The development of ferrites since 1946 reported that the electrical resistivity of ferrites over a million times those of metals has an enormous impact in the application of magnetic materials, particularly at high frequencies. This chapter includes the different methods for the preparation of ferrite system. The different physical properties like structural, electrical and magnetic properties of spinel ferrites depends upon various factors such as sintering temperature, sintering time, sintering condition, chemical composition, method of preparation nature and type of dopant, temperature, atmosphere, heating and cooling rate, particle size, pH, type of fuel etc.

Synthesis and characterization technique vary from material to material. Large numbers of synthesis methods are available for the preparation of ferrite materials. Synthesis of single phase material is very important for most practical applications. Among all methods of preparation the conventional ceramic method of sample preparation and sol-gel auto-combustion technique is discussed briefly. Further, one of the wet chemical method i.e. sol-gel auto-combustion method is used to synthesize single phase, homogeneous, nano-size spinel ferrite materials. It also includes the important properties of ferrite material like structural and morphological property, DC-electrical resistivity, dielectric property, magnetic property etc. [1-2]. The effect of irradiation on these physical properties of ferrite material is also discussed briefly. The change in various parameters of these physical properties of Co-Zn ferrite which makes them technologically applicable are also referred.
Ferrite material synthesis is not a big problem for young researchers; because of various methods are available depending upon the content and desired product. For the synthesis of high quality ferrite material one has to pay more attention towards the parameters such as chemical composition, nature and type of dopant, temperature, atmosphere, heating and cooling rate, particle size etc.

In order to meet these requirements ferrites can be prepared by number of synthesis methods like conventional ceramic method, as well as wet chemical methods like co-precipitation [3], sol–gel method [4], micro-emulsion method [5], hydrothermal [6], spray pyrolysis [7], reverse micelle [8], precursor [9]. These wet chemical methods effectively affect the crystal size and sintering temperature.

3.2.1 Ceramic method

Synthesis of single phase material is very important for most practical applications. Ceramic method is the most popular and conventional method of preparation among other methods. In this method raw materials like oxide and carbonates are taken stoichiometric proportion [10]. These oxides are mixed thoroughly and uniformly. The solid state chemical reaction takes place at much elevated temperature. Pre-sintering is the lowest sintering temperature and can start from (900°C). Similarly the final sintering temperatures can reach up to (1200°C). The pre-sintering and final sintering temperature can vary with the constituents of the mixture as well as the parameters of the desired product i.e. particle size, density, porosity etc. [11]
Conventional ceramic method involves following steps:

1) Calcination of constituents of oxides/carbonates.
2) Weighing and mixing of oxides/carbonates.
3) Grinding of the mixture for 3-4 h.
4) Pre-sintering at the temperature below the temperature of solid state chemical reaction.
5) Powdering of the samples.
6) Final sintering at the elevated temperature.
7) Slow cooling.

Conventional ceramic processing cannot yield particles of high surface area. Nano-crystalline ferrite materials cannot be prepared by ceramic method. During the grinding process there is a possibility of addition of impurities in the sample. The method requires high temperature for the synthesis of the sample. The mixture in ceramic method is less homogeneous as compared to wet-chemical methods. The method requires more time and somewhat tedious.

**3.2.2 Sol-gel auto-combustion method:**

Among different methods of synthesis of ferrite nanoparticles, sol-gel auto-combustion technique is quite simple and cost effective which involves both chemical and physical processes. It produces high purity and uniform nano-particles at comparatively low temperature [12].

More-ever there is no reaction of precursor materials with the containers and the materials are easily available. Brief outline of the synthesis procedure is given below. Sol–gel auto-combustion synthesis
The technique is also called as low-temperature self-combustion method, auto-ignition as well as gel-thermal decomposition method [13-15].

In this technique the chemical sol–gel and combustion process together forms spinel ferrite nano-materials. Recently, this method is used as an option to synthesize advanced spinel ferrite material, one-dimensional and two-dimensional nano-structure materials [16-19].

