UNIT III

MAGNETIC AND SUPERCONDUCTING MATERIALS

3.1 INTRODUCTION

Materials which get magnetised by the application of a magnetic field are called magnetic materials. They are classified into five categories. They are diamagnetic meterials, paramagnetic materials, ferromagnetic materials, antiferromagnetic materials and ferrimagnetic materials.

3.1.1. Magnetic dipole moment

Two poles with equal and opposite strength separated by a distance form the magnetic dipole. If m is the pole strength and *l* is the length of the magnet, then the dipole moment, $\mu_m = ml$. The magnetic dipole moment is measured in Am^2.

3.1.2. Bohr magneton

The orbital magnetic moment and the spin magnetic moment of an electron in an atom can be expressed in terms of atomic unit of magnetic moment called Bohr magneton.

1 Bohr Magneton = $\frac{e\hbar}{2m} \Rightarrow \mu B \Rightarrow 9.27 \times 10^{-24}\ Am^2$

3.1.3 Magnetic field strength and intensity of magnetisation

The magnetic field strength (H) is defined as the force experienced by a unit north pole placed at a given point in a magnetic field. It is measured in Am^{-1}. The intensity of magnetisation (M) is defined as termed as the magnetic dipole moment per unit volume. It is also measured in Am^{-1}.

3.1.4 Magnetic flux and magnetic flux density

The magnetic lines of force crossing normally through a closed area is the magnetic flux (ϕ). It is measured in Weber. The magnetic flux density or the magnetic induction (B) is the magnetic flux per unit area.

$$B = \frac{\phi}{A}$$

It is measured in Weber/m^2 or Tesla

3.1.5. Magnetic permeability

The magnetic permeability (μ) is defined as the ratio between the magnetic flux density in the material and the applied magnetic field.

$$\mu = \frac{B}{H}$$

Also,, $B = \mu_0(M + H)$

where μ_0 is the permeability of free space and is equal to 4π x 10^{-7} H/m. The relative permeability is the ratio between the permeability of the material and permeability of free space.

$$\mu_r = \frac{\mu}{\mu_0} \quad \text{or} \quad \mu = \mu_0\mu_r$$

3.1.6 Magnetic susceptibility

The magnetic susceptibility is a dimensionless parameter which describes the response of a magnetic material to an applied magnetic field. It is the ratio between the intensity of magnetisation and the applied field strength.

$$\chi_m = \frac{M}{H}$$

Also, $\mu_r = 1 + \chi_m$ (χ_m)

3.2 TYPES OF MAGNETIC MATERIALS

3.2.1 Diamagnetic Materials

In a diamagnetic material, the electronic orbits in an atom are oriented in such a way that the resultant dipole moment of paired electrons is zero since they have opposite orbital and spin moments. When an external magnetic field is applied, the material gets weak magnetization in a direction opposite to that of the applied field. (i.e. the magnitude of magnetic induction is less than that in vacuum).

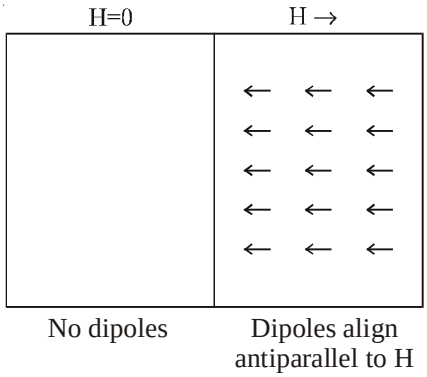


Fig. 3.1 Diamagnetism

Properties:

1. They repel the magnetic lines of force
2. They possess no permanent dipole moment.
3. The magnetic susceptibility χ_m is small and negative. ($\chi_m \cong 10^{-6}$). It is a constant and independent of the external magnetic field and temperature.
4. When the diamagnetic materials are placed between the poles of a strong electromagnet, they are attracted towards the region where the field is weak. eg., cadmium, gold, silver, tin, zinc etc.

3.2.2 Paramagnetic materials

Paramagnetic materials possess permanent dipoles. In the absence of external field, they are randomly oriented and the resultant dipole moment is nearly zero. When an external magnetic field is applied, weak magnetization occurs along the direction of the applied field.

