Electrotechnical Materials

Chapter 2

Ferromagnetic materials

II.1. Introduction

The materials used in electrical engineering at industrial frequencies are ferromagnetic, due to their high susceptibility and saturation magnetization. For frequencies above 10 *kHz*, ferrimagnetic materials are generally used. Although the latter have lower saturation magnetization, they have significantly lower magnetic losses, which is important as the operating frequency increases. One class of ferromagnetic materials can be used at high frequencies: amorphous materials, which are generally found in the form of very thin sheets.

They have a saturation induction intermediate between that of ferrites and that of conventional sheets.

Magnetic materials are generally divided into two classes: soft materials and hard materials (permanent magnets). Soft magnetic materials can be magnetized using weak magnetic fields. They are used in electrical machines to channel and concentrate the magnetic flux. Hard magnetic materials retain their initial magnetization even when a relatively high magnetic field is applied. They are used as a source of magnetic field in electrical machines. Coercivity is the inverse external magnetic field that must be applied to nullify the magnetization of a material that has been brought to saturation. Soft materials used in electrical machines have a much lower coercivity, in the range of tens to hundreds of amperes per meter, while hard magnetic materials used in modern permanent magnets have a much higher coercivity, in the range of hundreds of thousands of amperes per meter.

II.1.1. First magnetization curve, hysteresis cycle

These curves show how a ferromagnetic body reacts to magnetic excitation H.

Initial magnetization curve: This is the curve B = f(H) when the ferromagnetic body has no magnetization.

Material initially demagnetized (no magnetization). Under the action of an increasing magnetic field.

⇒ Displacement of the Bloch walls.

⇒ Enlargement of energetically favored domains and disappearance of others.

Hysteresis cycle: This is the curve B = f(H) when the ferromagnetic body already has magnetization.

As the material is magnetized, the field H is reduced.

⇒ Magnetization does not return to the same curve; in particular, for a zero field, magnetization remains greater than 0:

Linear zone: in this zone, B = μ.H with μ constant. It is this zone that is generally used for transformers and rotating machines.

Saturation of the ferromagnetic medium: when H becomes too large, B hardly varies at all.

The magnetic material is said to be saturated. We still have B = μ.H, but μ is no longer constant.

Remanent field Br: field that remains when H = 0 (i1 = 0).

Coercive excitation Hc: excitation H required to cancel the remanent field Br.

Hysteresis: this is the doubling of the B(H) characteristic of the magnetic material.

Therefore, B depends not only on H, but also on the previous magnetization.

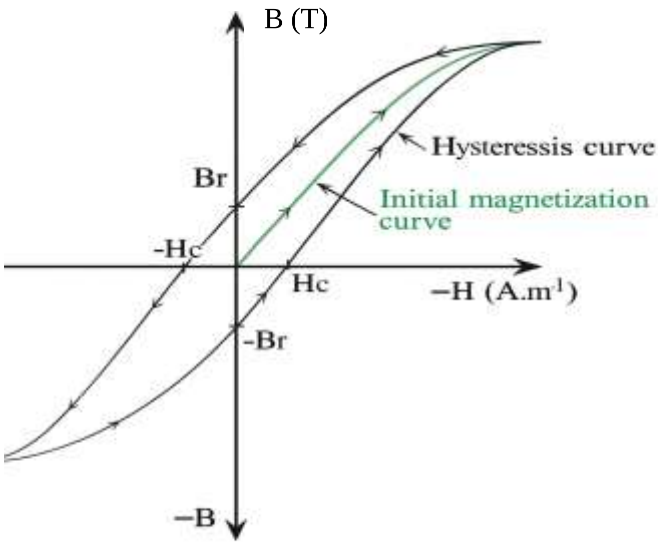

Fig. II.1. Hysteresis curve.

There are three zones in the initial magnetization curve: linear zone, saturation bend, saturation.

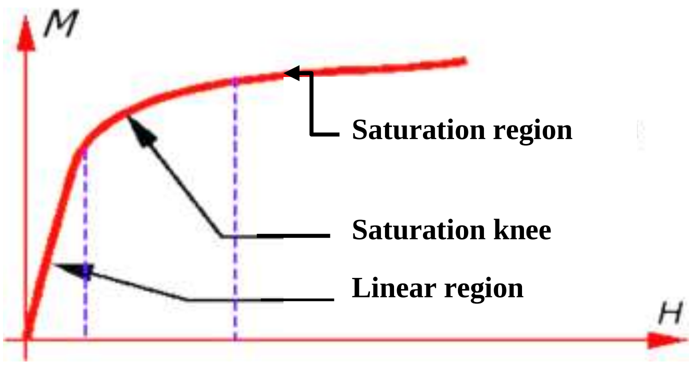

Fig. II.2. Zones of the first magnetization curve.