**Fig.3.1 Flow chart of steps in Sol-gel auto-combustion Technique**

- Cobalt nitrate
- Ferric nitrate
- Zinc nitrate
- Citric acid

1. Mixture of nitrates in stoichiometric proportion in distil water
2. Continuous stirring and heating at 80°C
3. Addition of ammonia to maintain pH at 8.
4. Clear sol formation after 2-3 hours.
5. Gel formation in 4-5 hours.
6. Dry-gel formation within 5-6 hours (small increased in temp.)
7. Powder sample as a product of sol-gel auto-combustion tech.
8. Annealing of as prepared sample
9. Formation of \( \text{Co}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_4 \) ferrite system.
Metal nitrate to fuel ratio 1:3

Adding Ammonia sol.

80°-90°C

Final product

**Fig. 3.2 Steps involved in sol-gel auto-combustion method.**

The products of sol-gel auto-combustion technique are usable for electronic and biological applications, high density magnetic and radar absorbing materials, magneto-electric composites etc. [20-24].

**Advantages of sol-gel auto-combustion method**

sol-gel method has acquired great importance during the last years. The sol-gel method offers many advantages, such as homogeneous mixing at molecule level, good stoichiometric control and low processing temperature, use of an aqueous-based processing system, and the production of active powders. The advantages of this technique are described below [25-30].
1. The intimate mixing of the elements in gel form results in reaching the ingredients in a short period of time.

2. It does not require grinding procedure to achieve homogeneous single phase ceramics, which avoids contamination.

3. The precise size control of the particles is also strength of sol-gel processing.

4. The possibility of controlling the porosity is highly attractive.

5. It is attributed to more uniform phase distribution in multi-component systems like ferrites.

6. Sol-gel auto combustion method is a cost effective method.

3.3 PROPERTIES OF SPINEL FERRITE

Various properties of ferrites such as high electric resistivity, low eddy current and dielectric losses, high Curie temperature, high permeability, moderate saturation magnetization etc. makes them useful in many applications. Chemically ferrites are very inert substances. Ionic compounds are in general are highly reactive, they readily undergo double decomposition. Oxides and many metals are basic and so are soluble in dilute acids, or water. The ferrites are very stable, even though they are ionic. The ionic bond is very strong, so that hardness, brittleness, and high melting-point are characteristic properties of ionic crystals. Ferrites have high dielectric constants, typical values are of the order of thousands at low frequencies, falling to about ten to twenty at microwave frequencies. This high dielectric constant is in part due to the close-packed structure of oxygen ions [31-33]. In this work the properties of spinel ferrite which are influenced by gamma irradiation are discussed in detail.
The principle factors which significantly differ the properties of nano-crystalline spinel ferrite from bulk materials are; increased in relative surface area, lower weight, or higher strength and quantum effects. These factors can affect the properties of spinel ferrites such as reactivity, optical, electrical and magnetic properties of materials. In spinel ferrite nano-particles, as the size of structural components decreases, electrical, dielectric and magnetic properties are influenced greatly. Understanding surfaces and interfaces of spinel ferrite nano-particles is key challenge for the researchers.

Various crystalline parameters like lattice parameter (a), inter-planner spacing (d), phase purity, X-ray density (d_X), bulk density (d_B), cation distribution, percentage porosity (P), crystalline sizes (t) etc. can be calculated from X-ray diffraction technique.

### 3.4.1 Inter-planner spacing (d)

A plane in a crystal is specified in terms of Miller indices (hkl). The inter-planar spacing (d) for the planes of indices (hkl) is equal to the distance between the nearest plane of crystalline lattice.