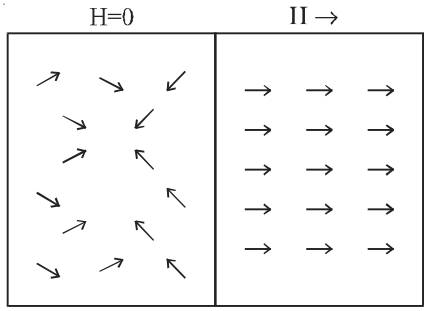


Fig. 3.2 Paramagnetism

Properties:

1. They weakly attract the lines of force
2. They possess permanent dipoles. But the net magnetic moment is zero
3. The magnetic susceptibility is small and positive. ($\chi_m \approx 10^{-6}$ to 10^{-2}). An increase in temperature decreases the paramagnetic effect. eg., aluminium, oxygen, platinum, titanium, etc.

The atoms of some transition elements and rare earth elements possess incompletely filled inner shells with unpaired electrons. These unpaired inner electrons in atoms cause strong paramagnetic effects.

3.2.3. Ferromagnetic materials

Ferromagnetic materials possess permanent dipoles and exhibit spontaneous magnetization. The ferromagnetic behaviour is due to the parallel alignement of magnetic dipoles in microscopic regions called domains. If the domains align randomly then the net magnetization is zero.

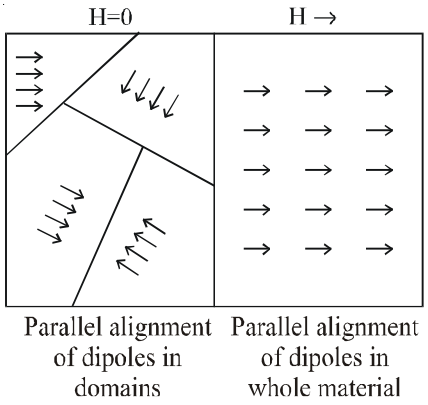


Fig. 3.3. Ferromagnetism

Properties:

1. They strongly attract the magnetic lines of force.
2. Dipoles in a domain alignthemselves parallel to one another.
3. The magnetic susceptibility is large and positive. Hence the ferromagnetic materials produce strong magnetization in weak field.
4. The magnetic susceptibility decreases when the temperature is increased. When the temperature reaches a critical temperature, the ferromagnetism of the material completely disappears and the material becomes paramagnetic. This temperature is called Curie temperature. When the temperature is greater than Curie temperature ferromagnetic material becomes paramagnetic materials.

3.2.4 Anti-ferromagnetic materials

The spins are aligned in antiparallel manner (fig. 3.4) due to unfavorable exchange interaction among them, resulting in zero magnetic moment. Even when the field is increased, it has almost induced magnetic moment.

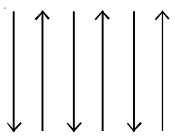


Fig. 3.4 Anti-ferromagnetism

Properties

1. The susceptibility is very small and is positive. It is given by $\chi = \frac{C}{T+\theta}$.
2. Initially, the susceptibility increases slightly as the temperature increases and beyond a particular temperature, known as Neel temperature susceptibility decreases with temperature.

Antiferro-magnetic materials

(i) Ferrous oxide (FeO)

(ii) Manganese Oxide (MnO_4)

(iii) Manganese Sulphide (MnS)

(iv) Chromium Oxide (Cr_2O_3)

(v) Ferrous Chloride ($FeCl_2$) and salts of transition elements.

3.2.5 Ferrimagnetic materials

In ferrimagnetic materials, the dipoles are aligned anti-parallel to each other. But the magnitudes of dipoles are not equal fig (3.5). Hence large magnetization occurs in a weak magnetic field. The magnetic susceptibility of a ferrimagnetic material is large and positive and depends on temperature. A group of ceramic ferrimagnetic materials are called ferrites.

