CHAPTER 2:

CRYSTAL STRUCTURE,
ANALYSIS AND SYNTHESIS
OF FERRITES

2.1 INTRODUCTION

The ferrites are ionic crystals of chemical composition \( \text{MFe}_2\text{O}_4 \) where \( M \) stands for any divalent metal ion. The oxygen ions form a close packed face centered cubic structure (fcc) (fig. 2.1) leaving the interstices of two kinds between them. The metal ions occupy suitably these interstices. The position of the metal ions in a void surrounded by six equidistant oxygen ions as the nearest neighbours is called octahedral B site and the position of a metal ion in a void packed by four oxygen ions is called a tetrahedral A site.

2.1 Crystal Structure of Ferrites:

According to crystal structure of the ferrites they are classified into three main groups.
1] Spinel.
2] Garnet
3] Hexagonal

1] Spinel:-

It is the simplest structure among the ferrites. Spinel ferrites have a cubic structure having general formula.

\[ M^{2+}Fe^{3+}O^{-2} \]

where M is divalent atom such as Mn, Mg, Ni etc.

2] Garnet:-

It is a cubic structure, having the general chemical formula.

\[ Ln_{3}^{3+}Fe_{5}^{3+}O_{12}^{2-} \]

where \( Ln_{3} \) is trivalent atom such as Y, Sm, Gd, Tb etc.

3] Hexagonal:-

The general chemical formula of the Hexagonal ferrites is
A\textsuperscript{II}Fe_{12}^{3+}O_{19}^{2-}

where A\textsuperscript{II} is divalent metal ion such as Ba, Pb etc.

Oxides can be used for the preparation of the ferrites.

The following reactions for the three types of ferrites are considered as-

- Spinel ferrites: \( M^{2+}O^2^- + Fe^{3+}O^2^- \rightarrow M^{2+}Fe_2^{3+}O_4^{2-} \)
- Garnet: \( 3Y_2O_3 + 5Fe_2O_3 \rightarrow 2Y_3Fe_5O_{12} \)
- Hexagonal ferrites: \( BaO + 6Fe_2O_3 \rightarrow BaFe_{12}O_{19} \)

2.1.2 SPINEL STRUCTURE OF FERRITES:

In general ferrites may be described as compounds derived from magnetite (FeOFe\textsubscript{2}O\textsubscript{3}) by substituting other metal atom in place of the divalent ion, suitably the atoms of metals such as Mn, Mg, Zn etc. If the divalent ion is replaced by other divalent metal ion the ferrite formed is called single ferrite or simple ferrite e.g. MnFe\textsubscript{2}O\textsubscript{4}, CuFe\textsubscript{2}O\textsubscript{4}, ZnFe\textsubscript{2}O\textsubscript{4} etc. If the divalent ion is partially replaced by one and partially by other divalent metal ion, the ferrite formed is termed as binary ferrite or mixed ferrite e.g. Mg\textsubscript{0.8}Ni\textsubscript{0.2}Fe\textsubscript{2}O\textsubscript{4}.

The mineral (MgAl\textsubscript{2}O\textsubscript{4}) and the magnetite (Fe\textsubscript{3}O\textsubscript{4}) are said to
have spinel structure.

The spinel ferrites crystallize in cubic system and the structure was determined first by Bragge's (1) and NishiKawa (2). The unit cell contains eight formula units and may be written as \(M_8F_{16}O_{32}\). 32 oxygen ions form face centered cubic (fcc) lattice, within this lattice two kinds of interstitial site are present, namely tetrahedral site (A-site) and octahedral site (B-site). In all there are 96 interstitial sites in unit cell, 64 tetrahedral sites and 32 octahedral sites. Out of these, eight tetrahedral sites and sixteen octahedral sites are occupied by cations (fig.2.2-2.4).

The crystal structure is best described by subdividing the unit cell into eight octants with edge \(a/2\), where 'a' is the size of the unit cell (fig.2.5). The location of the oxygen ions and the metal ions in every octant can then be easily described. Each octant contains four octahedral metal ions and these are situated at sites analogous to those of oxygen ions, i.e. one quarter length of the body diagonal from the other ends of the four body diagonals of the octant (fig2.6). Octahedral metal ions form fcc lattice with edge 'a' which is displaced with respect to each other by a distance \(a\sqrt{2}/4\) in the direction of phase diagonals of the cube.
2.1.3 U- PARAMETER OR OXYGEN PARAMETER :-

The displacement of oxygen ion along the body diagonal is known as oxygen parameter 'U'.

