Chapter One
Introduction

1.1 Prelude

Ferrite is a polycrystalline, sintered material with high electrical resistivity. The high resistance of ferrite makes eddy current losses extremely low at high frequencies. Therefore, unlike other magnetic components, ferrite can be used at considerably high frequencies. Manganese-zinc (Mn-Zn) ferrites can be used at frequencies up to several megahertz. The basic ferrite materials are obtained in an extremely high purity. These materials are mixed, calcined, milled, granulated, formed by pressing, and sintered at a temperature of 1000°C to 1400°C, and then machined. The electrical and mechanical properties of a particular ferrite material are obtained by the material formulation and the processing applied. Extraordinary exacting process controls are required to assure the high uniformity of product for which **TDK** (Japanese multinational electronics company) ferrites are well known. Through the above processes, ferrite materials can be optimized for specific applications.

1.2 Research Problem

- Magnets and its general properties.
- Types of magnetic materials and the difference in structure.
- Components of the ferrite and its most important general characteristics.
- Uses of ferrite magnet.

1.3 Literature Review

*Physical and Magnetic Properties of Manganese Ferrite Nanoparticles

In this paper, manganese ferrite ($MnFe_2O_4$) nanoparticles were synthesized using chemical bath deposition (CBD) method and characterized by XRD and TEM to determine different properties of nanoparticles. The results obtained showed the formation of manganese ferrite nanoparticles with an average particle size are in good agreement with previous reported experimental results and displayed good magnetic properties. Magnetic properties were determined using Vibrating Sample Magnetometer (VSM). Due to simplicity and low cost of this process, it could be used for synthesis of ferrites nanoparticles. These materials may be used in drug delivery systems, electronic devices and water remediation.
(Uma Shankar Sharma, Ram Naresh Sharma and Rashmi Shah August 2014) [1].

*Characterization of M-Type Barium Hexagonal Ferrite-Based Wide Band Microwave Absorber

This paper present the design, development and characterization of the hexagonal ferrite powder [$BaCo_{0.5\delta}Ti_{0.5\delta}Mn_{0.1}Fe_{(11.87-\delta)}O_{19}$] and [$Ba(MnTi)_{\delta}Fe_{(12-2\delta)}O_{19}$] at $\delta=1.6$ as a microwave absorber. The hexagonal ferrite powder has been developed by dry attrition and sintering procedure. The developed ferrite powder 60% by weight has been mixed in epoxy resin to form a microwave-absorbing paint. This paint was coated on a conducting aluminum sheet to study the absorption characteristics of a linearly polarized TE wave at X band. The results for single- and two-layer microwave absorbers for different coating thicknesses have been reported. It has been found that it shows the broadband characteristics with minimum absorption of 8 dB from 8 to 12 GHz for a coating thickness of 2 mm. These paints are very useful in military applications such as RCS reduction, camouflaging of the target and prevention of EMI, etc.

(M.RMeshram,Nawal KAgrawal,BharotiSinhaP.SMisra _ May 2016)[2].

***Magnetic Properties of Cu–Zn Ferrites Doped with Rare Earth Oxides**

Samples of Cu–Zn ferrites doped with different rare earth ions (La, Sm, Nd, Gd, and Dy) are investigated. X-ray diffraction patterns indicated the presence of a single spinel phase. The lattice parameter is found to be nearly independent of the doped rare earth ion type. The density is measured and the porosity is calculated for each sample. The magnetization is measured on toroidal samples using the induction method. The initial permeability μ_i is measured as a function of temperature at a constant frequency of 10 kHz and the Curie temperature T_C is determined. The variations of magnetization, relative permeability and the initial permeability as a function of the effective magnetic moment of the doped rare earth ion are discussed.(A. A. Sattar,A. H. Wafik,K. M. El-Shokrofy,M. M. El-Tabby–February 2016)[3].

***Microwave Applications of Soft Ferrites**

Signal processing requires broadband, low-loss, low-cost microwave devices (circulators, isolators, phase shifters, absorbers). Soft ferrites (garnets, spinels, hexaferrites), applied in planar microwave devices, are reviewed from the point of view of device requirements. Magnetic properties, specific to operation in high-frequency electromagnetic fields, are discussed. Recent developments in thick film ferrite technology and device design are reviewed. Magnetic losses related to planar shape and inhomogeneous internal fields are analyzed.

(MarthaPardavi-Horvath- June 2015) [4].

1.4 Objectives of The Study

- Determination of different types of magnets.
- Determination of ingredients for the preparation of Ferrite substance.
- Statement of the need for the use of Ferrite Magnetism as a type of magnetic material.
- Detection of basic structure and all properties and uses of ferrite material.

1.5 Presentation of The Thesis

Chapter one represents the introduction, while chapter two represents classes of magnetic material; chapter three is devoted to the applications of ferrite and finally chapter four is the conclusion and recommendations of the study.

Chapter Two
Classes of Magnetic Materials

2.1 Introduction

Magnetism is a class of physical phenomena that are mediated by magnetic fields. Electric currents And the magnetic moments of elementary particles give rise to a magnetic field, which acts on other currents and magnetic moments. The most familiar effects occur in ferromagnetic materials, which are strongly attracted by magnetic fields and can be magnetized to become permanent magnets, producing magnetic fields themselves. Only a few substances are ferromagnetic; the most common ones are iron, nickel , cobalt and their alloys. The prefix ferro- refers to iron, because permanent magnetism was first observed inlodestone, a form of natural iron are called magnetite, Fe_3O_4.Although ferromagnetism is responsible for most of the effects of magnetism encountered in everyday life, all other materials are influenced to some extent by a magnetic field, by several other types of magnetism. Paramagnetic substances such as aluminum and oxygen are weakly attracted to an applied magnetic field; diamagnetic substances such as copper and carbon are weakly repelled; while antiferromagnetic materials such as chromium and spin glasses have a more complex relationship with a magnetic field. The force of a magnet on paramagnetic, diamagnetic, antiferromagnetic materials is usually too weak to be felt, and can be detected only by laboratory instruments, so in everyday life these substances are often described as non-magnetic.The magnetic state (or magnetic phase) of a material depends on temperature and other variables such as pressure and the applied magnetic field. A material may exhibit more than one form of magnetism as these variables change [5].

2.2 Sources of Magnetism

Magnetism, at its root, arises from two sources:

1. Electric current.
2. Spin magnetic moments of elementary particles. The magnetic moments of the nuclei of atoms are typically thousands of times smaller than the electrons' magnetic moments, so they are negligible in the context of the magnetization of materials. Nuclear magnetic moments are nevertheless very important in other contexts, particularly in nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI).

Ordinarily, the enormous number of electrons in a material are arranged such that their magnetic moments (both orbital and intrinsic) cancel out. This is due, to some extent, to electrons combining into pairs with opposite intrinsic magnetic moments as a result of the Pauli exclusion principle (see electron configuration), or combining into filled subshells with zero net orbital motion. In both cases, the electron arrangement is so as to exactly cancel the magnetic moments from each electron. Moreover, even when the electron configuration is such that there are unpaired electrons and/or non-filled subshells, it is often the case that the various electrons in the solid will contribute magnetic moments that point in different, random directions, so that the material will not be magnetic. Sometimes, either spontaneously, or owing to an applied external magnetic field—each of the electron magnetic moments will be, on average, lined up. A suitable material can then produce a strong net magnetic field. The magnetic behavior of a material depends on its structure, particularly its electron configuration, for the reasons mentioned above, and also on the temperature. At high temperatures, random thermal motion makes it more difficult for the electrons to maintain alignment [6].

2.3 Main Points about Magnets

Almost everyone knows these six basic facts about how magnets behave:

1. A magnet has two ends called poles, one of which is called a north pole or north-seeking pole, while the other is called a south pole or south-seeking pole.
2. The north pole of one magnet attracts the south pole of a second magnet, while the north pole of one magnet repels the other magnet's North Pole. So we have the common saying: like poles repel, unlike poles attract.
3. A magnet creates an invisible area of magnetism all around it called a magnetic field.
4. The north pole of a magnet points roughly toward Earth's North Pole and vice-versa. That's because Earth itself contains magnetic materials and behaves like a gigantic magnet.
5. If you cut a bar magnet in half, it's a bit like cutting an earthworm in half! You get two brand new, smaller magnets, each with its own north and South Pole. (This is, of course, a joke. You don't get two worms if you cut a worm in half. But you do get two magnets.)
6. If you run a magnet a few times over an unmagnified piece of a magnetic material (such as an iron nail), you can convert it into a magnet as well. This is called magnetization [7].

2.4 Magnetic Fields in a Material

A magnetic field is the magnetic effect of electric currents and magnetic materials. The magnetic field at any given point is specified by both a direction and a magnitude (or strength); as such it is represented by a vector field. The term is used for two distinct but closely related fields denoted by the symbols **B** and **H**, where **H** is measured in units of amperes per meter (symbol: $A \cdot m^{-1}$ or A/m) in the SI. **B** is measured in tesla (symbol: T) and Newton per meter per ampere (symbol: $N \cdot m^{-1} \cdot A^{-1}$ or N/(m·A)) in the SI. **B** is most commonly defined in terms of the Lorentz force it exerts on moving electric charges. Magnetic fields can be produced by moving electric charges and the intrinsic magnetic moments of elementary particles associated with a fundamental quantum property, their spin. In special relativity, electric and magnetic fields are two interrelated aspects of a single object, called the electromagnetic tensor; the split of this tensor into electric and magnetic fields depends on the relative velocity of the observer and charge. In quantum physics, the electromagnetic field is quantized and electromagnetic interactions result from the exchange of photons [8].

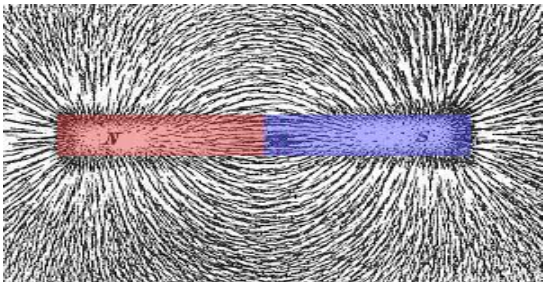

Fig (2.1) Magnetic Field

In a vacuum:

$$\mathbf{B} = \mu_0 \mathbf{H}, \qquad (2.1)$$

Where μ_0 is the vacuum permeability.

In a material,

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}). \qquad (2.2)$$

The quantity $\mu_0\mathbf{M}$ is called magnetic polarization.

If the field **H** is small, the response of the magnetization **M** in a diamagnet or paramagnet is approximately linear:

$$\mathbf{M} = \chi \mathbf{H}, \qquad (2.3)$$

The constant of proportionality being called the magnetic susceptibility. If so,

$$\mu_0(\mathbf{H} + \mathbf{M}) = \mu_0(1 + \chi)\mathbf{H} = \mu_r \mu_0 \mathbf{H} = \mu \mathbf{H}. \qquad (2.4)$$

In a hard magnet such as a ferromagnet, **M** is not proportional to the field and is generally nonzero even when **H** is zero [9].

2.5 Earth's Magnetic Field

The Earth's magnetic field is thought to be produced by convection currents in the outer liquid of Earth's core. The Dynamo theory proposes that these movements produce electric currents that, in turn, produce the magnetic field [10]. The presence of this field causes a compass, placed anywhere within it, to rotate so that the "north pole" of the magnet in the compass points roughly north, toward Earth's North Magnetic Pole. This is the traditional definition of the "north pole" of a magnet, although other equivalent definitions are also possible.

One confusion that arises from this definition is that, if Earth itself is considered as a magnet, the south pole of that magnet would be the one nearer the north magnetic pole, and vice versa. The north magnetic pole is so-named not because of the polarity of the field there but because of its geographical location. The north and south poles of a permanent magnet are so-called because they are "north-seeking" and "south-seeking", respectively [11].

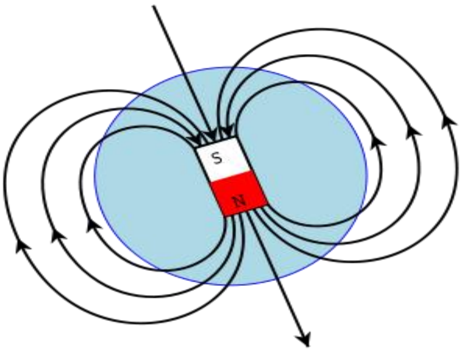

Fig (2.2) Earth's magnetic field

The figure is a sketch of Earth's magnetic field represented by field lines. For most locations, the magnetic field has a significant up/down component in addition to the north/south component. (There is also an east/west component, as Earth's magnetic and geographical poles do not coincide). The magnetic field can be visualized as a bar magnet buried deep in Earth's interior. Earth's magnetic field is not constant—the strength of the field and the location of its poles vary. Moreover, the poles periodically reverse their orientation in a process called geomagnetic reversal. The most recent reversal occurred 780,000 years ago [12].