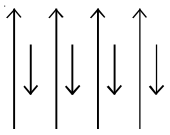


Fig. 3.5 Ferrimagnetism

3.3 THEORY OF FERROMAGNETISM

3.3.1 Weiss Theory of Ferromagnetism

Weiss postulated that the existence of an internal molecular field H_i in the crystal favours the parallel alignment of magnetic moments in a ferromagnetic material. The molecular field is proportional to the magnetization of the material.

$$\text{i.e. } H_i \alpha M \text{ or } H_i = \lambda M$$

where λ is the molecular field coefficient or Weiss constant.

Therefore the net effective magnetic field

$$H_e = H + H_i$$

Weiss arrived an expression for χ_m as

$$\chi_m = \frac{C}{T-\theta} \qquad \rightarrow (3.1)$$

where $C = \frac{\mu_0 N_A \mu_B}{3k_B}$ is a constant

$\theta = \lambda C$ is Curie temperature

where μ_0 – permeability for free space.

μ_B – magnetic moment (Bohr magneton : $9.27 \times 10^{-24} Am^2$)

N_A – Avagadro number

k_B – Boltzmann constant

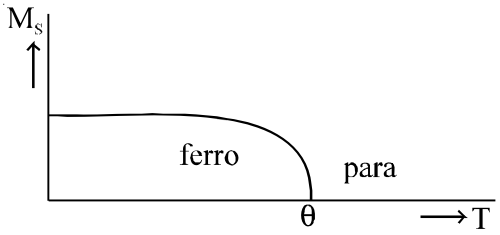


Fig. 3.6. Effect of temperature on saturation magnetisation of a ferromagnetic material

Eqn. (3.1) is Curie Weiss law or Curie Weiss equation. This expression describes fairly well the observed susceptibility variation in the paramagnetic region above the Curie point. When $\theta \rightarrow T$, $\chi_m \rightarrow \infty$. This means that there exists a spontaneous magnetism even in the absence of external field. The material is ferromagnetic below Curie temperature and paramagnetic above Curie temperature.

3.3.2. Domain theory of ferromagnetism

The domain theory of ferromagnetism was proposed by Weiss. According to him, any ferromagnetic or ferrimagnetic material that is at temperature below Curie temperature is composed of small regions in which the dipoles are aligned in same direction. Such a region is called domain and each domain is magnetized to its saturation magnetization (fig. 3.7). Adjacent domains are separated by domain boundaries or walls across which the direction of magnetization gradually changes (fig. 3.8).

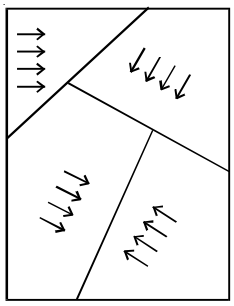


Fig.3.7. Domains in a ferromagnetic material

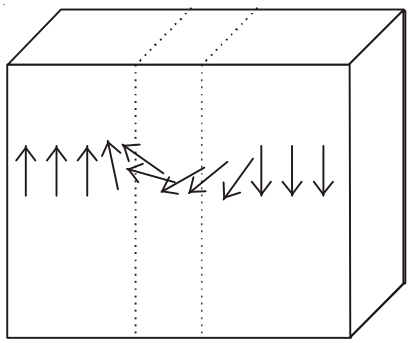


Fig. 3.8. Gradual change in dipole orientation across a domain wall

Normally domains are microscopic in size and for a polycrystalline specimen, each grain may consist of more than a single domain. The direction of magnetization varies from domain to domain and thus the net magnetization is zero in the absence of external magnetic field. When the external field is applied, the domains having moments parallel to the magnetic field grows at the expense of the adjacent unfavourably oriented domains. In the final saturation stage,

1. the unfavourably oriented domains are rotated parallel to the direction of the field.
2. all the unfavourably oriented domains have disappeared. (fig 3.9)

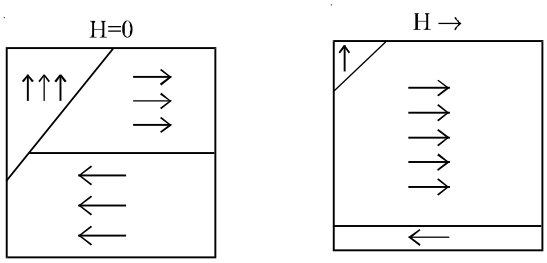


Fig.3.9. Growth of a favourably oriented domain in a magnetic field

When the external field is removed, the magnetized sample remains magnetized eventhough some of the magnetization is lost because of the tendency of the domains to rotate but to their original alignment. Thus hysteresis in a magnetic material occurs.

