**Discipline Course-I**

**Semester-II**

**Paper No: Electricity and Magnetism**

# Lesson: Magnetic Properties of Matter Lesson 4.2: Ferromagnetism, B-H curve, hysteresis

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## Chapter: Magnetic Properties of Matter

## Learning Objective

This lesson is dedicated to ferromagnetic materials and hence, it aims at the following student learning objectives.

- Origin of ferromagnetism
- Understanding the concept of exchange energy
- Understanding the concept of magnetic domains
- Alignment of magnetic domains and the B-H curve
- Concept of Hysteresis in a ferromagnetic material
- Properties and characteristic features of ferromagnetic materials

## Introduction

In this lesson, we will study the effect of external magnetic field on non-linear materials, also called as Ferromagnets. These materials show a strong attraction towards the magnetizing field, but unlike diamagnetic and paramagnetic materials. These materials retain their magnetism even if the external magnetic field is removed from the specimen. In the following sections, we will study the nature of microscopic magnetic dipoles present in ferromagnetic materials and how they are different from those present in a diamagnetic and in a paramagnetic material. This will be followed by the non-linear behavior of the magnetized object. In the last section, the concept of hysteresis will be discussed.

## Ferromagnet

(Idea taken from www.doitpoms.ac.uk/tlplib/ferromagnetic/index.php)

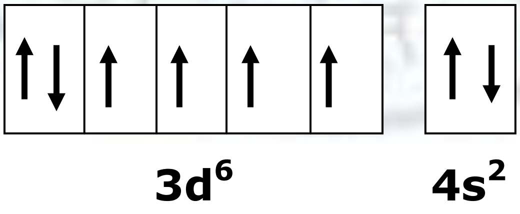
In order to understand the physics behind few materials behaving like ferromagnets, one has to understand all the forces and energies that are present at the microscopic level and how they balance each other, specifically in elements like Fe, Co, Ni.

### Exchange energy

The concept of exchange energy is explained below in the light of three elements, viz, Fe, Co, and Ni.

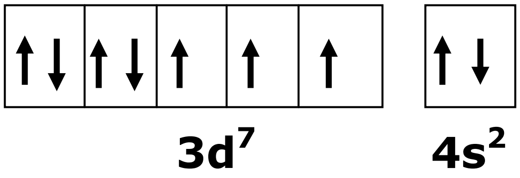
1. Iron (Fe)

- Atomic number: 26
- Electronics configuration: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^6\ 4s^2$
- Electronic structure of outer orbital



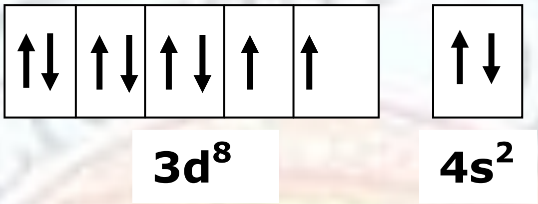
2. Cobalt (Co)

- Atomic number: 27
- Electronics configuration: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^7\ 4s^2$
- Electronic structure of outer orbital



3. Nickel (Ni)

- Atomic number: 28
- Electronics configuration: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^8\ 4s^2$
- Electronic structure of outer orbital



- In all the three cases, outer orbital shell is partially filled.
- There are unpaired electrons and hence a net spin magnetic moment
- Electrons adjacent to each other have parallel spins

We know that from Pauli's Exclusion Principle,

- Electrons in same energy shell cannot have similar spins. They can reside together in same orbital only if their spins are opposite. In turn, being close to each other, these electrons have a stronger Coulomb repulsion between them due to their charge.
- Electrons in adjacent orbital can have similar spins. Since they are relatively far away from each other, they interact with each other with a relatively smaller Coulomb repulsion.

⇨ Energy due to Coulomb repulsion is small when electrons are in different orbital shells and when they can have similar parallel spins. This energy is called as the **exchange energy** and is one of primary energies responsible for occurrence of small internal dipole moment in ferromagnets.

## Magnetic domains

As explained above, at the microscopic level, ferromagnets consist of unpaired electrons, such that they have a net spin magnet moment associated with them. A group of electrons having similar and parallel spin magnetic moment tend to align with each other. This structure is called as a **magnetic domain**. The typical size of a magnetic domain is about 10 microns. The material is said to have a **spontaneous magnetization**, which is present even in the absence of an external magnetic field. However, as shown in figure 1, the magnetic moments of adjacent domains are in different directions and are randomly organized. Hence their vector sum is zero. In other words, we can say that the net magnetic moment is zero. When magnetic field is applied, these microscopic magnetic domains tend to align in the direction of the magnetic field. Thus, the material gets magnetized.

