2 MAGNETIC MATERIALS

2.1 Introduction

The materials that can be magnetized are called as magnetic materials. The magnetic materials are finding a lot of applications such as magnetic memories, inductors, transformers, ferrites antennas, and loud speakers etc. Most of the engineering components are made up of permanent magnets. Even though five different types of magnetic materials are available, only the ferromagnetic material and ferrimagnetic materials are mostly used for the application purposes. The diamagnetic and paramagnetic materials are not mostly used. This chapter deals about the ferromagnetic and ferrimagnetic materials and their uses.

2.2 Definition of some fundamental terms

(i) Magnetic dipoles

Any two opposite poles separated by a suitable distance constitutes a dipole. A magnet is said to be a **magnetic dipole**. It has north and south poles. The distance of separation is the length of the magnet.

(ii) M**agnetic dipole mome**nt

The term magnetic dipole moment is defined as follows:

a. It is defined as the product of the magnetic pole strength and the length of the magnet. It is represented by the letter μ. Therefore, $\mu = m.\ell$.
b. Consider a current of i ampere is passed through a coil of wire and A be the area of cross section of the wire, then the term, **magnetic dipole moment** is defined as the product of the current and the area of cross section. That is, $\mu = i.A$. The unit for the magnetic dipole moment is A m^2.
c. Consider a magnet is suspended in a magnetic field. The magnet experience certain torque and hence it will rotate and rest at some position. The torque experienced by the magnet is given by, $\tau = \bar{\mu} \times \bar{B}$, where $\bar{\mu}$ is the magnetic moment and $\bar{B}$ is the magnetic flux density.

(ii) Magnetic lines of forces

The magnetic field in a magnetic material is studied by drawing the magnetic lines of forces. The magnetic lines of forces are also called as magnetic flux. The magnetic lines of forces originates from north pole and end at south pole.

(iv) Magnetic flux density, B

The magnetic flux passing through the unit area of cross section is known as the **magnetic flux density**. It is represented by the letter B. Its unit is Wb m^{-2}.

The magnetic flux density is given by B= $\frac{\phi}{A}$, where φ is the magnetic flux and A is the area of cross section.

The magnetic flux density is also given by, $B=\mu H$ (2.1)

The flux density in air or vacuum, $B_o=\mu_o H$ (2.2)

and $B=\mu_o(M+H)$ (2.3)

where M, H, μ_o, μ are magnetization, magnetic field strength, permeability of free space and permeability of the medium.

(v) Magnetic field strength, H

The magnetic field strength is the force experienced by a unit north pole placed in the magnetic field region. It is represented by the letter, H. Its unit is A m^{-1}.

(vi) Magnetization, M

The magnetic moment per unit volume is known as magnetization. Its unit is A m^{-1} and it is represented by the letter M.

(vii) Magnetic susceptibility, χ

The ratio between the magnetization and the magnetic field strength is known as the magnetic susceptibility. It has no unit and it is represented by the letter, χ .

$\chi = \frac{M}{H}$.

(viii) Magnetic relative permeability, μ_r

The ratio of the permeability of a medium to the permeability of a free space is known as magnetic relative permeability. It is represented by the letter, μ_r and it is given by, $\mu_r = \frac{\mu}{\mu_O}$. Here, μ_O is the permeability of free space and it is equal to, $\mu_O = 4\pi x 2^{-7}$ H m^{-1}.

The magnetic relative permeability is also defined as, $\mu_r = \frac{B}{B_O}$ (2.4)

where B and Bo are the magnetic flux density in a medium and magnetic flux density in vacuum.

(ix) Bohr magneton

The magnetic moment is expressed in the unit ampere – square meter (A-m^2). Since the magnetic moment of an atomic particle is very low, it is represented by another unit known as Bohr magneton. The value of one Bohr magneton is given by,

$$1 \text{ Bohr magneton} = \frac{eh}{4\pi m} \tag{2.5}$$

Substituting the values of e, m and h, we get

$$1 \text{ Bohr magneton} = \frac{1.6\times10^{-19}\times6.626\times10^{-34}}{4\pi\times9.1\times10^{-31}}$$

$$= 9.27 \times 2^{-24} \text{ A-m}^2$$

It is represented by the letter, β. The value of 1 Bohr magneton is equal to 9.27×2^{-24} A-m^{-2}.

2.3 Classification of the magnetic materials

The magnetic materials are broadly classified into two types. They are (i) those do not have permanent dipole moments and (ii) those having permanent dipole moments. The term **permanent dipole moment** means the presence of the dipole moment even in the absence of the magnetic field. It is represented by the letter μ_{P}.

(i) The materials those do not have permanent dipole moment

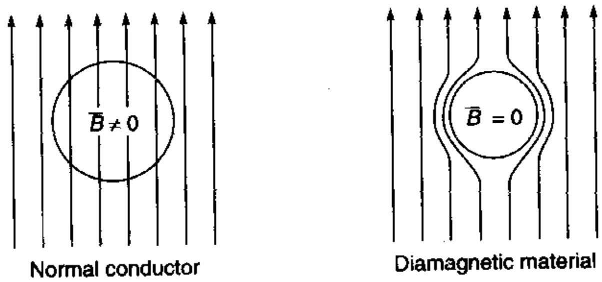
The diamagnetic material is the example for the materials those do not have the permanent dipole moments.

(ii) The materials those having permanent dipole moment

The paramagnetic materials, ferromagnetic materials, antiferromagnetic materials and ferrimagnetic materials are the examples for the materials those having permanent dipole moments.

(a) Diamagnetic material

The diamagnetic materials exhibit negative susceptibility. The relative permeability of the diamagnetic material is slightly less than unity. When a diamagnetic material is placed in a magnetic field, the magnetization vector **M** is in opposite direction to the applied field, H. The negative susceptibility of a diamagnetic material is due to the repulsive force experienced by the diamagnetic material with the applied magnetic field. Consider a diamagnetic material is placed in a non-uniform magnetic field. It experiences a force towards smaller fields. The diamagnetic property is due to the presence of closed shell or subshell in the material. Mostly the covalent and ionic crystals exhibit the diamagnetic property. The superconducting materials exhibits perfect diamagnetism (χ=-1).



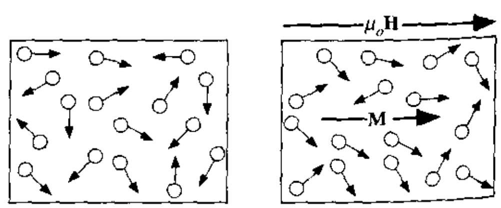
(a) (b)

Fig.2.1 Diamagnetic property

The examples for the diamagnetic materials are, (i) the covalent metals such as Si, Ge, diamond, (ii) some metals such as copper, silver, gold, (iii) some ionic solids such as alkalai halides (iv) superconductors, and (v) organic materials such as polymers.

(b) Paramagnetism

In a paramagnetic materials the dipoles are randomly oriented because the random collisions of the molecules. The paramagnetic materials exhibit positive susceptibility. When a magnetic field is applied, the individual magnetic moment takes the alignment along the applied field. The magnetization of a paramagnetic material increases with the increase of the applied field. The increase of temperature reduces the magnetization and it destroys the alignment of dipoles with the applied field.



(a) (b)

Fig.2.2 Paramagnetism (a) random orientation of dipoles in the absence of the field, (b) the dipoles align towards the field

Consider a paramagnetic material is placed in a non-uniform magnetic field. The paramagnetic material experiences a net force towards a greater field. The susceptibility of a paramagnetic material is given by

$$\chi = \frac{C}{T} \tag{2.6}$$

where C is the Curie constant, T is the temperature.

The examples for paramagnetic materials are Mg, gaseous and liquid oxygen, the ferromagnetic material (Fe) at high temperature, the antiferromagnetic material (Cr) at high temperature and ferrimagnetic material (Fe_3O_4) at high temperatures.

(c) Ferromagnetism

In a ferromagnetic material, all the dipoles are aligned parallel. If a small value of magnetic field is applied, a large value of magnetization is produced. Ferromagnetic material has permanent dipole moment and the susceptibility is positive. The magnetization in a ferromagnetic material is non-linear and it becomes saturated, if a large value of magnetic field is applied.

A ferromagnetic material exhibits two different properties. It behaves as a ferromagnetic below a certain temperature known as ferromagnetic Curie temperature. Above that temperature, it behaves as a paramagnetic. In the ferromagnetic region, it exhibits a well known curve known as hysteresis curve.

The susceptibility of a ferromagnetic material above the ferromagnetic Curie temperature, θ_f is given by

$$\chi = \frac{C}{T - \theta_f} \quad \text{when } T > \theta_f \qquad (2.7)$$

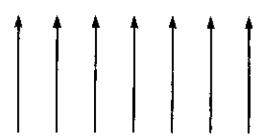


Fig.2.3 Alignment of dipoles in a ferromagnetic material

where C is the Curie constant and θ_f is the ferromagnetic Curie temperature. The transition and rare earth metals such as Fe, Co, Ni, Gd, Dy are the examples for ferromagnetic material.

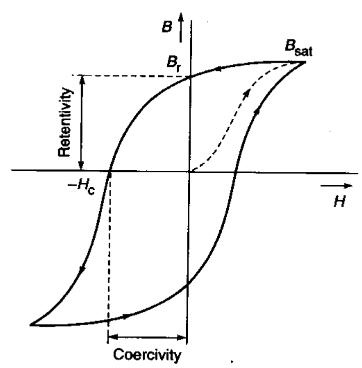


Fig.2.4 Ferromagnetic material-Hysteresis curve

(d) Antiferromagnetic materials

In an antiferromagnetic material the dipoles are aligned antiparallel. It has positive value of susceptibility, but it is small. In the absence of the magnetic field, the magnetization produced by one dipole is cancelled by the other one, because the magnitudes of the adjacent dipoles are same. So, the antiferromagnetic materials do not have magnetization in the absence of the magnetic field. The antiparallel alignment of dipole is due to quantum mechanical exchange forces. The antiferromagnetism occurs only below certain temperatures called as Néel temperature, T_N. Above the Néel temperature the material is paramagnetic.

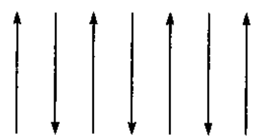


Fig.2.5 Antiferromagnetic material-Alignment of dipoles

The susceptibility of an antiferromagnetic material is given by

$$\chi = \frac{C}{T+\theta} \quad \text{when } T > T_N \qquad (2.8)$$

where C is the Curie constant and T_N is the Néel temperature. The examples for antiferromagnetic materials are the salts and oxides of transition metals like MnO, NiO, MnF_2, the transition metals like α-Cr, Mn.