The Domain theory can explain the following factors

1. If a magnet is divided into pieces, each piece will be a tiny magnet. This is because the domains continue to remain in the broken pieces.
2. A magnet when heated or roughly handled tends to lose its magnetism. This is because the alignment of the domains in the magnet is disturbed during heating and rough handling and hence the magnetism is reduced or lost.
3. In a soft magnetic material the domain walls are flexible and can be easily rotated. Hence they are easily magnetized or demagnetized. In a hard magnetic material the domain walls are rigid and hence they are very hard to be magnetized or demagnetized.
4. When a ferromagnetic material is suddenly magnetized it experiences a slight change in its length, which is due to the rearrangement of domains inside the material. This is called magnetostriction effect.

Types of energy involved in the process of domain growth

1. Exchange energy: This energy aligns individual atomic dipoles in a single domain. It arises from the interaction of electron spins. It depends upon the interatomic distance.

2. Crystal anisotropy energy: Magnetization is an anisotropic property in crystals. The crystal anisotropic energy is the energy of magnetization which is a function of crystal orientation.

Easy axis : The crystal is easily magnetised if the field is applied in this direction.

Hard axis : Magnetising the crystal is very hard if the field is applied in this direction.

Domain wall energy: It is the sum of the exchange energy and crystalline anisotropy energy in the domain wall region (fig. 4.12).

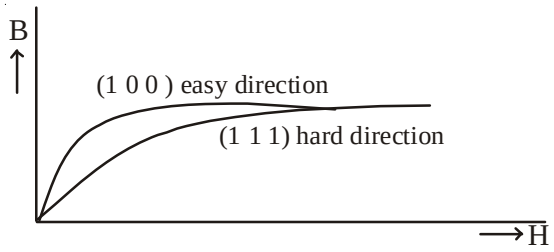


Fig. 3.10 Magneto crystalline anisotropy in bcc iron

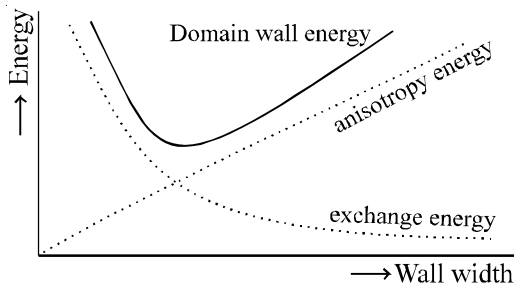


Fig. 3.11 Domain wall energy as a functin of wall width

3. Magnetostatic energy: Magnetostatic energy is the magnetic potential energy of a ferromagnetic material produced by the external field. This potential energy can be minimized in a ferromagnetic material by domain formation.

4. Magnetostrictive energy: The magnetostrictive energy is the energy due to the mechanical stresses generated by magnetostriction in the domains.

Reversible and irreversible domains

If a ferromagnetic material is subjected to a small external field, the domain wall is slightly displaced away from the minimum energy. Whenever the field is removed, the domain wall returns to the original position. This gives a reversible domain wall movement and the domain is called the reversible domain.

In larger external fields, the domain wall may be shifted to a more distance position where the energy curve has passed through a maximum and then diminished. On removing the field, the domain wall cannot cross the energy maximum and so it is unable to return to its initial position. This gives an irreversible domain wall movement and the domain is called the irreversible domain.

Experimental evidence for domains - Bitter powder method

The existence of domain structure can be understood from the bitter powder patterns. In this technique a drop of colloidal suspension of finely divided ferromagnetic powder is allowed to spread over the ferromagnetic material under investigation. The colloidal particles, collect along the domain boundaries since strong magnetic field exists near these domain boundaries. The collidal particles will be observed through a microscope and this observation directly gives the domain structure of the material.

Fig. (3.12) illustrates the growth of favourable domains in iron along the direction of the field. These structures are obtained using the Bitter colloidal iron oxide technique.