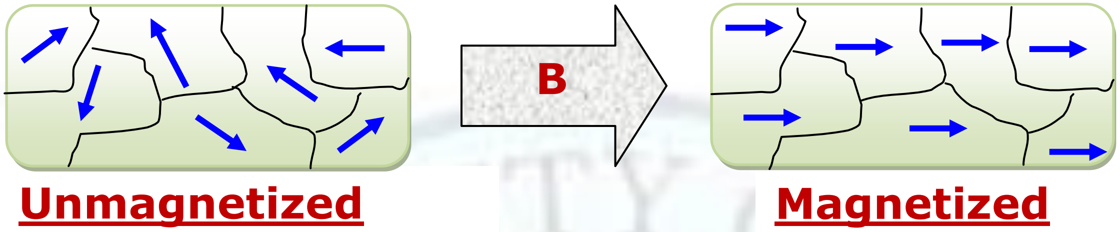


*Figure 1*

When magnetic field is applied, the domains which are already in the direction of magnetic field, start growing in size. This slowly reduces the size of neighboring domains.

But the first question which obviously comes to our minds is the origin of magnetic domains. Their occurrence in a ferromagnetic material, and their absence in diamagnetic and paramagnetic materials.

Domains are formed mainly due to minimization of internal magnetic energy of the material. The optimization of the below mentioned energies, result in the formation of domains.

1. **Magnetostatic energy**

(Refer to figure 2) Consider a single domain consisting of electrons having spins aligned in same direction (here the direction is horizontal and towards right in figure 2(a)). This acts as a small magnet and creates a de-magnetizing field outside the domain (in the opposite direction – red colored field). The energy due to this de-magnetizing field is referred to as the magnetostatic energy which needs to be minimized. This is done by dividing the original domain into a smaller domains having alignment of dipoles in the opposite direction. This increases the exchange energy among the domains, but decreases the magnetostatic energy. As shown in figure 2 (b), the de-magnetizing field has been reduced (red colored field is smaller). If the material is divided further into smaller domains with proper alignment of dipoles, we will be able to reduce the magnetostatic energy to a negligible magnitude (figure 2 (c)).

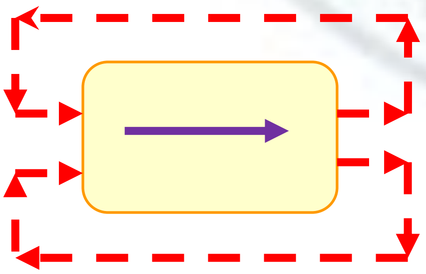


Figure 2 (a)

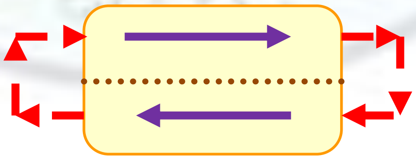


Figure 2 (b)

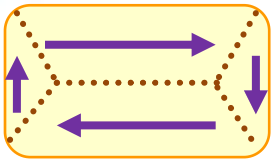


Figure 2 (c)

2. **Magneto-strictive energy**

Magneto-striction refers to the change in length of a ferromagnetic material when an external magnetic field is applied. Although the magnitude of change is small, yet it is important w.r.t. the size of domain. It is considered as positive when length increases in the direction of magnetization; and negative when the length decreases in the direction of magnetization.

As shown in the figure 3, we have a domain structure and magnetic field is applied. Due to this, there occurs a change in the length of the domain, both horizontally and vertically. In the figure, only one end is shown for simplicity.