(e) Ferrimagnetism

In ferrimagnetic materials such as ferrites, the dipoles are aligned antiparallel. But the adjacent dipoles are not equal in magnitude. So, they have magnetization even in the absence of the magnetic field. The origin of ferrimagnetism is due to the magnetic ordering of dipoles. These materials behave as ferrimagnetic only below certain temperature known as Curie temperature. Above the Curie temperature, it behaves as a paramagnetic material. The susceptibility of a ferrimagnetic material is positive and it is given by

$$\chi = \frac{C}{T \pm \theta} \text{ when } T > T_N \qquad (2.9)$$

where T_N is the Néel temperature and C is the Curie constant. Examples for ferrimagnetic materials are Fe_3O_4, $FeFe_2O_4$ (ferrous ferrite).

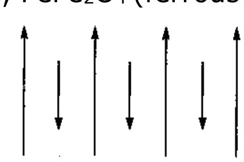


Fig.2.6 Ferrimagnetic material-Alignment of dipoles

2.4 Origin of permanent dipole moment

The magnetic moment of a magnetic material is related to its angular momentum. If a magnetic material possesses angular momentum, then it has dipole moment in the absence of the magnetic field. The permanent dipole moment arises due to the following factors. They are,

1. Orbital angular momentum of the electron
2. Spin angular momentum of the electron and
3. Nuclear magnetic moment.

(i) Orbital angular momentum of the electron

The orbital angular momentum of the electron arises due to the orbital motion of the electron. The relation between the orbital angular momentum and the magnetic moment is given by

$$\mu_m = -\frac{e}{2m} M_o \qquad (2.2)$$

where μ_m is the magnetic moment, M_O is the orbital angular momentum of the electron, e is the charge of the electron and m is the mass of the electron.

An electron is represented by four quantum numbers. They are the principal quantum number, n, the orbital quantum number, ℓ, the magnetic orbital quantum number m_l, and the magnetic spin quantum number, m_s. The principal quantum number takes the values of 1,2,3,4,...etc. The orbital quantum number takes the values of 0,1,2,3,4,...,n-1. The m_l value varies from - ℓ to ℓ including zero. The m_s value is either +½ or -½. The value of the orbital angular momentum is given by $M_o = \frac{h}{2\pi} m_l$.

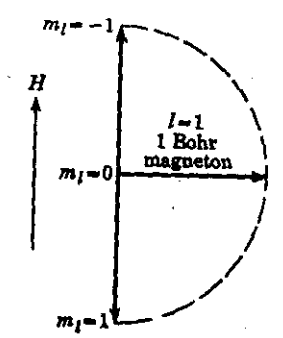


Fig.2.7 Illustration of three possible components of magnetic moment associated with orbital momentum quantum number in an external magnetic field

For, n=1, ℓ= 0 and m_l =0. Substituting the value of m_l =0, the angular momentum is zero and hence the magnetic moment is zero. Now, consider, n=2, ℓ= 0, 1. For n=2, ℓ= 0, and m_l =0 and hence the angular momentum and the magnetic moment is zero. For n=2, ℓ= 1, m_l = +1, 0 and -1. The value of the orbital angular momentum for m_l = +1, 0 and -1 are respectively given by, $M_O = \frac{h}{2\pi}$, 0, $M_O = -\frac{h}{2\pi}$. The possible value m_l in an external magnetic field is displayed in Fig.2.7. The value of the magnetic moment corresponding to n=2, ℓ= 1, m_l = +1, 0 and -1 are,

$\mu_m = -\frac{eh}{4\pi m}$, 0, and $\mu_m = \frac{eh}{4\pi m}$. For a completely filled electronic energy states, the total angular momentum is zero. For an unfilled electronic energy states, the total angular momentum and hence the total magnetic moment is not equal to zero. For an electrical engineer is concerned, the iron group element with atomic numbers 21 to 28 are important.

(ii) Spin angular momentum of the electron

The spin angular momentum arises due to the spinning motion of the electron. The spin angular momentum is given by $M_S = \frac{h}{2\pi} m_s$, where M_S is the spin angular momentum, m_s is the magnetic spin quantum number. The magnetic spin quantum number takes either +½ or -½. The spin angular momentum is given by $M_S = \frac{h}{4\pi}$, $M_S = -\frac{h}{4\pi}$. The relation between the magnetic moment and the spin angular momentum is given by, $\mu_m = -\frac{e}{m} M_S$. Substituting the value of the spin angular momentum, we get, $\mu_m = -\frac{eh}{4\pi m}$, $\mu_m = \frac{eh}{4\pi m}$. Two possible magnetic moment components associated with electron spin is shown in Fig.2.8. For completely filled electronic states, the total magnetic moment is zero. For unfilled electronic states, the total magnetic moment is not equal to zero.

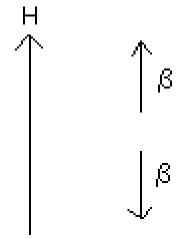


Fig.2.8 Two possible magnetic moment components associated with electron spin

(iii) Nuclear magnetic moment

The nuclear magnetic moment arises due to the spinning motion of the nucleons. The nuclear magnetic moment is given by $\mu_m = \frac{eh}{4\pi m_N}$, where m_N is the mass of the nucleons. The mass of the nucleon is 1.67 x 2^{-27} kg, whereas the mass of the electron is 9.1 x 2^{-31} kg. Since, the mass of the nucleon is very large, the nuclear magnetic moment is nearly 200 times lower than the magnetic moment due to the electrons and hence the nuclear magnetic moment is negligible.

2.5 Ferromagnetic materials

The dipoles of a ferromagnetic material are aligned parallel to each other. The parallel alignment produces magnetic moment even in the absence of the magnetic field.

2.5.1 Properties of ferromagnetic material

The ferromagnetic material behave as a paramagnetic material above a certain temperature, known as ferromagnetic Curie temperature, θ_f and exhibits a well known curve known as hysteresis curve below the ferromagnetic Curie temperature.

(i) Paramagnetic behaviour of a ferromagnetic material

A ferromagnetic material behaves as a paramagnetic material above a certain temperature known as ferromagnetic Curie temperature, θ_f . If a graph is drawn between $\frac{1}{\chi}$ and T, a curve as shown in Fig.2.9 is obtained. In the case of a paramagnetic material, a straight line is obtained and it passes through the origin. Similar straight line behaviour is obtained for the ferromagnetic material. It indicates that the ferromagnetic material is behaving as a paramagnetic material, above the ferromagnetic Curie temperature. For the ferromagnetic material, nearer to the X axis, the straight line is slightly curved. The point at which the curve intersects the X-axis is known as ferromagnetic Curie temperature. If the line is extrapolated by identifying the straight line portion, it will meet the X axis. The point of intersection of the extrapolated line at the X axis is known as paramagnetic Curie temperature, θ. The paramagnetic and ferromagnetic Curie temperatures of some materials are listed in Table 2.1.

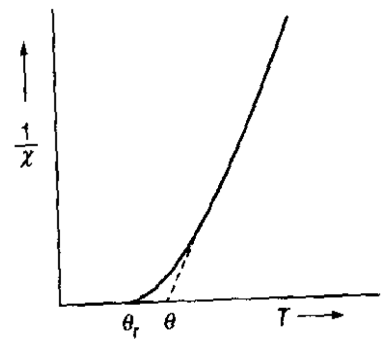


Fig.2.9. A plot of $\frac{1}{\chi}$ versus T curve for a ferromagnetic material

Material	θ in K	θ_f in K
Iron	293	243
Cobalt	1428	1393
Nickel	650	631

Table 2.1 Paramagnetic and ferromagnetic Curie temperature of some materials

(ii) Hysteresis Curve

Below the ferromagnetic Curie temperature, ($T<\theta_f$), the ferromagnetic material exhibit a well known curve known as hysteresis curve. If the magnetic field is gradually increased, the flux density increases and it becomes maximum. This maximum value of flux density is called as saturated flux density (B_{sat}). If the field is reversed, the ferromagnetic material is found to have flux density even though the applied field becomes zero (H= 0). This property, the presence of flux density even in the absence of the magnetic field, is said to be retentivity or remanent flux density (B_r). The magnetization corresponding to the applied magnetic field is equal to zero (H=0 and $M_r=\frac{B_r}{\mu_o}$) is known as spontaneous magnetization. If the field is further reduced, the flux density becomes zero. The field required to bring the magnetic flux density into zero is called as coercive field or coercivity ($-H_c$). If the field is further reduced, the flux density will become minimum. There is no further decrease in the value of the flux density beyond this value. If the field is increased, a closed loop as shown in Fig.2.2 is obtained. This closed loop between B and H is called as hysteresis loop or B-H curve. The B_{sat} and M_{sat} values of some ferromagnetic materials are listed in Table 2.2.

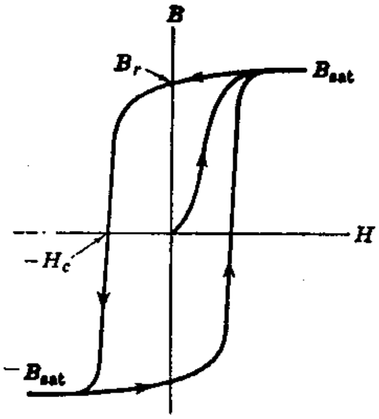


Fig.2.2 Hysteresis curve of a ferromagnetic material

Material	Crystal structure	Bohr magneton per atom	B_{sat} In T	M_{sat} 2^6 A m^{-1}	Curie temperature, T_C in K
Iron	BCC	2.22	2.2	1.75	243
Cobalt	HCP	1.72	1.82	1.45	1393
Nickel	FCC	0.60	0.64	0.50	631
Gadolinium	HCP	7.1	2.5	2.0	289

Table 2.2 B_{sat} and M_{sat} values of some ferromagnetic materials

2.5.2 Weiss theory of ferromagnetism

Weiss, in 1907, proposed two concepts to explain the properties of ferromagnetic materials. They are, namely, (i) the internal field concept and (ii) the domain concept.

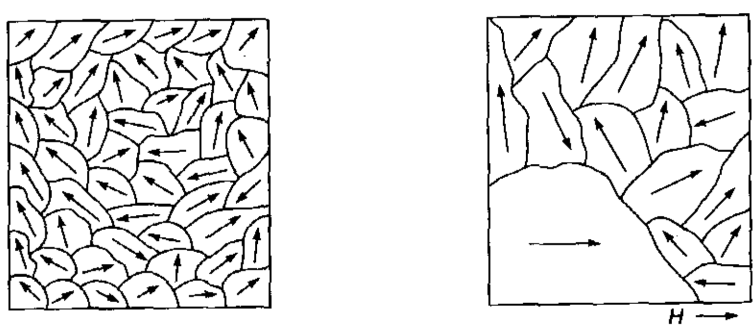
The magnetic field present at the location of a dipole is greater than the applied field. A dipole experiences the field due to the applied field and the field produced by the nearest neighbouring dipoles due to the interactions. The field produced by the interaction between the adjacent dipoles is known as internal field. The internal field is given by γM, where γ is the internal field constant and M is the magnetization. The internal field concept explains the spontaneous magnetization of ferromagnetic materials and the paramagnetic behaviour of ferromagnetic material.

