CHAPTER THREE

MATERIALS AND CHARACTERISTICS OF MAGNETS ON MACHINES

3.1. Introduction

In the ancient times people believed that the invisible force of magnetism was purely a magical quality and hence they showed little practical interest. However, with steadily increasing scientific knowledge over the passing centuries, magnetism assumed a larger and larger role. Today magnetism has attained a place of pride in electrical engineering. Without the aid of magnetism, it is impossible to operate such devices as electric generators, electric motors, transformers, electrical instruments etc. Without the use of magnetism, we should be deprived of such valuable assets as the radio, television, telephone, telegraph and ignition systems of our cars, airplanes, trucks etc. In fact, electrical engineering is so much dependent on magnetism that without it a very few our modern devices would not be possible.

3.2. Poles of a Magnet

If we take a bar magnet and dip it into iron filings, it will be observed that the iron filings cluster about the ends of the bar magnet. The ends of the bar magnet are apparently points of maximum magnetic effect and for convenience we call them the poles of the magnet. A magnet has two poles viz north pole and south pole. In order to determine the polarity of a magnet, suspend and pivot it at the center. The magnet will then come to rest north-south direction. The end of the magnet pointing north is called north pole of the magnet while the end pointing south is called south pole. The following points may be noted about the poles of a magnet :

- The poles of a magnet cannot be separated. If a bar of magnet is broken into two parts, each part will be a complete magnet with poles at its ends. No matter how many times a magnet is broken. Each piece will contain n-pole at one end and s-pole at the other.
- The two poles of magnet are of equal strength. The pole strength is represented by m.

3.3. Law of Magnet Force

- Like poles repel each other while unlike poles attract each other.
- The force between two magnetic is directly proportional to the product of their pole strengths and inversely proportional to the square of distance between them.

3.4. Magnetic Field

Just as electric field exist near a charged object , similarly magnetic field exist around a magnet. If an isolated magnetic pole brought near a magnet, it experiences a force according to coulomb's laws this region near the magnet where forces act on magnetic poles is call a magnetic field. The magnetic field is strongest near the pole and goes on decreasing in strength as we move away from the magnet. The space (or field) in which a magnetic pole experiences a force is called a **magnetic field.** The magnetic field around a magnet is represented by imaginary lines called magnetic lines of force by convention, the direction of these lines of force at any point is the direction along which an isolated unit N- pole placed at that point would move or tends to move. Following this convention, it is clear that magnetic lines of force would emerge from N-pole of the magnet, pass through the surrounding medium and re-enter the S-pole . Inside the magnet, each line of force passes from S-pole to N-pole as shown in figure(3.1) below, thus forming a closed loop or magnetic circuit.

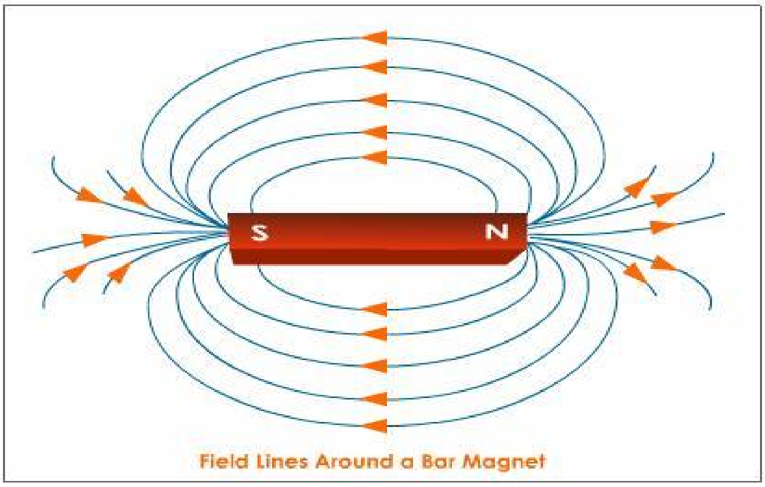


Figure (3.1) : Magnetic lines of force

Although magnetic lines of force have no real existence and are purely imaginary, yet they are a useful concept to describe the various magnetic effects.

