CHAPTER 2:

Ferromagnetic Materials

Chapter outline

2.1. Introduction:

Ferromagnetic materials are characterized by atomic magnetic moments that are caused by electron motion. Every magnetic moment is represented as a vector with a direction and an Am^2 unit. Atomic magnetic moments are aligned in the same direction throughout tiny zones called Weise domains (Fig. 2.1-a). Because of the exchange interaction, a quantum force that aligns the electron spins of neighboring atoms in the same direction, magnetic domains spontaneously (naturally) emerge in ferromagnetic materials. Magnetic domain structure determines the magnetic characteristics of ferromagnetic materials, such as iron, nickel, cobalt, and their alloys.

It is common for the magnetic domains of ferromagnetic materials to line up with a sufficiently high magnetic field. This physical phenomenon is known as magnetization (Fig. 2.1-b). Magnetization channels the magnetic field lines and allows for the intensification of the resultant magnetic field through the material. The material reaches a limit of magnetization, also referred to as saturation, when all of the magnetic moments line up with the external excitation field (Fig. 2.1-c).

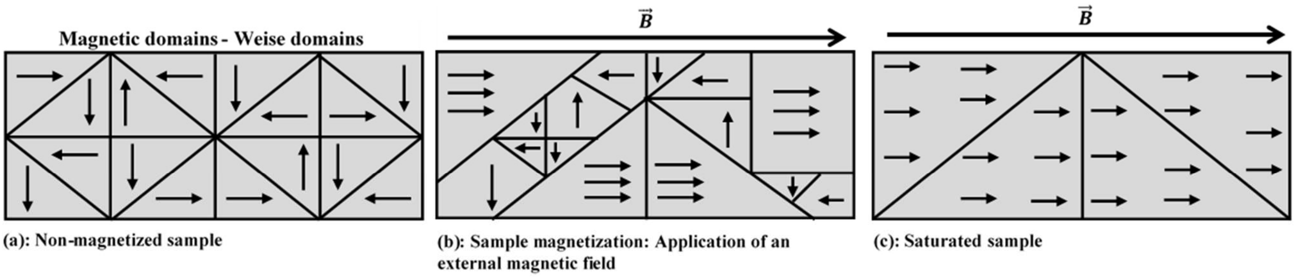

Fig. 2.1. Magnetization process in a ferromagnetic material

2.2. Ferromagnetic materials magnetization:

In physics, magnetization is a vector quantity that describes the macroscopic magnetic activity of a material. It is measured in amperes per meter (Am^{-1}) and is based on the electrons' orbital and spin magnetic moments.

Remember that each magnetic moment represents a vector quantity $(\vec{M})$ with a direction and a unit measured in Am^2. When considering a material sample with a small volume, the magnetization vector $(\vec{A})$ is the vector that is obtained by dividing the total number of magnetic moment vectors by the material sample's volume:

$$\vec{A} = \frac{1}{Vol}\sum_i \vec{M}_i \tag{2.1}$$

In vacuum, the relationship between the magnetizing intensity and the magnetic field $(\vec{B}_0)$ and its excitation $(\vec{H})$ is as follows:

$$\vec{B}_0 = \mu_0(\vec{H} + \vec{A}) \tag{2.2}$$

In any kind of material, it's given by:

$$\vec{B} = \mu(\vec{H} + \vec{A}) = \mu_r\vec{B}_0 \tag{2.3}$$

Where μ_0, μ and μ_r are respectively, vacuum, material and material relative permeabilities. Two categories of magnetization may be distinguished from the preceding equations:

- Spontaneous Magnetization $(\vec{A})$: Spontaneous magnetization is the natural magnetization $(\vec{A})$ that occurs in a subset of ferromagnetic materials without the requirement for external magnetic stimulation. The material's magnetic moments naturally align to produce this magnetization. The value of spontaneous magnetization in a material is usually quite small.
- Magnetization by an external magnetic field $(\vec{H})$: Generally, in ferromagnetic materials, the magnetization is zero in the absence of external magnetic excitation. Indeed, the existence of magnetic moments with non-uniform orientations results in a zero vector sum (except in the case where there are moments with small amplitude differences). When an external magnetic field $(\vec{H})$ is applied to the material, as indicated above, the magnetic moments orient in the same direction as the field, resulting in a forced magnetization.