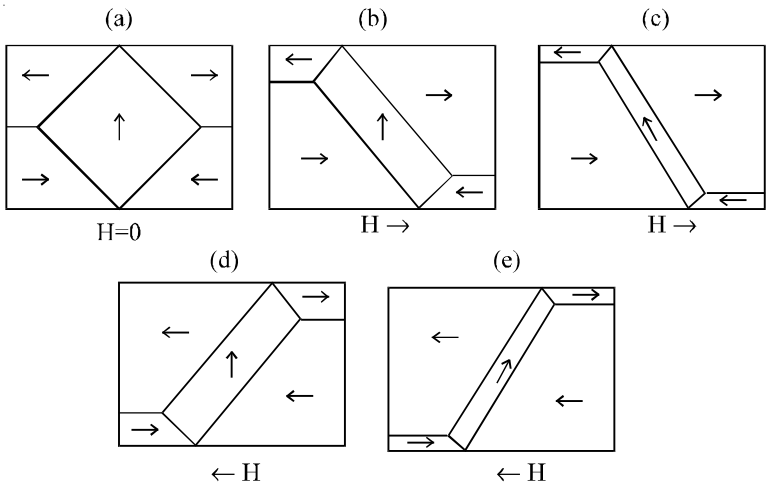


Fig. 3.12 Growth of domain in external field - Bitter powder patterns

3.3.3. Magnetic hysteresis

When ferromagnetic materials like Fe, Co, and Ni are taken through a cycle of magnetizing field (H), the magnetic induction (B) lags behind the magnetizing field. This lagging of magnetic induction behind the magnetic field is called as hysteresis. The curve drawn connecting B and H is known as B-H curve or Hysteresis loop. (fig. 3.13).

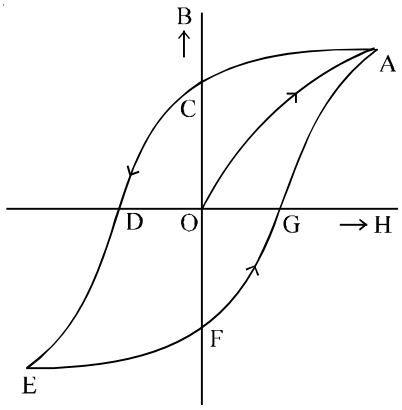


Fig. 3.13 Hysteresis loop for a ferromagnetic material

Consider a demagnetised ferromagnetic sample to which an external magnetic field is applied. As the applied field increases from zero, the magnetic induction B increases from zero along curve OA until saturation induction is reached. Upon decreasing the applied field to zero, the original magnetization curve is not retraced. There remains a residual magnetic induction (Point C in fig. 3.13). This residual magnetic induction left in the specimen when the magnetizing field is zero is known as **remanence or retentivity**. To decrease the residual magnetic induction to zero, a reverse magnetic field ($-H_c$) must be applied. (Point D in fig. 3.13). The negative magnetic field required to completely demagnetize the material is **coercivity** of the material. If the negative applied field is increased still more, the material attains saturation induction in the reverse direction at point E. Upon removing the reverse field, the magnetic induction will return to the remanent induction at F and upon application of a positive field, the B-H curve follows FGA to complete a loop. Further application of reverse and forward fields will retrace the loop ACDEFGA. This magnetization loop is referred as a hysteresis loop.

Due to hysteresis some amount of energy is dissipated in the form of heat energy. This dissipation in energy per unit volume of the material is called hysteresis loss. This loss is directly proportional to the area of the hysteresis loop. Also this hysteresis loss is referred to as the work done by the magnetizing and demagnetizing cycle.