### 3.4.2 Lattice constant (a)

The lattice constant, or lattice parameter, refers to the constant distance between unit cells in a crystal lattice. As lattice constant (a) have the dimension of length, its SI unit is meter. Lattice constant is typically of the order of several angstroms (Å).
3.4.3 X-ray density \((d_X)\) and Bulk density \((d_B)\)

The change in the X-ray density \((d_X)\) and bulk density \((d_B)\) may be due the existence of pores in the samples, which depends upon the method of preparation, sintering temperature and sintering conditions. Bulk density \((d_B)\) is defined as the mass of many particles of the material divided by the total volume they occupied. Bulk density is not an intrinsic property of a material; it can change depending on how the material is handled.

3.4.4 Porosity \(P\) (%)

Porosity in spinel ferrite nano-particles is a measure of voids (empty) spaces in the materials. It is a fraction of the volume of voids over the total volume, as a percentage porosity \((P)\) between 0–100%.

3.4.5 Crystallite size \((t)\)

Crystal size is usually measured from X-ray diffraction patterns. The crystallite size \((t)\) can vary from a few nanometers to several millimeters and it is estimated from well-known Scherrer’s method.

3.5 ELECTICAL PRPERTIES

3.5.1 DC-Electrical resistivity

DC-electrical resistivity is an important property of spinel ferrite. On the basis of the this study, one can improve the practical application of the ferrites as the property based application which includes various electronic applications, transformer cores, inductors, SMPS, converters, EMI filters, picture tube yokes, rotator, circulator, phase shifter etc.
The electrical transport in material is nature base i.e. Ionic, Electronic, Partially ionic [34-35].

a) **Ionic conductivity:**

In this type of electrical conductivity, DC- electrical conductivity decreases with respect to time and becomes zero after specific time i.e. it is the time dependent ele. transport through solids.

b) **Electronic transport:**

It is the time independent transport i.e. DC-electrical conductivity does not become zero with respect to time.

c) **Partially ionic or electronic:**

In this type of electrical transport the conduction decreases with respect to time but it stabilized at certain constant non-zero value.

The range of the resistivity of ferrite is about $10^{-4} \Omega m$ to $10^9 \Omega m$ at room temperature. For soft ferrites it is of the order of $10^6 \Omega m$, which shows the semiconductor behavior of soft ferrites. The conductivity of Cobalt ferrite is due to the presence of Fe$^{3+}$ (n-type) and Me$^{2+}$ (p-type) Where Me = Co ions.

3.5.2 **Hopping mechanism**

The conductivity arises due to the mobility of an extra electron from (Fe$^{3+}$) or the positive hole (Me$^{2+}$) through the crystal lattice. This moment is described by the hopping mechanism, in which the charge carriers jump from one ionic site to next ionic site. The conduction takes place when some external agency makes the activation of charge carriers. In Co-Zn ferrite, the crystal lattice is cubic spinel structure in
which, distance between two (A) site cations is larger than that of the
distance between adjacent [B] site cations. As tetrahedral and octahedral
sites are energetically not equivalent, the conductivity is mostly
dependent upon electron exchange between [B] site cation. For example
in Fe$_3$O$_4$ though the conductivity is due to hopping of electron from Fe$^{2+}$
to Fe$^{3+}$ ion at B site, in this mechanism initial and final states are
equivalent [36-38]

$$Fe^{2+} + Fe^{3+} \leftrightarrow Fe^{3+} + Fe^{2+} \quad \ldots 3.1$$

### 3.6 DIELECTRIC PROPERTIES

Ferrite materials have wide range of applications in microwave as
well as radio frequencies. The property of low conductivity at carrier
frequencies has made them useful for microwave applications. Ferrite
material shows significantly low losses for microwave applications. The
electric transportation in ferrite materials produces atomic and
molecular changes in crystalline lattice. The bi-polar and di-polar
polarization takes place under the influence of electric field. Ferrite as an
ionic material, the ionic polarization in the crystalline lattice occurs,
which displaces the cation and anion sub-lattices. [39]

The free charges or polarized charges in this crystalline lattice
accumulated at the grain boundaries and resist the transportation of
moving charges within the crystallography. This attributes to the
dielectric study knowing various polarization phenomenons in
crystallography viz. space charge polarization, atomic polarization,
orientational dipole polarization etc.
3.6.1 Polarization in dielectrics

It is defined as the induced dipole moment per unit volume. When an electric field is applied to a solid material consisting of positive and negative charges, the negative charges are displaced in the direction of the field while the positive charges are displaced to opposite direction of
the field. This type of displacement of positive and negative charges by
the application of an external electric field produces polarization.
Polarization mechanism are of following four types.