Due to the low value of spontaneous magnetization in ferromagnetic materials, the magnetic field is assimilated to that generated by the magnetization arising from external stimulation:

$$\vec{B} = \mu(\vec{H} + \vec{A}) \approx \mu\vec{H} \tag{2.4}$$

2.2.1. Magnetization and Hysteresis Cycle:

Starting with a demagnetized material $(\vec{H} = \vec{0},\ \vec{A} = \vec{0})$, plotting the change of the magnetic induction at $(\vec{B})$ as a function of the external excitation $(\vec{H})$ demonstrates that $(\vec{B})$ follows the so-called first magnetization curve as the field intensity grows. This curve first rises linearly before hitting an asymptote called "magnetic saturation," which is determined by a saturation induction (B_S). If the magnetic field is gradually reduced, the magnetization shows a clear curve in the opposite direction. At zero field, the magnetization is shifted away from the origin by an amount called residual induction (B_r), figure (2.2).

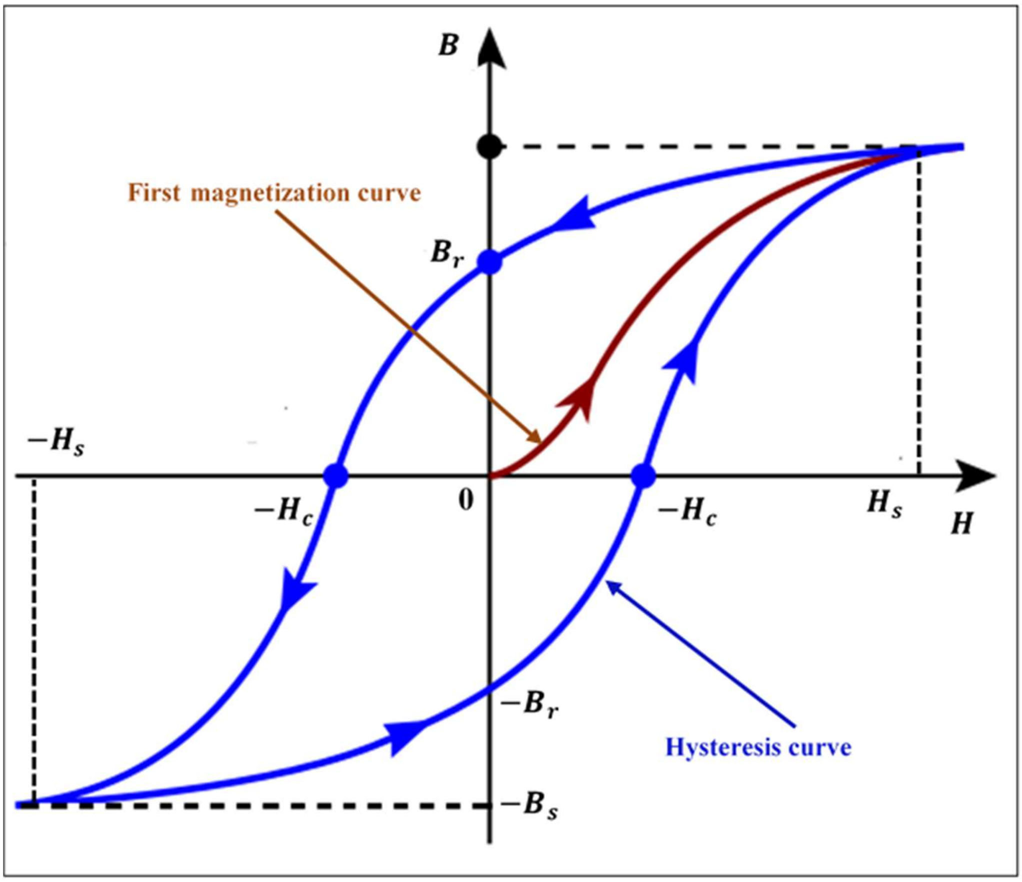

Fig. 2.2. The magnetization curve of a ferromagnetic material

The magnetization gradually decreases as the field decreases further, reaching zero for a magnitude of the excitation field known as the coercive field $(\vec{H}_c)$. The magnetization then reverses and approaches the minimum that is achieved for negative field values.

When all magnetization values are plotted against the magnetic field, a hysteresis curve is created. The hysteresis curve's form is determined by the following factors:

- Saturation field (H_S): The field strength at which a material achieves magnetic saturation;
- Saturation induction (B_S): The highest induction that a material may achieve; even as the excitation field increases, the magnetic induction stays constant above this value;
- Residual induction (B_R): The induction value that the material maintains after the cancellation of the excitation field;
- Coercive field (H_c): The value of the excitation field that must be delivered to the material in order to remove the residual magnetic induction.