3.5. Magnetic Flux

The magnetic field cannot be detected by any of our senses but its effect can be observed in many ways. To identify the magnetic field quantitatively (i.e. with numbers), we generally use the term magnetic flux. The amount of magnetic field produced by a magnetic source is called **magnetic flux**. Magnetic flux is denoted by Greek latter Ø. If 10 magnetic lines come out of the north pole or enter the south pole of a magnet then magnetic flux Ø = 10 lines or Maxwell's. The SI unit of magnet flux is weber.

3.6. Magnetic Flux Density

The magnetic flux density is the flux per unit area at right angles to the flux as shown in Figure (3.2) below i.e.

$$Flux\ density = B = \frac{\emptyset}{A} wb/m^2\ or\ Tesla(T) \qquad (3.1)$$

Where $\emptyset$= flux in weber.

A = area in m^2 normal to flux.

Flux density is a measure of field concentration i.e. amount of flux in each square meter of the field. In practice, it is much more important than the total amount of flux.

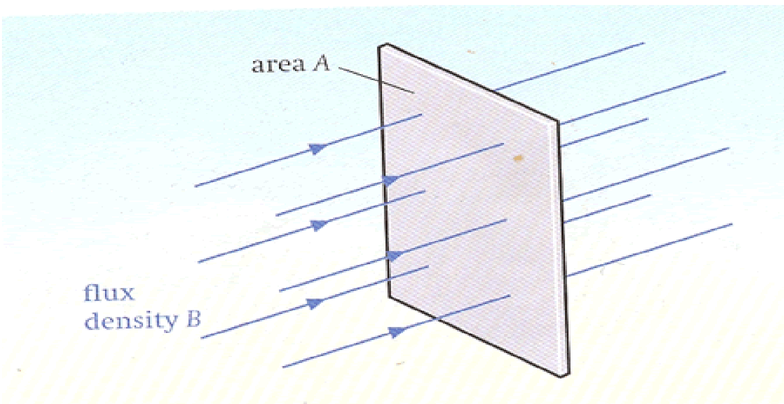


Figure (3.2) : Flux density

3.7. Magnetic Intensity or Magnetizing (H)

Magnetic field strength at any point within a magnetic field is numerically equally to the force.

Experienced by a *N*-pole of one weber placed at that point. Hence, unit of *H* is N/Wb.

Suppose, it is required to find the field intensity at a point A distant r meters from a pole of m weber's. Imagine a similar pole of one weber placed at point A. The force experienced by this pole is

$$F = \frac{m \times 1}{4\pi \times \mu_0 \times r^2} N \qquad (3.2)$$

$$H = \frac{M}{4\pi \times \mu_0 \times r^2} N/Wb \qquad (3.3)$$

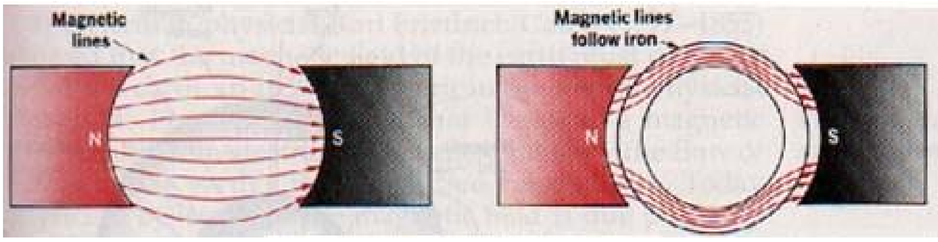
- The magnetic intensity is a vector quantity, possessing both magnitude and direction.
- If a pole of m wb is placed in a uniform magnetic field of strength H newton's per wb, then force acting on the pole, $F = mH\ newton$

3.8. Absolute and Relative Permeability

Permeability of a material means its conductivity for magnetic flux. The greater the permeability of a material, the greater is its conductivity for magnetic flux and vise-versa. Air or vacuum is the poorest conductor of magnetic flux. The absolute permeability μ_0 of air or vacuum is $4\pi \times 10^{-7}$H/m. The absolute permeability μ of magnetic materials is much greater than μ_0 . The ratio $\mu/\ \mu_0$ is called the relative permeability of the material and is denoted by μ_r. Obviously the relative permeability for air or vacuum would be $\mu_0/\ \mu_0=1$. The value of μ_r for all non-magnetic materials is also 1. However, relative permeability of magnetic materials is very high. For example soft iron has a relative permeability of 8000 whereas its value for permalloy(an alloy containing 22% iron and 78% nickel) is as high as 50,000.