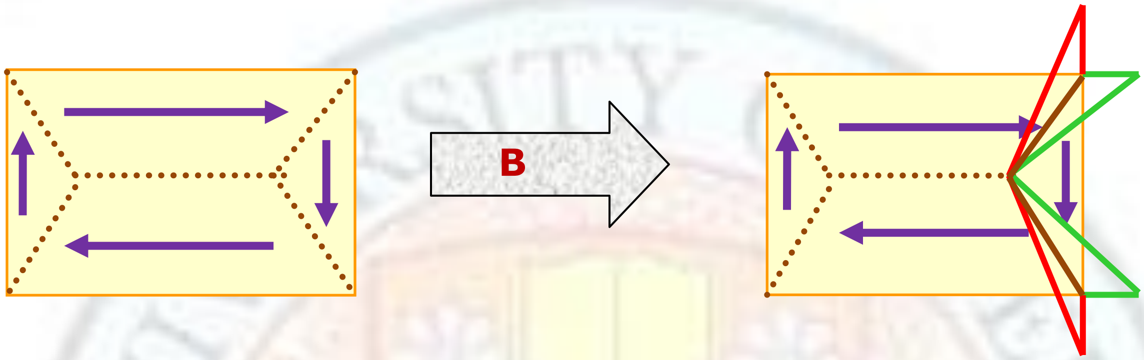


*Figure 3*

The walls of the domain increase in both directions (red color and green color). It is obviously difficult to arrange the new dimension of the domain in the crystal structure. Therefore, it produces a strain, thereby giving rise to magneto-strictive energy. In order to minimize this energy, it is required to reduce the original size of domain. This in turn requires an increase in the number of domains. But, an increased number will also increase the magneto-crystalline energy (as discussed below).

### 3. **Magneto-crystalline energy**

All the materials are composed of atoms arranged in a certain lattice structure. Therefore it is obvious that any material shows a quick response to the external magnetizing field, only if the direction of field is along a certain crystallographic axis. Hence we define an 'easy' direction and a 'hard' direction where, the response is respectively 'fast' and 'difficult', for the same magnetizing field. This gives rise to the concept of 'magneto-crystalline energy', which is the difference between energies associated with 'easy' and 'hard' magnetization. We can minimize the magneto-crystalline energy by forming domains such that magnetization vector is along the 'easy' crystallographic direction. It is clear from the hypothesis, that magneto-crystalline energy will be more if we have large number of domains, because it will be difficult to arrange all of them in the 'easy' magnetization direction. Hence, materials with large sized domains along proper direction are preferred over the large number of domains.

## B-H curve

The response of a ferromagnet material to the applied magnetic field can be described in terms of a **B**-**H** curve. Here, **H** is the applied magnetic field and **B** is the total magnetic field inside the material. In equation form, one can write,

Total field = Applied magnetic field + Magnetic field due to induced magnetic moment

$$\Rightarrow \mathbf{B} = \mathbf{B}_{\mathbf{applied}} + \mathbf{B}_{\mathbf{induced}}$$

The following section explains the behavior of a domain in the presence of external magnetic field.

## Alignment of magnetic domains

When an external magnetic field is applied to the ferromagnetic material, it provides energy to the constituent domains. The domains then compete with the crystal imperfection. The optimization of magneto-static, magneto-strictive, and magneto-crystalline results in net magnetization of the material. We have the following stages:

1. We have a ferromagnetic material and we start applying magnetic field. Pink arrow in figure 4 gives the direction of magnetic field. The hexagon shows a schematic of original direction of magnetic domains.

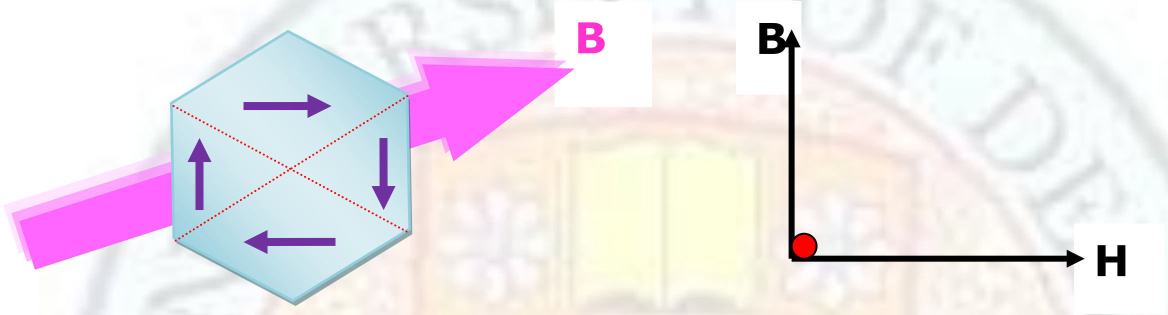


*Figure 4*

2. The domains which have their magnetic moments best aligned in direction of the applied field start growing in size at the cost of other randomly oriented domains. The material starts getting magnetized. As can be seen in figure 5, the **B**-**H** curve is linear and the effect of external magnetic field is reversible in this stage.