In ideal case, \( U = 3/8 \), but in actual practice it is slightly greater, because in closed pack (fcc) structure, the tetrahedral interstices usually permit ions with a maximum radius \( (0.30\text{Å}) \) whereas the octahedral one would allow ions having radius \( (0.55\text{Å}) \). But in case of spinel lattice these permissible radii at A and B sites are too small to accommodate large ions, such as Mg \( (0.75\text{Å}) \), Mn \( (0.80\text{Å}) \), Ni \( (0.74\text{Å}) \) into these sites. Hence the lattice has to be expanded with the displacement of nearest neighbouring oxygen ion along the body diagonal of the cube. That is the tetrahedral holes or sites are made large due to displacement of ions, the octahedral holes or sites reduce in size and as a result both of them become nearer in size. Some time the octahedral coordinate cations get shifted a little out of their center position (3), which also changes the space group.

The radii of the sphere in both types of site are given by the expression.

\[
\begin{align*}
  r_A &= \left( U - \frac{1}{4} \right) a \sqrt{3} - R_0 \\
  r_B &= \left( \frac{5}{8} - U \right) a - R_0
\end{align*}
\]
Where,

$r_A$ and $r_B$ are radii of the tetrahedral and octahedral site cation respectively

$R_0$ is the radius of the oxygen ion.

2.1.4 STRUCTURAL CO-ORDINATES OF CUBIC SPINEL :-

Wyckoff (4) gives the spinel space group as $O_7^7$ (Fd3m). The structural co ordinates of the tetrahedral, octahedral and oxygen ions in terms of lattice parameter ‘a’ are given as [Where oxygen parameter ‘U’ can have any value from 0.375 to 0.395 with respect to oxygen at center.]

The equivalent positions are

$(0,0,0), (1/2,1/2,0), (1/2,0,1/2) \& (0,1/2,1/2)$

Atomic position of A-site cations (8f)

$(0,0,0), (1/4,1/4,1/4)$

Atomic position of B site cations (16c)


Atomic position of oxygen ions (32b)

$(u,u,u);(u,\bar{u},u)(\bar{u},u,\bar{u})(\bar{u},\bar{u},u)$
\[ [1/4-u, 1/4-u, 1/4-u] \]
\[ [1/4+u, 1/4-u, 1/4+u] \]
\[ [1/4+u, 1/4+u, 1/4-u] \]
\[ [1/4-u, 1/4+u, 1/4+u] \]

Co-ordinates of remaining ions are obtained by translations
\[ (0,1/2,1/2), (1/2,0,1/2), (1/2,1/2,0) \]

From the translations it is obvious that the unit cell (of cube edge =a) consists of the two different groups of four cubes with edge a/2 (octants) with ideal ionic positions. The 8f and 16c positions with nearest neighbours in spinel structure are shown in fig(2.7). However, cation substitution causes cell expansion. The expansion is along the digonal of the cube as shown in fig.(2.8). The projection of the spinel ionic positions to a cube face for an ideal spinel system (for which u=3/8) is shown in fig.(2.9).

2.2 CATION DISTRIBUTION:

2.2.1 INTRODUCTION:

The behaviour of electrical and magnetic properties of the spinel ferrites is governed by the distribution of cations (divalent and trivalent metal ions) among the octahedral and tetrahedral sites of the spinel lattice.
2.2.2 Types of ferrites :-

Depending on the distribution of divalent and trivalent metal ions between the A and B sites the ferrites are classified as-

1] Normal Spinel
2] Inverse Spinel
3] Random Spinel

1] Normal Spinel :-

In the normal spinel all the 8 divalent metal ions ($M^{2+}$) occupy the tetrahedral A sites and remaining 16 trivalent ions ($Fe^{3+}$) occupy the octahedral B sites. This cation distribution can be generally shown as

$$(M^{2+})^A [Fe^{3+]^B} O_4^{2-}$$

where $M^{2+}$ is divalent atom such as $Zn^{2+}$, $Cd^{2+}$ etc.

2] Inverse Spinel: -

In the inverse spinel structure of a ferrite all divalent
$M^{2+}$ ions lie on B-site and the trivalent $Fe^{3+}$ ions in equal numbers lie at A and B sites. This cation distribution can be shown as-

$$( Fe^{3+} )^A [ M^{2+} Fe^{3+} ]^B O_4$$

where $M^{2+}$ is divalent atoms such as $Co^{2+}$, $Ni^{2+}$, etc.