II.1.2. Hysteresis cycle of different materials

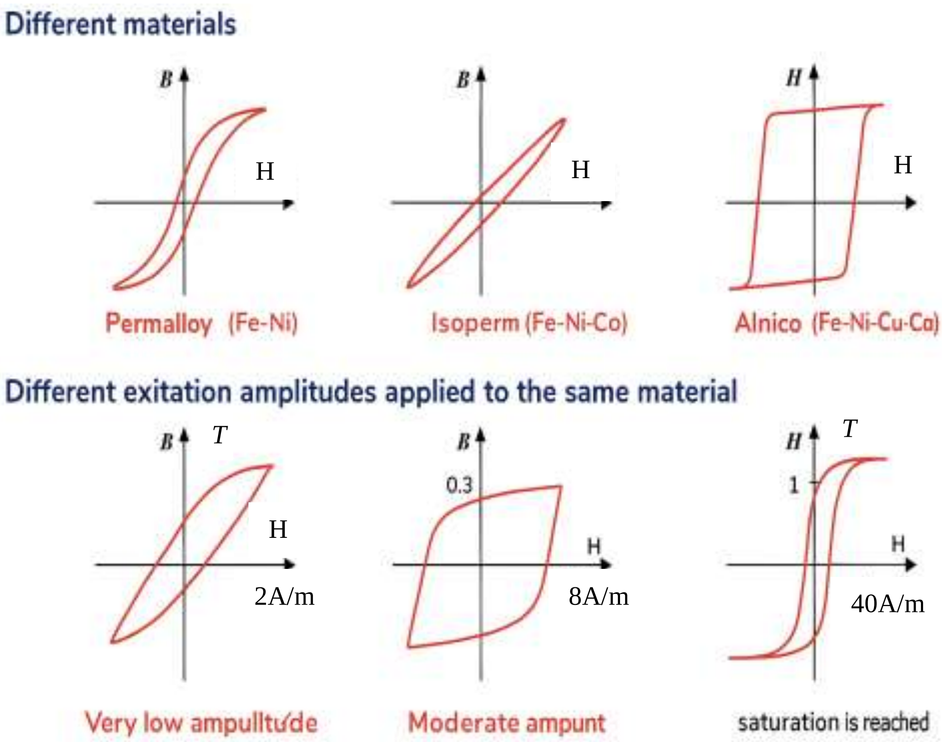

Fig. II.3. Hysteresis cycle of different materials.

II.2. Classification of ferromagnetic materials

These materials are used to channel the magnetic flux in the air gap of rotating electrical machines (magnetic circuits). They are also the source of the excitation magnetic field (permanent magnets).

II.2.1. Soft ferromagnetic materials

These are materials that have a remanent magnetization that is easy to cancel. They are characterized by:

- ✓ Magnetization increases rapidly with the applied field.
- ✓ A relatively high BR
- ✓ Rather low HC

⇒ Easy demagnetization

- ✓ Low hysteresis loop area (*the loop is narrow*).

Example: iron, certain iron and nickel steels, ferrites

Application:

They are used for motors and transformer magnetic circuit sheets.

Example of alloys used for transformer sheets: FeSi 3.5% Si

Saturation at 2 T

$B_r \approx 0$

$H_c \approx 0$

$\mu_r = 7000$ at 50 Hz

Grain-oriented FeSi

Saturation at 3 T

$B_r = 1.4$ T

Hc = 8 A/m

μr > 40,000 at 50 Hz

II.2.2. Hard ferromagnetic materials

These are materials that have strong remanent magnetization that is difficult to cancel. They are characterized by:

- ✓ magnetization increases slowly with the applied field
- ✓ relatively low $_{BR}$
- ✓ relatively high $_{HC}$

⇒ Difficult to demagnetize: application to permanent magnets

- ✓ Large hysteresis loop area (*the loop is wide*)
- ✓ Magnetic losses (proportional to the area of the cycle) are quite significant.

Example: magnetite, AlNiCo alloy, special steels.

Application:

They are used to make permanent magnets.

Examples of alloys used for magnets.