3.8.1. Concept of Relative Permeability

The relative permeability of a material is a measure of the relative ease with which that material conduct magnetic flux compared with the conduction of flux in air. Figure(3.3) below illustrates the concept of the relative permeability. In fig (3.3), at (a) the magnetic flux passes between the poles of a magnet in air. Consider a soft iron ring placed between the same poles as shown at (b) in fig(3.3), since soft iron is a very good conductor of magnetic flux, the flux follows a bath entirely within the soft iron itself. The flux density in soft iron is much greater than its in air. In fact, flux density in soft iron will be 8000-times the flux density in air. Due to high relative permeability of magnetic materials (e.g. iron, steel and other magnetic alloys), they are widely used for the cores of all electromagnetic equipment.



(a) (b)

Figure (3.3): (a) the magnetic flux passes between the poles of a magnet in air. (b) magnetic flux follows the soft iron ring which is more permeable than air.

3.9. Relation between B and H

The flux density B produced in a material is a directly proportional to the applied magnetizing force H. In other words, the greater the magnetizing force, the greater in the flux density and vice-versa i.e.

$$\frac{B}{H} = constant = \mu \qquad (3.4)$$

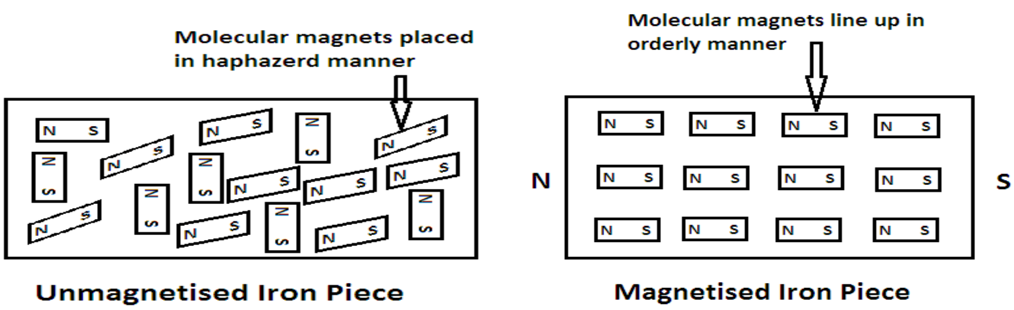
The ratio B/H in a material is always constant and is equal to the absolute permeability of the material. This relation gives yet another definition of absolute permeability of a material.

$$B = \mu_o \times \mu_r \times H \qquad (3.5)$$

3.10. Molecular Theory of Magnetism

There have been various theories developed from time to time for the explanation of magnetism. The theory proposed by Weber in 1852 and modified by Ewing in 1890, is the most popular explanation. According to this theory, molecules of all substances are basically magnets in themselves, each having a N and S pole. In other words every substance consist of a very large number of tiny magnets called molecular magnets.

- Before a piece of iron has been magnetized, these molecular magnets lie in disorderly position as shown in figure(3.5) (a) so that cools of molecular magnets neutralize each other .Hence the iron piece does not show any magnetism i.e. no poles are developed at the end.



(a) (b)

Figure (3.4): Unmagnetized and magnetized iron piece.

- When a magnetizing force is applied to the iron bar (by rubbing a magnet or passing electrical current through a wire wound over it) the molecular magnets are turned and tend to line up in an orderly manner, with N-pole of wound molecular magnet facing the S-pole of another as shown in figure (3.5) (b) above. The result is that magnetic field of molecular magnets aid each other and two definite N and S poles are developed at the end of the iron bar. Hence the iron piece get magnetized.

3.11. Magnetic Material

The magnetic properties of a magnetic material depend on the orientation of the crystals of the material and decide the size of the machine or equipment for a given rating, excitation required, efficiency of operation etc.. The some of the properties that a good magnetic material should possess are listed below:

- . Low reluctance or should be highly permeable or should have a high value of relative permeability μ_r.
- High saturation induction (to minimize weight and volume of iron parts).
- High electrical resistivity so that the eddy emf and the hence eddy current loss is less.
- Narrow hysteresis loop or low coercivity so that hysteresis loss is less and efficiency of operation is high.
- A high curie point. (Above Curie point or temperature the material loses the magnetic property or becomes paramagnetic, that is effectively non-magnetic).
- Should have a high value of energy product (expressed in joules / m^3).