3] Random Spinel :-

In the random spinel structure of a ferrite both the divalent and trivalent atoms occupy both sites A and B, which can be shown as

$$(M^{2+}_{1-x} Fe^{3+}_x)^A [ M^{2+}_x Fe^{3+}_{2-x} ]^B O_2^- 4$$

where $M^{2+}$ is divalent

e.g. $(Mn_{0.8} Fe_{0.2})^A [Mn_{0.2} Fe_{1.8}]^B O_2^- 4$

The general chemical formula for cation distribution can be expressed as-

$$(M_{1-x}M_x')^A[M_xM'_2-x]B O_2^- 4$$

where $M$- divalent metal ion

$M'$ - trivalent metal ion

A - tetrahedral site

B - octahedral site

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For different values of x, spinel can be classified as,

For \( x = 0 \), Normal spinel
For \( x = 1 \), Inverse spinel
For \( 0 < X < 1 \) Random spinel

### 2.2.3 FACTORS EFFECTING CATION DISTRIBUTION :-

The cation distribution between the A-site and B-sites depends on the following factors.

1] Ionic radius
2] Covalent bonding and hybridization
3] The electrostatic energy

#### 1] Ionic Radius. :-

Radius of tetrahedral site is smaller than that of the octahedral site. One may expect that smaller ions will prefer to occupy the tetrahedral sites pushing large ions to octahedral sites. Trivalent ions are usually smaller than divalent ions. Therefore trivalent ions may occupy A- sites and divalent ions may occupy B-site.

#### 2] Covalent bonding and hybridization
It is observed that ions having filled ‘d’ shells often have tendency to form \( sp^3 \) hybrid orbital and occupy the tetrahedral A sites in spinel lattice (e.g. \( \text{Zn}^{2+}, \text{Ge}^{4+} \)) (5). The ions with \( d^3 \) and \( d^8 \) electronic configuration have a tendency to form \( d^2 sp^3 \) hybrid orbital and occupy the octahedral sites in spinals (e.g. \( \text{Cr}^{3+}, \text{Ni}^{2+} \)) (6).

3) Electrostatic Energy :

The electrostatic energy known as modeling energy plays an important role in the distribution of cations among the tetrahedral and octahedral sites.

The modeling energy is the electrostatic energy gained when the ions are brought together from infinite distance to form the spinel lattice. In the normal arrangement, the metal ions with the smallest +ve charge are surrounded by four oxygen ions and metal ions with higher +ve charge are surrounded by six oxygen ions which is electrostatically most favorable. From the calculation by Vervey et. al. (7), it follows that for the spinel consisting of divalent and trivalent metal ions, the inverse structure has the lowest lattice energy in the case \( U \) (oxygen parameter) < 0.379, whereas the normal structure has the lowest lattice energy, when \( U > 0.379 \).
2.3 CRYSTAL STRUCTURAL ANALYSIS :-

2.3.1 Introduction :-

The spinel systems synthesized by ceramic technique were studied by different experimental techniques, so as to determine their crystal structure and transport properties. In the following pages a brief description of the various techniques used, the method of analysis of data and the parameters of interest that can be obtained is given.

2.3.2 X – RAY DIFFRACTION :-

It is used to determine the crystal structure (8,9). The diffraction occurs only when the wavelength of the wave motion equals the magnitude of the repeated distance between the scattering centers. This fulfillment can be achieved by the Bragg’s law.

\[ 2d \sin \theta = n\lambda \]

\( d \) being interplanar distance

\[ n < 2d \quad (\theta<\sin\theta<1) \]

In diffraction, the least value of ‘n’ being unity, the condition met at any observable angle ‘2\( \theta \)’ is.

\[ \lambda = 2d \]
Bragg’s law can be written as

\[ \lambda = 2 \frac{d'}{n} \sin \theta \]

The coefficient of \( \lambda \) being unity, a reflection of any order can be conveniently considered as the first order reflection from planes real or imaginary, spaced at 1/n of the previous spacing. Replacing conveniently \( d'/n \) by \( d \), we have,

\[ \lambda = 2d \sin \theta \]

The number of whole wavelengths lying in the path difference between rays scattered by adjacent (hkl) planes is known as the order of diffraction beam. If there is no real plane midway between the (100) planes, it can be imagined forming first order reflection from adjacent (200) planes. In the same way (300), (400) etc. reflections may be equivalent to the third, fourth etc. orders from (100) planes.