3.4. HARD AND SOFT MAGNETIC MATERIALS

Hard magnetic material **Soft magnetic material**

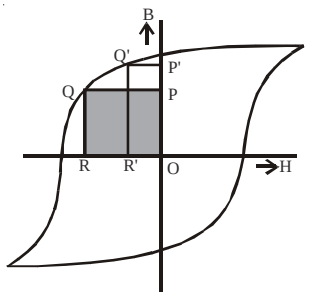


Fig. 3.14 (a) Hysteresis loop for a hard ferromagnetic material

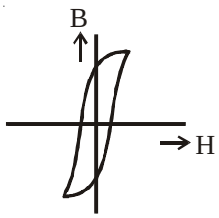


Fig. 3.14 (b) Hysteresis loop for a soft ferromagnetic material

1. The above figure shows the nature of hysteresis loop of hard magnetic material.	The above figure shows the nature hysteresis loop of magnetic material.
2. Hard magnetic materials are magnetic materials which cannot be easily magnetised and demagnetised.	Soft magnetic materials are magnetic materials which be easily magnetised and demagnetised.
3. They have large hysteresis loss due to large hysteresis loop area.	They have small hysteresis loss due to small hysteresis loop area.
4. These materials have small values for permeability and susceptibility.	These materials have large values for permeability and susceptibility.
5. The eddy current loss is more due to its smaller resistivity.	The eddy current loss is more due to its higher resistivity
6. In a hard magnetic material the domain wall movement is difficult owing to crystal imperfections and is . irreversible in nature	To obtain soft magnetic material the domain wails must be able to move easily and reversibly so that magnetisation changes by large amounts for small changes in the magnetising field.
7. The coercivity and retentivity are large.	The coercivity and retentivity are small.
8. In these materials, the irregularities (in the crystal structure) like mechanical strains will be more. Its magneto static energy is large.	These materials are tree from irregularities (in the crystal structure) like strains or impurities. Its magneto static energy is very small.

9. These are produced by heating the material and then plunging it suddenly into cold oil (quenching process) which sets up internal stresses.So mechanical strains are purposely introduced to make it hard magnetic material.	These are manufactured as follows: Heating the pure material to a temperature where sufficient movement of the atoms is possible for them to settle into an ordered lattice, followed by a slow cooling (annealing process) so as not to disturb it.
10. Examples : Alnico alloy, Cunifes, Cunico	Examples: Iron silicon alloy, ferrous nickel alloy, ferrite and garnets.
11. Applications: These are used to produce permanent magnets. Permanent magnets are used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices and magnetic separators.	Applications : These are used in electro-magnetic machinery and in transformer cores. These are used in switching circuits, microwave isolators, shift registers and matrix storage of computers and to produce electromagnetics.

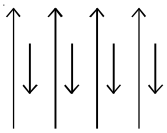
Energy Product

The energy product of a hard magnetic material is defined as the area of the largest B-H rectangle that can be constructed within the second quadrant of the hysteresis curve. In fig. 3.14(a) , the rectangle OPQR possesses larger area. Hence area of this rectangle is the energy product or $(BH)_{max}$ of the material.It is measured in kJ/m^3. The value of the energy product refers the energy required to demagnetize a permanent magnet. i.e. larger is the harder is the material in terms of its magnetic properties.

3.5 FERRIMAGNETISM - Ferrites

In some ceramic materials, different ions have different magnitudes for their magnetic moments, and when these magnetic moments are aligned in an antiparallel manner, there is a net magnetic moment in one direction. This group of ceramic ferrimagnetic materials are called ferrites. The magnetization produced in ferrites is large enough to be of commercial value. But their saturation values are not as high as those for ferromagnetic materials. They have domain structure and hysteresis loops similar to those of ferromagnetic materials.

In ferrimagnetic materials, the dipoles are aligned anti-parallel to each other. But the magnitudes of dipoles are not equal fig (3.5). Hence large magnetization occurs in a weak magnetic field. The magnetic susceptibility of a ferrimagnetic material is large and positive and depends on temperature. A group of ceramic ferrimagnetic materials are called ferrites.



Structure of ferrites

Ferrites are the magnetic compounds consisting of two or more different kinds of atoms. Generally ferrites are expressed as $X^{+}Fe_2^{3+}O_4$ where X^{2+} stands for suitable divalent metal ion such as Mg^{2+}, X^{2+}, $Fe_2^{3+}O_4$, Zn^{+}, Fe^{2+}, Mn^{+}, Ni^{2+} etc.