2.2.2. Temperature's effect on magnetization:

It should be noted that ferromagnetic materials have magnetic properties at ambient temperature. High temperatures cause the material to lose its magnetic properties. For ferromagnetic materials, the Curie temperature (T_c) is a characteristic temperature at which their ferromagnetic properties cease to exist, for example; Iron $(T_c = 770°C)$, Cobalt $(T_c = 1131°C)$, Nickel $(T_c = 358°C)$. As the material cools, these properties reappear.

2.3. Ferromagnetic material types and their uses

Two types of ferromagnetic materials can be distinguished based on the hysteresis curve's shape and the values of its characteristic quantities:

- Soft magnetic materials
- Hard magnetic materials or permanent magnetic materials

2.3.1. Soft magnetic materials

These materials are distinguished by an extremely thin (narrow) hysteresis cycle that has the following characteristics (Fig. 2.3):

- Magnetic saturation is attained at low applied field levels, and magnetization changes quickly as the excitation field changes. These materials have very high magnetic susceptibility, which describes a material's capacity to magnetize.
- High residual induction, but easily cancelable.
- Lower coercive field strength (less than kA/m). The material may be easily magnetized and demagnetized, even at low excitation field levels.
- Temperature accelerates the demagnetization of the material.
- There is little energy lost as heat because of the hysteresis loop's small shape. This energy is known as magnetic losses and is represented in Jm^{-3} and relates to the area of the hysteresis loop.
- This kind of material is ideal for high-frequency applications because of the previously described properties, especially its high susceptibility and minimal magnetic losses.

Soft ferromagnetic materials are mostly composed of iron (Fe), cobalt (Co), nickel, chromium (Cr), manganese (Mn), molybdenum (Mo), and other elements.

Soft ferromagnetic materials, as previously stated, have small hysteresis loops in order to reduce hysteresis losses. Typically, magnetic circuits are made of iron alloys with components chosen according to the frequency of use, and they are laminated to reduce eddy currents. There are three primary categories:

A. Low frequency electrical steels (f=50Hz):

These are brittle iron steel sheets that have been alloyed with silicon (1–5%) to improve resistivity. There are two types of sheets: grain-oriented and non-grain-oriented.

- Non-grain-oriented sheets are produced via hot rolling, chemical pickling, cold rolling again, and heat treatment. They are used in low-power transformers (less than 100kW) and rotating electrical machines.
- Grain-oriented sheets undergo many cycles of cold rolling followed by heat treatment. These sheets have better magnetic properties in the rolling direction. They are often found in electrical equipment with high power (>1MW).

B. Fe-Ni, Fe-Co alloys: (mid-frequency: f<100kHz):

Magnetic circuits are obtained by alloying iron with nickel or cobalt, with significant percentages for the latter two. Given the high prices of nickel and especially cobalt, the resulting magnetic circuits are quite expensive.

C. Soft ferrites: (high frequency: f<1000kHz):

Magnetic circuit is only an iron oxide-based ceramic ($XFe_{12}O_{19},\ X = Mn, Ni\ ou\ Zn$). After being pounded into a powder, the combination is assembled by sintering it at temperatures of around 1200°C. Although the resultant circuit is incredibly solid and very resistant, it is also quite fragile.