Ferrite (iron oxide)

Saturation at ≈ 0.6 T

Br ≈ 0.4 T

Hc ≈ 200 kA/m

Samarium-Cobalt (Sm-Co)

Saturation at ≈ 1 T

Br = 0.8 T

Hc = 500 kA/m

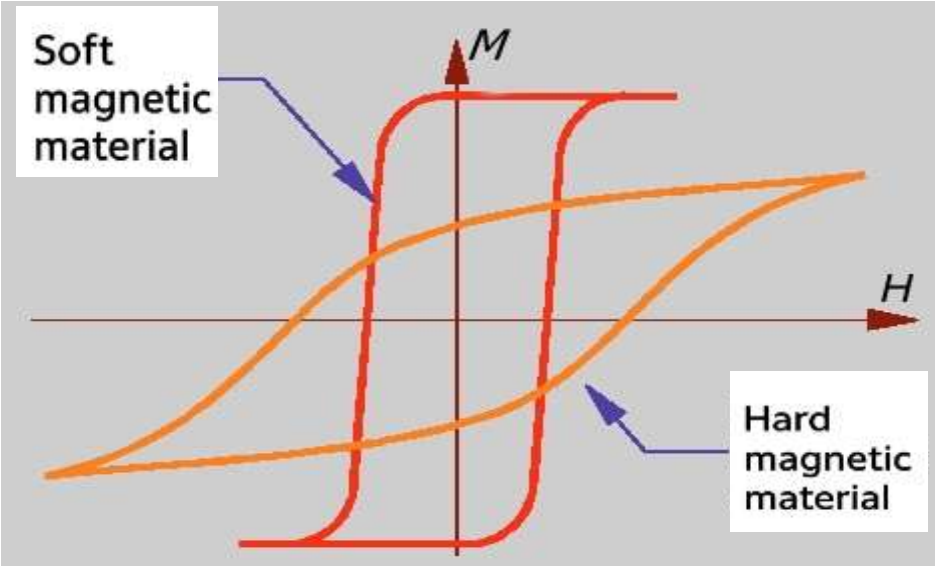

Fig. II.4. Hysteresis cycle of hard and soft materials.

II.3. Characterization of permanent magnets

II.3.1 History

Permanent magnets were first developed using steel or chromium-cobalt. Around 1935, researchers began studying alloys of iron-aluminum, nickel, cobalt, and copper. These melted or sintered alloys are known as ticonal or alnico. In 1951, they began using barium and strontium ferrites. Currently, ticonal and ferrite alloys are commonly used and are the two most widely used types of permanent magnet materials.

With modern materials, demagnetization due to aging or the action of a magnetic field (not too intense) can be considered negligible. This property also makes it possible to produce magnets with opposite poles very close to each other

One another. These different properties have made it possible to abandon the traditional shapes of permanent magnets, such as horseshoes or long bars. It is now possible to produce magnets in a variety of shapes that are very practical.

In electrical measuring devices (galvanometers, ammeters, and voltmeters), they have led to significant improvements in sensitivity and reliability. In certain motors and generators (car alternators, dynamos, magnetos), they are used instead of electromagnets. They are also used in electronics for loudspeakers and microphones.

Permanent magnets come in various shapes (bars, U-shaped). They attract all ferrous substances (filings, nails, etc.) with their ends, called magnetization poles: north and south poles. Two poles of the same name repel each other, while two poles of opposite names attract each other. It is impossible to isolate a magnet pole by breaking it.

They create magnetic induction from magnetic energy acquired once and for all. A permanent magnet is more effective when its remanent magnetization is high and its coercive field is strong (no risk of demagnetization).