A ferromagnetic material consists of a large number of localized regions called as domains. The domain concept is used to explain the hysteresis property of the ferromagnetic material.

The Weiss theory explains most of the property of the ferromagnetic material. However, it has some drawbacks. According to Weiss theory, the ferromagnetic Curie temperature and paramagnetic Curie temperatures are same. But the experimental results says that these two values are different. The internal field constant, and the interaction energy (~kT) evaluated from Classical theory (Weiss theory) are 200 times smaller than the actual value. This means that the interaction energy is due to the wave nature of electrons and hence they are quantum mechanical concepts. They are explained using quantum mechanics based on the exchange interaction concepts.

(a) Magnetic domains

Consider a ferromagnetic material is heated above its Curie temperature and cooled without applying the magnetic field, the magnetic domains are produced. The domains are the localized small region in which all the dipoles are aligned in one direction. A ferromagnetic material is found to have a number of domains and the dipoles of the adjacent domains are randomly oriented so that the resultant magnetization in the absence of the field is zero. The adjacent domains are separated by a region called as domain wall or Bloch wall. The arrangement of domains in a polycrystalline iron sample is shown in Fig.2.11 (a). If a magnetic field is applied to a ferromagnetic material, the domains that are parallel to the applied field increase in its size, whereas the size of the domains that are pointed in other directions to the applied field decreases.



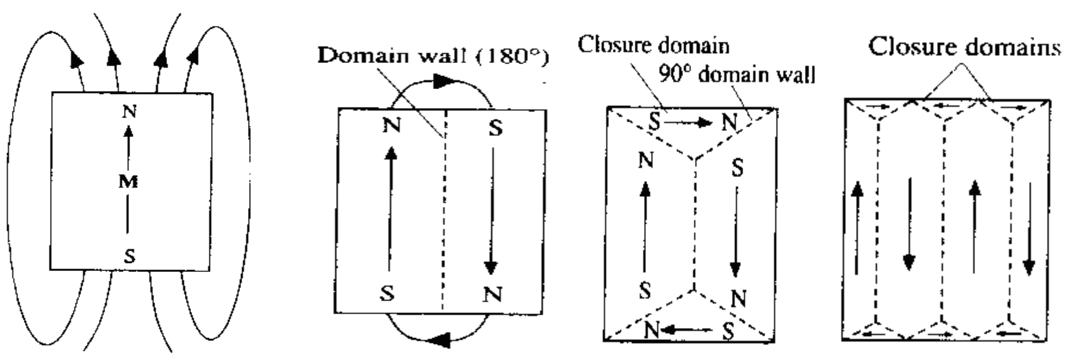
(a) (b)

Fig.2.11 Domains in a ferromagnetic material (a) in the absence of the field and (b) in the presence of the field

The internal energy of the domain is contributed by the following energies: (i) magnetostatic energy, (ii) anisotropy energy (iii) domain wall energy and (iv) magnetostriction energy.

(i) Magnetostatic energy

Consider a ferromagnetic material consisting of single domain. One end is the north pole of the magnet and the other end is the south pole of the magnet. The magnetic lines of forces originate from the north pole and they end at the south pole. The potential energy stored in a magnetic material is called as magnetostatic energy. The potential energy of this material can be reduced by creating another domain. Consider these domains are in the antiparallel direction. The region that separates these two domains is said to be domain wall or Bloch wall. The second domain is created by reducing the potential energy and it is rotated through an angle of 180° from the first domains. Similarly more number of domains are created by reducing the magnetostatic energy (potential energy). Fig.2.12(c) has four domains. These domains closes the ends of the magnetic material with sideway domains and hence they are said to closure domains. In Fig.2.12 (d), the potential energy is further reduced and more number of domains are created. Thus, the creation of magnetic domains continues until the potential energy reduction in creating an additional domain is equal to the increase in potential energy for creating an additional wall. The specimen has minimum potential energy and the net magnetization becomes zero.

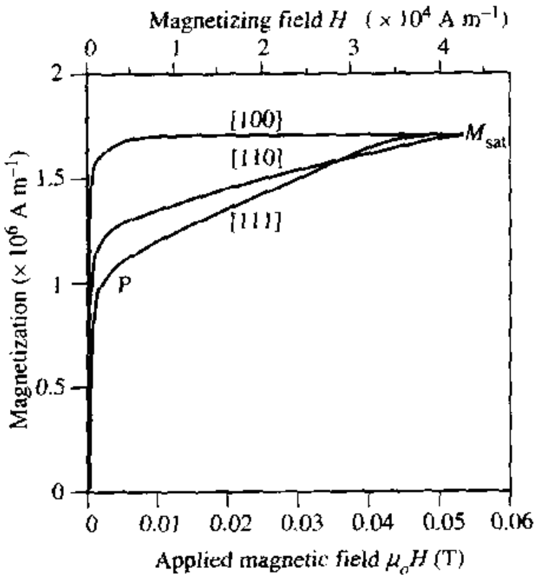


(a) (b) (c) (d)

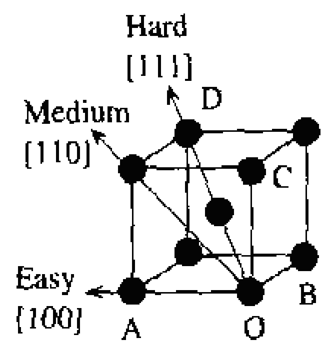
Fig.2.12 (a) A magnetized material with one domain, (b) Creation of two domains, (c) Closure domains at the ends of the magnet, and (d) a number of domains are created

(ii) Anisotropy energy

Iron is easily magnetized along [20] direction. It is difficult to magnetize iron along [111] direction. In order to magnetize iron along [111] direction one has to spend a larger magnetic field than magnetizing it along [20] direction. Magnetizing iron along [111] direction demands a magnetic field of nearly four times as that of the field required to magnetize it along [20] direction. Therefore, [20] direction for iron is said to be an easy direction, whereas the [111] direction for iron is said to be hard direction. Iron needs a medium value of magnetic field to magnetize it along [12] direction. Therefore, [12] direction for iron is said to be medium direction. A plot of magnetization versus applied magnetic field for iron along [20], [12], and [111] directions are shown in Fig.2.13 (a) and the directions [20], [12] and [111] for iron is shown in Fig.2.13 (b)..



(a)



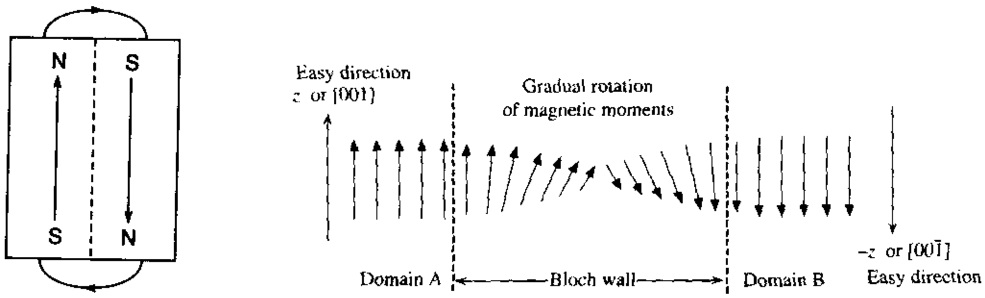
(b)

Fig.2.13 (a) Application of magnetic field to iron along different direction
(b) Different directions of iron

The excess energy required to magnetize a material along a particular direction than its easy direction is known as anisotropy energy. It is denoted by the letter, K. The anisotropy energy for iron along [20] direction is zero and for the [111] direction, it is about 40 kJ m^{-3}. For nickel, [20] direction is the hard direction, [12] is the medium direction and [111] direction is the easy direction.

(iii) Bloch wall energy or domain wall energy

Consider a magnetic material with two domains. Consider these two domains are antiparallel with each other as shown in Fig.2.14a. The rotation of the domain wall does not take place abruptly. The spin magnetic moments rotates within the domain wall gradually. The exchange force and the anisotropy energy are responsible for the rotation within the domain wall. The exchange force requires a very thick (infinitely thick) domain wall to achieve 180^{O} rotation, whereas the anisotropy energy requires a spacing of one atomic scale for the rotation of magnetic moments through 180°. That is, the exchange force demands a very thick wall and the anisotropy energy demands a thin wall. Therefore, the domain wall has a thickness of an equilibrium value which minimizes the total potential energy, which is the sum of the exchange energy and anisotropy energy. The minimum potential energy, which determines the domain wall thickness, is known as domain wall energy. The domain wall thickness for most of the material lies in the order of 200 to 300 Å. The iron has a domain wall thickness of ~ 0.1 μm.



(a) (b)

Fig.2.14 Magnetic domain in a magnetic material (b) Gradual rotation of domains

(iv) Magnetostriction energy

Consider a magnetic field is applied to a ferromagnetic material along its easy direction, then the length of the material increases. For iron [20] direction is the easy direction. If a magnetic field is applied to iron along [20] direction the length of the material increases and if the magnetic field is applied to iron along its transverse direction, [02] and [001] the length decreases. This phenomenon is known as magnetostriction effect.

The longitudinal strain, $\frac{\Delta l}{l}$, is said to be magnetostriction constant and it is denoted by λ. The magnetostriction constant is positive, when the field is applied along the easy direction. Consider the crystal reaches a saturation magnetization, and then the magnetostriction constant also reaches saturation. The maximum strain is called as the saturation strain. It is typically equal to 2^{-6} to 2^{-5}. The crystal lattice strain energy associated with magnetostriction is called as magnetostriction energy.

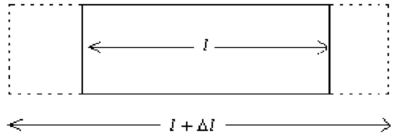


Fig.2.15 Magnetostriction effect in a ferromagnetic material

The magnetostriction constant is negative for nickel and positive for iron along the easy direction. It may be controlled by suitably alloying. For 85% Ni and 15% Fe, it is zero.