I) Electronic or Induced Polarization ($P_E$)

II) Atomic or Ionic Polarization ($P_I$)

III) Dipolar or Orientation Polarization ($P_o$)

IV) Interfacial or Space Charge Polarization

The dielectric property of ferrite materials in terms the frequency
dependent parameters like dielectric constant ($\varepsilon$), dielectric loss ($\varepsilon''$),
capacitance (F), impedance, inductance (H), quality factor (Q), D-factor
($\tan \delta$), conductance, admittance (S), resistance, reactance, susceptance
(S) etc. can be determined [40-43].

3.6.2 Dielectric constant ($\varepsilon$)

Dielectric constant is used to determine the ability of an insulator
to store the electrical energy. It is the ratio of induced capacitance of
metallic plates with insulator to the induced capacitance of the metallic
plates with air/vacuum. Dielectric constant depends upon the
polarization produced in the material.

3.6.3 Dielectric loss ($\varepsilon''$)

The electric energy that is converted into heat in a dielectric
subjected to a varying electric field. It is a portion of energy of alternating
electrical field in a dielectric medium that is converted into heat.

3.6.4 Dielectric loss tangent ($\tan \delta$)

It is a tangent of loss angle and also called as dissipation factor D.
Ferrites as a ferri-magnetic material, magnetic properties plays an important role in their application point of view. Materials which can be magnetized are called magnetic materials. The response of materials is different at electronic, atomic, molecular and microscopic level to an applied magnetic field. In different materials, the magnetic effect varies from weak to strong. The magnetization \( I \) defined as magnetic moment per unit volume and is given by

\[
I = \chi H \quad \text{....3.2}
\]

Where \( \chi \) is known as magnetic susceptibility.

Magnetization is a process by which resultant magnetic moment of group of atoms or ions is increased by aligning the individual moments. The magnetization arises from the spin and the orbital motion of electrons in the material. The orbital motion of an electron about the nucleus gives rise to magnetic moment \( \mu_L \) which is related to the orbital to the angular momentum \( M_L \). The magnetic moment can be discussed with the expression:

\[
\mu_L = \frac{e}{2mc} M_L \quad \text{....3.3}
\]

Two spin magnetic moment \( \mu_s \) is given by,

\[
\mu_s = \frac{e}{2mc} . 2M_s \quad \text{....3.4}
\]

The magnetic moment \( \mu_L \) is related to the total angular momentum \( M_J \) by the relationship.
\[ \mu_L = \frac{e}{2mc} g M_j \] ....3.5

And,

\[ g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \] ....3.5

where ‘g’ is called as Lande’s ‘g’ factor and its value is 1 when S = 0 and 2, and when L = 0.

### 3.7.1 Classification of magnetic materials

The magnetic behavior of a material is due to electron orbital motion, electron spin and nuclear spin. All these are the sources of atomic current flowing in the circular loops. According to the magnetic properties, the magnetic materials can be classified into five different types as shown in the Table 3.1 [44-45]

**Table 3.1**

<table>
<thead>
<tr>
<th>Sr.no</th>
<th>Magnetic Material</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diamagnetic</td>
<td>MgO</td>
</tr>
<tr>
<td>2</td>
<td>Paramagnetic</td>
<td>Gd$_2$O$_3$</td>
</tr>
<tr>
<td>3</td>
<td>Ferromagnetic</td>
<td>EuO</td>
</tr>
<tr>
<td>4</td>
<td>Anti-ferromagnetic</td>
<td>NiO</td>
</tr>
<tr>
<td>5</td>
<td>Ferrimagnetic</td>
<td>Fe$_3$O$_4$</td>
</tr>
</tbody>
</table>
a) Diamagnetic materials