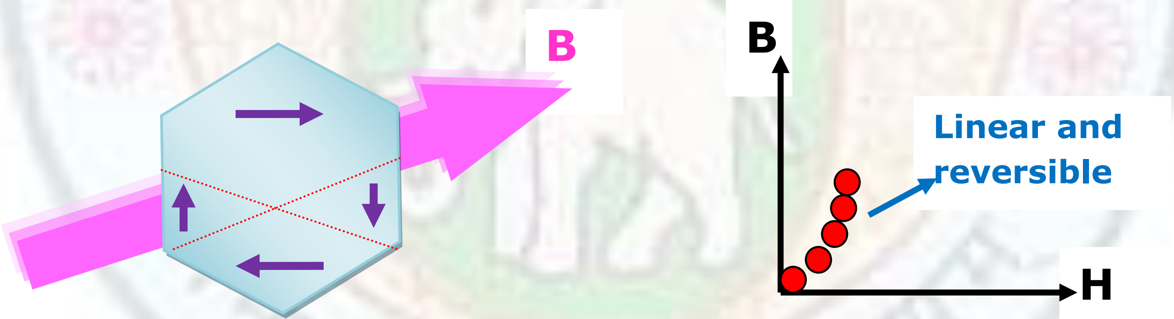


*Figure 5*

3. The size of other domains becomes negligible and the material is almost completely magnetized. See figure 6.

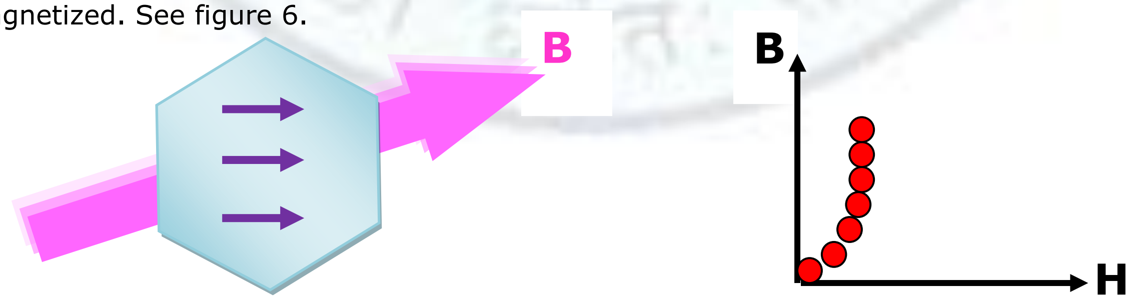


*Figure 6*

4. Domains which were originally oriented along 'easy' magnetization direction also start rotating such that their axes become parallel to applied magnetic field. This gives rise to **saturation magnetization** in the **B-H** curve, as seen in figure 7.

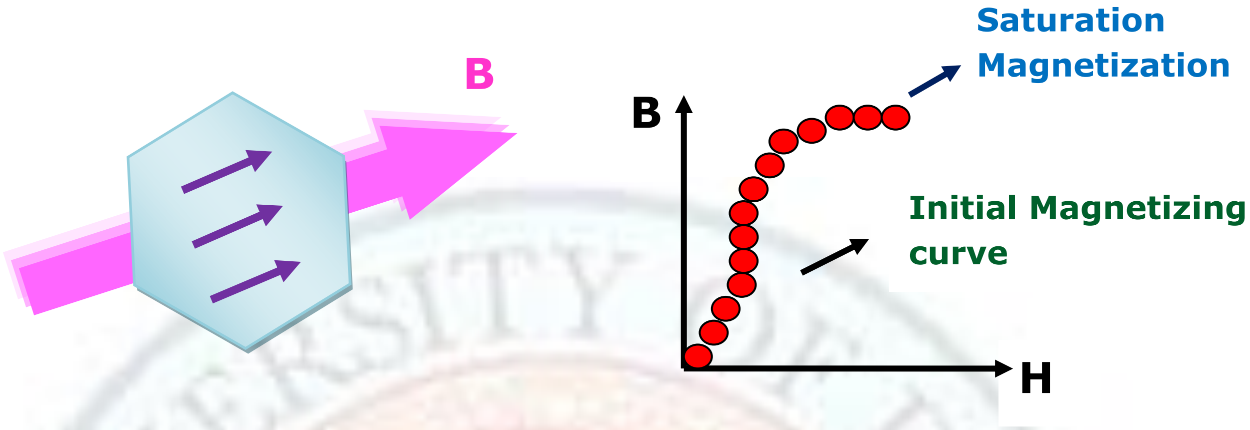


*Figure 7*

## Hysteresis

The word 'hysteresis' is derived from a Greek word, which means 'lagging'. It means lagging of an effect with respect to the cause producing it. In ferromagnetism, it refers to lagging of magnetic flux density **B** (or **M)** behind the magnetizing field intensity **H.** It is therefore, a curve between **B** and **H** (or **M** vs **H**) over a complete cycle of magnetizing field intensity. It occurs due to two main reasons,