2.6 Magnetic Force

The phenomenon of magnetism is "mediated" by the magnetic field. An electric current or magnetic dipole creates a magnetic field, and that field, in turn, imparts magnetic forces on other particles that are in the fields.

Maxwell's equations, which simplify to the Biot–Savart law in the case of steady currents, describe the origin and behavior of the fields that govern these forces. Therefore, magnetism is seen whenever electrically charged particles are in motion—for example, from movement of electrons in an electric current, or in certain cases from the orbital motion of electrons around an atom's nucleus. They also arise from "intrinsic" magnetic dipoles arising from quantum-mechanical spin. The same situations that create magnetic fields—charge moving in a current or in an atom, and intrinsic magnetic dipoles—are also the situations in which a magnetic field has an effect, creating a force. Following is the formula for moving charge; for the forces on an intrinsic dipole. When a charged particle moves through a magnetic field **B**, it feels a Lorentz force **F** given by the cross product:

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \tag{2.5}$$

Where

q is the electric charge of the particle, and
v is the velocity vector of the particle

Because this is a cross product, the force is perpendicular to both the motion of the particle and the magnetic field. It follows that the magnetic force does not work on the particle; it may change the direction of the particle's movement, but it cannot cause it to speed up or slow down. The magnitude of the force is

$$F = qvB \sin \theta \tag{2.6}$$

Where θ is the angle between **v** and **B**.

One tool for determining the direction of the velocity vector of a moving charge, the magnetic field, and the force exerted is labeling the index finger "V", the middle finger "B", and the thumb "F" with your right hand. When making a gun-like configuration, with the middle finger crossing under the index finger, the fingers represent the velocity vector, magnetic field vector, and force vector, respectively [9].

2.7 Magnetic Materials

The response of a material when subjected to an external magnetic field is the root of magnetism. The spinning electrons in the material behave like tiny magnets. These tiny magnets are aligned in the direction of applied magnetic field and thereby the material is magnetized. First let us define certain basic magnetic properties. An applied magnetic field H incites a response from a two materials called magnetic induction B. The relationship between B and H can be defined by equation:

$$B = \mu_0 H + \mu_0 I \qquad (2.7)$$

Where:
I is the magnetic moment per unit volume.
μ_0 is a constant called the permeability of free space.

There are also common terms for ratios between some of these different quantities because the magnetic properties of a material are often defined by how they vary with an applied magnetic field. So, the ratio of I to H is called the susceptibility and is indicative of the ease with which a material can be magnetized by an applied magnetic field. The susceptibility is given by:

$$\chi = I/H \qquad (2.8)$$

The ratio of B to H is called the permeability and it is the property of the material which allows magnetic lines of force (field) to penetrate the material. And permeability is given by:

$$\mu = B/H \qquad (2.9)$$

From equation (2.8) and (2.9) we can derive a relationship between the susceptibility and the permeability,

$$\mu/\mu_0 = 1 + \chi \qquad (2.10)$$

The orbital and spin motion of electrons and interaction between these electrons is the origin of magnetism. Different type's magnetic materials are due to difference in their response to external magnetic fields. Some materials are much more magnetic than others .The reason is in some materials there is a strong interaction between the atomic magnets, where as in other materials there is no interaction between the atomic magnets. Depending upon the magnetic behavior of materials, they can be classified into the following five major groups [13]:

1.Diamagnetic Substances.
2.Paramagnetic Substances.
3.Ferro Magnetic Substances.
4.Ferri Magnetic Substances.
5.Anti Ferro Magnetic Substances.

2.7.1 Diamagnetism

Diamagnetism appears in all materials, and is the tendency of a material to oppose an applied magnetic field, and therefore, to be repelled by a magnetic field. However, in a material with paramagnetic properties (that is, with a tendency to enhance an external magnetic field), the paramagnetic behavior dominates [14]. Thus, despite its universal occurrence, diamagnetic behavior is observed only in a purely diamagnetic material. In a diamagnetic material, there are no unpaired electrons, so the intrinsic electron magnetic moments cannot produce any bulk effect. In these cases, the magnetization arises from the electrons' orbital motions, which can be understood classically as follows:

When a material is put in a magnetic field, the electrons circling the nucleus will experience, in addition to their Coulomb attraction to the nucleus, a Lorentz force from the magnetic field. Depending on which direction the electron is orbiting, this force may increase the centripetal force on the electrons, pulling them in towards the nucleus, or it may decrease the force, pulling them away from the nucleus. This effect systematically increases the orbital magnetic moments that were aligned opposite the field, and decreases the ones aligned parallel to the field (in accordance with Lenz's law). This results in a small bulk magnetic moment, with an opposite direction to the applied field.

2.7.2 Paramagnetism

In a paramagnetic material there are unpaired electrons, i.e. atomic or molecular orbitals with exactly one electron in them. While paired electrons are required by the Pauli exclusion principle to have their intrinsic ('spin') magnetic moments pointing in opposite directions, causing their magnetic fields to cancel out, an unpaired electron is free to align its magnetic moment in any direction. When an external magnetic field is applied, these magnetic moments will tend to align themselves in the same direction as the applied field, thus reinforcing it.

2.7.3 Ferromagnetism

A ferromagnet, like a paramagnetic substance, has unpaired electrons. However, in addition to the electrons' intrinsic magnetic moment's tendency to be parallel to an applied field, there is also in these materials a tendency for these magnetic moments to orient parallel to each other to maintain a lowered-energy state. Thus, even in the absence of an applied field, the magnetic moments of the electrons in the material spontaneously line up parallel to one another. Every ferromagnetic substance has its own individual temperature, called the Curie temperature, or Curie point, above which it loses its ferromagnetic properties. This is because the thermal tendency to disorder overwhelms the energy-lowering due to ferromagnetic order. Ferromagnetism only occurs in a few substances; the common ones are iron, nickel, cobalt, their alloys, and some alloys of rare earth metals.

2.7.4 Antiferromagnetism

In an antiferromagnet, unlike a ferromagnet, there is a tendency for the intrinsic magnetic moments of neighboring valence electrons to point in opposite directions. When all atoms are arranged in a substance so that each neighbor is 'anti-aligned', the substance is **antiferromagnetic**. Antiferromagnets have a zero net magnetic moment, meaning no field is produced by them. Antiferromagnets are less common compared to the other types of behaviors, and are mostly observed at low temperatures. In varying temperatures, antiferromagnets can be seen to exhibit diamagnetic and ferromagnetic properties. In some materials, neighboring electrons want to point in opposite directions, but there is no geometrical arrangement in which each pair of neighbors is anti-aligned. This is called a spin glass, and is an example of geometrical frustration.

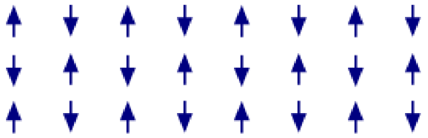

Fig (2.3) Antiferromagnetism

2.7.5 Ferrimagnetism

Like ferromagnetism, **ferrimagnets** retain their magnetization in the absence of a field. However, like antiferromagnets, neighboring pairs of electron spins tend to point in opposite directions. These two properties are not contradictory, because in the optimal geometrical arrangement, there is more magnetic moment from the sublattice of electrons that point in one direction, than from the sublattice that point in the opposite direction. Most ferrites are ferrimagnetic. The first discovered magnetic substance, magnetite, is a ferrite and was originally believed to be a ferromagnet; Louis Néel disproved this, however, after discovering ferrimagnetism [15].

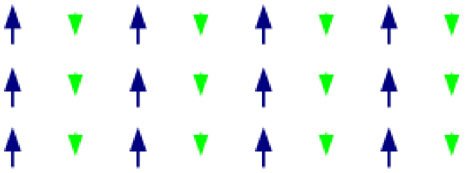

Fig (2.4) Ferrimagnetic ordering

2.8 Magnetic Properties

The magnetic has some properties is represented below.

2.8.a Magnetization and Saturation

When a magnetic field is applied to a ferromagnetic material, domains tend to align in the direction of the field by domain boundary movement and hence, the flux density or magnetization increases. As the field strength increases domains which are favorably oriented to field direction grow at the expense of the unfavorably oriented ones. All the domains are aligned to the field direction at high field strengths and the material reaches the saturation magnetization, M_s.

The initial slope of the B-H curve at H = 0 is called initial permeability, μ_i, which is a material property.

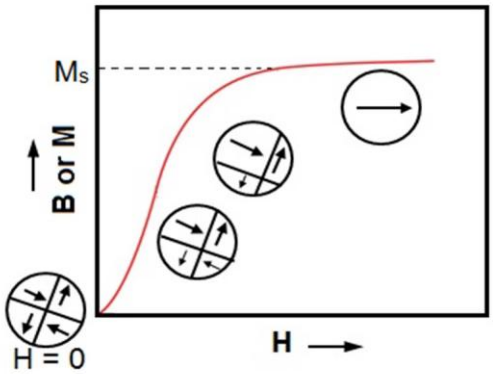

Fig (2.5) Magnetization and Saturation

2.8.b Coercivity

The progress in the twentieth century which has spawned such a range of magnetic applications can be summarized in three words – mastery of coercivity. No new ferromagnetic material has been discovered with a magnetization greater than that of 'permendur', Fe_65CO_{35}, for which Ms = 1950 kA m^{-1}, but coercivity which barely spanned two orders of magnitude in 1900, from the softest soft iron to the hardest magnet steel, now ranges over eight orders of magnitude, from less than 0.1 A m^{-1} to more than 10 MA m^{-1}[15].

2.8.c Susceptibility

At temperatures above T_C, where the ferromagnetic order collapses, and the material becomes paramagnetic, the atomic moments of a few Bohr magnetons experience random thermal fluctuations. Although Ms is zero, an applied field can induce some alignment of the atomic moments, leading to a small magnetization M which varies linearly with H, except in very large fields or very close to the Curie point. The susceptibility, defined as

$$\chi = M/H \qquad (2.11)$$

is a dimensionless quantity, which diverges as $T \rightarrow T_C$ from above. Above T_C it often follows a Curie–Weiss law

$$\chi = C/\,(T - T_C) \qquad (2.12)$$

Where C is known as the Curie constant. Its value is of order 1 K.
The magnetic response to an applied field of materials which do not order magnetically may be either paramagnetic or diamagnetic. In isotropic paramagnets, the induced magnetization **M** is in the same direction as **H**, whereas in diamagnets it is in the opposite direction. Superconductors exhibit diamagnetic hysteresis loops below their superconducting transition temperature T_{sc}, and their susceptibility can approach the limiting value of −1. The susceptibility of many paramagnets follows a Curie law,

$$\chi = C/T \qquad (2.13)$$

but for some metallic paramagnets and almost all diamagnet χ is independent of temperature. The sign of the room-temperature susceptibility is indicated on the magnetic periodic table and the molar susceptibility χ_{mol} is plotted for the elements in Fig. (2.6). There it is appropriate to look at the molar susceptibility because some of the elements are gasses at room temperature. A cubic meter of a solid contains roughly 10^5 moles, so χ_{mol} is approximately five orders of magnitude less than χ [16].

2.8.d Hysteresis

If the field is reduced from saturation by magnetic reversal, a hysteresis develops. As the field is reversed the favorably oriented domains tend to align in the new direction. When H reaches zero some of the domains still remain aligned in the previous direction giving rise to a residual magnetization called remanence, Mr. H_c, the reverse filed strength at which magnetization is zero, is called Coercivity.

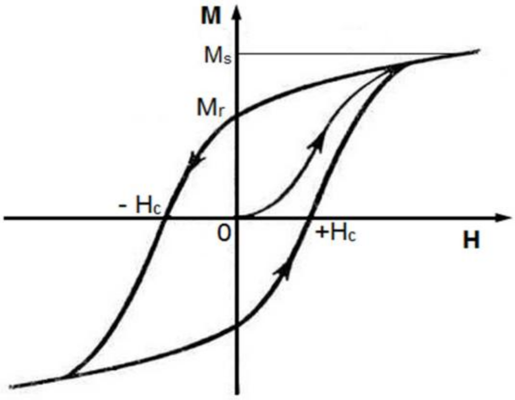

Fig (2.6) Hysteresis

2.8.e Magnetic domains

The magnetic moments of atoms in a ferromagnetic material cause them to behave something like tiny permanent magnets. They stick together and align themselves into small regions of more or less uniform alignment called magnetic domains or Weiss domains. Magnetic domains can be observed with a magnetic force microscope to reveal magnetic domain boundaries that resemble white lines in the sketch. There are many scientific experiments that can physically show magnetic fields. When a domain contains too many molecules, it becomes unstable and divides into two domains aligned in opposite directions so that they stick together more stably as shown at the right. When exposed to a magnetic field, the domain boundaries move so that the domains aligned with the magnetic field grow and dominate the structure (dotted yellow area) as shown at the left. When the magnetizing field is removed, the domains may not return to an unmagnetized state. This result in the ferromagnetic material's being magnetized, forming a permanent magnet. When magnetized strongly enough that the prevailing domain overruns all others to result in only one single domain, the material is magnetically saturated. When a magnetized ferromagnetic material is heated to the Curie point temperature, the molecules are agitated to the point that the magnetic domains lose the organization and the magnetic properties they cause cease. When the material is cooled, this domain alignment structure spontaneously returns, in a manner roughly analogous to how a liquid can freeze into a crystalline solid.