In a diamagnetic material the atoms does not have a net magnetic moment in the absence of applied field. They do not contain any unpaired electron when an external field (H) is applied, the spinning of electrons takes place and this motion produces a magnetization (M) in the opposite direction to the applied field. The magnetic susceptibility in this kind of magnetic material is negative. All materials have a diamagnetic effect, however, it is in case that the diamagnetic effect is masked by the larger paramagnetic or ferromagnetic term.

b) Paramagnetic materials

In a paramagnetic material the individual ions, atoms or molecules possess magnetic moments. These arise when the system contains an odd number of electrons as well as when an inner electron shell is unfilled. The magnetic susceptibility is positive. According to the Langevin model, which is true for materials with non-interacting localised electrons, states that each atom has a magnetic moment which is randomly oriented as a result of thermal agitation. The application of a magnetic field creates a slight alignment of these moments and hence a low magnetization in the same direction as the applied field. As the temperature increases, the thermal agitation increase and it will become harder to align the atomic magnetic moments. Hence, the susceptibility will decrease. This behavior is known as the Curie law and it is shown by the equation below,

\[ \chi = \frac{C}{T} \]

[3.6]
where ‘C’ is a material constant called the Curie constant.

In fact, the Curie law is a special case of the more general Curie-Weiss law, which is derived from Weiss theory, proposed for ferromagnetic materials, that incorporates the interaction between magnetic moments.

\[
\chi = \frac{C}{T - \theta}
\]

It is important to note that this equation is only valid when the material is in a paramagnetic state. It is also not valid for many metals as the electrons contributing to the magnetic moment are not localized. However, the law does apply to some metals, viz. the rare-earths, where the 4f electrons are closely bound. The Pauli model of paramagnetism is true for a material where the electrons are free and interact to form a conduction band. This is valid for most paramagnetic metals. According to this model, the conduction electrons are considered essentially to be free and under an applied field. An imbalance between electrons with opposite spin is set up leading to a low magnetization in the same direction as that of the applied field.

c) Ferromagnetic materials

Ferromagnetism is only possible when atoms are arranged in a lattice and the atomic magnetic moments can interact to align parallel to each other. In the periodic table of elements, only Fe, Co and Ni are ferromagnetic at and above the room temperature. In ferromagnetic materials magnetic moment is large. They have positive susceptibility, which varies according to the Curie-Weiss law above the \( T_C \). Just as in para-magnetic materials, there is sufficient interaction between
neighboring dipoles of the ferromagnetic materials. This effect is explained in classical theory by the presence of a molecular field within the ferromagnetic material, which was first postulated by Weiss in 1907.

d) Anti-ferromagnetic materials

When the magnetic moments are anti-parallel to each other and the net magnetic moment is zero then the substance is anti-ferromagnetic. The magnetic dipole moments of adjacent atoms in ferromagnetic material have equal magnitude but the opposite direction to each other.

Anti-ferromagnetic materials have positive susceptibility. With the different temperatures, they have small magnetic moment. There are always equal numbers of two alignments so that in the absence of magnetic field there is no resultant magnetization. Anti-ferromagnetic materials become paramagnetic above the transition temperature $T_N$, and susceptibility $\chi$ is given by equation

$$\chi_m = \frac{C}{T + \theta} \quad \text{....3.8}$$

where $C$ is Curie constant,

French scientist Neel developed the theory of anti-ferromagnetism. He used the Weiss molecular field theory concept of ferromagnetism. Below the Neel point, the susceptibility to some extent is temperature dependent which is one of the criteria of identifying anti-ferromagnetism. At the temperature above the Neel point, anti-ferromagnetic materials follow Curie-Weiss law.
e) **Ferrimagnetic materials**

Ferrimagnetic materials are popular as ferrites. They have magnetic moments of adjacent atoms in opposite direction. There exists a large magnetic moment and susceptibility is positive. Several oxide magnetic materials have been found to be ferrimagnetic. These oxides possess a net resultant magnetism due to the unequal anti-parallel spin moment. The ions have opposed spin arrangement, but unlike anti-ferromagnetic materials they do not cancel each other. Therefore, there is a resultant permanent magnetic moment.