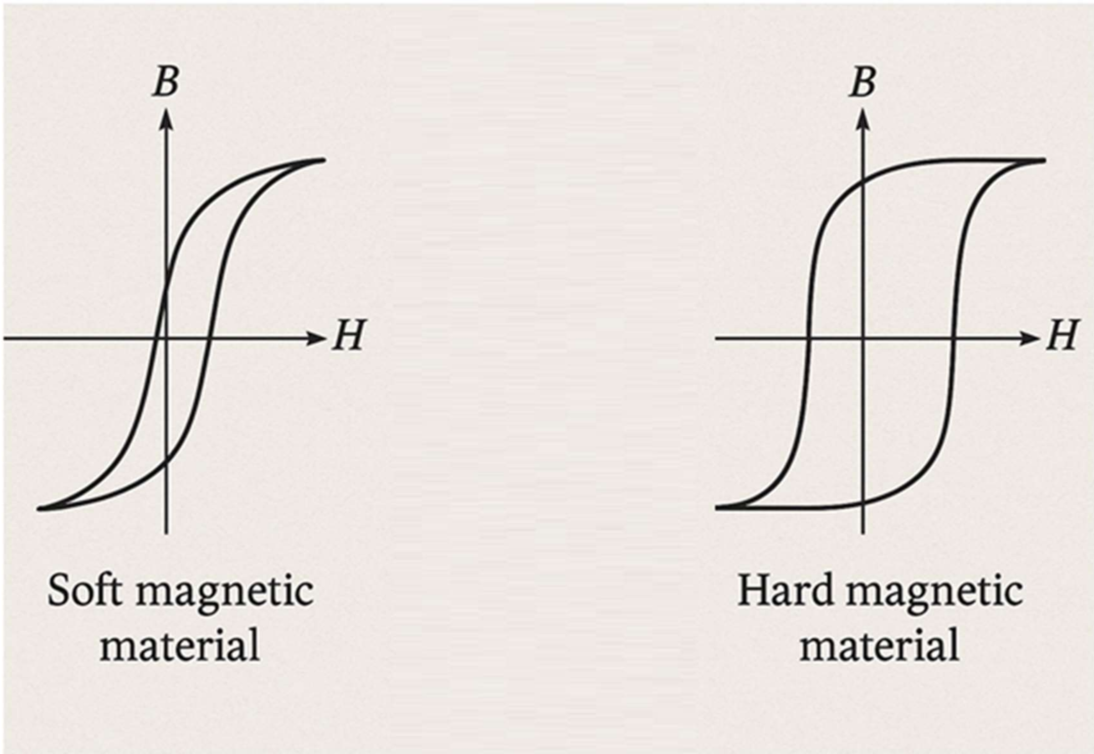

Fig. 2.3. Hysteresis cycles for soft and hard ferromagnetic materials

Soft ferromagnetic materials have diverse applications, including:

- Rotating and static electrical machines
- Safety devices: residual current circuit breakers, magnetic shielding
- Machine tools
- Transportation (trains, trams, electric vehicles, etc.)
- Switching power supplies and small instruments, such as relays, tachometers, and measurement devices
- Telephony
- Various automobile equipment, such as fuel pumps, fans, windshield wipers, and starters
- Household appliances
- Toys

2.3.2. Hard magnetic materials

In contrast to soft magnetic materials, hard ferromagnetic materials have a very wide hysteresis cycle that has the following characteristics (Fig. 2.3):

- For magnetization to attain saturation, strong excitation field levels and a considerable time are needed.
- The saturation magnetization is quite high. It has a maximum value of around 10 Tesla.
- After removing the external excitation field, they still have a remanent induction of 0.2 to 1.3 Tesla.
- A strong coercive field (between 50 and 1500 kA/m). This indicates that an extremely strong external magnetic field is required to cancel out or reverse the material's inherent magnetism.
- Even at very high temperatures, the remanent induction is maintained.
- Hard ferromagnetic materials are excellent candidate for permanent magnets because of the above-described characteristics.

There are different types of hard magnetic materials used as permanent magnets. Depending on the process used for hardening, three main categories are distinguished:

A. Alnico Materials:

This substance is an alloy of cobalt (Co), nickel (Ni), and aluminum (Al). Iron (Fe), copper (Cu), and sometimes titanium (Ti) are added to these elements. These materials may generate a magnetic field of up to 0.15 Tesla. The magnetization can be in any direction (isotropic materials) or in a single direction (anisotropic materials), where the magnetization is stronger. These materials have the highest Curie temperature (approximately 800°C). Alnico materials are manufactured by casting or sintering.

The manufacturing process for alnico-based magnets involves heating above the critical temperature, followed by cooling in the presence of a magnetic field, and finally heat treatment to become magnetized.

B. Hard Ferrites:

Hard ferrite magnets are generally composed of iron oxide ceramics. They can be isotropic or anisotropic. They have a relatively low coercive field ($Hc \approx 2{,}5 \times 105^5 A/m$). The Curie temperature of these materials is generally between 125°C and 300°C.

Isotropic magnets are produced using the dry method (pressing). These magnets are then magnetized in a magnetic field. They can easily be magnetized in different directions, as needed. Anisotropic magnets, on the other hand, are produced using the wet method (injection of the metal into a mold under a magnetic field). Magnetization is then only possible in the direction predetermined during production. These magnets are more economical and more widespread.