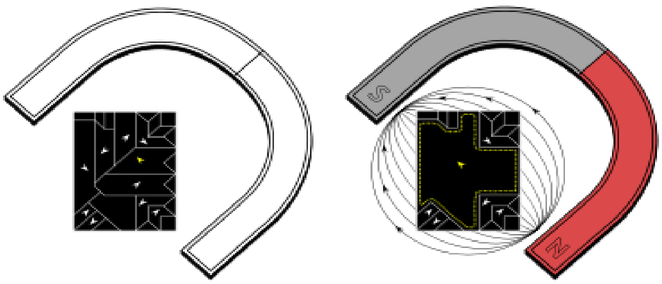

Fig (2.7) Magnetic domains Left: Magnetic domains boundaries (white lines) in ferromagnetic material (black rectangle). Right: Effect of a magnet on the domains.

2.8.f Effect of Temperature

The atomic vibration increases with increasing temperature and this leads to misalignment of magnetic moments. Above a certain temperature all the moments are misaligned and the magnetism is lost. This temperature is known as Curie temperature, T_c. Ferro and ferrimagnetic materials turn paramagnetic above Curie point.

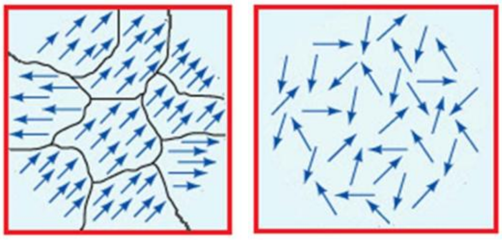

Fig (2.8) Effect of Temperature below T_c left above T_c right

2.8.g Superconductivity

Superconductivity is disappearance of electrical resistance below a certain temperature. The temperature below which superconductivity is attained is known as the critical temperature, T_C. The superconducting behavior is represented in a graphical form in the figure below.

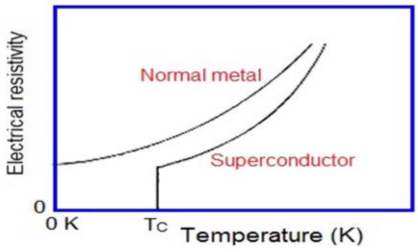

Fig (2.9) normal and superconductor metal

2.9 Magnet Applications

Magnetic materials, recording media, heads and sensors constitute a market worth over \$30 billion per year. Since the population of the Earth is approaching 7 billion, this means an average of about \$5 per head. The world's goods are unevenly distributed. The richest billion, living mainly in North America, Europe and East Asia, consume the lion's share, but most people derive some benefit from magnetic technology, whether in the form of a cassette recorder, an electric pump in a tube well or a communal mobile phone. The breakdown is by material, distinguishing hard magnets with $H_c > 400$ kA m^{-1}, soft magnets with $H_c < 10$ kA m^{-1} and magnetic recording media with intermediate values of coercivity. In this breakdown, it is easy to account for bulk permanent magnets and soft magnetic magnets which are commodities sold by the kilogram at a price depending on the grade and form. The disc and tape media used for magnetic recording incorporate a film of magnetic material on a rigid or flexible substrate. Sophisticated magnetic multilayer structures used in read/write heads for magnetic recording, magnetic sensors and magnetic random-access memory, are the first products of the spin electronic age. It is more difficult to assign a value to the magnetic constituent of a medium or a device which is composed of nonmagnetic as well as magnetic materials. The value added by the complex processing far exceeds the cost of the minuscule amounts of magnetic raw material involved. Further breakdowns are made in terms of materials and applications. In the hard magnet sector, the great bulk of production and over half the value is represented by the hard ferrites $Ba_2Fe_{12}O_{19}$ and $Sr_2Fe_{12}O_{19}$. These materials are used for colourful fridge magnets, as well as numerous motors, actuators, sensors and holding devices. Rare-earth compounds, especially $Nd_2Fe_{14}B$, are important in high-performance applications, and magnets based on Sm–Co alloys continue to be produced in smaller quantities. Hard discs generally use thin films of a Co–Pt alloy. Thin film heads for magnetic recording typically use films of Fe–Ni or Fe–Co alloys in the writer and thin film stacks comprising Fe–Co and Mn-based alloys in the reader. These are soft magnetic films with a good high-frequency response, except for the Mn alloy which is an antiferromagnet. For flexible magnetic recording media, tapes and floppy discs, acicular fine particles of Fe, or Co-doped γ -Fe_2O_3, are commonly used. Bulk soft magnetic materials are principally electrical steels. These Fe–Si alloys are produced in sheets about 300 μm thick for laminated temporary magnet cores in transformers and electrical machines. The better grades are grain-oriented with a specific crystalline texture. Soft ferrite is used for radiofrequency and microwave applications. Ferromagnetic metallic glasses, thin ribbons ($\approx$ 50 μm thick) of rapidly quenched amorphous Fe- or Co-based alloys are used in an intermediate frequency range (kHz–MHz).To put everything in context, imagine a shopping basket with the average person's worth of magnetic materials. It would include about 30 g of ferrite magnets, 1 g of rare-earth magnets, 1 m^2 of flexible recording media, an eighth of a hard disc, a quarter of a thin film head, 0.25 m^2 of electrical sheet steel, 30 g of soft ferrite and a few square centimeters of metallic glass. Perhaps 95% of the market for magnetic materials is accounted for by barely a dozen different ferromagnetic and ferrimagnetic materials. That this is only a tiny fraction of the thousands that are known to order magnetically is testimony to the difficulty of developing new materials with the right combination of properties to bring to the market. The Curie temperature, for example, must be well above the maximum operating temperature for any practical magnetic material. A typical operating temperature range is −50 to 120 ◦C, so the Curie temperature needs to be at least 500 or 600 K. The distribution of magnetic ordering temperatures in Fig. 1.8 shows that only a small fraction of all known magnetic materials meet this requirement. Nevertheless, the magnetics industry has a far wider materials base than the semiconductor industry, with its overwhelming reliance on silicon.Magnetism is a pervasive and largely unnoticed component of the technology underpinning modern life. Our electricity is generated by movement of conductors in a magnetic field. Key components of audiovisual equipment, telephones, kitchen machines and the microwave oven are magnetic. Electrical consumer goods, where something moves when you switch on, invariably involve temporary or permanent magnets. Powerful medical imaging depends on magnetic resonance. Magnetic sensors offer contactless monitoring of position or velocity. Unimaginable amounts of information are stored and retrieved from magnetic discs in computers and servers throughout the world. Some nonvolatile memory is magnetic. In 2008, consumers bought 500 million hard disk drives and over a billion permanent-magnet motors. Magnetics is the partner of electronics in the global information revolution. Ask any one of the wealthy billion how many magnets they own. A correct answer could be a couple of hundred or some billions depending on whether or not they possess a computer. On a hard disc drive every bit counts as an individually addressable magnet. Fifty years ago the answer might have been two or three [17].

Chapter Three
Applications of The Ferrite Magnet

3.1 Introduction

The term “ferrites”—from the Latin word for iron—means different things to different scientists. To metallurgists, ferrite means pure iron. To geologists, ferrites are a group of minerals based on iron oxide. To an electrical engineer, ferrites are also a group of materials based on iron oxide, but ones that have particular useful properties: magnetic properties and dielectric properties. Having magnetic properties means that a piece of ferrite will attract iron-based materials and will attract magnets of opposite polarity and repel magnets of like polarity. Magnetite, or lodestone, is a naturally occurring iron oxide that is considered a ferrite by both geologists and engineers. Over 2,000 years ago the ancient Greeks recognized the strange properties of lodestone, and almost 1,000 years ago the Chinese used it to invent the magnetic compass. Having dielectric properties means that even though electromagnetic waves can pass through ferrites, they do not readily conduct electricity. This gives them an advantage over iron, nickel, and other transition metals that have magnetic properties (“ferromagnetic”) in many applications because these metals also conduct electricity. Materials can become magnetic because each of the molecules that make up the material function have a “magnetic moment” —that is they function like a very tiny magnet. When they all line up the overall material can produce a magnetic field. In the “ferrimagnetic” ferrites—as opposed to the “ferromagnetic” metals—there is not one alignment but a distinctive arrangement of parallel and perpendicular magnetic moments. This arrangement gives them their interesting properties [18]. This effect can be achieved through several different crystal structures. Different ferrites lend themselves to different applications, as we will see. Because their magnetism depends on an orderly crystal structure, both ferromagnetic and ferrimagnetic materials can lose their magnetism if they’re heated too high or subjected to mechanical stresses Although theoretically an engineer’s ferrite could be a single crystal or a collection of crystals grown together—like the geologist’s ferrite—in practice ferrites are made from pressing together iron oxide powders under high heat. Because of this, ferrites can be put into a ceramic or rubber matrix and molded into an endless variety of sizes and shapes. Because there are different types of ferrites, different mixtures of iron oxides—with other materials added as well—can be produced with the exact desired combination electrical and magnetic properties. Ferrites, therefore, have many very important uses. Whenever a fixed magnet, as opposed to an electromagnet, is needed, ferrites are there. Certain types of electric generators and electric motors use fixed magnets, and ferrites are ideal for these applications. They are used as cores for inductors and transformers. Cassette and video tapes use ferrites coated onto the plastic base to record the signal. And many computers up to the 1970s used magnetic core memories where the cores were made of ferrite (in fact, because of their reliability, ferrite core memories were used in the Space Shuttle until 1990. Perhaps the most important use of ferrites in recent times is as a medium for transmitting microwaves. This is because some ferrites at very high frequencies (beginning above about 500 MHz, and very strongly in the microwave range of 1 to 30 GHz) exhibit a nonreciprocal effect. That means that electromagnetic waves passing through them behave differently traveling in different directions. This phenomenon allows the construction of one way transmission lines, junctions that can control the "traffic" of microwaves, and other microwave control devices. Our modern telecommunications system would not be possible without ferrites. Ferrites are a class of ferrimagnetic ceramic chemical compounds consisting of mixtures of various metal oxides, usually including iron oxides. Their general chemical formula may be written as AB_2O_4, where A and B represent different metal cations. Ferrite is a ceramic-like material with magnetic properties, which is used in many types of electronic devices [19].

3.2 Definition of Ferrite

Ferrites are explained as any of a group of nonmetallic, ceramic-like, usually ferromagnetic compounds of ferric oxide with other oxides, especially a compound characterized by extremely high electrical resistivity. A ferrite is usually described by the formula $M(Fe_xO_y)$, where M represents any metal that forms divalent bonds, such as nickel ferrite ($NiFe_2O_4$).

Ferrite may refer to [20]:

- Ferrite (iron) - iron or iron alloys with a body-centered cubic crystal structure.
- Ferrite (magnet) - ferromagnetic ceramic materials used in magnetic applications.
- Ferrite bead - components placed on the end of data cables to reduce interference.
- Calcium aluminoferrite - a mineral found in cements.
- Ferrite core - a structure on which the windings of electric transformers and other wound components are formed.

3.3 Crystal Structure

Ferrites are a class of spinels. They adopt a crystal motif consisting of cubic close-packed (FCC) oxides (O^{2-}) with a cations occupying one-eighth of the octahedral holes and B cations occupying half of the octahedral holes. The magnetic material known as "ZnFe" has the formula $ZnFe_2O_4$, with Fe^{3+} occupying the octahedral sites and half of the tetrahedral sites. The remaining tetrahedral sites in this Spinel are occupied by Zn^{2+}.

3.4 Preparation of Ferrites

Ferrites were first prepared by ceramic methods, involving milling, mixing, pressing, sintering, and finishing as basic operations, to obtain bulk materials with grains in the micrometric scale. However, as a result of the general current tendency to circuit integration and miniaturization, ferrites are prepared in the form of thick and thin films and, more recently, as nano structured materials. Ferrite thin films can be polycrystalline or epitaxial films. Major methods to obtain ferrite thin films are electroplating (or ferrite plating), magnetron sputtering (single and multi target), pulsed laser deposition [21], and molecular beam epitaxial [16]. An additional route to tuning ferrite properties for specific applications is the production of hetero structures, that is, the artificial layering of ferrites with isostructural and non-isostructural materials, such as Fe_3O_4/NiO (53), Fe_3O_4/C_oO (56), and $(Mn,Zn)Fe_2O_4/C_o\ Fe_2O_4$, and incorporating them into planar devices. The combination of ferrite layers with piezoelectric layers is leading to new and exciting applications. By reducing the scale to the nanometric size, new and technologically interesting properties have been obtained. Nanocrystalline magnetic materials have been obtained by a variety of methods, such as co precipitation, citrate precursor [22], hydrothermal [23], sonochemical [21], sol-gel [23], mechanical alloying [20], shock wave [25], reverse micelle [26], forced hydrolysis in a polyol [27], and even by using egg white as an aqueous medium [28].