- Reversal of direction of magnetizing field
- Change in size and number of magnetic domains

Whenever a ferromagnetic material is magnetized up to its saturation limit, it remains in that state indefinitely. In order to de-magnetize the material one has to either,

- Heat the material:
    - Heating the material gives thermal energy to the constituent domains, which then tend to align in a random orientation. Hence, the magnetization gets reduced.
    - All ferromagnets have a critical temperature above which the thermal motion of constituent dipoles results in a loose of spontaneous magnetization of the material. This temperature is called as **Curie's temperature**. Above $T_C$, a ferromagnetic material tends to change phase and behaves like a paramagnetic material.

- Apply magnetic field in the reverse direction:
    - When the magnetizing field is applied in the reverse direction, then the dipoles tend to align in the direction of the field. Hence they have to pass through a demagnetized state.
    - When the applied magnetic field is changed, it gives rise to a noise in the magnetic output. This noise occurs due to presence of crystallographic defects in the material, due to which the size and number of magnetic domains change rapidly.

### Hysteresis loop

Consider figure 8. (It has to be inserted here)

It shows the behavior of magnetic flux density **B** in a ferromagnetic material due to an external magnetic field **H**. The dashed curve starts at the origin (point a) and reaches saturation point b. This is the initial magnetization curve which we have already discussed in the previous section. Once the material has reached its saturation magnetization stage, its future depends on the applied magnetic field **H** as follows.

1. At point b,

- If **H** is increased further, there will be no change in the magnetization of the material as it has already reached saturation.
- If **H** is decreased, the magnetic domains try to align in the direction of new magnetic field, i.e. in the opposite direction.
- The curve does not follow the initial magnetization curve. Instead it reaches point c.
- This implies that even if **H** is zero, the magnetic flux density **B** is not zero.
- There exists a remnant magnetization because domains have not reached their original state by now.
- The magnetism still present in the material is called as **residual magnetism**, and the ability of the material to retain magnetism is called as **retentivity**.

2. At point c,

- If **H** is further decreased, the curve reaches point d.
- Magnetic flux density **B** reduces to zero.
- Material is completely de-magnetized.
- Magnetic domains are now aligned in random direction.
- Amount of magnetic field required to reduce the residual magnetism to zero is called as **coercive field**.

3. At point d,

- Further increasing **H** in the reverse direction, starts magnetizing the domains again. But this time, domains get oriented in the opposite direction.
- Saturation magnetization occurs at point e on the B-H curve.

4. At point e,

- If H is increased, the curve follows the path efgb
- At point g, the material again gets completely de-magnetized.
- Initial magnetization curve is never followed twice.

## Power loss due to hysteresis

Let certain current i be flowing through a coil having N turns. The voltage induced due to the current flow is e. Then,
Power associated with the magnetic field of a coil= $P = e.i$

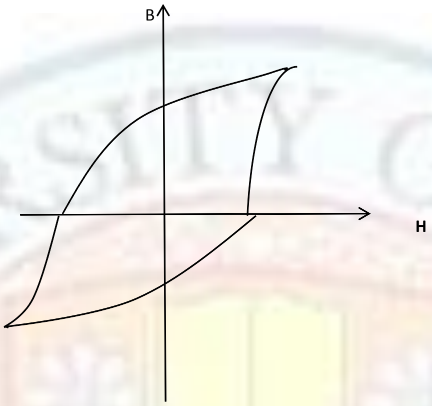
- But from the theory of electromagnetic induction, we know that voltage induced in a coil is equal to number of turns in the coil times the rate of change of magnetic flux ($d\varphi/dt$) associated with the coil, i.e. $e = N\,(d\varphi/dt)$
- $\varphi$ = magnetic flux density x area of the magnetic loop = BA
- From Ampere's law, $N\, i = H\, l$
- Area times length (Al) = volume v