C. Intermetallic materials (rare earth-based):

These substances consist of rare earth and transition metal. They appeared in the 1960s, later than the previous two. The strong magneto-crystalline anisotropy of the rare earth is associated with the strong magnetization of the transition metal. Powder metallurgy is used to obtain this type of material. These materials have a high coercive force ($Hc \approx 1 \times 105^7 A/m$) and a fairly high Curie temperature (between 300°C and 750°C).

Magnets can be obtained from different rare earths (RCo_5, $R_2Fe_{14}B$, $R_2Fe_{17}N_3$, where R represents a rare earth). Neodymium is the most often utilized substance; one example is the neodymium magnet, which is $Nd_2Fe_{14}B$. Samarium and cobalt magnets ($Sm_2Co_{17}N_3$) are also widely used, particularly for their very high thermal resistance, superior to that of neodymium magnets (750 °C versus 310 °C).

Rare earth magnets are generally quite mechanically fragile and are therefore sensitive to shocks and wear. They are the most expensive and are primarily used to make high-power magnets. They are notably found in the alternators of high-power wind turbines, which can contain up to 600 kg of rare earth.

Permanent magnets made from hard ferromagnetic materials have numerous applications, including:

- Electromotors (permanent magnet electric machines, reluctance machines, etc.)
- Microphones and loudspeakers
- Magnetic separators
- All kinds of fasteners (closures, magnetic pads, signage, etc.)
- Holding devices for machine tools
- Magnetic recording (audio and video tapes, rewritable CDs, computer hard drives)
- Magnetic ticketing, electronic banking with bank cards
- Circular encoders (ABS in cars)
- Electric guitar pickups
- Radiology and imaging in medicine

2.4. Iron Losses:

Various losses accompany the use of ferromagnetic materials for the realization of magnetic circuits, in particular for a variable magnetic field (case of soft materials). These losses, known as iron losses (P_{Iron}), are caused by eddy currents (eddy current losses (P_{Edc}) and the hysteresis cycle (hysteresis losses (P_{Hys}).

$$P_{Iron} = P_{Hys} + P_{Edc} \tag{2.5}$$

- Hysteresis losses: These are brought on by the hysteresis cycle that arises from the delay between the magnetic induction and the excitation field's progression. The frequency value and the hysteresis area determine these losses. Based on the frequency value, the right material must be selected in order to minimize these losses.
- Losses from eddy current: The magnetic field is changeable (alternating) in the majority of magnetic circuit applications. Since the materials employed in these circuits are often metallic, or conductive, magnetic induced currents known as eddy currents (I_{edc}) form and result in joule losses in the materials, which are referred to as eddy current losses, in accordance with Faraday's law:

$$P_{Edc} = r \cdot I_{edc}^2 \tag{2.6}$$

In order to minimize iron losses due to eddy current, the magnetic circuit is often laminated with very thin sheets (Fig. 2.4).

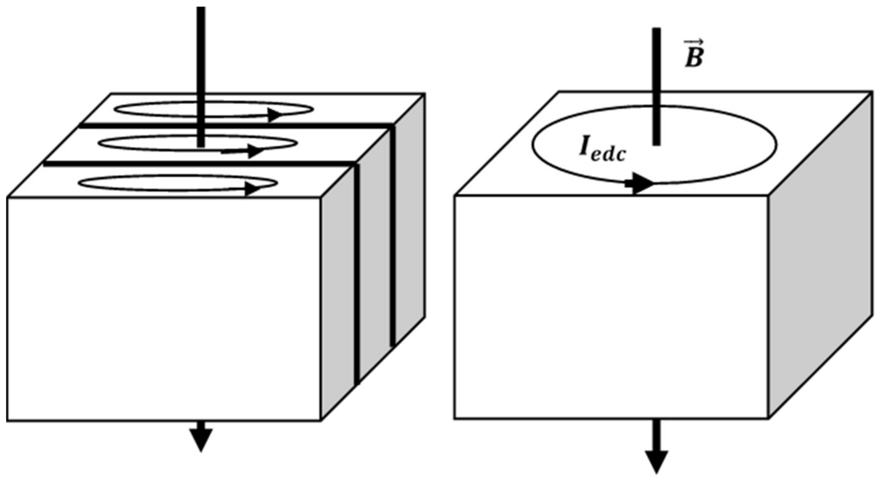

Fig. 2.4. Eddy current mitigation