3.4.1 Production

Ferrites are produced by heating an intimate mixture of powdered precursors (which are often carbonates of the metals chosen) and then pressed in a mold. During the heating process, calcinations (thermal decomposition) of carbonates occur. The general reaction of a metal carbonate (where M is the metal ion) may be written as follows:

$$MCO_3 \rightarrow MO + CO_2 \qquad (3.1)$$

For example, barium carbonate ($BaCO_3$) and strontium carbonate ($SrCO_3$) are converted to their oxides, BaO and SrO, respectively. The resultant mixture of oxides undergoes sintering (in which the solid particles adhere to one another). The cooled product is then milled to tiny particles (smaller than two micrometers (µm)), the powder is pressed into a shape, dried, and re-sintered. The shaping may be performed in an external magnetic field, to achieve a preferred orientation of the particles (anisotropy).Small and geometrically easy shapes may be produced with dry pressing. However, in such a process small particles may agglomerate and lead to poorer magnetic properties compared to the wet pressing process. Direct calcinations and sintering without re-milling is possible as well but leads to poor magnetic properties. Electromagnets are pre-sintered as well (pre-reaction), milled, and pressed[27]. However, the sintering takes place in a specific atmosphere, such as that is low in oxygen. The chemical composition and especially the structure vary strongly between the precursor and the sintered product.

3.5 General Properties

Ferrites are electrically non-conductive ferrimagnetic ceramics. They are usually mixtures of iron oxides, such as hematite (Fe_2O_3) or magnetite (Fe_3O_4), and oxides of other metals. Like most other ceramics, they are hard and brittle. In terms of their magnetic properties, they are often classified as "soft" or "hard," referring to low or high coercivity of their magnetism, respectively. Ferrites are often classified as "soft" or "hard" in terms of their magnetic properties [28]:

- Soft ferrites - used in transformer or electromagnetic cores. They have a low coercivity (manganese-zinc ferrite, nickel-zinc ferrite).
- Hard ferrites- have a high coercivity. They are cheap, and are widely used in household products such as refrigerator magnets (strontium ferrite, barium ferrite).

Soft ferrite does not retain significant magnetization, whereas hard ferrite magnetization is considered permanent. Ferrite components are pressed from a powdered precursor and then sintered (fired) in a kiln. The mechanical and electromagnetic properties of the ferrite are heavily affected by the sintering process which is time-temperature-atmosphere dependent. Ferrite shrinks when sintered. Depending on the specific ferrite, this shrinkage can range from 10% to 17% in each dimension. Maintaining correct dimensional tolerances as well as the prevention of cracking and war page related to this shrinkage are fundamental concerns of the manufacturing process.

3.5.1Soft Ferrites

Ferrites that are used in transformer or electromagnetic cores contain nickel, zinc, or manganese compounds. They have a low coercivity and are called **soft ferrites**. Because of their comparatively low losses at high frequencies, they are extensively used in the cores of Switched-Mode Power Supply (SMPS) and radio frequency (RF) transformers and inductors [29]. A common ferrite, abbreviated "MnZn," is composed of the oxides of manganese and zinc.

3.5.1.1 Materials and Geometries

As mentioned earlier, soft ferrites are a class of ferrite materials based on the spine1 or cubic crystal structure. They are produced in two material categories, manganese-zinc and nickel-zinc.

3.5.1.2 Manganese-Zinc Ferrites

This type of soft ferrite is the most common, and is used in many more applications than the nickel-zinc ferrites. Within the MnZn category a large variety of materials is possible [29].The material selection is mainly a function of the application that needs to be accommodated. The application dictates the desirable material characteristics, which in turn determines the chemical composition of the ferrite material. Manganese zinc ferrite is primarily used for frequencies less than 2 MHz. It identifies the composition which gives optimum performance for saturation flux density (Bs), low losses (Q) and high initial permeability (pi). It also identifies the Curie temperature (T,) lines for 100 and 250°C.From this composition chart, it is clear that not one composition, not one MnZn ferrite, can fulfill all design objectives.

3.5.1.3 Nickel-Zinc Ferrites

This class of soft ferrites is characterized by its high material resistivity, several orders of magnitude higher than MnZn ferrites. Because of its high resistivity NiZn ferrite is the material of choice for operating from l-2 MHz to several hundred megahertz. To cover such a wide frequency range and different applications, a large number of nickel-zinc materials have been developed over the years.It should be noted that certain nickel chemistries, especially those containing cobalt, can be adversely changed by some types of stress. Mechanical shocks from dropping or from some grinding operations are one possibility. Strong magnetic fields from holding devices and fixtures or magnetic chucks used in machining operations may also provide this stress. These resulting changes can include increasing of permeability and core loss (lowering of Q)[29]. These changes cannot be reversed by degaussing or other electric/magnetic processes. In some cases, a thermal anneal at high temperature can restore some of the initial properties. The core manufacturer can provide details for treatment appropriate to core and process.

3.5.2 Hard Ferrites

In contrast, permanent ferrite magnets (or "hard ferrites"), which have a high remanence after magnetization, are composed of iron and barium or strontium oxides. In a magnetically saturated state they conduct magnetic flux well and have a high magnetic permeability. This enables these so-called ceramic magnets to store stronger magnetic fields than iron itself. They are the most commonly used magnets in radios. The maximum magnetic field B is about 0.35 tesla and the magnetic field strength H is about 30 to 160 kilo ampere turns per meter (400 to 2000 oersteds).

The most common hard ferrites are:

- **Strontium ferrite**, $SrFe_{12}O_{19}$ ($SrO\cdot6Fe_2O_3$), used in small electric motors, micro-wave devices, recording media, magneto-optic media, telecommunication and electronic industry.
- **Barium ferrite**, $BaFe_{12}O_{19}$ ($BaO\cdot6Fe_2O_3$), a common material for permanent magnet applications. Barium ferrites are robust ceramics that are generally stable to moisture and corrosion-resistant. They are used in e.g. loudspeaker magnets and as a medium for magnetic recording, e.g. on magnetic stripe cards.
- **Cobalt ferrite**, $CoFe_2O_4$ ($CoO\cdot Fe_2O_3$), used in some media for magnetic recording.

3.5.2.1 Barium ferrite

Barium ferrite abbreviated BaFe, BaM, is the chemical compound with the formula $BaFe_2O_4$. This and related ferrite materials are components in magnetic stripe cards and loudspeaker magnets. BaFe is described as $Ba^{2+}(Fe^{3+})_2(O^{2-})_4$. The Fe^{3+} centers are ferromagnetically coupled [29]. This area of technology is usually considered to be an application of the related fields of materials science and solid state chemistry. Barium ferrite (BaFe) is a highly magnetic material, has a high packing density, and is a metal oxide. It has been used regularly in studies dating as far back as 1931. however has found popularity recently with its use in magnetic card strips, speakers, and magnetic tapes. One area in particular it has found success in is long-term data storage; material is magnetic and resistant to temperature, corrosion, and oxidization. Barium comes from the Greek word barys, which means "heavy". Iron (Fe) was originally called ferrum, which is a Latin name meaning "holy metal". The word "iron" comes from the Anglo-Saxon word Iren.

3.5.2.1.1 Chemical structure

The Fe^{3+} centers, with a high-spin d^5 configuration, are ferromagnetically coupled. This area of technology is usually considered to be an application of the related fields of materials science and solid state chemistry. A related family of industrially useful “hexagonal ferrites” is known, also containing barium. In contrast to the usual Spinel structure, these materials feature hexagonal close-packed framework of oxides. Furthermore, some the oxygen centers are replaced by Ba^{2+} ions. Formulas for these species include $BaFe_{12}O_{19}$, $BaFe_{15}O_{23}$, and $BaFe_{18}O_{27}$. Thus, $BaFe_{12}O_{19}$ is related to $Fe_{12}O_{20}$, with the empirical formula Fe_3O_4, i.e. magnetite [30].

3.5.2.1.2 Properties of Hard Ferrites

Recent development has focused on the use of Barium Ferrite as a long term data storage option. The material has proven to be resistant to a number of different environmental stresses, including humidity and corrosion. Because Ferrites are already oxidized it cannot be oxidized any further. This is one reason Ferrites are so resistant to corrosion [30]. Barium ferrite also proved to be resistant to thermal demagnetization, another issue common with long term storage [31]. When Barium Ferrite magnets increase in temperature, their high intrinsic coercivity improves, this is what makes it more resistant to thermal demagnetization. Ferrite magnets are the only type of magnets that actually become noticeably more resistant to demagnetization when they get hotter. This characteristic of Barium Ferrite makes it a popular choice in motor and generator designs and also in loudspeaker applications. Ferrite magnets can be used in temperatures up to 300 degrees C, which makes it a perfect to be used in the applications mentioned above. Ferrite magnets are extremely good insulators and don't allow any electrical current to flow through them and they are brittle which shows their ceramic characteristics. Ferrite magnets also have good machining properties, which allows for the material to be cut in many shapes and sizes [31]. Barium ferrites are robust ceramics that are generally stable to moisture and corrosion-resistant [30]. BaFe is also an oxide so it does not break down due to oxidation as much as a metal alloy might; giving BaFe a much greater life expectancy [27].

3.5.2.1.3 Mechanical Properties

Metal particles (MP) have been used to store data on tapes and magnetic strips but they have reached their limit for high capacity data storage. In order to increase their capacity by (25x) on data tape the MP had to increase the tape length by (45%) and track density by over (500%) which made it necessary to reduce the size of the individual particles. As the particles where reduced in size the pass ivizing coating needed to prevent the oxidation and deterioration of the MP had to become thicker. This presented a problem for as the passivation coating got thicker it became harder to achieve an acceptable signal to noise ratio. Barium ferrite completely out classes MP, mostly because BaFe is already in its oxidized state and so is not restricted in its size by a protective coating. Also due to its hexagonal pattern it is easier to organize compared to the unorganized rod like MP. Another factor is the difference in the size of the particles, in MP the size ranges from 40-100 nm while the BaFe is only 20 nm. So the smallest MP particle is still double the size of the BaFe particles [32].

3.6 Characteristics of Ferrite Magnets

Ferrite permanent magnets have good machining properties which allows them to be cut into different shapes and sizes - they are cut with diamond tooling; standard drills and wire spark erosion techniques do not work (they are electrically insulating so current does not pass through them due to their extremely high electrical resistance, hence their other name of Ceramic Magnets). Ferrite magnets are made by wet or dry pressing and sometimes by extrusion. Wet pressing gives stronger magnetic properties (e.g. Ferrite C_8). Dry pressing gives improved dimensional tolerances (e.g. Ferrite C_5). The magnets are then sintered to fuse the powder together and are then machined to final shape [30]. The extrusion method can be applied to produce arc segment shapes which are then cut to length. Sometimes new tooling is required to produce the ferrite magnets if existing tooling does not allow the shape to be produced. Typical tolerances for ferrite magnets are +/-0.25mm although +/-3% are also used. When Ferrite magnets get hotter, their high intrinsic coercivity actually improves (improving resistance to demagnetization) making them extremely popular in motor and generator designs and also in loudspeaker applications (only ferrite magnets become noticeably more resistant to demagnetization when heated). Ferrite magnets have a positive temperature coefficient of Intrinsic Coercivity (it changes by +0.27 %/deg C from ambient) and only ferrite shows this amount of this characteristic. However the magnetic output does fall with temperature (it has a negative temperature coefficient of Induction of -0.2 %/degC from ambient). The end result is that Ferrite magnets (ceramic magnets) can be used at high temperature with very few issues. Ferrite magnets can be used up to +250 degrees C (and in some cases up to +300 deg C) making it ideal for use in electrical machines and most high temperature applications. At sub-zero temperatures e.g. less than -10 to -20 deg C, ferrite magnets may start to show a reduced pull force (the temperature and the degree of weakening depends on the magnet shape and is application specific; in most applications the temperature of operation is not low enough for this effect to happen). This is because if its +0.27 %/deg C temperature coefficient of Intrinsic Coercivity - the H_{ci} falls as the magnet gets colder. Ferrite can demagnetize if put in too cold an environment but it is the total magnetic circuit design that determines how cold the magnet must be before any weakening is noted (e.g. operating at temperatures as low as -60 deg C is possible with careful design) [31,32]. The ferrite grades have physical properties which are similar between the grades. Below is an overview of these properties:-

Table (3.1): Summary of Physical Properties of Ferrite magnets / Ceramic magnets

Characteristic	Symbol	Unit	Value
Density	D	g/cc	4.9 – 5.1
Vickers Hardness	Hv	D.P.N	400 - 700
Compression Strength	C.S	N/mm^2	680 - 720
Coefficient of Thermal Expansion	C//	10-6/°C	15
	C^	10-6/°C	10
Electrical Resistance	R	micro Ω.cm	1 x 10^{10}
Thermal Conductivity	k	w/cm°C	0.029
Tensile Strength	σUTS, *or* SU	Pa	34 x 10^6
Modulus of Elasticity		Pa	1.8 x 10^{11}
Flexural Strength	σ	Pa	62 x 10^6
Compression Strength	C.S.	Pa	895 x 10^6
Hardness		Mohs	7
Poisson's Ratio	v		0.28
Curie Temperature	Tc	°C	450

Table (3.2) Temperature Characteristics of Ferrite Magnets

MAGNET	Rev.Temp.Coef. of Induction (Br), a, %/°C (20-100°C)	Rev.Temp.Coef. of Coercivity (Hci), b, %/°C (20-100°C)	Max. Working Temperature
			(based on High working point)
Ferrite	-0.2	+0.27	300 ºC = 572 ºF

3.6.1 Structural Use of Ferrite / Ceramic Magnets

There is a risk of chipping or breaking the magnets because all magnets are inherently brittle. It is advised to not put magnets in conditions of mechanical stress e.g. in load bearing situations. Like all magnets, because ferrite is brittle it should not be exposed to high compressive forces.