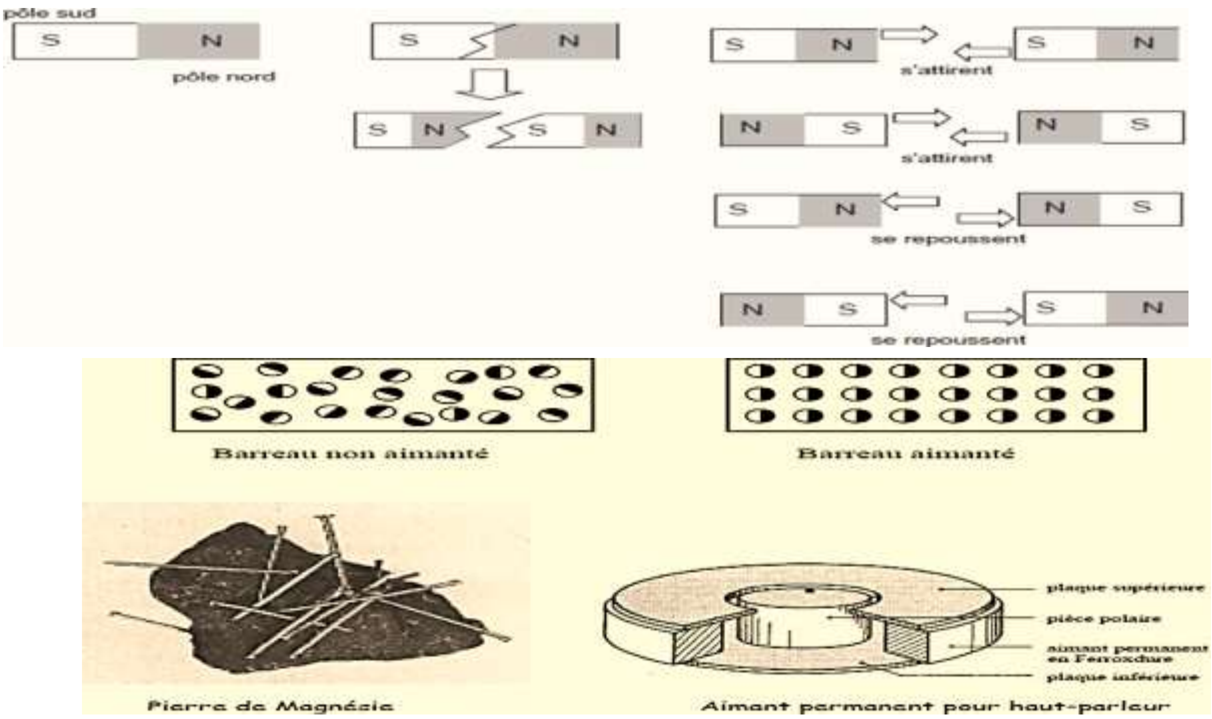

Fig. II.5. Characteristics of permanent magnets

II.4.2. Magnetic fields

In the region around a permanent magnet, there is a magnetic field that can be represented by magnetic lines of force similar to electric lines of force.

Unlike electric lines of force, magnetic lines of force do not originate at any point or terminate at any point; rather, they appear in the form of loops.

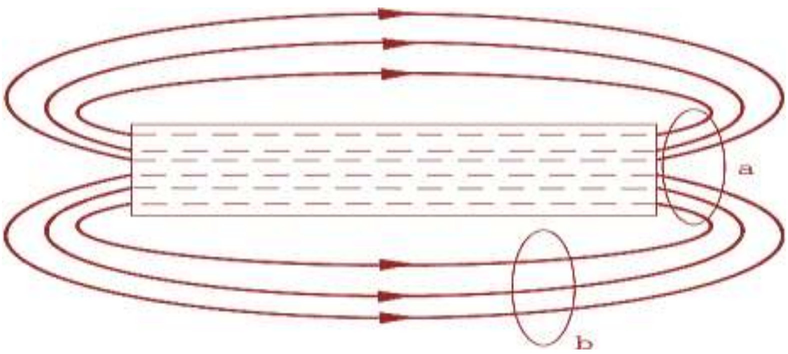

Fig. II.6. Direction of magnetic field lines.

The lines of force run from the north pole to the south pole on the outside of the magnet bar, and from the south pole to the north pole on the inside. They are evenly spaced and symmetrically distributed around the bar.

The lines of force occupy the smallest possible area and their inter-polar length is minimal. The strength of the magnetic field in any region depends directly on the number of lines of force per unit area. In the figure above, the field strength is twice as great at point a as at point b, even though the two areas are identical.

Magnets create a magnetic field, represented by a vector *B* whose direction and sense at a given point are defined as follows:

- Direction: that of the axis of a magnetized needle, Figure II.8, (compass) placed at the point in question.
- Direction: the south-north direction of this same needle.

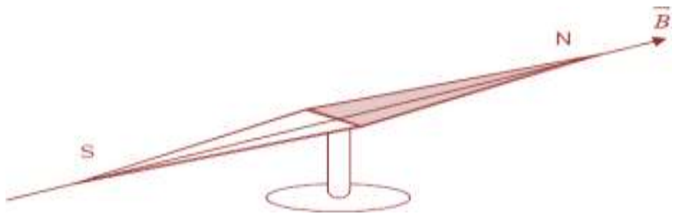

Fig. II.7. Compass orientation in a magnetic field.