(b) Hysteresis curve (M versus H curve) for a polycrystalline material

A polycrystalline material consists of a number of grains. It is prepared by heating a ferromagnetic material above its Curie temperature and then by cooling without applying the magnetic field. It consists of a number of grains and the grains consist of domains. A small grain is made of single domain, where as a large size grain consists of a number of domains.

Consider the polycrystalline material is subjected to a magnetic field. If the field is increased, the magnetization slowly increases. The domains those are parallel to the direction of the applied field increases in its size. Let the structure of domains in the unmagnetized state at the point 'O' is as shown in Fig.2.16. The shape of the domain at the point 'a' in Fig.2.16, indicates the domain that is parallel to the applied field increases in its size. When the domain wall is growing, it has to overcome some obstacles in the crystal such as imperfection, impurities, second phases and so on. If the field is sufficiently increased, the domain wall overcomes these obstacles and hence there is a jerk in the domain wall motion. This process involves energy conversion into heat. The jerk produces a small jump in the magnetization curve. This phenomenon is known as Barkhausen effect.

If the field is further increased, the magnetization increases. The domains those are parallel to the applied field increases whereas the domains that are pointing in other directions shrink. The domains shape at the points 'o','a','b','c', and d is shown in Fig.2.16. The curve *oabcd* is known as initial magnetization curve. At c, some grains are oriented along the direction of magnetization. At d, the entire specimen is made up of a single domain. If the field is further increased, then there is no increase in the size of the domain, which indicates that there is no further increase in the magnetization of the material.

If the field is slowly decreased, the size of the domain decreases and hence some new domains begin to grow. Even though the field is reduced to zero, the specimen has some value of magnetization indicating that the specimen does not regained its original domain structure as similar to its structure before the material gets magnetized (i.e., the structure at 'o'). This property is said to be remanent or residual magnetization or retentivity (B_r). If the field is further applied in the reverse direction, the magnetization becomes zero, when the field is at $-H_C$. The field $-H_C$ is called as coercive field or coercivity. The coercivity is the field required to bring the magnetization into zero. At $-H_C$, the material regains its actual domain structure.

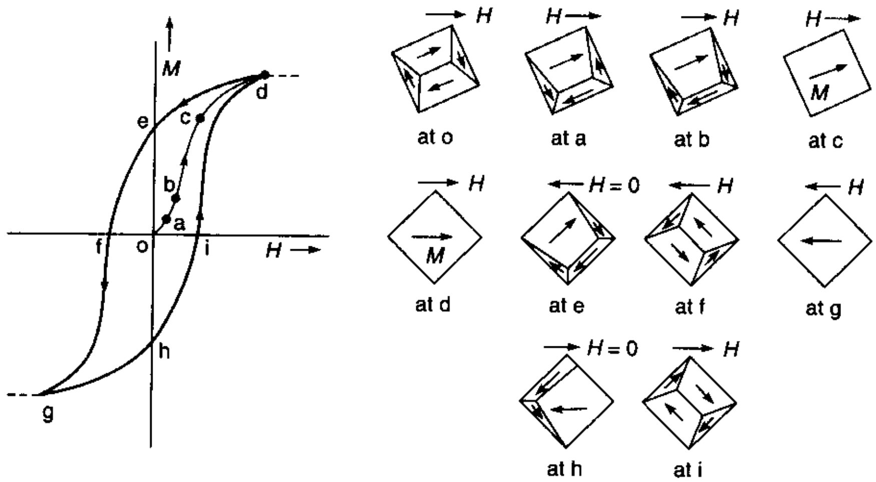


Fig.2.16 Hysteresis curve

If the field is further decreased, the domains that is parallel to the applied field increases, whereas the domains that are in the other directions decreases. At g, the lowest value of magnetization occurs indicating that the specimen is fully occupied by a single domain. If the field is further decreased, there is no decrease in the magnetization value indicating that the entire specimen is fully occupied by a single domain. If the field is slowly increased, the curve takes the path ghid and then the curve is closed. This closed loop is called as hysteresis loop.

2.5.3 Origin of ferromagnetism and Heisenberg's exchange interaction

The ferromagnetic property is exhibited by transition elements such as iron, cobalt, and nickel at room temperature and rare earth elements like gadolinium and dysprosium. The ferromagnetic materials possess parallel alignment of dipoles. This parallel alignment of dipoles is not due to the magnetic force existing between any two dipoles. The reason is the magnetic potential energy is very small and it is smaller than thermal energy.

The electronic configuration of iron is $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $3d^6$, $4s^2$. For iron the 3d subshell is an unfilled one. This 3d subshell has five orbitals. For iron the six electrons present in the 3d subshell occupies the orbitals such that there are four unpaired electrons and two paired electrons as shown in Fig.2.17. These four unpaired electrons contribute a magnetic moment of 4β. This arrangement shows that the parallel alignment of four unpaired electrons.

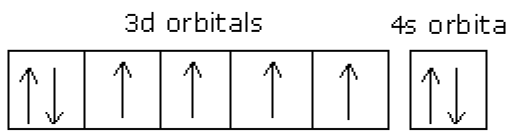


Fig.2.17 Orientation of electrons spins in 3d subshell in iron atom

The parallel alignment of dipoles in iron is not due to the magnetic interaction. It is due to the Pauli's exclusion principle and electrostatic interaction energy. The Pauli's exclusion principle and electrostatic interaction energy are combined together and constitute a new kind of interaction known as exchange interaction. The exchange interaction is a quantum mechanical concept.

The exchange interaction between any two atoms depends upon the interatomic separation between the two interacting atoms and the relative spins of the two outer electrons. The exchange interaction between any two atoms is given by

$$E_{ex} = -J_e S_1 . S_2 \qquad (2.11)$$

where J_e is the numerical value of the exchange integral, S_1 and S_2 are the spin angular momenta of the first and second electrons.

The exchange integral value and the exchange interaction energy values are negative for a number of elements. It represents the spin angular momentum S_1 and S_2 are opposite directions and hence the antiparallel alignment of dipole. This explains the antiparallel alignment of dipoles in antiferromagnetic materials.

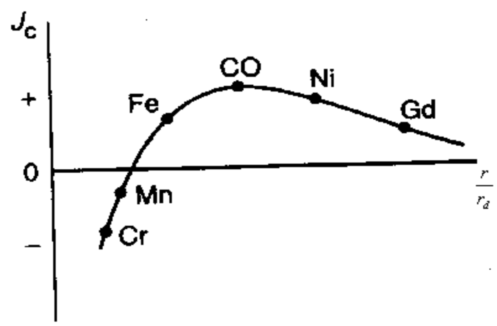


Fig.2.18 The exchange integral as a function of (r/r_d)

In some materials like iron, cobalt and nickel the exchange integral value is positive and the exchange energy is negative and this will shows the spin angular momentum are in same direction. This will produces a parallel alignment of dipoles.

A plot between the exchange integral and the ratio of the interatomic separation to the radius of 3d orbital ($\frac{r}{r_d}$) is shown in Fig.2.18. For the transition metals like iron, cobalt, nickel and gadolinium the exchange integral is positive, whereas for manganese and chromium the exchange integral is negative. The positive value of the exchange integral represents the material is ferromagnetic and the negative exchange integral value represents the material is antiferromagnetic. In general, if the ratio, $\frac{r}{r_d} > 3$, the material is ferromagnetic, otherwise the material is antiferromagnetic. It should be noted that manganese is suitably alloyed so that $\frac{r}{r_d} > 3$, then it will become ferromagnetic.

2.6 Antiferromagnetic material

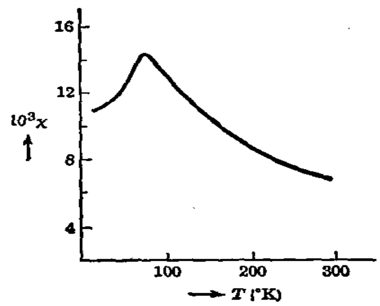
In an antiferromagnetic material, the adjacent dipoles are aligned antiparallel. The dipoles are equal in magnitude and hence the magnetic moment produced by one dipole is cancelled by the other one. Therefore, the resultant magnetic moment of antiferromagnetic materials is nearly zero in the absence of the magnetic field. The susceptibility of an antiferromagnetic material is given by

$$\chi = \frac{C}{T+\theta'}, \text{ where } T > T_N. \qquad (2.12)$$

where C is the Curie constant and T_N is the Nėel temperature.

For an antiferromagnetic material, if a graph is plotted between, χ and T, initially the susceptibility increases with the increase of temperature and it reaches a maximum value and then it decreases as shown in Fig.2.19. The temperature corresponding to this maximum value of χ is known as Nėel temperature, T_N.

The antiferromagnetic alignment is explained by using two interpenetrating cubic unit cells as shown in Fig.2.20. The interpenetrating cubic cells, look like a body centered unt cell. The corner atoms of the cubic unit cell are made of one type of atom and the body centered atom is made of another type of atoms. The dipoles of the corner atoms are pointed in the downward direction, whereas the dipoles of the body centered atom is pointed in the upward direction.



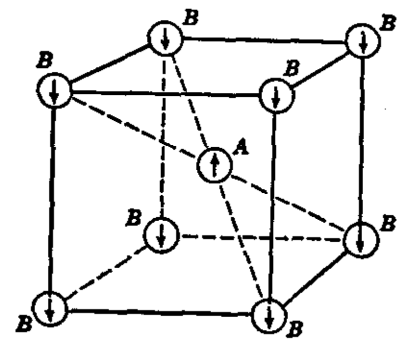


Fig.2.19 A plot of χ versus T for for antiferromagnetic material

Fig.2.20 Cubic crystal structure of antiferromagnetic material

The susceptibility of an paramagnetic, ferromagnetic and antiferromagnetic materials are given by

$$\chi = \frac{C}{T} \quad \text{for a paramagnetic material,} \qquad (2.13)$$

$$\chi = \frac{C}{T - \theta_f} \quad \text{for a ferrimagnetic material} \qquad (2.14)$$

$$\chi = \frac{C}{T + \theta'}, \text{ where } T > T_N \text{ for an antiferromagnetic material} \qquad (2.15)$$

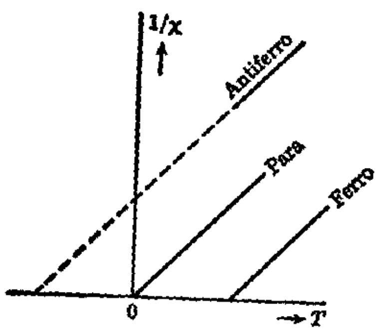


Fig.2.21 A plot of $\frac{1}{\chi}$ versus T for paramagnetic, ferromagnetic and antiferromagnetic materials

If a graph is drawn between $\frac{1}{\chi}$ and T, for paramagnetic, ferromagnetic and antiferromagnetic materials, straight lines as shown in Fig.2.21 is obtained.