3.6.2 Ferrite / Ceramic Magnets and Corrosion Resistance

Because the material within the magnet material is already in oxide forms, it cannot be oxidized further. Therefore ferrite / ceramic magnet have superb corrosion resistance. Water and salt water have no effect at all on ferrite magnets – they simply will not rust (in simplified terms, ferrite magnets contains iron oxide, which is what rust is) [33, 34].

3.7 Other Types of Ferrites

3.7.1. Spinels

Spinel ferrites possess the crystal structure of the natural spinel $MgAl_2O_4$, first determined by Bragg [35]. This structure is particularly stable, since there is an extremely large variety of oxides which adopt it, fulfilling the conditions of overall cation-to-anion ratio of 3/4, a total cation valency of 8, and relatively small cation radii. Spinel structure is shown in Figure (3. 1) Cation valency combinations known are 2, 3 (as in $Ni^{2+}Fe_3^{+2}O_4$); 2, 4 (as in CO_2GeO_4); 1, 3, 4 (as in $LiFeTiO_4$); 1, 3 (as in $Li_{0.5}Fe_{2.5}O_4$); 1, 2, 5 (as in $LiNiVO_4$); 1, 6 (as in Na_2WO_4). In ferrites with applications as magnetic materials, Al^{3+} has usually been substituted by Fe^{3+}. An important ferrite is magnetite, $Fe^{2+}Fe^{3+}2O_4$ (typically referred as Fe_3O_4), probably the oldest magnetic solid with practical applications and currently a very active research field, due to the fascinating properties associated with the coexistence of ferrous and ferric cations. Another important material by its structure, as well as by its applications in audio recording media, is magnetite or γ-Fe_2O_3, which can be considered as a defective Spinel ɤO_4, where ɤ represents vacancies on cation sites.

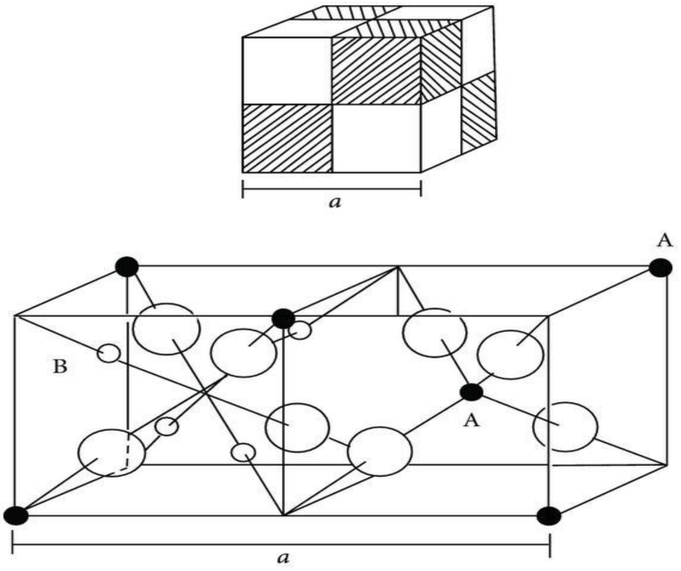

Figure (3.1): The unit cell of the Spinel structure, divided into octants to show the tetrahedral (small, black spheres A) and octahedral (small white spheres B) sites. Oxygen's are the large white spheres [32].

The overall symmetry of oxygen's is fcc (face centered cubic), which defines two types of interstitial sites: 64 tetrahedral sites and 32 octahedral sites, for a unit cell containing 8 times the basic formula AB_2O_4. Only one-eighth of tetrahedral sites and half of octahedral sites are occupied by cations. The space group is Fd3m.In $MgAl_2O_4$, Al and Mg cations occupy the octahedral and tetrahedral sites, respectively. This cation distribution, known as a normal Spinel, is usually indicated as $(Mg)[Al_2]O_4$; that is, square brackets contain the octahedral sites occupancy ("B" sites), while parenthesis show the cations in tetrahedral sites ("A" sites). A radically different cation distribution, where half of trivalent cations (denoted by T^{3+}) occupy A sites and B sites are shared by divalent cations (denoted by D^{2+}) and the remaining trivalent cations $(T^{3+})[T^{3+}D^{2+})O_4$, is known as the inverse Spinel. An intermediate cation distribution can be expressed as $(D_{1-\delta}\ T_{\delta})\ [D\delta T_{2-\delta}]O_4$, where δ is the degree of inversion. In many intermediate Spinel, δ depends on the preparation technique and, more specifically, on the cooling rate after sintering or annealing [37]. A remarkable characteristic of Spinel structure is that it is able to form an extremely wide variety of total solid solutions. This means that the composition of a given ferrite can be strongly modified, while the basic crystalline structure remains the same. An example is the Zn-Ni system, with general formula $Zn_xNi_{1-x}Fe_2O_4$, where $0 \leq x \leq 1$. In the present example, the end compositions $NiFe_2O_4$ (for x = 0) and $ZnFe_2O_4$ (x = 1) can be obtained. $NiFe_2O_4$ is an inverse Spinel: in contrast, $ZnFe_2O_4$ is a normal Spinel. The properties of these compounds are very different: Ni ferrite is ferrimagnetic with a Curie temperature ≈858 K, while Zn ferrite is antiferromagnetic, with a Néel temperature about 9 K. This means that the general properties of the ferrite can be easily "tailored" just by varying the composition.

Table (3.3): Some cations forming Spinel solid solutions.

1+	2+	3+	4+
Li	Mg	Al	Ti
Cu	Ca	Ti	V
Ag	Mn	V	Mn
	Fe	Cr	Ge
	Ni	Fe	
	Cu	Ga	
	Zn	Rh	
	Cd	In	

The cation distribution in Spinel was an interesting problem for some time; currently, it has been established that it depends essentially on various factors. First the elastic energy (the lattice deformation produced by cation radii differences) has to be considered. It refers to the degree of distortion of the crystal structure, as a result of differences in dimensions of the several cations within the specific Spinel. In principle, small cations should occupy the smallest sites (tetrahedral sites), while larger cations should locate on the larger octahedral sites. However, trivalent cations are generally smaller than divalent ones, leading to some tendency to the inverse structure. The next factor to be considered is electrostatic energy (Madelung energy), which has to do with the electrical charge distribution. In a simple way, cations with high electrical charge should occupy the sites with larger coordination number (octahedral), and cations with smaller valency should be more stable when occupying the tetrahedral sites. The crystal field stabilization energy comes next to account for cation site "preference." This energy has to do with the geometry of d orbitals and the arrangements these orbitals can established within the crystal structure [38, 39]. The five d orbitals no longer have the same energy but are split according to the electric field distribution established by anions on the particular crystal site. The physical basis for these differences in energy is simply the electrostatic repulsion between the electrons and the orbitals of the surrounding p orbitals of anions.

Since bonding in most ferrites has an ionic character, cations are surrounded by anions, and conversely anions have cations as nearest neighbors. Magnetic ordering in ferrites (as in many oxides) tends to form antiferromagnetic arrangements, as interactions between cations have to be established through the anions. However, in most cases a resulting magnetic moment remains due to the fact that magnetic lattices contain different numbers of cations. In the case of Spinel, the magnetic structure can be inferred from a small part of the structure, as shown in Figure (3.2) Super exchange interactions can then be schematized as a triangular arrangement. The strongest interactions are AOB, which occur between tetrahedral and octahedral cations, followed by BOB (cations on neighboring octahedral sites).

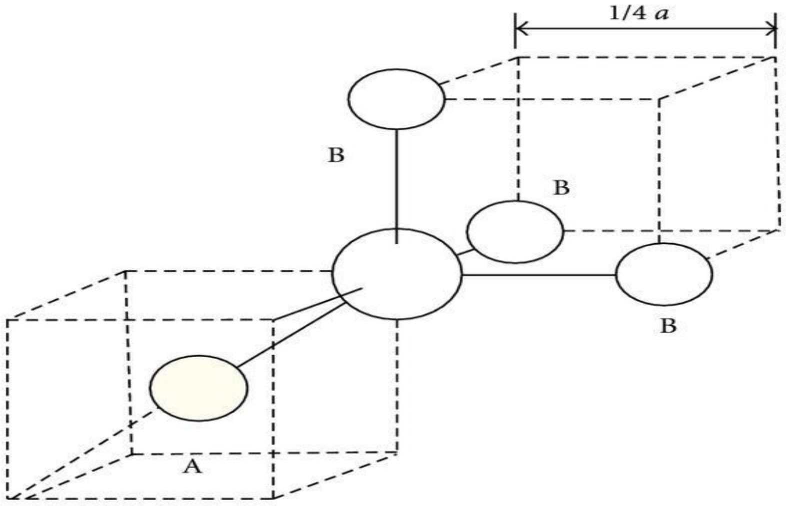

Figure (3.2): Detail of the A and B sites around an oxygen, to show AB and BB interactions.

The relative strength of these interactions can be illustrated by the Curie temperature of Li and Zn ferrites (both Li and Zn are paramagnetic cations). $Li_{0.5} Fe_{2.5} O_4$ is an inverse Spinel, with a cation distribution that can be expressed as $Fe [Li_{0.5} Fe_{1.5}] O_4$, while Zn ferrite is a normal Spinel, $(Zn)[Fe_2]O_4$. Iron ions have an antiparallel order in both ferrites, but as they both occupy octahedral sites, they compensate completely in Zn ferrite [40,41,42]. In the case of Li ferrite, they have also an antiparallel order, but they belong to different sublattices, with different number. As a result, Zn ferrite is anti-ferromagnetic (with zero resulting magnetization), and Li ferrite is ferromagnetic, with a magnetization (per formula unit) of about 0.5 Bohr magneton (close to 0 K). The strength of interactions is apparent in the transition temperatures: the Curie point for Li ferrite is the highest observed in Spinel 958 K, while Néel temperature for Zn ferrite is the lowest in Spinel 9 K. An interesting system is $Zn_xNi_{1-x} Fe_2O_4$, which is normal for Zn and inverse for Ni. The general site occupancy can be expressed as: $(Zn_xFe_{1-x})[Ni_{1-x} Fe_{1+x}]O_4$. The composition varies from Ni ferrite (x = 0) to Zn ferrite (x = 1). Starting with Ni ferrite, the decrease in occurs as if Zn entering in A sites "push" Fe toward B sites, filling the octahedral sites left by the decreasing Ni ions. As in all inverse ferrites, the low-temperature global magnetization depends on the divalent cation (as Fe ions are antiparallel). The presence of Zn decreases the magnetization in A sublattice and increases the B sublattices. The addition of a paramagnetic cation thus leads to an increase in total magnetization. However, as Zn increases in A sites, AOB interaction weakens, and for , BOB interaction is comparable to AOB interaction leading to a triangular structure (known as Yafet-Kittel [42]).The Curie temperature shows also a large variation with composition for ZnNi ferrites, = 858 K for x = 0 (Ni ferrite), and as mentioned above, Zn ferrite is antiferromagnetic, with = 9 K.