The \( n^{th} \) order reflection from (hkl) planes of spacing \( d \) may be viewed as a first order reflection from (nh, nk, nl) planes of spacing \( d = d'/n \). This matches with the definition of miller indices, since (nh nk nl) indicates the miller indices of planes parallel to the (h k l) planes with 1/n spacing of the latter.
The number of diffraction directions $2\theta_1$, $2\theta_2$, $2\theta_3$, etc. can be traced and photographed from the (100) planes by using a monochromatic incident beam at the angle $\theta_1$, $\theta_2$, $\theta_3$ etc. which produce I$^{\text{st}}$, II$^{\text{nd}}$, III$^{\text{rd}}$ etc. order reflections.

The diffraction from the other planes is also expected. The combination of Bragg’s law and the plane spacing expression of a particular crystal under investigation predict the diffraction angles for any set of planes.

For cubic crystal the interplaner distance ‘d’ in (hkl) set of planes is

$$\frac{1}{d^2} = \frac{h^2 + k^2 + l^2}{a^2}$$

where ‘a’ is unit cell size.

Combining with the Bragg’s law, we have,

$$\sin^2 \theta_{hkl} = \frac{\lambda^2}{4a^2} (h^2 + k^2 + l^2)$$

------------ (b)

For known value of ‘$\lambda$’ this equation predicts all possible Bragg’s angles ‘$\theta$’ for diffraction that occurs from the planes (hkl).

If the crystal is tetragonal with axes a and c the equation becomes
\[
\sin^2 \theta_{\text{hkl}} = \frac{\lambda^2}{4} \left( \frac{h^2 + k^2}{a^2} + \frac{l^2}{c^2} \right)
\]

----- (c)

where ‘a’ and ‘c’ are lattice parameter.

Thus the diffraction directions as predicted by equations (b,c) are used to determine the shape and size of the unit cell. The measurements of directions of diffracted beams speculate the shape and size of crystal’s unit cell while their intensities give the information regarding the position of atoms.

2.3.2 X- RAY DIFFRACTION AND STRUCTURAL ANALYSIS :-

Knowing the wavelength of X-rays used and measuring various diffraction angles ‘\(\theta\)’ the interplaner distance ‘\(d\)’ in a crystal can be determined. This is called structural analysis.

The structural analysis can be achieved by different diffraction methods. Diffraction occurs whenever the Bragg’s law (10) is satisfied. The way of satisfying the Bragg’s condition may be achieved by varying either ‘\(\lambda\)’ or ‘\(\theta\)’ during experiment.

The ways in which these quantities are varied give following diffraction methods.
2.3.2.1. Laue method :-

In this method a single crystal is held stationary (θ is fixed) in the path of continuous wavelength (λ). The crystal selects out and diffracts the discrete value of ‘λ’, for which the planes have inter spacing ‘d’ satisfying Bragg’s law. The diffraction pattern due to Laue method consists of a series of spots. This method is convenient for the rapid determination of crystal orientation and symmetry. The Laue method is practically never used for the crystal structure determination.

2.3.2.2. Rotating Crystal method :-

A single crystal rotates (θ varied) about a fixed axis in a monochromatic beam (λ is fixed) of X – rays. The variation in ‘θ’ brings different atomic planes into position for reflection.

In course of rotation of the crystal the beam gets diffracted whenever the value of ‘θ’ satisfies the Bragg equation. A modified
rotating crystal method can be used for structure determination when the available specimen is a single crystal (12). Several variations of the rotating crystal method are in common use.

2.3.2.3. Powder method:

The powder method of X-ray diffraction was first developed by P. Debye and S. Scherrer (13) in 1916 and independently by A.W. Hull (14) in 1917. This method can be used properly to get the knowledge of structural information about the sample under investigation.

In this method, the film is placed on the cylindrical surface of D. S. camera and the specimen holder rotates about the axis of the camera in a mono energetic beam of X-rays. The small amount of smoothly ground powder can be coated on the surface of a fine glass fiber with the help of glue or petroleum jelly. The specimen prepared is then mounted in its holder by proper adjustments.

The crystallites in a powder get completely randomly oriented, so that the reciprocal lattice vectors of all the crystallites point in the same directions. The reciprocal lattice points lie on the surface of a sphere of radius $|\sigma_{hkl}|$. Each reciprocal lattice sphere oriented by every possible value of $\sigma_{hkl}$ cuts the Ewald’s sphere. A
narrow filmstrip is used to record the representative portion of the
cuts (fig 2.11).