✓ **Field lines**

To visualize the magnetic field, iron filings can be sprinkled onto a sheet of paper placed over a magnet. The filings arrange themselves into closed curves called **field lines**, which are tangent at each point to the magnetic field vector and oriented in the direction of the field. There are an infinite number of them.

In the case of a magnet, the field lines are oriented from the north pole to the south pole outside the magnetized material. All of these lines together form a magnetic spectrum. It should be noted that on Earth, the field lines emerge from what is known as the geographic South Pole, which therefore corresponds to a magnetic North Pole.

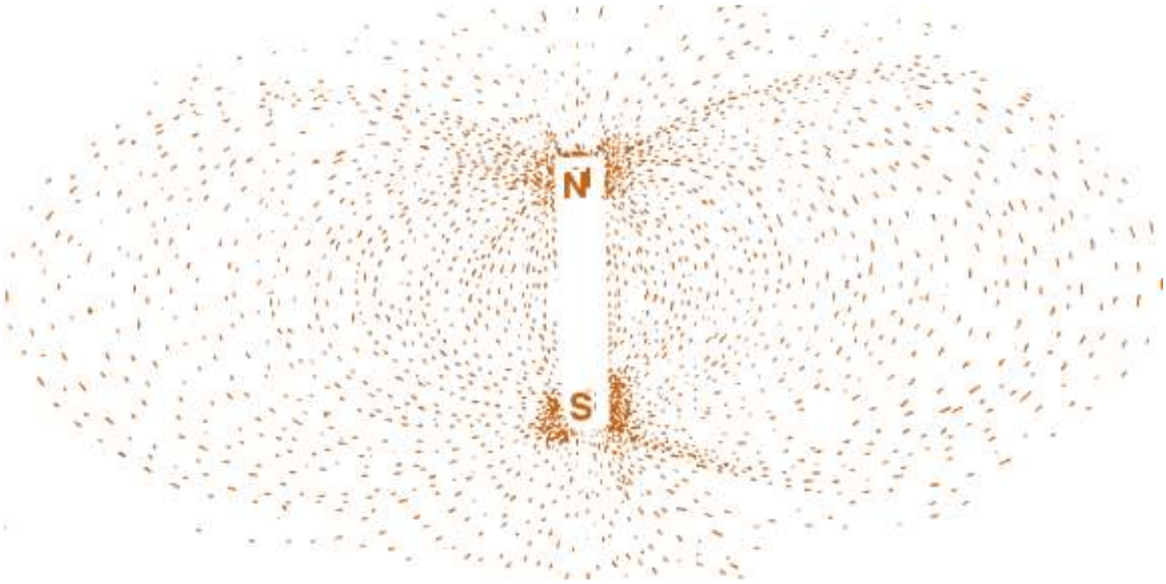

Fig. II.8. Magnetic spectrum described by iron filings around a magnetized bar.

- **Field tube**

In space, a bundle of field lines resting on two contours (C1) and (C2) forms a field tube.