3.7.2 Garnets

The crystal structure is that of the garnet mineral, $Mn_3Al_2Si_3O_{12}$. The magnetic garnets include Fe^{3+} instead of Al and Si, and a rare earth cation (R) substitutes Mn, to give the general formula $R_3Fe_5O_{12}$ for ferromagnetic garnets [44, 45]. The crystal structure has cubic symmetry and is relatively complex; the unit cell has 8 formula units (160 atoms) and belongs to the space group -Ia3d. In contrast with Spinel, the oxygen sublattice is not a close-packed arrangement, but it is better described as a polyhedra combination. Three kinds of cation sites exist in this structure: dodecahedral (eightfold), octahedral (sixfold), and tetrahedral (fourfold) sites. Rare earth cations, R, occupy the largest, dodecahedral sites, while Fe^{3+} cations distribute among the tetra- and octahedral places. The cation distribution is generally expressed as $(Fe_3)[Fe_2]O_{12}$; bracket denotes dodecahedral sites, parenthesis are used for tetrahedral site occupancy, and octahedral sites are indicated by square brackets . Rare earth cations (from La^{3+} to Lu^{3+}) enter the dodecahedral sites, and as Spinel, garnets can form total solid solutions. A wide variety of cation substitutions has been reported [43]. Yttrium iron garnet, $Y_3Fe_5O_{12}$ also known as "YIG," has remarkable magnetic properties. The magnetic structure of garnets can be described by three magnetic sublattices, with a super exchange interaction through oxygen's. Dodecahedral and octahedral ions are parallel, while tetrahedral cations adopt an antiparallel orientation. At very low temperatures, global magnetization (per formula unit) is roughly (3 μR-μFe), where μR and μFe are the rare earth and the iron magnetic moments, respectively. The differences in thermal behavior among the three sublattices lead to the compensation of magnetic moments. As temperature increases, the magnetization in each sublattice is affected by the thermal agitation and decreases. This reduction in magnetization is slow in iron sublattices, but, due to its larger size, the decrease is quite steeply in the dodecahedral sublattice. At a certain temperature, the reduction in magnetization in rare earth sublattice exactly compensates the difference between octal- and tetrahedral sublattice, and global magnetization exhibits a zero value. For GdIG, this temperature is 300 K. The fact that magnetic structure is dominated by iron sublattices can also be observed in the Curie temperature: virtually all iron garnets show the same transition point (~560 K).

3.7.3 Hexaferrites

All of hexagonal ferrites are synthetic; barium hexaferrite ($BaFe_{12}O_{19}$) possesses the same structure as the natural mineral magnetoplumbite, of approximate formula $PbFe_{7.5} Mn_{3.5} A_{l0.5} Ti_{0.5} O_{19}$. Rather than sharing a common crystal structure, hexaferrites are a family of related compounds with hexagonal and rhombohedral symmetry. The main compositions can be represented in the upper section of the MeO-Fe$_2$O $^{3-}$BaO ternary phase diagram. Me is a divalent cation such as Ni, Mg, CO, Fe, Zn, Cu, for instance. All the magnetic hexaferrites are found on the BaFe$_{12}$O$_{19}$ Me$_2$Fe$_4$O$_8$ and BaFe$_{12}$O $_{19}$Me$_2$BaFe$_{12}$O$_{22}$ joins (Figure 3.8.3.2). If the end members are designated as M (BaFe$_{12}$O$_{19}$), S (Me$_2$Fe$_4$O$_8$), and Y (Me$_2$BaFe$_{12}$O$_{22}$); the joins are M-S and M-Y, respectively. Some of the main compositions are found in Table (3.4).

Table (3.4): Formulae of some hexaferrites and their formation from end members of the ternary phase diagram.

Designation	Formula
M	$BaFe_{12}O_{19}$
Y	$Ba_2Me_2Fe_{12}O_{22}$
W (MS)	$BaMe_2Fe_{16}O_{27}$
X (M2S)	$Ba_2Me_2Fe_{28}O_{46}$
U (M2Y)	$Ba_4Me_2Fe_{36}O_{60}$
Z (M2Y2)	$Ba_6Me_4Fe_{48}O_{82}$

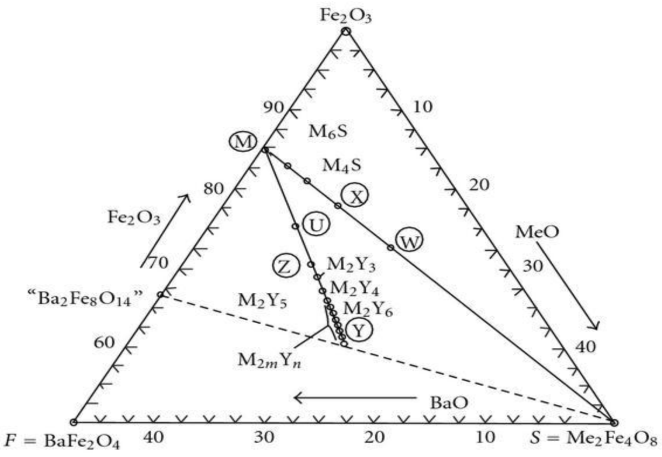

Figure (3.3): Upper triangle of the Fe$_2$O$_3$-BaO-MeO phase diagram showing the several compositions of hexaferrites .

Hexaferrites can also form an extensive variety of solid solutions. Ba can be substituted by Sr, Ca, and Pb. Fe $^{3+}$ can be substituted by trivalent cations such as Al, Ga, In, Sc [8], or by a combination of divalent + tetravalent cations, such as CO $^{2+}$ + Ti $^{4+}$. A more complete account of these solid solutions can be found in [47].The magnetic structure in hexaferrites is complex, as a consequence of their complex crystal structure. In BaFe$_{12}$O$_{19}$, iron ions occupy five different sublattices, with a total magnetization 20 μB per formula unit, at low. The most interesting feature of hexaferrites is their high coercivity.

3.8 Uses of Ferrite

The applications of ferromagnetic oxides, or ferrites, in the last 10 years are reviewed, including thin films and nanoparticles. The general features of the three basic crystal systems and their magnetic structures are briefly discussed, followed by the most interesting applications in electronic circuits as inductors, in high-frequency systems, in power delivering devices, in electromagnetic interference suppression, and in biotechnology. As the field is considerably large, an effort has been made to include the original references discussing each particular application on a more detailed manner. Ferrites are a large class of oxides with remarkable magnetic properties, which have been investigated and applied during the last ~50 years [52, 53]. Their applications encompass an impressive range extending from millimeter wave integrated circuitry to power handling, simple permanent magnets, and magnetic recording. These applications are based upon the very basic properties of ferrites: a significant saturation magnetization, a high electrical resistivity, low electrical losses, and a very good chemical stability. Ferrites can be obtained in three different crystal systems by many methods, and the feasibility to prepare a virtually unlimited number of solid solutions opens the means to tailor their properties for many applications. For many applications, ferrites cannot be substituted by ferromagnetic metals; for other, ferrites often compete with metals on economic reasons. The possibility of preparing ferrites in the form of nanoparticles has opened a new and exciting research field, with revolutionary applications not only in the electronic technology but also in the field of biotechnology. Ferrite cores are used in electronic inductors, transformers, and electromagnets, where the high electrical resistance of the ferrite leads to very low eddy current losses. They are commonly seen as a lump in a computer cable, called a **ferrite bead**, which helps prevent high-frequency electrical noise (radio frequency interference) from exiting or entering the equipment. Early computer memories stored data in the residual magnetic fields of hard ferrite cores, which were assembled into arrays of core memory. Ferrite powders are used in the coatings of magnetic recording tapes. One such type of material is iron (III) oxide. Ferrite particles are also used as a component of radar-absorbing materials or coatings used in stealth aircraft and in the expensive absorption tiles lining the rooms used for electromagnetic compatibility measurements. Most common radio magnets, including those used in loudspeakers, are ferrite magnets. Ferrite magnets have largely displaced Alnico magnets in these applications. It is a common magnetic material for electromagnetic instrument pickups, because of price and relatively high output. However, such pickups lack certain sonic qualities found in other pickups, such as those that use Alnico alloys or more sophisticated magnets [54, 55].

- Permanent magnets.
- Ferrite cores for transformers and toroidal inductors.

- Computer memory elements.
- Solid-state devices.

Ferrites are composed of iron oxide and one or more other metals in chemical combination and their properties include:

- Hard.
- Brittle.
- Iron-containing.
- Polycrystalline.
- Generally gray or black.

Ferrite is also known as ferrate.

Properties of ferrites include:

- Significant saturation magnetization.
- High electrical resistivity.
- Low electrical losses.
- Very good chemical stability.

3.9 Other Applications of Ferrites

The ferrites have some application below that:

3.9. 1 Inductors

Ferrites are primarily used as inductive components in a large variety of electronic circuits such as low-noise amplifiers, filters, voltage-controlled oscillators, impedance matching networks, for instance. Their recent applications as inductors obey, among other tendencies, to the general trend of miniaturization and integration as ferrite multilayers for passive functional electronic devices. The multilayer technology has become a key technology for mass production of integrated devices; multilayers allow a high degree of integration density. Multilayer capacitors penetrated the market a few decades ago, while inductors started in the 1980s. The basic components to produce the inductance are a very soft ferrite and a metallic coil [56].

In addition, to provide a high permeability at the operation frequency, the ferrite film should be prepared by a process compatible with the integrated circuit manufacturing process. Sputtering provides films with high density, but the composition is sometimes difficult to control with accuracy, and the annealing processes can attain high temperatures. Pulsed laser deposition leads to high-quality films; however, a method involving the preparation of the ferrite film by a combination of sol-gel and spin-coating seems easier and with a lower cost [57].Layered samples of ferrites with piezoelectric oxides can lead to a new generation of magnetic field sensors. The basis of their performance is the capability of converting magnetic fields into electrical voltages by a two-step process. First, the magnetic field produces a mechanical strain on the magnetic material (due to its magneto striction); this strain then induces a voltage in the piezoelectric layer. These sensors can provide a high sensitivity, miniature size, and virtually zero power consumption. Sensors for ac and dc magnetic fields, ac and dc electric currents, can be fabricated. Sensors based on nickel ferrite ($Ni_{1-x}Zn_xFe_2O_4$ with x = 1–0.5)/lead zirconate-titanate ($PbZr_{0.52}Ti_{0.48}O_3$) have shown an excellent performance [59,60]. Both ferrite and zirconate-titanate films are prepared by tape casting; typically, 11 ferrite layers were combined with 10 piezoelectric layers (both layers 18 µm thick, $3 \times 6\ mm^2$ area).

3.9.2 High Frequency

There has been an increasing demand of magnetic materials for high-frequency applications such as telecommunications and radar systems, as microwave technology requires higher frequencies and bandwidths up to 100 GHz. Ferrites are nonconducting oxides and therefore allow total penetration of electromagnetic fields, in contrast with metals, where the skin effect severely limits the penetration of high-frequency fields [61]. At such frequencies, domain walls are unable to follow the fields (dispersion of domain walls typically occurs about 10 GHz), and absorption of microwave power takes place by spin dynamics. The usual geometry is to align spins first with a DC magnetic field H and apply the microwave field perpendicular to. The spins process around their equilibrium orientation at the frequency of the microwave field. The classical description of this dynamics is the Landau-Lifshitz equation [62] of motion, which can be written in its undamped form:

$$\frac{dM}{dt} = \gamma MXH_j \qquad (3.\ 2)$$

Where M is the magnetization, γ is the gyromagnetic ratio (ratio of mechanical to magnetic moment, and $\gamma = ge/2mc = 2.8$ MHz/G), is the total internal field acting upon the spin. The magnetization and the field terms can be separated in the static and time-dependent parts as:

$$H = H_i + he^{iwt}, M = M_s + me^{i\omega t} \qquad (3.3)$$

These equations show a singularity at

$$\omega = \omega_0 = \gamma H_0 \qquad (3.4)$$

is the total field on the spins (external and internal); Recent results obtained in a Ni-Zn ferrite. Equation (3.4) expresses the ferromagnetic resonance (FMR) conditions and is known as the Larmor equation. FMR is associated with the uniform (in phase) precession of spins. The upper limit of applications of ferrites is FMR, since the interaction with the microwave field becomes negligible as ω > . Spinels are therefore applied at frequencies up to 30 GHz, while this limit is about 10 GHz for garnets and can attain 100 GHz for hexaferrites. The absorption of microwaves by ferrites involves losses; a damping or relaxation term is normally added to port (3). In polycrystalline ferrites, losses are associated with defects and the anisotropy field distribution, and with electrical conduction a common problem, especially in spinels, is the presence of Fe $^{2+}$, which promotes a hopping conduction process in combination with Fe $^{3+}$. The physical origin of losses in polycrystalline ferrites, through its effects on the line width, has been recently investigated in detail; the dominant role of grain boundaries is apparent [64, 65].Some of ferrite applications rely on the fact that the spin rotation depends on the orientation of the external field, which allows the control of the interaction with the microwave field. For one direction of the field, the ferrite transmits the microwave field; for the opposite, it strongly absorbs it. This is the basis of nonreciprocal devices.

Typical devices are circulators, isolators, phase shifters, and antennas. Circulators were developed for radar systems and are now used in mobile phones. They allow the use of the same device for transmission and reception of the response signal. As shown schematically in Figure (3.4), any signal entering through port 1 exits by port 2, with no connection with port 3. If the generator is connected to port 1 and the antenna to port 2, this is the path of the outgoing signal. The incoming signal enters through port 2 (the antenna) and is directed to port 3, to the receiver. This allows the handling of a strong outgoing signal (ports 1-2) together with a very sensitive detector (ports 2-3), with no risk of damaging the receiver and using the same antenna. Circulators are usually fabricated with garnets.

