the figure. Instead, the B values trace the curve 2 which shows that even when H is zero, B is not so. That is, the material has been permanently magnetised. The value of B at the point r, denoted by B_r is called the **Remanent Induction.** To make the value of B zero, H has to be increased in the reverse direction. The magnitude of H at which B is zero (denoted as H_C in the diagram) is known as **Coercive Force** or **Coercivity** of the material.

As H is increased in the reverse direction, curve 2 is traced till the magnetisation saturates in the reverse direction. As H is reduced back to zero, the B-H relationship follows the curve 3. Again when H is zero, a residual negative B value exists. As H is reversed and increased, curve 3 is followed until the magnetisation saturates. This closed loop in the B-H plane is known as the **Hysteresis Loop** in ferromagnetic materials in which B lags behind the H.

Hysteresis Loss:

When a magnetic material is taken through a cycle of magnetisation, there occurs always a loss in energy. A work is done by the magnetising field (H) in aligning the individual magnetic dipoles parallel to its direction. However, during demagnetisation when H = 0, B 0, rather some magnetism is left within the material. To remove the magnetism from the specimen, coercive force has to be applied. This energy loss equivalent to coercive force is called as Hysteresis loss.

Let us consider an iron bar of length l and area of cross section A, having n turns of insulated copper wire wound over it. The passage of electric current causes the magnetisation of the iron bar.



Making a bar electromagnet

Fig 2.2: Magnetisation of an iron bar using electric current

Now, magnetic flux linked with n turns, $\phi = nBA$ (1)

According to Faraday's law of electromagnetism, an induced emf is produced in the wire that opposes the change in current in the wire.

i.e. e = (2)

From equations (1) and (2),

e =

Or, $e =$ (3)

Again, power supplied to do the external work against induced emf is given as,

$$P = eI \quad (4)$$

From equations (3) and (4),

$P =$

Now, small work done dW in a small time dt is given as,

$$dW = Pdt$$

$=$

$$= (nI)AdB \quad (5)$$

Again as, $H =$

Or, $nI = Hl$

Therefore, $dW = (Hl)AdB$ (6)

Hence, total work done over a full cycle of magnetisation is found by integrating equation (6)-

Or, $W = V$

Where, $V = Al$ is the volume of the specimen and is the area enclosed by the B –H curve or hysteresis loop.

Therefore, Energy loss per unit volume, E =

Or, = Area enclosed by B – H loop.