By the geometry of Ewald’s sphere (fig 2.12) and diffracted
angle θ, hkl values can be determined for a particular value of θ.
Using Bragg’s law

\[ 2d_{hkl} \sin \theta_{hkl} = \lambda \]

The inter planer spacing d can be calculated.

X-ray analysis for ferrites, using X-ray diffraction was
carried out by Barth and Posnjak (15).

2.6 I.R. Spectroscopy

The atoms in solids vibrate at frequencies approximately \(10^{12}\)
to \(10^{13}\) Hz. The vibration modes involving pairs or groups of
bonded atoms can be excited to higher energy states by absorption
of radiation of appropriate frequency. The electromagnetic radiation
whose wavelength lies in the range 0.72μ (micron) to
approximately 1000μ is known as infrared radiation. The entire
infrared region can be divided into three regions. The region of
electromagnetic radiation whose wavelength lies from 0.72μ to
1.5μ is called near infrared regions.

The second region of the radiation whose wavelength lies
from 1.5μ to 20μ is called middle infrared region. The third region
radiation whose wavelength lies from 20μ to 1000μ is called far infrared region. The near infrared and far infrared regions are least used for spectroscopic purpose because absorption of organic molecules in these regions is very small. The middle region is found to be very useful for studying the symmetry of molecules.

When a molecule (or atom) interacts with electromagnetic radiation of the proper frequency \((10^{12} \text{ to } 10^{13} \text{ Hz})\), it absorbs energy and the molecule is set into vibrations. If the transmission energy is plotted as the function of radiation frequency the energy distribution shows absorption at certain frequency.

The IR spectroscopy is used to determine the local symmetry in crystalline and non crystalline solids. It helps to study the ordering phenomenon in ferrites, deformation of cubic spinel and force constant. Four IR frequencies \(v_1, v_2, v_3, v_4\) are observed in case of spinel ferrites. These are attributed to local symmetry of tetrahedral and octahedral sites in the unit cell.

Waldron [16] is the first to report the infrared spectra of spinels. He found the four infrared active modes. Two of them, having the higher frequency, were supposed to arise from the motion of the oxygen ions, and the remaining two were assigned to the motions of the cations only. Later on White, De Angelis and
Lutz using group theory and considering the full cubic crystallographic unit cell (whereas Waldron considered rhombohedral unit cell) confirmed the four modes but the origin of the modes was found to be more complex. Very thorough investigation of infrared spectra of normal spinels was done by Preudhomme and Tarte (17). They assigned the higher frequency band (600 cm\(^{-1}\)) to tetrahedral site and the lower frequency band (400 cm\(^{-1}\)) to octahedral site. They also noticed the gradual increase in the absorption of higher frequencies. Hafner, Trate and others [18,19] applied IR spectroscopy to investigate the absorption bands in many normal as well as inverse spinel.

The third mode of vibration has been observed by Brabers et. al. (20) in case of MnFe\(_2\)O\(_4\) at 335 cm\(^{-1}\). The bands in the region 300 – 700 cm\(^{-1}\) are assigned to the fundamental vibrations of the ions of the crystal lattice.

Thus infrared spectroscopy is useful to understand the structure-based properties of the specimen. In case of mixed magnetic oxides, which crystallize in face centered cubic spinel structure, the electric and magnetic properties of these materials are decisively dependent on the precise cationic and anionic positions in the crystal. In such cases the vibration, electronic and magnetic
dipole spectra can give information about the position and valence of the ions in the crystal lattice. The frequency of the vibration depends on the cation mass, the lattice parameters, the cation oxygen bonding force and its bond length. IR spectroscopy is used, to study cationic order, coordination number and deformation produced due to the accommodation of cations in the spinel structure.

2.4 SYNTHESIS OF FERRITES :-

2.4.1. Introduction

The method of preparation plays a very important role with regard to the structural, electrical and magnetic properties of spinal ferrite (21).

The production of ferrite structure occurs by counter diffusion of metallic ions through the oxygen lattice with no appreciable surface diffusion or vapor transport (22). Thus oxides must be finely divided and intimately mixed to be highly reactive.

The ferrites are in general prepared by

1) Ceramic Method.

2.4.1 Ceramic Method:

Typical flow chart showing various steps performed during the preparation of ferrite material using ceramic method is shown in figure (2.13).