2.7 Ferrites

Ferrites are mixed oxide ceramics, black or dark grey in colour, and very hard and brittle. The electrical resistivity of ferrites is very high, typically in the order of 2 to 2^{12} Ω-cm. The ferrites have strong magnetic properties. The ferrites have well defined magnetic transition temperature called the Curie temperature (or sometimes called the Néel temperature).

In ferrites the adjacent dipoles are aligned antiparallel and they are not equal in magnitude. Since the adjacent dipoles are not equal in magnitude, the resultant magnetic moment in the absence of the magnetic field is not equal to zero. If a small value of the magnetic field is applied to a ferrite, it produces a large value of the magnetization. The dipoles in ferrites are aligned antiparallel as shown in Fig.2.6.

(a) Structure of ferrites

There are three technically important ferrites are (i) spinels, (ii) garnets and (iii) hexaferrites. Spinels and garnets are magnetically soft, whereas the hexaferrite is hard. Let us discuss only the spinel structure.

(i) Spinels

The chemical formula for the unsubstituted spinel is $M^{2+}Fe_2^{3+}O_4^{2-}$, where M^{2+} represents the metallic divalent ions such as Fe^{2+}, Mn^{2+}, Cd^{2+}, Zn^{2+}, Mg^{2+}, Cu^{2+}, Co^{2+} etc. If the metallic ion M^{2+} is replaced by a ferrous ion (Fe^{2+}), then it is said to be a ferrous ferrite, $Fe^{2+}Fe_2^{3+}O_4^{2-}$. Similarly, if M^{2+} is replaced by Zn^{2+}, then it is said to be zinc ferrite $Zn^{2+}Fe_2^{3+}O_4^{2}$.

The crystal structure of spinels is cubic. There are 8 corner atoms in the cubic unit cell. Each and every corner atoms has one ferrite molecules. There are eight ferrite molecules in a ferrite unit cell. Therefore, there are 8 ferrous (Fe^{2+}) ions, 16 ferric (Fe^{3+}) ions and 32 oxygen (O^{2-}) ions in a ferrous ferrite unit cell. If oxygen atoms are considered alone, it constitutes a FCC structure. There are sixteen octahedral sites and eight tetrahedral sites in a spinel ferrite unit cell. A metallic ion surrounded by six oxygen atoms is called as octahedral site. A metallic ion surrounded by four oxygen atoms is called as tetrahedral site. So, in one spinel ferrite molecule there are two octahedral sites and one tetrahedral site.

(ii) Inverted spinel structure

Consider only one ferrite molecule. It has two octahedral sites and one tetrahedral site. Consider the octahedral and the tetrahedral sites are represented as shown in Fig.2.22. In the case of a ferrous ferrite, since the ferrous ion is a magnetic material, it prefers to occupy the octahedral site. The remaining one octahedral site and the tetrahedral sites are occupied by the ferric ion. This type of structure is said to be inverted spinel structure. The ferrimagnetism arises only because of the Fe^{2+} ions are coupled magnetically. There is no net moment arises from equal number of Fe^{3+} ions in the two sublattices (octahedral and tetrahedral sites).

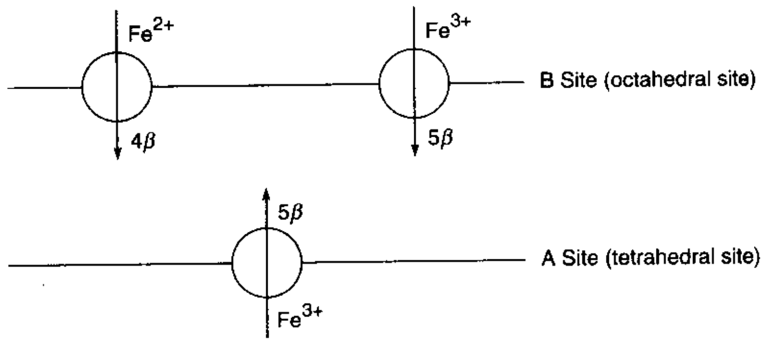


Fig.2.22 Inverse spinel structure of ferrite

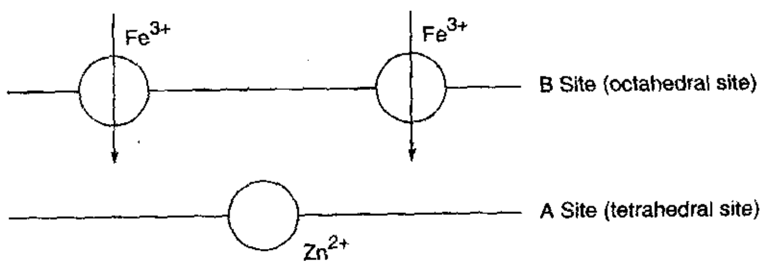


Fig.2.23 Normal spinel structure of ferrite

(iii) Normal spinel structure

Consider a zinc ferrite. Zinc is a non-magnetic material. The ferric ions prefers to occupy the octahedral site and the zinc ions occupy the tetrahedral site as shown in Fig.2.23. Therefore, the zinc ferrite is called as normal spinel and it is not a ferrimagnetic material because all the Fe^{3+} ions are on octahedral site.

Calculation of the magnetic moment

The magnetic moment of a ferrite molecule is calculated as follows. The ferrous ion has four unpaired electrons, whereas a ferric ion has five unpaired electrons. Consider an unpaired electron produces a magnetic moment of one Bohr magneton (1β), then the magnetic moment of a ferrous ion is 4β and that of ferric ion is 5β. If antiparallel alignment is considered, the total magnetic moment is 4β. The experimental value of the magnetic moment of ferrous ferrite is 4.1β. If all the dipoles are aligned parallel, the total magnetic moment is $4\beta + 5\beta + 5\beta = 14\beta$. This calculation confirms the antiparallel alignment of dipoles.

(b) Properties of ferrites

a) Ferrites are metal oxide ceramics, black or grey in colour
b) Ferrites are very hard and brittle.
c) The ferrites have strong magnetic properties due to ferrimagnetism.

d) The magnetic dipoles are aligned antiparallel and they are not equal in magnitude.
e) Ferrite has well defined magnetic transition temperature called the Curie temperature.
f) Ferrites have three technically important structures, namely, spinels, garnets and hexaferrites.
g) The spinels and garnets are magnetically soft whereas the hexaferrite is hard.

(c) Applications of ferrites

a) Small toroids in MgMn, CuMn or LiNi spinel materials are used in large numbers as data storage materials.
b) Garnets are used in magnetic bubble memory. For the magnetic bubble memory a magnetic film is coated on a non-magnetic substrate. The magnetic film with composition $Y_{2.9}La_{0.1}Fe_{3.8}Ga_{1.2}O_{1.2}$ coated on a substrate $Gd_3Ga_5O_{12}$ (gadolium gallium garnet) is used for bubble memory.
c) $BaFe_{12}O_{19}$ can be used in severe demagnetization environment and at low temperature. It is suitable for loudspeaker and transducer.
d) $SrFe_{12}O_{19}$ can be used in dynamic applications with large external magnetic field. It is used in dynamic applications with large external demagnetization fields e.g., motor stators, torque drives etc.
e) Ferrites are used for the preparation of microwave devices like circulators, isolators and phase shifter.
f) Ferrites rods are used to produce low frequency ultrasonic waves using magnetostriction principles.
g) Hard ferrites are used for the preparation of permanent magnets. They are used for the preparation of windscreen, wiper motor, loudspeaker etc.

2.8 Soft and hard magnetic materials

The magnetic materials are classified into soft and hard magnetic materials based on their magnetic properties.

(a) Soft magnetic material

The magnetic materials that are easy to magnetize and demagnetize them are called as soft magnetic materials. In a soft magnetic material, the domain wall move easily. Therefore, the application of a small values of magnetic field produces a large value of magnetization.

The soft magnetic materials are prepared so that they become very soft. The required composition of the materials is taken and they are heated above their melting points and the liquid solution is slowly cooled. The slow cooling of the melt makes them as soft and free from impurities.

(i) Properties

(i) The B-H curve of a soft magnetic material is narrow and steep.

(ii) The hysteresis loop has a small area and hence the hysteresis power loss per cycle is low.

(iii) The resistivity of the soft magnetic material is very high and hence eddy current loss is low.

(iv) The soft magnetic material has high permeability and susceptibility.

(v) The soft magnetic materials have low coercivity.

(vi) The soft magnetic materials are free from impurities.

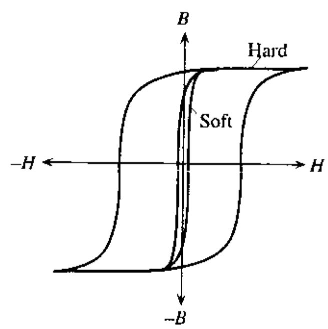


Fig.2.24 Hysteresis curve for soft and hard magnetic materials

(ii) Examples for soft magnetic materials and uses

a) Silicon iron (Fe, 2-4%Si)

It possesses high resistivity and low eddy current losses. So, it is widely used in electrical machinery such as transformer.

b) Supermalloy (79%Ni-14 to16%Fe-6 to 4%Mo)

It possesses high permeability. It is used to prepare low loss electrical devices. Ex., transformers, magnetic amplifiers.

c) 78Permalloy (78.5%Ni, 21.5%Fe)

It is used to prepare low loss electrical devices such as audio transformer, HF transformer, recording heads and filters.

d) Glass metals (Fe-Si-B)

It is used to prepare low loss transformer core.

e) Ferrites

(i) Mn-Zn ferrites

It has low conductivity and negligible eddy current losses. It is used in HF transformer, inductors (example pot cores, recording heads)

(ii) Mn ferrite and Mn-Zn ferrites

The Mn ferrite such as $MnFe_2O_4$ and Mg-Zn ferrite $Mg_{(1-X)}Zn_XFe_2O_4$ are used for high frequency applications.

(b) Hard magnetic materials

The magnetic materials that are difficult to magnetize and demagnetize them are called as hard magnetic materials. Since the coercivity of the hard magnetic material is high, the material needs a large value of magnetic field to demagnetize it. The rotation of domain walls is also needs very high magnetic field and the rotation of domains is difficult.

The materials are purposely made as hard. Therefore, the materials are prepared by heating above their melting points and then they are suddenly cooled by quenching in a liquid. The impurities are purposely added to these materials so as to make them as hard.