Magnetic materials can broadly be classified as Diamagnetic, Paramagnetic, Ferromagnetic, Antiferromagnetic and Ferromagnetic materials. Only ferrimagnetic materials have properties that are well suitable for electrical machines. Ferromagnetic properties are confined almost entirely to iron, nickel and cobalt and their alloys. The only exceptions are some alloys of manganese and some of the rare earth elements.

The relative permeability μ_r of ferromagnetic material is far greater than 1.0. When ferromagnetic materials are subjected to the magnetic field, the dipoles align themselves in the direction of the applied field and get strongly magnetized. Further the Ferromagnetic materials can be classified as Hard or Permanent Magnetic materials and Soft Magnetic materials.

a) Hard or permanent magnetic materials have large size hysteresis loop (obviously hysteresis loss is more) and gradually rising magnetization curve. Ex: carbon steel, tungsten steal, cobalt steel, alnico, hard ferrite etc.

b) Soft magnetic materials have small size hysteresis loop and a steep magnetization curve Ex: cast iron, cast steel, rolled steel, forged steel etc., (in the solid form). Generally used for yokes poles of dc machines, rotors of turbo alternator etc., where steady or dc flux is involved.

3.12. History and Characteristics of Permanent Magnets

Excluding the natural magnet, magnetic (Fe3O4), the development and manufacture of permanent magnet materials began in the early twentieth century with the production of carbon, cobalt and wolfram steels. These permanent magnet materials, the magnetic properties of which were rather poor, remained the only permanent magnet materials for decades. A remarkable improvement in the field was due to the discovery of AlNi and especially AlNiCo materials. The next significant step forward was taken in the 1960s, when the compounds of rare-earth metals and cobalt were invented. The most important materials were SmCo5 and Sm2Co17. Previously, a serious problem with permanent magnet materials was the easy demagnetization of the materials. The best permanent magnet materials are quite insensitive to external field strengths and the influence of an air gap. Only short-circuit currents in hot machines may constitute a risk of demagnetization in certain structures. The most significant permanent magnetic materials in commercial production are the following:

- AlNiCo magnets are metallic compounds of iron and several other metals. The most important alloying metals are aluminum, nickel and cobalt.
- Ferrite magnets are made of sintered oxides, barium and strontium hexa-ferrite.
- RECo magnets (rare-earth cobalt magnets) are produced by a powder metallurgy technique, and comprise rare–earth metals(mainly samarium) and cobalt in the ratio of 1:5 and 2:17. The latter also includes iron, zirconium and copper.
- Neodymium magnets are neodymium–iron–boron magnets, produced by a powder metallurgy technique.

Neodymium magnets were invented in 1983. They are produced by a powder metallurgy process developed by Sumimoto, or by a 'melt-spinning' process developed by General Motors. These materials typically comprise about 65% iron, 23% neodymium and 12% boron, with small amounts of aluminum and niobium. In some cases, dysprosium and cobalt are also employed. Neodymium magnets are sensitive to changes in temperature. The intrinsic coercive force drops notably when the temperature rises. However, by employing other rare-earth metals as alloying elements for neodymium, the operating temperature can be raised to 180°C. Due to their properties, neodymium magnets can be employed in electromagnetic hoists, magnetically suspended trains, generators, magnetic separation devices and in various motors.

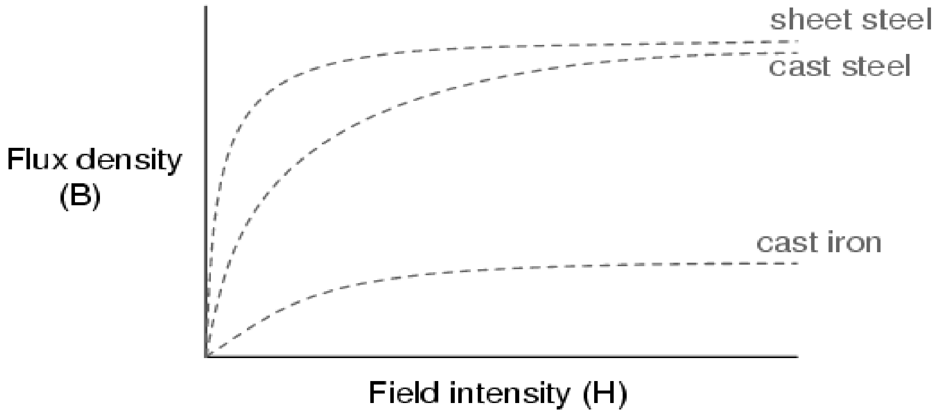
3.13. Application of Permanent Magnets in Electrical Machines