Ferrimagnetism is observed in the compounds which have more complex crystal structures than the pure elements. Within these materials the exchange interactions lead to parallel alignment of atoms in some of the crystal sites and anti-parallel alignment of others. Usually the ferrimagnetic materials have lower saturation magnetization. Paramagnetic materials have positive $\chi_m$ of the order of $10^{-5}$ and it obeys Curie law and Curie Weiss law. Ferromagnetic materials have very large positive $\chi_m$ whereas Anti-ferromagnetic materials have small positive $\chi_m$. On the basis of applications of magnetic materials they are further divided as soft magnetic materials and hard magnetic materials.

3.7.2 **Soft magnetic materials**

In soft magnetic materials, very small external applied magnetic field can produce large change in the magnetic flux density. These materials can easily be magnetized and demagnetized with the help of applied external magnetic field. The examples of soft magnetic materials are metallic Fe, Ni, FeCo, NiFe, FeSi etc. in ceramic viz. Fe$_3$O$_4$, NiFe$_2$O$_4$, Ni-ZnFe$_2$O$_4$, ferrites, garnets, etc. Soft magnetic materials can be
classified on the measure of coercivity, which should be as low as 
\( H_c \leq 1000 \) e. Soft ferrites are also broadly classified depending on the 
frequency of use which in turns decides the type of chemical 
composition that is required. They can be classified as Low frequency soft 
magnetic material, medium, high and microwave frequency soft 
magnetic materials. Recently, new researchers discover a new class of 
ultra-soft nano-crystalline magnetic materials, in which large initial 
permeability and saturation magnetization are observed.

Few characteristics of soft magnetic materials are discussed as follows:

- They have high saturation magnetization \( J_s = \mu_0 M_s \).
- They possess high permeability \( \mu_t \).
- Soft magnetic materials have high electrical resistivity \( \rho \).
- Very low coercivity \( H_c \) is observed in these materials.
- Soft magnetic materials show high Curie temperature \( T_C \).
- In soft magnetic materials low magneto-crystalline 
anisotropy \( H_A \) is observed.
- They shows low hysteresis losses.

### 3.7.3 Hard magnetic materials

Hard magnetic materials are also known as permanent magnetic 
materials. They cannot be easily magnetized or demagnetized. Wide 
applications of hard magnetic materials are in motors, generators, 
loudspeakers toys, flexible and rubber magnets, magnetic latches and 
magnetic levitation etc. Magnetic hardness is due to the fine particles 
having shape and crystalline anisotropy. A large crystalline anisotropy is 
characteristic feature of hexa-ferrites. Hence a large coercivity is an
inherent property of hexa-ferrites. The coercivity of these materials should be as high as possible. These materials can retain a large amount of residual magnetism after removal of external applied magnetic field. These magnetic properties depend upon following metallurgical conditions of the material viz.

1) The size, shape and orientation of grains,
2) The concentration and distribution of various crystal imperfections.
3) State and impurities of lattice, residual traces and atomic arrangement in solids.

### 3.8 Magnetic Properties

Magnetic properties are divided into two groups intrinsic and extrinsic properties. Saturation magnetization ($M_s$) and Curie temperature ($T_c$) are of the kind of intrinsic properties, whereas extrinsic properties can be classified as static and dynamic property. Some of the properties belongs to this category are induction ($B$), permeability ($\mu$), hysteresis loop and associated energy loss, coercivity ($H_c$) and remenance magnetization ($M_r$) referred as static properties. Eddy current loss, resonance of spin and domain walls are dynamic properties [46-48].