(i) Properties

1. The B-H curve is broad and it is almost rectangular. Therefore, the area of the hysteresis curve is large and hence the hysteresis loss is also high.
2. The hard magnetic materials have relatively large coercivity. So they need a large value of magnetic field to demagnetize it.
3. The permeability and susceptibility values are low.
4. The eddy current loss is high.
5. The hard magnetic materials have large impurities and lattice defects. They have large magnetostatic energy.

(ii) Examples

NdFeB, Alnico (Fe-Al-Ni-Co-Cu), Strontium ferrite, Hard particles γ-Fe_2O_3, Rare earth cobalt, Sm_2Co_{15}, carbon steel, tungsten steel, chromium steel.

(iii) **Applications**

1. Alnico is used for wide range of permanent magnet applications.
2. Strontium ferrite is used for the preparation of loud speakers, telephone receiver, various toys, dc motor, starter motor.
3. γ-Fe_2O_3, is used for the magnetic coating in audio and video tapes, floppy disks

4. NdFeB is used for a wide range of applications. Small motors, (eg., in hand tools), and walkman equipment, CD motors, MRI body scanners, computer applications.
5. Carbon steel is used as magnets for toys, compass needle, latching relays, and certain types of meters.
6. Tungsten steel is used to prepare dc motors.
7. Chromium steel is used to prepare best permanent magnets.

2.9 Magnetic recording and reading

(i) Magnetic recording

The magnetic materials are used for analog and digital recording of data. Let us consider the analog recording of data in an audio tape. The audio tape is a polymer backed tape that has a magnetic coating over it. It uses a recording head to record the information on the audio tape. The recording head is a toroid type electromagnet and it has a small gap typically around 1 μm. The input signal is initially converted into a current signal. Usually a microphone is used to convert a sound signal into electrical signal. The electrical signal is passed through the coil of the electromagnet. When the current signal is passing through the coil of wire, it gets converted into magnetic field. The magnetic field, while passing through the electromagnet produces fringing magnetic field in the gap. Usually, the recording head touches the audio tape and hence the fringing magnetic field magnetizes the magnetic material coated on the tape. The fringing field changes according to the current signal and hence magnetization in the audio tape also changes. The electrical signal is recorded in the audio tape as a spatial magnetic pattern. As the tape advances the information are recorded in the audio tape continuously. This type of recording is said to be longitudinal recording.

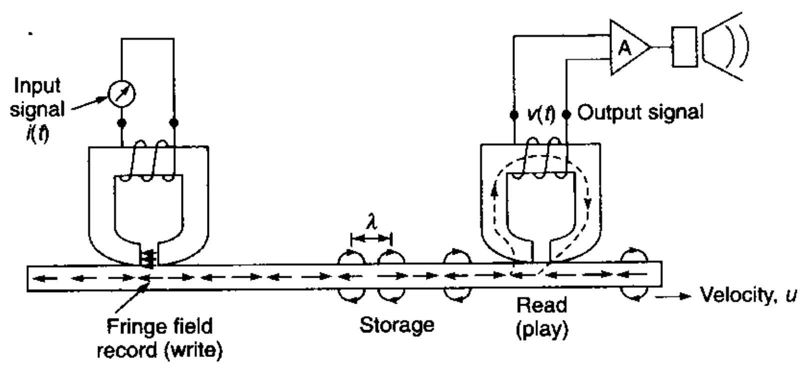


Fig.2.25 Magnetic recording and read out

(ii) Magnetic reading

The process of retrieving the data from the tape is known as reading. For reading of data the same recording head is used as reading head. The reading process is based on the Faraday's law of induction. During reading process, the magnetic field stored in the tape passes through the reading head. A portion of the field penetrates through the core and flows around the whole core and hence it links the coil. Whenever the magnetic field is passing through the coil, it induces an emf. As the tape is moving with a constant speed, the play head produces continuous voltage signal. This induced emf is filtered and then amplified. The amplified voltage signal gets converted into sound using a head phone or ear phone.

Let f be the frequency of the spatial signal and u be the velocity of the tape, then the distance advanced by the tape is $\Delta x = \frac{u}{f}$. This Δx represents the spatial wavelength. The low spatial wavelength and greater frequency, f provides more number of storing of information.

(iii) Recording head material

A recording head material should produce the magnetization easily so as to follow the input signals. This property requires, the recording head should be a soft magnetic material. It should produce a strong fringing magnetic field at the gap so as to magnetize the material in the tape. It requires the material should have low coercivity and large saturation magnetization.

The materials like permalloys (Ni-Fe alloys), sendust (Fe-Al-Si alloys), and some sintered soft ferrite (eg. MnZn and NiZn ferrites) and the amorphous materials such as CoZrNb alloys are used for preparing the recording head.

2.2 Magnetic data storage

The process of storing the data (audio or video) using the magnetic principle is known as magnetic data storage.

(i) Magnetic data storage materials

The materials used for storage purpose should retain the spatial magnetization pattern (information) recorded on them. This needs the materials with high remanent magnetization, M_r.

The information stored in the material should not be erased by stray fields. This requires high coercivity. The high coercivity will prevent the recording process. Therefore, the coercivity should not be too high. Therefore, the materials having a medium coercivtiy and high remanent magnetization are used for storage purposes.

Typical materials such as γ-Fe_2O_3, Co-modified γ-Fe_2O_3, or Co(γ-Fe_2O_3), CrO_2 and metallic particles like iron are used for the storage of data.

(ii) Magnetic tape

A magnetic tape is a plastic ribbon coated with magnetic material such as iron oxide or chromium oxide. The data are recorded in the magnetic tape by means of magnetization. The magnetized and non-magnetized regions are represented as 1s and 0s. The data in a magnetic tape is erased and reused. The magnetic tapes with breadth ½ inch or 1/4 inch and length 50 to 2400 feet are available.

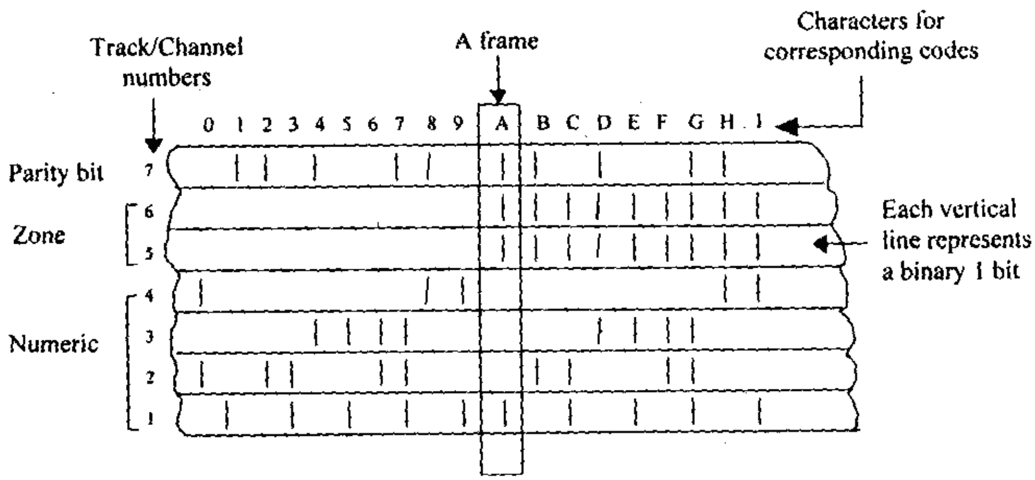


Fig2.26 Data recording in a 7 track magnetic tape

(a) Data storage organization

The magnetic tape storage is divided into vertical columns, called as frames and horizontal column called as tracks or channels. The old version of magnetic tape has 7 tracks. The first six tracks were used for recording of data in BCD (binary coded decimal) code, and the seventh track is used for recording the parity bit or check bit. The parity bit is used to check whether there is any loss of any character or bit from a string of 6 bit from the input or output data during operation. Defending on the total number of bits is odd or even, the parity is called as odd parity or even parity. If the total number of bit, whether it is odd then the parity bit is one so as to make even parity. To make odd parity, the parity bit is zero if the total number of bit is odd. Fig.2.26, the A frame has odd parity and hence the parity bit becomes one so as to make the parity even.

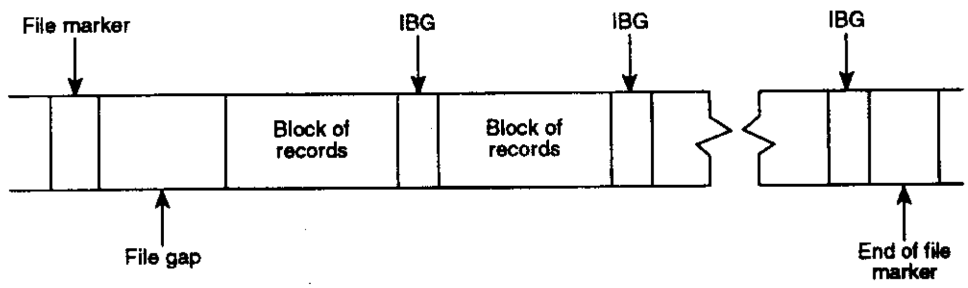


Fig.2.27 Data organization in a magnetic tape

Another version of the magnetic tape has 9 tracks. The first eight tracks are used for recording the byte of data and the 9th track is used for recording the parity bit. In a 9 track tape, the data are recorded by nine different read/write heads. They record the data in nine parallel tracks.

In order to write the information in a tape, the tape is kept ready such that one end is wound in a spool and the other end is threaded manually in a take up spool. There is metal foil at the beginning of the tape (BOT), called as a marker. Whenever a write command is given, the data are recorded only after the tape moves with its full speed. During this time, the tape will move a distance of 0.6 inch. This distance is called as inter block gap (IBG). After this gap, the data are recorded in a block. The length of the block is at least ten times as that of the IBG, so as to reduce the wastage of tape. After recording the data in a block, there is a gap called as IBG. Again the data are recorded in another block. Similarly a number of blocks are written in a serial order and the end of data (EOD) is represented by a metal foil known as file marker. Now, the tape is rewound and kept for reading.

Since the data are recorded one by one in different blocks and there is no address to the data, the data are retrieved in the order in which they are written. For example, if any one wants to retrieve the data recorded on the last block, all the earlier data has to be read before reading the required data.

In older system, only 800 bpi (byte per inch) can be recorded, whereas the newer system has a recording density of 77,000 bpi. The storage capacity of a magnetic tape having a length of 2400 feet is 2400 x 12 x 512 x 800x 2 (for two sides) = 23 GB. The actual storage capacity of the tape varies from 35% to 70% of its total storage capacity because IBG reduces the storage capacity.

(iii) Magnetic hard disk

It is a direct access secondary storage device. The hard disks are made of a rigid metal such as aluminium. The hard disk plates are coming in many different sizes ranging from 1 to 14 inch diameter. Both sides of aluminium disks are coated with magnetic materials. The surface of a disk is divided into a number of concentric circles, called as tracks. The tracks are numbered from the outer track to the inner track.