Hence, $P = v\,(H dB/dt)$

This implies,
Total energy loss per unit volume due to a small section of the hysteresis loop= $\int H.\frac{dB}{dt}dt = \int H.dB$ = area of an incremental portion of the hysteresis loop

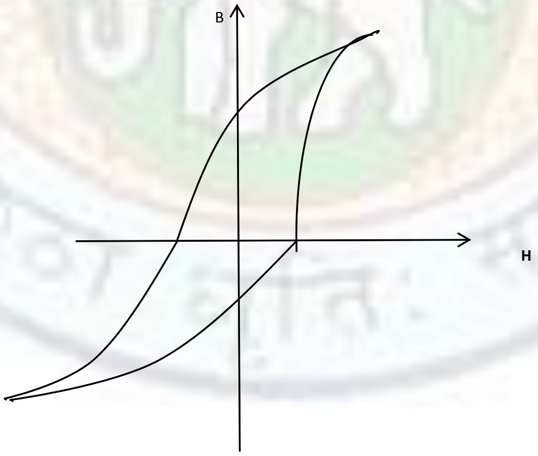
## Different hysteresis loops

1. **Wide loops (Figure 9)**



- Have large remanence
- Have large coercive field
- Low permeability
- They show high resistance to de-magnetization
- They have high hysteresis energy loss
- Belong to hard magnets
- They are permanent magnets
- Used in loud speakers, sensors

2. **Narrow loops (Figure 10)**

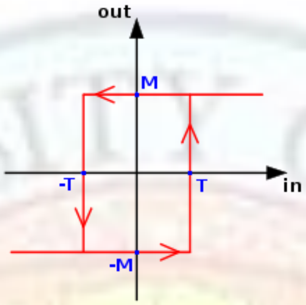


*(Figure 10)*

- Have large remanence
- Have small coercive field
- High permeability
- Saturation point is reached with a relatively small **H**

- Have less energy loss
- Belong to soft magnets which are used in device applications where alternating magnetic field are employed.
- To minimize effects of eddy currents, the materials have small conductivity, large resistivity and low ohmic loss
- Used in motors, generators

3. **Rectangular loops (Figure 11)**



(Figure 11 – in implies **H**, out implies **B** or **M**)

- Have medium remanence
- Have medium coercive field
- Used in audio-video tapes, floppy, hard disk, magnetic amplifier and pulse transformer

## Did You Know?

1. **Steinmetz's Law:** Charles Proteus Steinmetz made several discoveries which enabled a better understanding of magnetic hysteresis. In early century, these discoveries proved very useful for the design of electromagnets. He gave the expression for hysteresis power loss from iron, at different frequencies of the signal. According to him,

$$P_h = A\ f\ B^{1.6}$$

Where,

$P_h$ = hysteresis power loss, A = constant, f = frequency of signal, B = magnetic flux density

For reference, value of Steinmetz's constant A for very soft iron and hard cast steel are, ~500 and ~7000, respectively.

2. **Magnetic hyperthermia**

(Taken from en.wikipedia.org/wiki/Magnetic_hyperthermia)

The term implies, treatment of cancer using some property of magnetic materials. It is clear by now, that ferromagnets show a hysteresis effect when kept in alternating magnetic field. The hysteresis loop dissipates energy in the form of heat. Therefore, magnetic nano-particles are injected at the tumor site of the patient. The patient is made to lie on an alternating magnetic field. This produces heat at the tumor site, thus killing the cancer cells.

3. **Difference between retentivity and residual magnetic flux**

As discussed before, retentivity is the ability of ferromagnets to retain magnetism even when external magnetic field (**H**) is reduced to zero. Residual magnetic flux is the flux that is present when **H** is zero. Both these quantities will be equal only if the material is magnetized up to saturation limit. If direction of **H** is reversed before the ferromagnet reaches the saturation point then, residual magnetic flux will be less than the retentivity.

4. **Difference between power loss due eddy currents and hysteresis**

| | **Power loss due to Eddy currents** | **Hysteresis power loss** |
|---|---|---|
| **1.** | Depends on thickness of the material | Does not depend on thickness of the material |
| **2.** | Proportional to square of maximum magnetic flux density | Proportional to 1.6 power of maximum magnetic flux density |
| **3.** | Proportional to square of frequency of the signal | Directly proportional to frequency of signal |

5. Saturation magnetization is maximum at 0 K, when thermal motion of microscopic dipoles is least.

## Properties of ferromagnetic material

1. Susceptibility:
   a. Very large
   b. Can range from few 1000 to as high as 100,000

2. Permeability:
   a. Large in magnitude as compared to permeability of free space.
   b. Can be negative, zero, positive and go up to infinity
   c. It is a non-linear parameter
   d. Its value depends on the history of magnetization of the material.