Examples

(a) If X^{2+} is replaced by Ni^{2+}, then the ferrite ($Ni^{2+}Fe_2^{3+}O_4$) is formed, thus named as **nickel ferrite,**

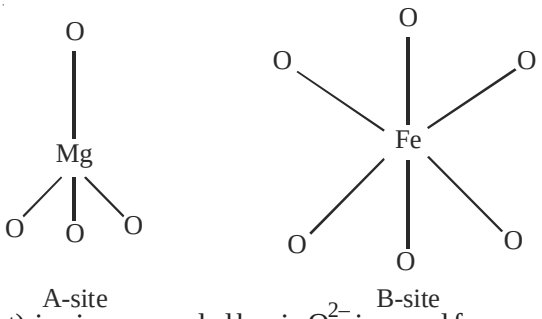
(b) If X^{2+} is replaced by Fe^{2+} then the ferrite ($Fe^{2+}Fe_2^{3+}O_4$) is formed, thus named as **ferrous ferrite.**

Ferrites formed usually have a face centered cubic structure of oxygen ions closely packed together with the divalent and trivalent metal ions in the interstitial sites. This structure is called **spinal structure.** There are two types of ferrite structures

(i) Regular spinal (ii) Inverse spinal

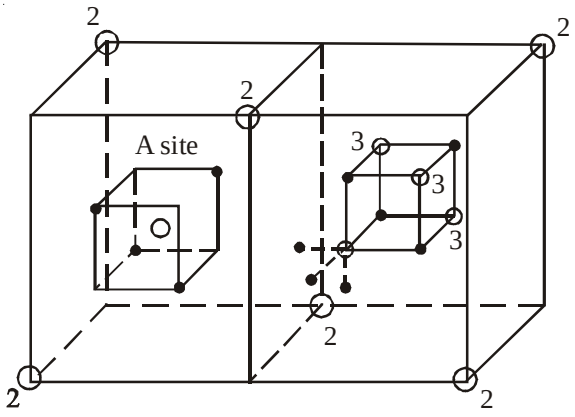
Regular spinal: (Mg^{2+} Fe^{3+} O_4)

In this type each divalent metal ion is surrounded by four O^{2-} ions in a tetragonal fashion. For example, if the metal ion is Mg^{2+}, then the structure is as shown in figure 3.15(a) and it is called 'A' site. Totally in a unit cell, there will be 8 tetrahedral (8A) sites.



Each Fe^{3+} (trivalent) ion is surrounded by six O^{2-} ions and forms an octahedral fashion as shown in figure 3.15. Totally, there will be 16 such octahedral sites in the unit cell. This is indicated by 'B' site.

Thus in a regular spinal, each divalent metal ion (Mg^{2+}) exists in a tetrahedral form (A site) and each trivalent metal ion (Fe^{3+}) exists in an octahedral from (B site). Hence the sites A and B combine together to form a regular spinal ferrite structures as shown in fig. 3.16.



2 - Divalent metal ion, 3 - Trivalent metal ion

● - Oxygen ion

Fig. 3.16

Inverse spinal $Fe^{3+}\left[Fe^{2+}\ Fe^{3+}\ O_4^-\right]$

In this structure the Fe^{3+} ion (trivalent) occupies all the A sites (tetrahedral) and half of the B sites (Octahedral) also. Thus the left out B sites will be occupied by the divalent (Fe^{2+}). The inverse spinal structure is as shown in fig. 3.17.

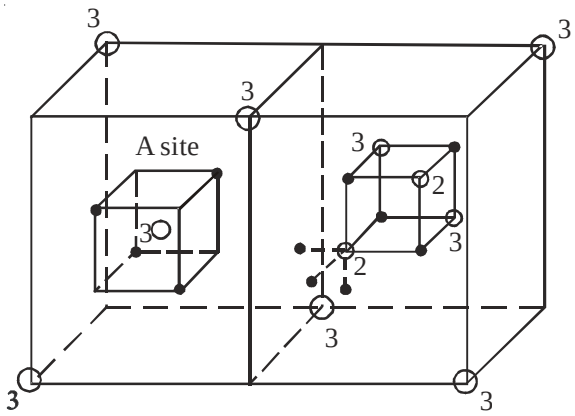


Fig.3.17

Types of interaction present in the ferrites

The spin arrangement between the A site and B site is in an antiparallel manner and it was explained by Neel. According to him, in ferrites, the spin arrangement is antiparallel and there exists some interaction between the A and B sites which is represented as AB interaction.