Permanent magnets are applied in a wide range of small electrical machines. They are utilized for instance in the excitation of DC machines and synchronous machines, and in hybrid stepper motors. Permanent magnets are increasingly occurring in large machines too. There are already permanent magnet synchronous machines of several megawatts in for instance direct driven wind-power generators. Permanent magnets can in some cases be employed as magnet bearings. In that case, the repulsive reaction between two permanent magnets is utilized. In the design of a magnetic circuit with a permanent magnet material, more iteration is required than in the design of magnetic circuits of ordinary machines. Since the permeability of a permanent magnet material roughly equals the permeance of a vacuum, the permanent magnet material has a very strong influence on the reluctance of the magnetic circuit, and thus also on the inductances of the armature winding of the rotating-field machine.

3.14. B-H curves

The B-H curve (or magnetization curve) indicates the manner in which the flux density (B) varies with magnetizing force (H). Fig (3.8) below shows the general shape of B-H curve of a magnetic material. The non-linearity of the curve indicates that the relative permeability ($\mu_r = \frac{B}{\mu_0 \times H}$)

of a magnetic material is not constant but depends very largely upon the flux density.



Fig(3.5): B-H curves for a magnetic materials

While carrying out magnetic calculation, it should be ensured that the values of μ_r and H are taken at the working flux density. For this purpose, the B-H curve of the material in question may be very helpful. In fact, the use of B-H curves permits the calculations of magnetic circuits with a fair degree of ease.

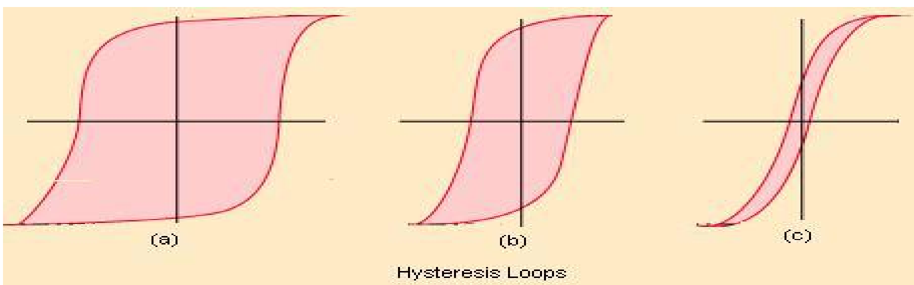
3.15. Magnetic Hysteresis

When a magnetic material is subjected to a cycle of magnetization (i.e. it is magnetizing first in one direction and then in the other), it is found that the flux density B in material lags behind the applied magnetizing force H. This phenomenon is known as hysteresis. Also, when a magnetic is subjected to a cycle of magnetization, an energy loss take place due to the molecular friction in the material. That is, the molecular magnets of the material resist being turned first in one direction and then the other. Energy is thus expended in the material in overcoming this opposite. This loss is in the form of heat and is called hysteresis loss. The obvious effect of hysteresis loss is the rise of temperature of the machine.

3.16. Importance of Hysteresis Loop

The shape and size of the hysteresis loop largely depends upon the nature of the material. The choice of a magnetic material for particular application often depends upon the shape and size of the hysteresis loop. A few cases are discussed below by way of illustration:

- The smaller the hysteresis loop area of a magnetic material, the less is the hysteresis loss. The hysteresis loop for silicon steel has a very small area as shown in figure (3.9)(c) below. For this reason, silicon steel is widely used for making transformer cores and rotating machines.
- The hysteresis loop for hard steel indicates that this material has high retentivity and coercivity as shown in figure(3.9)(a). Therefore, hard steel is quite suitable for making permanent magnets. But due to large area of the loop, there is greater hysteresis loss. For this reason, hard steel is not suitable for the construction of electrical machines.
- The hysteresis loop for wrought iron shows that this material has fairly good residual magnetism and coercivity as shown in figure (3.9)(b). Hence, it is suitable for making cores of electromagnets.



Figure(3.6): Hysteresis loops of such types of materials.