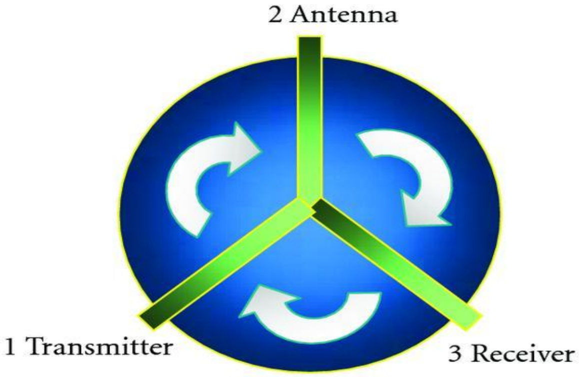

Figure (3.4): Schematic representation of a circulator.

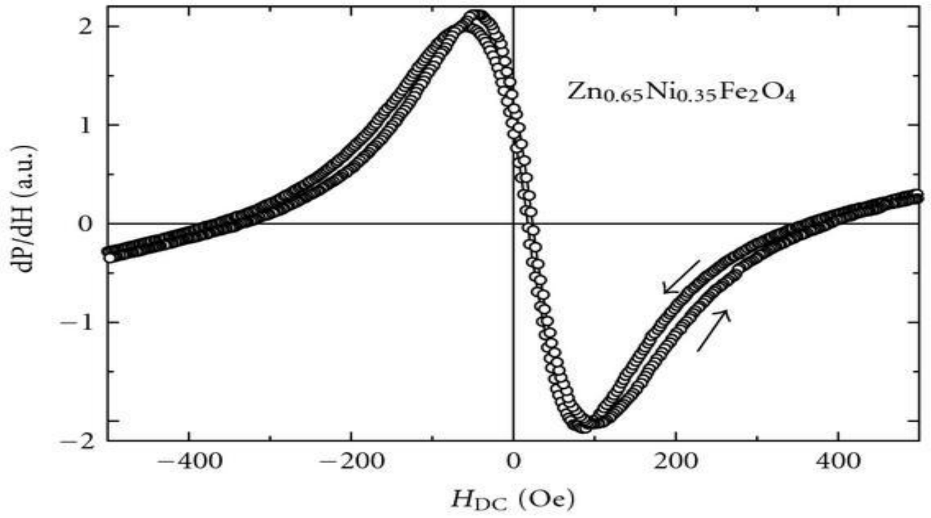

Figure (3.5): Low- field microwave absorption (LFA) of a Ni-Zn ferrite at 9.4 GHz room temperature and room temperature. A small hysteresis is observed for increasing and decreasing applied field.

Recently, a non resonant absorption of microwave power at very low magnetic fields has been receiving attention. This absorption, known as LFA (for low-field microwave Absorption), has shown to be clearly dominated by the anisotropy field, of the ferro- or ferrimagnetic material [65]. In many respects, this absorption is similar to giant magneto impedance, GMI [66], that is, the change in electric impedance of a material when subjected to a DC magnetic field [67]. A significant difference with GMI is that LFA does not need that the electrical conductivity of the sample be of metallic type. No practical applications of LFA have been proposed, so far; however, it is possible to expect that similar applications to GMI can be made (sensors for magnetic field, DC electric current, mechanical stress, etc.), with the additional advantages over classic GMI of high frequencies and insulator magnetic materials.

3.9.3 Power

Power applications of ferrites are dominated by the power supplies for a large variety of devices such as computers, all kinds of peripherals, TV and video systems, and all types of small and medium instruments. The main application is in the systems known as switched-mode power supplies (SMPSs). In this application, the mains power signal is first rectified it is then switched as regular pulses (typically rectangular) at a high frequency to feed into a ferrite transformer, and finally it is rectified again to provide the required power to the instrument. An increase in power delivery and efficiency can be obtained by increasing the working frequency of the transformer.A recent approach to increase efficiency of the ferrite cores is based on the decrease of eddy currents, by increasing resistivity. Beside the use of non conducting additives that locate preferentially on grain boundaries (and limit the intergrain conductivity), MnZn and NiZn are combined as $Mn_xNi_{0.5-x}Zn_{0.5}Fe_2O_4$ and obtained through a citrate precursor method [68].An additional difficulty appears in the case of power applications at high temperature, as is the case of some automotive power devices. Due to the closeness to the car engine, the working temperature increases from the usual 80–100°C for standard applications, to 140°C. A proposed solution involves the modification of the MnZn ferrites (used previously for these applications) in order to produce a higher fraction of Fe^{2+} [69], such as $(Mn_{0.76}Zn_{0.17})Fe_2O_4$. This ferrous concentration presents a minimum in the magneto crystalline anisotropy close to 140°C, and therefore, a minimum in losses appears at this temperature. The change is obtained through a careful control of the oxidation atmosphere during sintering and cooling. As in all other applications, a strong need for miniaturization has also marked the developments in this area in the last few years. In addition to standard methods to obtain ferrite thin films (such as sputtering, laser ablation, sol-gel), screen or stencil printed ceramic-polymer composites have been investigated [70], combining the remarkable magnetic properties of ferrites with the process ability of polymer thick films. These polymer thick films can be cured at temperatures about 200°C or less, leaving only the polymer binder and the ferrite filler. This technique allows the fabrication of highly integrated power circuits. The coil is obtained by patterning copper on a flexible polyimide substrate; the ferrite-polymer composite film is then printed above and below the plane of the coil. The magnetic ceramic filler is formed by MnZn ferrite particles about 10 μm, obtained by a standard method. The inductance value remains stable up to 124 MHz.A different method based on a batch-fabrication method of 3D transformers and inductors has also been proposed [71]. The magnetic core is made of two half magnetic pieces and a printed circuit board (or flexi foil) carrying the electric windings around the core. The 3D ferrite cores are micro structured out of a 1 mm thick ferrite wafer using a newly developed batch-type micro powder blasting process [72]. These transformers are well suited for low-power applications at working frequencies up to 1 MHz.

Losses in ferrites depend essentially on hysteresis loss at low frequencies, conductivity (or eddy current) loss, and relaxation-resonance loss at high frequencies; their modeling is complex. A model based on the Preisach theory [73] has been applied to predict the hysteretic behavior of soft ferrites for applications in power electronics [74], with good results at low frequencies. On the other hand, by using a network model based on the total energy loss (not only hysteresis loss), a good agreement with experimental results for power, signal, and electromagnetic interference has been found [75]. The approach offers a mechanism for the inclusion of parameters such as temperature or stress variations.

3.9.4 Electromagnetic Interference (EMI) Suppression

The significant increase in the amount of electronic equipment such as high-speed digital interfaces in notebooks and computers, digital cameras, scanners, and so forth, in small areas, has seriously enhanced the possibility of disturbing each other by electromagnetic interference (EMI). In particular, the fast development of wireless communications has led to interference induced by electric and magnetic fields. Electromagnetic interference can be defined as the degradation in performance of an electronic system caused by an electromagnetic disturbance [76]. The noise from electric devices is usually produced at frequencies higher than circuit signals. To avoid, or at least reduce EMI, suppressors should work as low-pass filters, that is, circuits that block signals with frequencies higher than a given frequency value.There are several approaches to build EMI suppressors: soft ferrites [77], ferromagnetic metals [78], ferromagnetic metal/hexaferrite composites [79], encapsulated magnetic particles [80], and carbon nanotube composites [81].Ferrite components for EMI suppressors have been used for decades. In the recent years, however, there have been special needs for these materials as a consequence of the miniaturization trends, increase in integration density, and increase in higher clock frequency, especially in communication, computing, and information technologies. Ferrite multilayer components have been developed as a response to these needs, formed essentially by a highly conductive layer embedded in a ferrite monolithic structure, produced by ceramic co-processing technologies. Typically, Ni-Zn ferrites are used for the 20–200 MHz frequency range. Multilayer suppressors behave like a frequency-dependent resistor; at low frequencies, losses in the ferrite are negligible. As frequency increases, losses increase also, and, as ferromagnetic resonance is approached, the inductor behaves as a frequency-independent resistor and no longer as an inductor.

Hexaferrites represent an interesting alternative to cubic ferrites as EMI suppressor components; they possess higher resonance frequencies, relatively high permeability's (at microwave frequencies), and high electrical resistivity. Metallic ferromagnets, in contrast, show a larger saturation magnetization, but, as frequency increases, they exhibit a strong decrease in permeability due to eddy currents However, in combination with hexaferrites, they have shown a strong potential for EMI suppressor devices [79]. Co_2Z and Zn_{2Y} hexaferrite particles (10–30 μm), mixed with metallic Ni particles (2-3 μm), and prepared with a polymer (polyvinylidene fluoride) by hot pressing at low temperature led to high shield effectiveness.Carbon nanotube-polystyrene foam composites have shown a high EMI shielding effectiveness based on a mechanism associated with the reflection of electromagnetic radiation [81]; no magnetic material is used.Ferrite nanoparticles in combination with carbon nanotubes can efficiently absorb microwave radiation. Carbon nanotubes/$COFe_2O_4$ spinel nanocomposite was fabricated by a chemical vapor deposition method using $COFe_2O_4$ nanoparticles as catalysts [80]. The microwave absorption (2^{-18} GHz range) was enhanced. For carbon nanotubes, dielectric loss contributes to the energy loss of electromagnetic waves, while, for pure CO ferrite, the effects of microwave absorption are associated with magnetic losses, but both isolated mechanisms are poor absorbers. For the nanocomposites, however, the microwave absorption improves because of a better match between the dielectric loss and the magnetic loss, which originates from the combination of paramagnetic nanotubes and ferromagnetic material. The dispersed $COFe_2O_4$ nanoparticles absorb the microwave signals by resonance effects due to shape anisotropy and dipolar interactions between particles. Such effects are weakened in congregated particles.

3.9.5 Biosciences

Magnetic materials in the form of nanoparticles, mainly magnetite (Fe_3O_4), are present in various living organisms [81] and can be used in a number of applications. Magnetic nanoparticles can, of course, be prepared in the laboratory by means of the well-known methods; however, magnetic biogenic particles have better properties than synthetic ones: they have a definite size range and width/length ratio and high chemical purity, they are almost perfect crystallographic ally, and sometimes they possess unusual crystallographic morphologies. Extracellular production of nanometer magnetite particles by various types of bacteria has been described [82]. In many cases, the biogenic particles retain a lipid layer which makes them very stable and easily biocompatible. Many biotechnological applications have been developed based on biogenic and synthetic magnetic micro- and nanoparticles [83]. Magnetic nanoparticles have been used to guide radio nuclides to specific tissues. An approach has been developed to directly label a radioisotope with ferrite particles [84] in vivo liver tissue in rats. Therapeutic applications are feasible by further conjugation with other medicals.

In magnetic resonance imaging (MRI), magnetite super paramagnetic particles are selectively associated with healthy regions of some tissues (liver, for instance); since these particles change the rate of proton decay from the excited to the ground state (which is the basis of MRI), a different, darker contrast is obtained from these healthy regions of tissue [84].Thermal energy from hysteresis loss of ferrites can be used in hyperthermia, that is, the heating of specific tissues or organs for treatment of cancer. The temperature in tumor tissues rises and becomes more sensitive to radio- or chemotherapy. In addition of magnetite [59], several Spinel ferrites (M–Zn, with M = Mn, CO, Fe^{2+}, and Fe^{2+}–Mn) are under investigation [84] as well as hexaferrites [80].Enzymes, oligonucleotides, antibodies, and other biologically active compounds can be immobilized, as an important technique used in biotechnology. Such immobilized compounds can be targeted to a specific place or can be removed from the system by using an external magnetic field. The compounds can exert their activity on the specific place or tissue or can be used as affinity ligands to trap the cells or target molecules [85].

Magnetic nanoparticles can also be used in a variety of applications: modification, detection, isolation, and study of cells [86], and isolation of biologically active compounds [87], for instance.

3.10 Quick Summary for Soft/Hard Ferrite Applications

3.10.1 Classifications

Soft ferrite applications fall into three major areas [85]:

- Low signal ferrites.
- Power handling ferrites.
- Interference suppression ferrites.

There are other uses for ferrites, such as memory storage systems, microwave gyro rotational devices, and thermal switching devices, but most of the materials produced today focus on these three classifications.

3.10.2 Low Signal Level

Low signal level ferrites may be grouped into four sub classifications[85]:

- High Q inductors.
- Common mode inductors.
- Wideband and matching transformers.
- Pulse transformers.

In all of these, the core windings excite the core to low levels of operating flux density. Each of the subclasses requires unique features in the ferrite core. Some of these are common, but there are preferred shapes and material types for each.

3.10.2.1 High Q Inductors

The majority of High Q Inductors are used in analog devices, particularly in telecommunications applications. A component must resonate at the desired frequency, be stable over time and temperature range, and have high permeability combined with negligible energy loss. Finally, the inductor should occupy the smallest possible volume and be cost effective [86].Although telecommunications is the largest and most critical segment, High Q Inductors are also used in many other electronic areas. These include communications, entertainment, controls and other industries. Ferrite manufacturers provide standard inductor geometries, influenced by IEC standards. These are in the configurations of pot cores, RM cores, and in some cases, toroids.