Apart from this, there are two more interactions (i.e.,) AA and BB interaction which is negative and considerably weaker than AB interaction.

The tendency of AB interaction is to align all A spins parallel to each other and the antiparallel to all B spins, but the tendency of AA and BB interaction is to spoil the parallel arrangement of A and B spins respectively.

Since AB is very strong as compared with AA and BB, the effect of AB interaction dominates and gives rise to antiparallel spin arrangement.

Magnetic moment of ferrite molecule

Saturation magnetization of a ferrite molecule can be calculated from the number of unpaired spins of Fe^{2+} and Fe^{3+}

Let us consider an example of Ferrite say Ferrous ferrite having the formula Fe^{2+} Fe_2^{3+} O_4 for calculating the magnetic moment.

In Ferrous ferrite we have two types of ions namely Fe^{2+} and Fe^{3+}

(i) Fe^{2+} ions have six electrons in 3d shell. Out of 6 electrons two electrons are paired with each other and hence left with 4 unpaired electrons. Therefore Fe^{2+} gives rise to 4 Bohr magneton.

Fe^{3+} ions have five electrons in 3d shell and hence all these 5 are unpaired electrons. Therefore Fe^{3+} gives rise to 5 Bohr magneton.

Since we have two Fe^{3+}, totally, the Fe_2^{3+} gives rise to 2 x 5 = 10 Bohr magnetons.

Total magnetisation of Fe^{2+} + Fe_2^{3+} = 4 +10 = 14 Bohr magneton. (i.e.) 14 μB

Theoretically we get 14 μB but experimetally the total magnetic moment got is only 4.08 μB. The reason for this discrepancy is as follows:

If all the spins are aligned parallel then the total magnetisation is 14 μB. But in ferrites half of the magnetic spins of Fe_2^{3+} ions are parallel to one direction and the remaining half of Fe_2^{3+} ions are parallel in opposite direction as shown in fig 3.18 and hence they cancel each other.

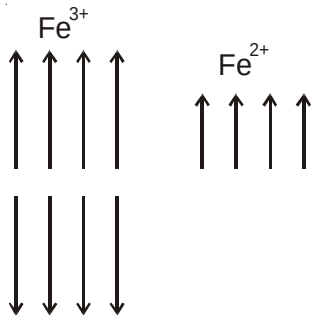


Fig. 3.18

Therefore, the net magnetic moment is only due to Fe^{2+} ions alone (i.e.,) hence we get the total magnetisation as $4\mu B$, which has a good agreement with the experiment value i.e., $4.08\mu B$.

Similarly we can calculate the total magnetic moment of any ferrite molecule with respect to the number of unpaired electrons in the divalent metal ions.

Applications

1. Ferrite rods are used in radio receivers to increase the sensitivity.
2. Since the ferrites have low hysteresis loss and eddy current loss, they are used in two port devices such as gyrator, circulator and isolator.

   Gyrator: It transmits the power freely in both directions with

   phase shift of π radians.

   Circulator: It provides sequential transmission of power between the ports

   Isolator: It is used to display differential attenuation.
3. They are also used for power limiting and harmonic generation,
4. They are used in computers and data processing circuits.
5. They are used to produce ultrasonics by magneto-stricrion principle.
6. Ferrox cubes (ferrites with rectangular hysteresis loop) are used in switching circuits and in matrix storage devices of computers.
7. Ferrites are used in audio and video transformers [Ni-Zn ferrites]

~~3.6. MAGNETIC RECORDING AND READOUT MECHANICSM~~

~~Now a days, large number of informations are stored in (or) retrieved from the storage devices, by using the magnetic phenomena. The main part of these magnetic storage devices is magnetic recording heads and they function according to the principle of magnetic induction.~~

~~Generally ferro or ferrimagnetic materials are used in the storage devices, because in this type of materials only the magnetic interaction between any two dipoles align~~