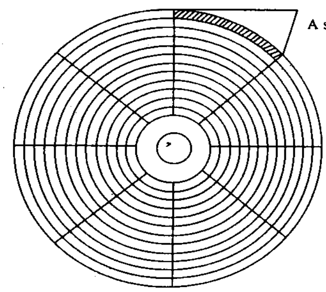


Fig.2.28 Sectors of a disk

Each track is further divided into sectors. The disk surface is divided into invisible pie shaped segments. If there are eight such pie-shaped segments, each track is divided into 8 sectors. If there are 200 tracks and 8 sectors per track, then a disk contains 200 x 8 = 1600 sectors.

A sector is a smallest unit with which any disk can work. It typically contains 512 bytes. In a hard disk, a number of magnetic plates are arranged into a spindle one below the other. This arrangement is said to be disk pack. A disk pack is sealed and mounted on a disk drive. Such a disk drive is known as Winchester disk drive.

The disk pack is rotated by a motor about its axis at a speed of 3600 rpm. The disk drive also has an access arm assembly. Different read/write heads are attached in the access arm. The upper surface of the top disk and the lower surface of the bottom disk are generally not used because these surfaces may be easily scratched. For example, if a disk drive contains four disk platters, then there are six read/write heads, except the top surface of the disk upper disk and the bottom surface of the lower disk. The read/write heads are arranged in the access arm assembly such that they can be moved simultaneously.

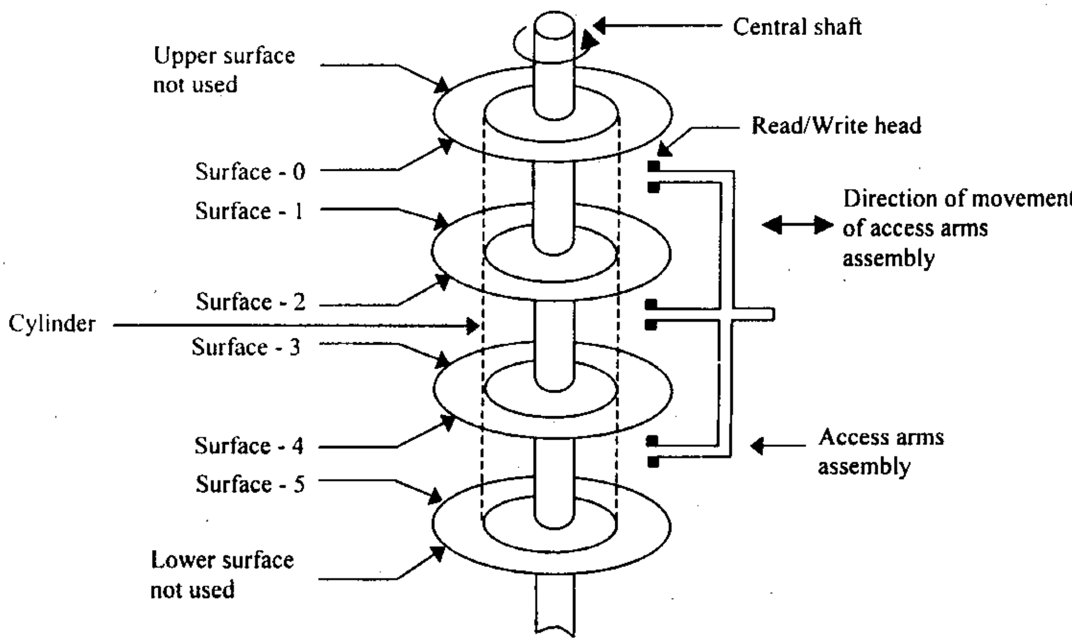


Fig.2.29 A hard disk pack containing four platters

The fast access of data is achieved using a concept known as cylinder. A set of corresponding tracks in all the recording surfaces of a disk pack together form a cylinder. For, example, the 2^{th} track of the entire recording surface constitutes the 2^{th} cylinder. If there are 200 tracks in a disk, there are 200 cylinders. When a read command is given to the read/write head, all the read/write heads will assemble in a particular track, say for example 20^{th} track. In one revolution, the data stored on the 20^{th} track of 0 (zero) surfaces are read. In the next revolution, the data stored in 20^{th} track of 1^{st} surface are read. Then the data stored in the 20^{th} track of the 2^{nd} surface are read. Similarly, up to the last surface the data are read in the same track. The disk address may consist of sector number, cylinder number and surface number.

The storage capacity of a hard disk having 5.25 inch diameter, 2 disk plates, 2655 tracks and 125 sectors per track and each sector can store 512 bytes per sector is 18 x 2655 x 125 x 512 = $3x2^9$ bytes ≈ 3 GB (3 Giga bytes).

(iv) Floppy disk

A floppy disk is a round piece of flexible plastic, coated with magnetic material. It is covered by a square plastic container or vinyl jacket cover. The container protects the disk surface and it has a wiping action to remove the dust particle. Floppy disk can be bend and flexible and hence it is called as floppy disk. It is also called as floppies or diskettes.

There are two different types of floppies are available. They are, (i) 5.25 inch and (ii) 3.5 inch floppy disk.

(a) 5.25 inch floppy disk

It is a 5.25 inch circular flexible Mylar computer tape material. The magnetic oxide is coated on both sides of the disk. It is packaged in 5.25" square plastic envelope with a long slit for read/write access, a hole for index mark sensing and a hole for the hub. The floppy disk is inserted into the floppy drive with its plastic cover. The inner side of the envelope is free and smooth and it provides smooth rotation of the disk. The disk is rotated by a servomechanism. When the disk is inserted into the drive, then the disk will rotate with a speed of 300 rpm. The read/write head touches the disk through the read/write slit and hence the read/write operation is performed.

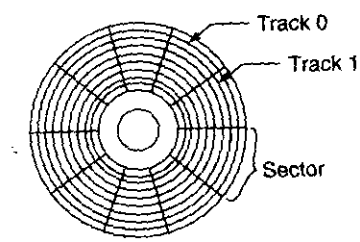
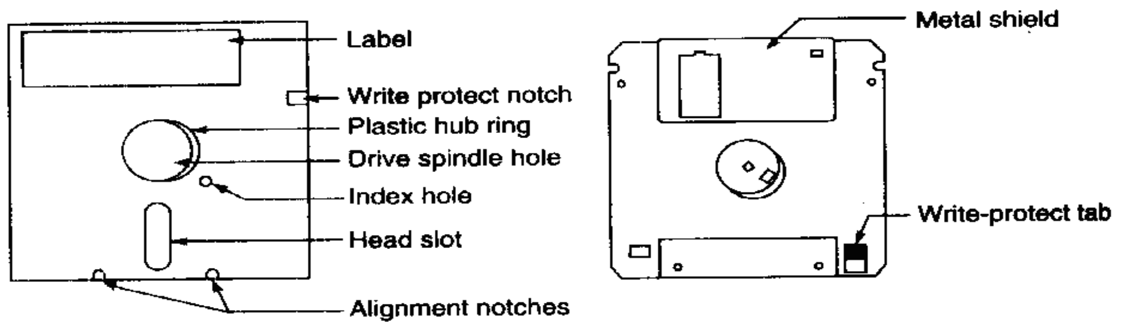


Fig.2.30 Sectors and tracks in floppy disk

The surface of the floppy disk is also divided into a number of concentric circles, called as tracks. Each track is further divided into sectors. A low density disk has 40 tracks, 9 sectors per tracks. In a low density disk, one can record 4000 bits per inch and 512 bytes per sector and hence a floppy disk can store 9 x 4000 x 512 x 40 = 180 kB of data. For a high density disk, with 14000 bpi (bits per inch) and for both sides, one can store up to 1.25 Mbytes.



(a) (b)

Fig.2.31 (a) 5.25 inch floppy disk and (b) 3.5 inch floppy disk

(b) 3.5 inch floppy disk

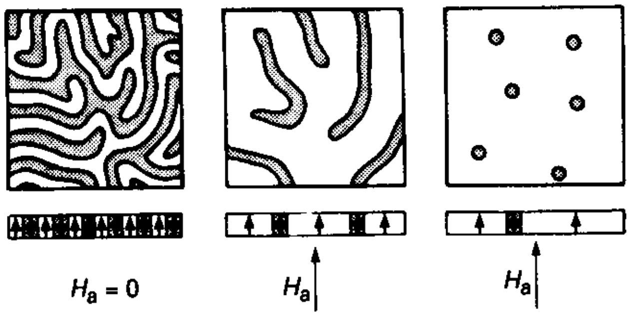
The 3.5 inch disk has a diameter of 3.5 inch. It is encased in a 3.5 inch square, hard-plastic jacket cover. It has an opening for read/write head. The opening is covered by a sliding metal piece. When the disk is inserted into the floppy drive, the cover slides back to expose the opening. The read/write head will come into contact with the disk surface.

The 3.5 inch disk is available in three different capacities, namely, (i) double density, (ii) high density and (iii) very high density. The double density, high density and very high density floppy disks can store up to 720 kB, 1.44 MB and 2.88 MB respectively.

2.11 Magnetic bubble memory

The magnetic bubble memory is a type of computer memory. It uses an epitaxially grown thin film of materials such as orthoferrite or garnet coated on a substrate, usually garnet. Garnet has a wavy domain structure as shown in Fig.2.32(a). If a single crystal plate (~μm thickness) with orthogonal easy direction is subjected to an increasing magnetic field (H_a) also normal to the plate, the antiparallel domains shrink as shown in Fig.2.32 (b), until over a narrow range of (H_a), small cylindrical domains are formed [Fig.2.32(c)]. They are called as magnetic bubbles. The diameter of the bubble is typically 2 to 5 μm. Each bubble can carry one bit of information. The plate should be free from imperfection, parallel and flat.

The bubbles can be moved by applying the magnetic field. For moving the bubbles in a controlled manner along a particular direction, a pattern of small permalloy bars are created on the surface. These bars are produced using photoengraving.



(a) (b) (c)

Fig.2.32 (a) Wavy domains in garnet, (b) the domain shrinks due to field, (c) magnetic bubble formed

The movement of the bubble from one place to other can be achieved by applying magnetic field. Consider two permalloy bar as shown in Fig.2.33(a). Consider there is a magnetic bubble with its north pole upward in one of the bar (say bar 1). In the absence of the field, the permalloy bars are unmagnetized. If a field is applied, the permalloy bar1 gets magnetized and the bubble in the north pole of the magnet move towards south pole of the bar [Fig.2.33(b)]. In order to move the magnetic bubble from one bar to another bar, one has to change the direction of the field. Then the bubble moves to bar2 and then the bar2 gets magnetized [fig.2.33(c)].