In a ceramic method (23,24) very pure and fine grains constituents in oxide form are taken. They are thoroughly and uniformly mixed. Then the following stages are carried out.

1] Pre – sintering

2] Remilling

3] Final sintering

4] Cooling

The description of each step is as follows.

1] Pre-sintering:

The mixture of raw materials is fired at a temperature some 200°C below its final firing temperature, this process is called pre-sintering.

Swallow and Jordan (25) note the following purpose of the
pre-sintering.

1] It decomposes carbonates and higher oxides that reduce the evolution of gas in the final sintering process.

2] It helps to prepare the material homogeneous.

3] It controls the shrinkage of the material occurring during the final firing.

Particle reaction takes place to form the final product during pre-sintering. The amount of reaction depends upon the reactivity of the components and the pre-sintering temperature. The pre-sintering temperature can be maintained up to $1000^\circ$C for several hours depending upon the constituents of the materials. The correct partial pressure of oxygen in the furnace must be maintained throughout the firing cycle in order to retain the stoichiometry and valence states achieved otherwise those will be destroyed during the cooling period.

2] Remilling :-

The powder obtained from pre-sintering is then remilled which results in a large bulk density in the sintered product, which
gives improved electrical properties.

3] Final sintering : -

The powder obtained from remilling is then final sintered. The properties of final product depend upon the sintering process. Generally the sintering temperature is 900\(^0\)C to 1600\(^0\)C, for the period of 4 to 24 hours. The product containing Li, Cd are usually sintered at highest temperature. Uniform ferrites can be obtained by sintering the sample for a long period for a desired temperature.

4] Cooling : -

The cooling conditions also affect the properties of the final product. Since the ferrites have very low thermal conductivity, it is essential that they are cooled slowly after sintering. That is the rate of heating and cooling must be almost the same. The distribution of metal ions can be quenched by means of quick cooling from the sintering temperature.

2.4.3 Wet – Chemical Method (Co-precipitation method)

The wet – chemical method (Co-precipitation method) of
preparation of ferrite yields homogenous fine and reproducible ferrite powders (26, 27) using the salts of constituent ions. The wet-chemical method is classified as –

A] Spray drying
B] Freeze drying
C] Hydro-thermal oxidation

A] Spray drying :

In this method, constituents in an appropriate ratio are dissolved in a solvent and they are sprayed in the form of droplets into a hot chamber. The solvent evaporates instantaneously leaving behind an intimate mixture of reactants, which on heating at elevated temperature give the required product.

B] Freeze Drying :

In this method, low temperature bath is used to prepare ferrites. An aqueous solution of salt is prepared by mixing the salts in the proper proportions. This solution is sprayed into the low temperature bath maintained at liquid nitrogen temperature. The solution gets solidified as fine beads of ice. The frozen solvent is
removed at low pressure. To yield the final product, the salt is decomposed at an elevated temperature.

C] Hydro – thermal oxidation:

In this method, ferrites can be prepared directly from the solution. The alkaline solution is added to a stoichiometric solution of metallic salts with iron in the divalent state. This results in a suspension of the mixture of Hydroxides. The suspension is kept at a temperature between 60 to 90°C. When air is bubbled uniformly into this suspension, it promotes the oxides reaction, converting the precipitates into ferrites. This method avoids thermal decomposition of salts.
STRUCTURE OF METALS

Figure 2.1: A unit cube showing fcc packing of identical atoms
Fig. 2.2 Tetrahedral site

Fig. 2.3 Octahedral site

Figure 2.4: Surrounding of oxygen ion in spinel
Fig. 2.5: Surrounding of the oxygen ions and metal ions in two adjacent sites of the spinel

Figure 2.6: Surrounding of B-site ions by other B-site ion in the spinel ferrite
Fig. 2.7 8f 16c & nearest neighbors in spinel structure

Fig. 2.8 Expansion of unit spinel cell
Figure 2.9: Projections of the ionic positions in spinel structure.
Figure 2.10: Diffraction of X-rays from successive planes
Figure 2.11 (a) Diffracted cones with angle $4\theta$, and (b) the uncoiled film part of the diffracted cones.
Figure 2.12: - Diffraction of X-rays by randomly oriented crystals (Ewald's sphere)
Figure (2.13):- Flow chart of the in the stages preparation of ferrites.
Fig 2.14 Typical flow chart of the stages in the preparation of cobalt ferrite powder by sol-gel method.
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