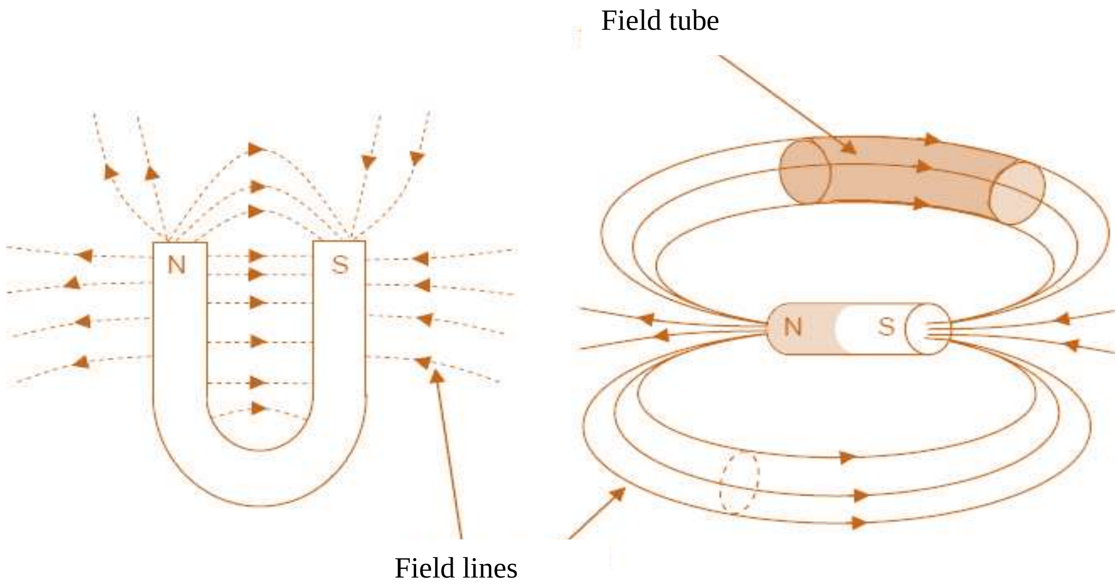

Fig. II.9. Resulting magnetic spectrum

- **Magnetization by influence**

A soft iron bar placed near a magnet, even without touching it, temporarily acquires the properties of a magnet (Fig. II.10). We say that the bar is magnetized by influence.

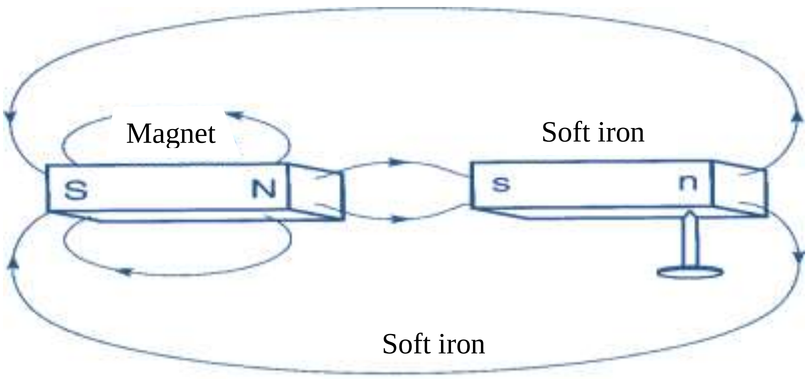

Fig. II.10. Phenomenon of magnetization by influence.

The soft iron bar has two poles and becomes a complete magnet. Its end closest to the north pole of the magnet will become a south pole. The bar becomes magnetized as follows: a south pole is formed at the end where the lines of force enter the bar and a north pole at the end where they exit.

This phenomenon of magnetization by influence explains the attraction exerted by a magnet on an iron bar: when the bar is brought close to one pole of the magnet, an opposite pole is established in the bar and causes the attraction.

We can verify that the soft iron bar has also acquired the property of attracting iron by suspending a nail from it.

When the soft iron bar is moved away from the magnet, the magnet's influence is no longer felt, the magnetization of the soft iron disappears, and the nail falls.

- ✓ **Effect of soft iron on a magnetic field**

Fig. II.11 shows what happens when a piece of soft iron is placed in the magnetic field of a magnet: the lines of force are distorted

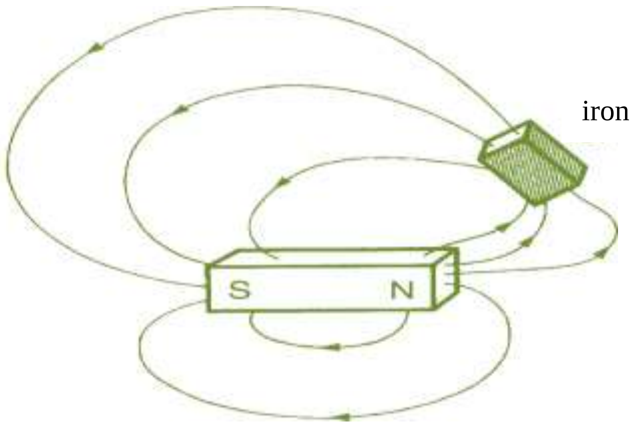

Fig. II.11. The lines of flux tend to pass through a piece of iron placed near a magnet.

It is as if they are trying to pass through the iron rather than continue through the air. The lines of force appear through the iron. We say that iron is more permeable to lines of force than air, because they pass through it more easily. Iron is a better conductor of magnetic flux than air.

II.4. Conclusion

Ferromagnetic materials are currently used in various fields such as permanent magnets and high-density magnetic recording. These materials are characterized by their intrinsic properties (depending on chemical composition) and extrinsic properties (depending on microstructure).

The hysteresis cycle represents the response of a material to an applied field. It gives the interesting magnetic characteristics of a sample. In general, from a practical point of view

The hysteresis cycle of ferromagnetic materials is used to determine certain physical quantities such as remanent magnetization and coercive field. Based on the shape of the hysteresis cycle, ferromagnetic materials can be divided into two main categories: soft and hard materials.