Manufacturers' literature describes the magnetic and physical parameters of the cores [87].

3.10.2.2 Common Mode Inductors

The most frequent use of common mode inductors is in power conditioning or power supply components. Although this is a relatively narrow application segment of the soft ferrite market, large quantities of cores are utilized. Their function is to insure that the power being supplied to an electronic device is "clean". Additionally, they prevent common mode noise generated by the equipment from escaping into other circuitry. The common mode inductor forms the heart of the low pass power filter [88].The core may operate at moderate flux densities, but is generally designed to function at low amplitudes. Many of the characteristics desired in materials for High Q Inductors are also needed for these filters Demands on temperature stability, high quality factor, and precision inductance are not as stringent. Most common mode inductors utilize toroids, but in some cases un gapped pot cores or PQ cores may be employed. When using toroids, the core must be insulated from the winding with high resistance barrier.

3.10.2.3 Wide Band and Matching Transformers

Although some energy is transferred in wideband transformers, they are used primarily to match impedances, provide precise current or voltage ratios and serve as interfaces between balanced and unbalanced circuits. Wideband transformers are designed to operate over a wide frequency range with low insertion loss in the mid-band area [89].Communications systems employ the largest number of wideband transformers. The materials utilized depend upon the frequency where low and high end cut-offs occur and the width of the pass band. Material requirements are high initial permeability (compatible with the frequency used), low loss, and magnetic stability.

3.10.2.4 Pulse Transformers

While pulse transformers are required to function over a wide frequency band, the fact that their signal wave shape is not sinusoidal makes them unique, both in their function as well as their ferrite requirements. The effect of the ferrite on the generally rectangular pulse shape is an important measure of their performance. The transformer, to function effectively, should transfer the pulse shape without appreciable distortion. Ferrites are utilized as low-power pulse transformer cores in Data circuits involving [90]:

- Impedance matching.
- Balanced to unbalanced circuits.
- Isolation.

- Precise voltage or current transformation.

Core properties impact all three areas. The two significant pulse ferrite parameters are the pulse permeability (l +). And a measure of the non-linearity of the magnetizing current commonly referred to as the voltage-time product (ET).

The Ferrite types used in pulse applications exhibit [91]:

- High permeability.
- Low core loss
- High saturation flux density.
- Good magnetic stability.

3.10.3 Hard Ferrite Applications

Barium Ferrite is used in tape drives and floppy disks, among other things. Barium ferrite is a very applicable material used in many industry fields in today's day and age. The material is seen around the world in applications such as recording items such as tapes and other media devices, permanent magnets, and also magnetic stripe cards (credit cards, hotel keys, ID cards). Due to the stability of the material, it is able to be greatly reduced in size, making the packing density much greater. In the late media devices, acicular oxides were used which produced the coercivity values necessary to record. Although in the past few decades barium ferrite has replaced the acicular oxides; without any dopants, the acicular oxides produce very low coercivity values, making the material very magnetically soft. The barium ferrite which has recently taken the oxide's place produces much higher coercivity levels which make the material magnetically hard, therefore making the ferrite better for recording materials [90].The rate of growth in the production of RE-Magnets has continued unabated, despite fluctuations in the world economy. Thus, sintered NdFeB magnets are exhibiting a current growth rate of ~12% whereas the growth rate for bonded NdFeB magnets is in excess of 20%.The total value of hard magnets now exceeds that of soft magnets and the gap is widening[85]. The reason for this spectacular growth has been due partially to the booming global PC market, as around 60% of NdFeB magnet production goes into disc-drive applications, primarily voice-coilmotors (VCMs).This is by no means the whole story however and a summary of the very wide range of applications for RE-magnets is given below, with many of these being capable of substantial further growth.In general terms, permanent magnets are far more important than is generally realized and this is perhaps, best illustrated by their use in the motor car. In the early fifties a car would have one magnet (the speedometer) whereas some modern cars can have over a hundred permanent magnet motors. Currently these are almost exclusively based on Sr-ferrite (SrFe12019) and the penetration of NdFeB magnets into this area requires a significant cost reduction, an increase in the maximum operating temperature and improvement in corrosion resistance [89].The potential benefits of using NdFeB magnets would be a significant reduction in volume and weight and an improved efficiency [90]. This will probably be a major influence in the use of these magnets in the future. Growing concern about global warming has scientific and technological implications and many of these impinge on the use of NdFeB magnets. Future uses could include their more widespread use in “white goods” such as washing machines, refrigerators etc, in order to improve energy efficiency and hence reduce CO_2 emissions. Another large use could be in generators for domestic combined heat and power units and in clean energy production such as windmills. The biggest potential however is in electric vehicles (EVs) which could be hybrid vehicles or totally driven by electricity in the form of batteries or a fuel cell [87].There has been an enormous increase of interest and activity in this area over the past 5 years and the Japanese have been the first to commercialize these vehicles[88].

3.10.4 Examples of Applications for Permanent Magnetic Materials:

Automotive: Starter motors, Anti-lock braking systems (ABS), Motor drives for wipers, Injection pumps, Fans and controls for windows, seats etc, Loudspeakers, Eddy current brakes, Alternators.

Telecommunications: Loudspeakers, Microphones, Telephone ringers, Electro-acoustic pick-ups, Switches and relays.

Data Processing: Disc drives and actuators, Stepping motors, Printers.

Consumer Electronics: DC motors for showers, Washing machines, Drills, Low voltage DC drives for cordless appliances, Loudspeakers for TV and Audio, TV beam correction and focusing device, Compact-disc drives, Home computers, Video Recorders, Clocks.

Electronic and Instrumentation: Sensors, Contactless switches, NMR spectrometer, Energy meter disc, Electro-mechanical transducers, Crossed field tubes, Flux-transfer trip device, Dampers.

Industrial: DC motors for magnetic tools, Robotics, Magnetic separators for extracting metals and ores, Magnetic bearings, Servo-motor drives, Lifting apparatus, Brakes and clutches, Meters and measuring equipment.

Astro and Aerospace: Frictionless bearings, Stepping motors, Couplings, Instrumentation, Travelling wave tubes, Auto-compass.

Biosurgical: Dentures, Orthodontics, Orthopedics, Wound closures, Stomach seals, Repulsion collars, Ferromagnetic probes, Cancer cell separators, Magneto motive artificial hearts, NMR / MRI body scanner[88].

3.11 Commercial Images:

Ferrite magnets are a cost effective option when strength is not the most important consideration as shown on figure (3.6) ,(3.7) ,(3.8) ,(3.9) ,(3.10) ,(3.11) ,(3.12) ,(3.13)) [88].

Fig (3.6) 21.9 mm x 1.8 mm silver plated C8 ferrite disk

Fig (3.7)12 mm x 3 mm ferrite disk

Fig (3.8)10.8 mm x 6.3 mm x 4.4 mm C8 ferrite block

Fig (3.9)11.4 mm x 12 mm C5 ceramic ferrite rod / disk

Fig (3.10)12 mm x 10 mm x 5 mm C5 ferrite block

Fig (3.11)15.2mm x 3.2mm x 6mm C5-Y25 Countersunk ferrite rings - CS face North

Fig (3.12)75 mm x 50 mm x 10 mm C8 ferrite block

Fig (3.13) 25 mm Ferrite Banner Hook

Chapter Four
Conclusion and Recommendations

4.1 Discussion

The basic properties and applications of magnetic materials were studies, and properties and applications of type of Ferrite magnetic (soft and hard) was investigated. Ferrites are ferromagnetic compounds of ferric oxide with other oxides, especially a compound characterized by extremely high electrical Resistivity. Uses of Ferrite e.g. Permanent magnets, Ferrite cores for transformers and toroidal inductors, Computer memory elements, Solid-state devices.

4.2 Conclusion

* Ferrites are explained as any of a group of nonmetallic, ceramic-like, usually ferromagnetic compounds of ferric oxide with other oxides; especially a compound characterized by extremely high electrical resistivity, the high resistance of ferrite makes eddy current losses extremely low at high frequencies.

* Soft ferrites are Ferrites that are used in transformer or electromagnetic cores contain nickel, zinc, or manganese compounds. They have a low coercivity.

* Hard ferrites are permanent ferrite magnets (or hard ferrites) which have a high remanence after magnetizations are composed of iron and barium or strontium oxides.

* Ferrite cores are used in electronic inductors, transformers, and electromagnets, where the high electrical resistance of the ferrite leads to very low eddy current losses. They are commonly seen as a lump in a computer cable, called a ferrite bead, which helps prevent high-frequency electrical noise (radio frequency interference) from exiting or entering the equipment. It is that there is not a problem with the price of iron oxidation raw materials at low cost. In addition, it also has excellent corrosion resistance and oxidation resistance. It is very stable and difficult to demagnetize the magnetic properties are not inferior to the rare-earth magnet, but the coercive force is large.

4.2.1 Advantages of Ferrites

Ferrites have a paramount advantage over other types of magnetic materials: high electrical resistivity and resultant low eddy current losses over a wide frequency range. Additional characteristics such as high permeability and time/temperature stability have expanded ferrite uses into quality filter circuits, high frequency transformers, wide band transformers, adjustable inductors, delay lines, and other high frequency electronic circuitry. As the high frequency performance of other circuit components continues to be improved, ferrites are routinely designed into magnetic circuits for both low level and power applications. Another factor in choosing ferrites is the higher cost of magnetic metals. For the most favorable combination of low cost, high Q, high stability, and lowest volume, ferrites are the best core material choice for frequencies from 10 KHz to 50 MHz. Ferrites offer an unmatched flexibility in magnetic and mechanical parameters.

4.2.1.1 Summary of Ferrite Advantages

- Low cost
- Large selection of materials
- Shape versatility
- Economical assembly
- Temperature and time stability
- High resistivity
- Wide frequency range (10 KHz to 50 MHz)
- High Q/small package

4.2.2 Disadvantages

It is easy to crack as pottery mechanical strength is low. In addition, it is less expensive quantity is gathered, but the response to the prototype can be difficult because it becomes the mold required for production.

4.3 Recommendations

*Experiments must be carried out in order to compare between hard and soft ferrite material to investigate their different properties.
*Study of the effect of temperature on magnetic materials as well as on soft and hard ferrites and their effect on the structure and general characteristics.
*Studying the general structure of some soft and hard ferrite materials in order to compare them.
*High carbon silicon steel (grain oriented), used as a core material, for modern transformers working on high flux density(M_2H,N_3H,M_4 grad is about 1.69 to1.9 T). Important is reversibility of magnetic field(flux density),with change in magnetizing current polarity or hysteresis loop area, lower the area, hysteresis loss will reduced, with reduction in, fixed(no load) loss of transformer considerably . For the reactor core, magnetizing current should be considerable, with higher inductive reactance.
* As far as materials are concerned other than the crystalline metallic materials, metallic glasses are also used for cores of high frequency equipment as these have very low magnetic coercivity and some them also show high magnetic

permeability. Soft ferrites are also used having higher electrical resistance. These materials may not show very high saturation magnetization but their other qualities make them useful for core applications.

* Most relevant point is the lowest frequency as well as higher frequency components of magnetic reversal in the core so as to control the core loss. If the basic frequency is less than few hundreds of Hz, then Fe-Si alloys are the best. You can go for grain oriented steel for lower loss, but the higher the operating frequency, the thinner should be the laminations and lower should be the maximum flux density. Typical practical values of maximum flux density in transformers varies from 1.7T at 50Hz to 0.7T at 400Hz. Increased high frequency components (as in an inverter) can force you to reduce flux density to control core loss. At few kHz of basic frequency, you can go for Amorphous cores, but maximum flux density in transformer application will be less than 1T to control core loss. At higher frequencies, Ferrite is the best and can work at about 0.3T till few hundred kHz in transformers (but select suitable grade). Note that the low flux density does not make Ferrites attractive at lower frequencies. However, other material, if used at the higher frequencies, will have to be operated at still lower flux density to control core loss, increasing their size compared to Ferrites.

*There are different key parameters that are characterisitics of your application which will guide you to the suiting material. In power applications, loss, both of the core and of the windings is the most important parameter that needs to be minimized. In order to find a minimum, you start with experiences - yours and those of others. For example, people would suggest using MnZn Ferrites in the 100-1000 kHz range. This is the base frequency, namely the switching frequency of your inverter. However, to be sure to choose the right material you should also consider alternative materials that are recommended in the desired frequency range: iron powder cores and air, for example. If you compare with the alternatives, you can do that by the so-called performance factor or by a certain design with a defined volume, current rating and inductance. You will find that using air makes your winding number extremely large leading to excessive ohmic losses. On the other hand, the powder core will need the lowest winding count but has excessive core loss .Unfortunately, magnetic core producers are not providing suitable data that would ease the comparison between different core material classes (iron powder, Ferrite, etc.). However, comparison sheets exist that allow you to find alternative Ferrite materials from other vendors for a given Ferrite material.

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