The bubbles can be detected by making to pass through a strip of Indium antimonide (InSb) which has high magneto-resistance. The magnetoresistance is the resistance offered by a material, when a magnetic field is applied.

(i) Advantages

1. Magnetic bubble memory is non-volatile
2. Because of the small size of the bubbles, the density of bubble is very high.
3. If one bit of information is stored in one bubble, one can store 2 million bit cm^{-2}.

(ii) Drawback

1. The magnetic bubble memory is not a random access memory. Therefore, the information must be read serially. The achievable speed may be few hundred kbits s^{-1}.

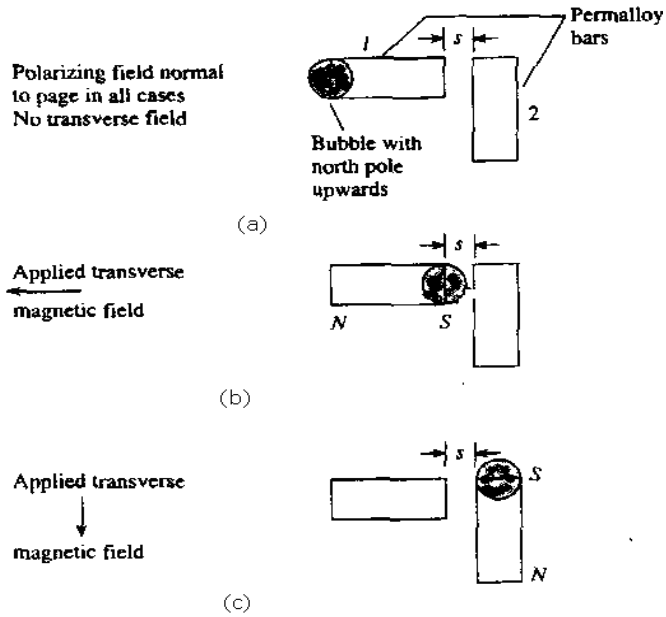


Fig.2.33 Movement of bubbles from one bar to another-magnetic bubble memory
(a) the bubble is in the north pole of bar1, (b) the bubble is in the south pole of bar2, (c) the bubble is transferred to bar2

SOLVED PROBLEM

1. In a magnetic material, the field strength is found to be 2^6 A m^{-1}. If the magnetic susceptibility of the material is 0.5 x 2^{-5}, calculate the intensity of magnetization and flux density of the material.

Given data

Magnetic field strength, H = 2^6 A m^{-1}

Magnetic susceptibility, χ = 0.5 x2^{-5}

Solution

Susceptibility, $\chi = \frac{M}{H}$

Magnetization, M=χ H=0.5 x2^{-5} x2^6= 5

Flux density, B =μ_o(M+H)

B = 4πx2^{-7}(5+0.5x2^{-5})

=0.6914 Wb m^{-2}

Magnetization, M= 5 A m^{-1}

Flux density, B = 0.6914 Wb m^{-2}.

2. The saturation magnetic induction of nickel is 0.65 Wb m^{-2}. If the density of nickel is 8906 kg m^{-3} and its atomic weight is 58.7, calculate the magnetic moment of the nickel atom in Bohr magneton.

Given data

Saturation magnetic induction, B = 0.65 Wb m^{-2}

Density ρ = 8906 kg m^{-3}

Atomic weight of Ni M_{at}=58.7

Solution

Number of atoms per m^{-3}= $\frac{density \times Avogadro's\ cons\tan t}{atomic\ weight}$

$$= \frac{8906 \times 6.022 \times 10^{23} \times 10^3}{58.7}$$

=9.136 x2^{28} m^{-3}

Magnetic moment, μ_m= $\frac{B}{N\mu_o} = \frac{0.65}{9.136 \times 10^{28} \times 4\pi \times 10^{-7}}$

=5.6594 x 2^{-24}

$$= \frac{5.6594 \times 10^{-24}}{9.27 \times 10^{-24}} = 0.61\mu_B.$$

Magnetic moment of nickel atom= 0.61 μ_B.

3. If a magnetic field of 1800 A m^{-1} produces a magnetic flux of 3 x2^{-5} Wb in an iron bar of cross sectional area 0.2 cm^2. Calculate permeability.

Given data

Magnetic field H = 1800 A m^{-1}

Magnetic flux Φ = 3 x 2^{-5} Wb

Area of cross section A = 0.2 cm^2

Solution

Magnetic flux density, $B = \frac{\phi}{A} = \frac{3\times10^{-5}}{0.2\times10^{-4}}$ =1.5 Wb m^{-2}

Magnetic flux density, B = $\mu_o\mu_r H$

Relative permeability, $\mu_r = \frac{B}{\mu_o H} = \frac{1.5}{4\pi\times10^{-7}\times1800}$

=662.87

The permeability of the material is 662.87.

4. Calculate the saturation magnetization for Ni ferrite. The lattice parameter for the Ni ferrite is 0.835 nm and the magnetic moment per unit cell is 18.4μ_B.

Given data

Magnetic moment μ = 18.4μ_B

Lattice parameter a = 0.835 nm

Solution

Magnetization $M = \frac{magnetic\ moment}{volume}$

$$= \frac{18.4\times9.27\times10^{-24}}{(0.835\times10^{-9})^3}$$

5. A magnetic field strength of 2 x 2^5 A m^{-1} is applied to a paramagnetic material with a relative permittivity of 1.01. Calculate the value of B and M.

Given data

Magnetic field strength H = 2 x 2^5 Am^{-1}

Relative permeability μ_r = 1.01

Solution

Magnetic flux density, $B = \mu_o \mu_r H$

$= 4\pi x\ 2^{-7} \times 1.01 \times 2 \times 2^5$

$= 0.2539$ Wb m-2

Magnetic flux density, $B = \mu_0(M+H)$

Magnetization, $M = \frac{B}{\mu_o} - H = \frac{0.2539}{4\pi \times 10^{-7}} - 2\times 10^5$

$= 0.01965$ A m^{-1}

Magnetic flux density, B=0.2539 Wb m^{-2}

Magnetization, M = 0.01965 A m^{-1}.

6. The magnetic material is subjected to a magnetic field of strength 500 Am^{-1}. If the magnetic susceptibility of the material is 1.2, calculate the magnetic flux density inside the material ($\mu_o=4\pi$ x 2^{-7} H/m).

Given data

Magnetic field strength H = 500 A m^{-1}

Susceptibility $\chi = 1.2$

$\mu_o=4\pi x\ 2^{-7}$ H/m

Solution

Susceptibility $\chi = \frac{M}{H}$

$M = \chi H = 1.2 \times 500 = 600$ A m^{-1}

Magnetic flux density, $B=\mu_o(M+H)$

$= 4\pi x\ 2^{-7}$ X (600+500)

$= 1.382 \times 2^{-3}$ Wb m^{-2}.

Magnetic flux density, B=1.382 x 2^{-3} Wb m^{-2}.

SHORT QUESTIONS

1. What are magnetic materials?
2. What is a magnetic dipole?
3. Define the term magnetic dipole moment.
4. What do you mean by magnetic lines of forces?
5. Define the term magnetic flux density.
6. Define magnetic field strength.
7. What is magnetization?
8. What is meant by magnetic susceptibility?
9. Define the term magnetic relative permeability.

10. What is Bohr magneton? What is its value?
11. Mention the five different types of magnetic materials.
12. What is a diamagnetic material? Mention any two properties of diamagnetic material.
13. What is a paramagnetic material? Mention any two properties of paramagnetic material.
14. What are ferromagnetic materials? Mention any two properties of ferromagnetic materials.
15. What are antiferromagnetic materials? Mention any two properties of antiferromagnetic materials.
16. What are ferrimagnetic materials? Mention the ferrimagnetic materials.
17. What are magnetic domains?
18. What is magnetostatic energy?
19. What are anisotropic energy?
20. What is domain wall energy?
21. What is magnetostriction energy?
22. What are ferrites?
23. Describe the spinel structure of ferrites.
24. Describe the inverse spinel structure of ferrites.
25. Write the properties of ferrites.
26. Write any two applications of ferrites.
27. What are soft magnetic materials?
28. Write about the properties of soft magnetic materials.
29. Mention the uses of soft magnetic materials.
30. What are hard magnetic materials?
31. Mention the properties of hard magnetic materials.
32. Mention the applications of hard magnetic materials.
33. What are the materials used as recording head materials?
34. Mention the materials used as magnetic data storage.

DESCRIPTVE TYPE QUESTIONS

1. What are domains? Discuss about the domain concept and hence explain the hysteresis curve.
2. What is meant by Exchange energy? Explain the origin of ferromagnetic using Heisenberg's exchange interaction energy concept.

3. What are soft and hard magnetic materials? Mention the properties and applications of hard and soft magnetic materials.
4. What are antiferromagnetic materials? Explain the antiparallel alignment of dipoles in antiferromagnetic materials.
5. What are ferrites? Explain the structure of ferrites. Mention the properties and applications of ferrites.
6. Explain with neat sketch the process of magnetic recording and reading of data.
7. What are data storage materials? Explain about the magnetic tape, floppy disks and hard disks.
8. What is magnetic bubble memory? Explain in detail the working of a magnetic bubble memory.

EXERCISE PROBLEM

1. Magnetic field intensity of a paramagnetic material is 2^4 A m^{-1}. At room temperature, its susceptibility is 3.7 x 2^{-3}. Calculate the magnetization in the material.
2. In magnetic material the field strength is found to be 2^6 Am^{-1}. If the magnetic susceptibility of the material is 0.5 x 2^{-5}, calculate the intensity of magnetization and flux density in the material.
3. The magnetic susceptibility of copper is -0.5x 2^{-5}. Calculate the magnetic moment per unit volume in copper when subjected to a field whose magnitude inside copper is 2^6 A m^{-1}.
4. The unit edge of Fe_3O_4 is about 0.8 nm and there are eight Fe^{++} atoms in the cell. Calculate the magnetization. For iron, the six outer electrons have five spins in one direction and the sixth in the other, giving a net moment of 4 Bohr magneton.
5. A paramagnetic material has a magnetic field intensity of 2^4 A m^{-1}. If the susceptibility of the material at room temperature is 3.7 x 2^3. Calculate the magnetization and flux density of the material.
6. The saturation value of the magnetization of iron is 1.75 x26 Am-1. Given that iron has a body centered cubic structure with an elementary cube edge of 2.86 Å, calculate the average number of Bohr magnetons contributed to the magnetization per atom.