3. Strongly attracted to external magnetic field and retain their magnetism even if external magnetic field is removed.

4. Any ferromagnet is primarily characterized by four parameters,
   a. Permeability
   b. Curie’s temperature
   c. Remnant magnetization
   d. Coercive field

## Anti-ferromagnetism and Ferrimagnetism

### Anti-ferromagnetism

- It is a type of magnetism which arises because the adjacent atoms (magnetic domains) of a material align in opposite directions. Therefore, even if a magnetic field is applied to the material, there occurs a negligible magnetization. See figure 12, showing domain alignment in outermost orbital of chromium.

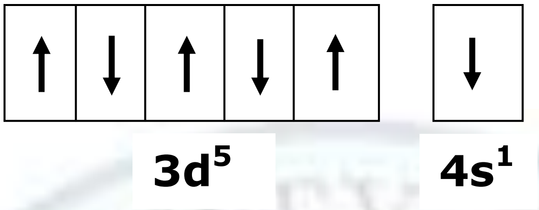


*Figure 12*

- Example: Chromium, Manganese

**Ferrimagnetism**

- It is a type of magnetism which arises because the magnetic dipoles of adjacent atoms align in opposite direction. However, there is incomplete cancellation of magnetic moment. Hence the material gets magnetized in presence of external magnetic field.
- Example: oxides of iron, nickel and cobalt
- Most useful example is of ferrites which are ceramic compounds of iron. They are non-conducting and have less ohmic loss as compared to ferromagnets. Therefore, these materials are used in cores of transformer operating at radio frequency.

## Summary

In this lesson we have studied the following properties of ferromagnetic material.

- The concept of exchange energy and the inherent magnetic moment due to net spin dipole moment in a ferromagnetic material.

- The origin of magnetic domains and various factors responsible for their size and number in a ferromagnetic material.

- The non-linearity in the B-H curve of a ferromagnet. We have studied how the alignment of magnetic domains gives rise to a non-linearity in the permeability of the material.

## Definitions

**Coercivity:** It is that value of magnetic field **(H)** which is required to reduce the residual magnetic flux density **(B)** of the ferromagnetic material to zero.

**Curie's Temperature**: Temperature above which a ferromagnetic material changes phase and behaves like a paramagnetic material. This happens because thermal motion of the dipoles at such high temperatures becomes so strong that they tend to align in random orientation and hence the spontaneous magnetization is lost.

**Permanent magnet:** It is a material which remains magnetized even when the external source of magnetic field is switched off.

**Remanence/residual magnetization:** It is the amount of magnetic field (**B**) present in the material when the external magnetic field (**H**) is reduced to zero. Remanence is a measure of ease with which the magnetic domain walls move. If they move easily, then remanence will be low and vice versa.

**Retentivity:** It is the ability of ferromagnetic material to retain its magnetism, even when the magnetizing field is removed from the system.

**Saturation Magnetization:** It is the maximum magnetic moment that can be induced by an external magnetic field within a material.

# Exercises

## Fill in the Blanks

1. The typical size of a magnetic domain is _____.

2. As the size of a domain increases, _____ energy also increases.

3. As we increase the number of domains in an atom, _____ energy also increases.

4. Properties of a material change from ferromagnetic to paramagnetic, above a temperature called as _____.

5. The variation of magnetic flux density (B) with a variable magnetic field (H) for a ferromagnetic material is _____ in nature.