#### 3.8.1 Saturation magnetization ($M_s$)

The maximum attainable intensity of magnetization per unit volume is known as saturation magnetization of ferromagnetic material. It is denoted by ($M_s$). The experimental method for the determination of saturation magnetization has reviewed by Mc Guire and Flanders. The saturation magnetization can be determined by using high field
hysteresis loop technique. The magnetization is a powerful tool to study the different parameter such as domain wall motion, anisotropy, magnetic hardness or softness of material, magnetic ordering etc. When the magnetic field is applied to the ferromagnetic material, the magnetization may vary from zero to saturation value. This behavior is expressed by Weiss [46] introducing the idea of existence of domains.

### 3.8.2 Curie temperature

Ferromagnetic materials exhibit a characteristic temperature known as the Curie temperature \( T_C \). This is the critical temperature at which thermal energy is just enough to destroy the spontaneous magnetization. Thus, the Curie temperature marks the transition point at which a ferromagnetic material is converted into paramagnetic material upon heating.

### 3.8.3 Magnetic induction (I)

Sometimes, performance of a ferromagnetic material involved induction, rather than magnetization. This is so define the inuction as;

\[
B = \mu_0 (H + M)
\]

### 3.8.4 Permeability (\( \mu \))

The magnetic permeability (\( \mu \)) is defined as ratio of magnetic induction (\( B \)) to magnetic field (\( H \)) or strength of applied field. The ratio of flux density and applied field is called absolute permeability [49-50].

\[
\frac{B}{H} = \mu_0 \left(1 + \frac{M}{H}\right) = \mu_{\text{absolute}}
\]
This absolute permeability is the product of the magnetic constant of free space and the relative permeability,

\[ \frac{B}{H} = \mu_0 \mu_r \] ....3.11

The following four permeability's are particularly important.

a) Initial permeability, \((\mu_i)\): The limiting value approached by normal permeability when \(H\) is reduced to zero.

b) Maximum permeability, \((\mu_{\text{Max}})\): the largest value of normal permeability obtained from a \((B-H)\) curve.

c) Intermediate permeability, \((\mu_\delta)\) is equal to \(B_\delta/H_\delta\), where \(H_\delta\) is an alternating field in addition to a constant biasing field and \(B_\delta\) is the alternating induction caused by \(H_\delta\).

d) Differential permeability \((\mu_d)\) is equal to \(dB/dH\) and is simply the slope of \(B-H\) curve at each point [51-53].

### 3.8.5 Hysteresis loop

![Hysteresis loop diagram](image)

Fig 3.5 Parameters of magnetization from the hysteresis loop.
In the B-H curve B lags behind H and thus the closed B-H curve is called hysteresis loop. This loop appears in the four-quadrant as shown in Fig.3. In the B-H plot, the area enclosed by hysteresis loop represents an energy given by

$$W_b = \int H \, dB$$

3.8.6 Coercivity (Hc) and Retentivity

Hysteresis loop (Fig.3.5) shows a characteristic field known as the coercive force (Hc) and a characteristic induction known as remanence (Br). Coercivity generally used to determine whether a material is soft or hard. The (Hc) less than 400 Am$^{-1}$ (5 Oe) indicate that material is soft magnetic material and Hc with values greater 8000 Am$^{-1}$ (100 Oe) indicates hard magnetic materials. During the cycle of magnetization Br (Fig.3.5) is the amount induction remained ever after the field H is made zero is known as remanence or retentivity [54-55].

3.8.7 Eddy current and energy losses

When an alternating field is applied to magnetize a ferromagnetic body, an electromagnetic force (e.m.f.) is setup in the body. If the material is also a good conductor, as with metal and alloys, the induced e.m.f. is produced appreciable amount of currents in different regions, these currents are known as the eddy currents and their occurrence gives rise to energy loss through Joule (resistance heating). Thus, in a.c. application, metallic ferromagnet suffers the hysteresis as well as the eddy current losses.
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