6. Chromium and Manganese belong to _____ category of magnetic materials.

**Answers:**

1. 10 microns

2. Magneto-strictive

3. Magneto-crystalline

4. Curie’s temperature

5. non-linear

6. anti-ferromagnetic

## True/ False

1. For ferromagnetic materials, **M** is a single valued function of **H**.

2. Retentivity of a ferromagnetic material is always same as its residual magnetic flux.

3. The loss in power due to hysteresis effect depends on the thickness of the ferromagnetic material.

4. Permanent magnets have large remanence and large coercivity.

5. Magnets used in motors and generators have large remanence but small coercivity.

6. Saturation magnetization is minimum at 0 K.

7. Permeability of a ferromagnetic material can be negative.

**Answers:**

1. False. Ferromagnets show hysteresis and hence there is more than one value of **M** for a given **H**.

2. False. They will be equal only if the material is magnetized up to saturation limit.

3. False. It is independent of the thickness of the material.

4. True

5. True

6. False. It is maximum at 0K.

7. True

## Short answer question

1. What are the two main characteristics of a ferromagnetic material?

Ans:

- Occurrence of spontaneous magnetization: This refers to a net magnetization within an extremely small volume of a ferromagnetic material even in the absence of an external magnetic field. The magnitude of the internal magnetic moment obviously depends on the spin magnetic moment of the constituent electrons.
- Concept of order temperature: Below Curie's temperature, a ferromagnet is ordered.

2. What information do we get from the area under the hysteresis loop?

Ans: It gives the magnetic energy loss per unit volume of the material per cycle of magnetization. This energy is lost in the form of heat.

3. List the differences between soft and hard magnets.

## Long answer questions

1. What do you understand by the term 'exchange energy'? Explain with suitable examples.

2. Explain the difference between spontaneous magnetization and saturation magnetization?

3. What happens when an external magnetic field is applied to a ferromagnetic material?

4. State the methods used to de-magnetize a ferromagnetic material.

5. Write a short note on:

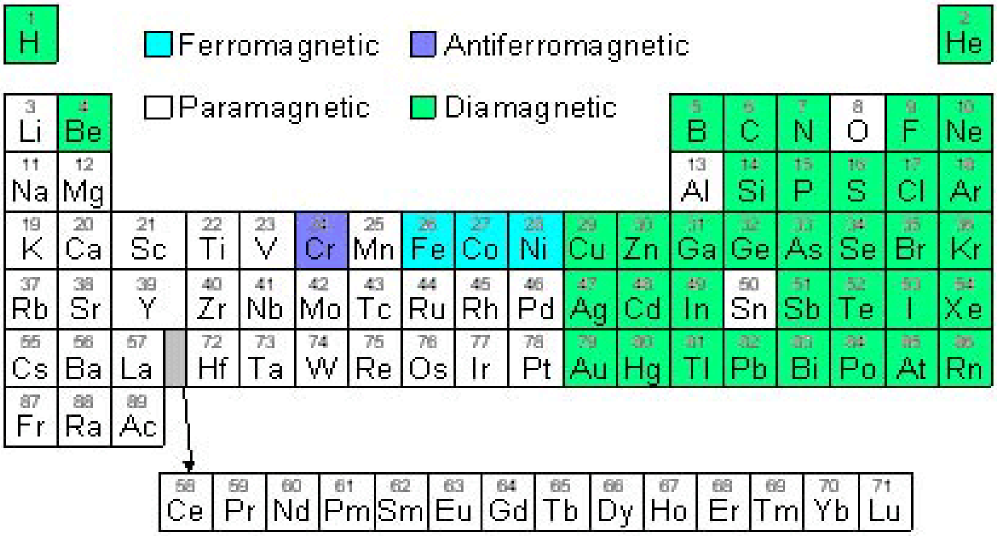
    a. Magnetostatic energy

    b. Magnetostrictive energy

c. Magnetocrystalline energy

## Did You Know?

1. The periodic table shown below shows the distribution of various elements in reference to their magnetic properties. The various elements in the table have been categorized as diamagnetic, paramagnetic, ferromagnetic and anti ferromagnetic.



## References

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- Introduction to Electrodynamics by David J. Griffiths, Pearson Education
- Electricity and Magnetism by D. L. Sehgal, K. L. Chopra, N. K. Sehgal, Pub: Sultan Chand and sons
- Electricity and Magnetism by E. M. Purcell, Berkeley Physics Course, Pub: Mc Graw Hill Science

2. Internet:

- Idea of ferromagnetic materials is mainly taken from:
  - www.doitpoms.ac.uk/tlplib/ferromagnetic/index.php
  - http://pms.iitk.ernet.in/wiki/index.php/Ferromagnetism

- Idea of hysteresis is mainly taken from:
  - en.wikipedia.org/wiki/Magnetic_hysteresis

- en.wikipedia.org/wiki/Barkhausen_effect
- http://pms.iitk.ernet.in/wiki/index.php/Hysteresis
- Phys.thu.edu.tw/~hlhsiao/mse-web_ch20.pdf