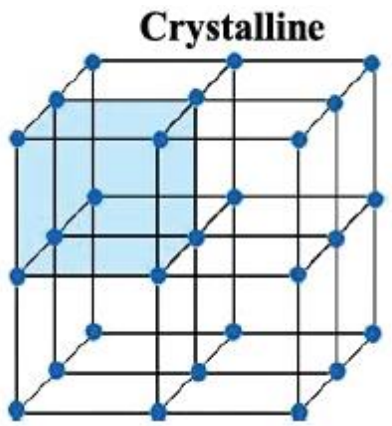
UNIT 21 PHYSICS OF SOLID

PHYSICS OF SOLIDS

Solid-state physics is a branch that focuses on understanding solid materials' physical properties and behavior under different conditions, such as temperature, pressure, and electromagnetic fields. It deals with the study of solids at the atomic and molecular levels to explain their macroscopic properties.

CLASSIFICATION OF SOLIDS:

solids can be classified into the following categories based on their structure and bonding characteristics.



1. CRYSTALLINE SOLIDS

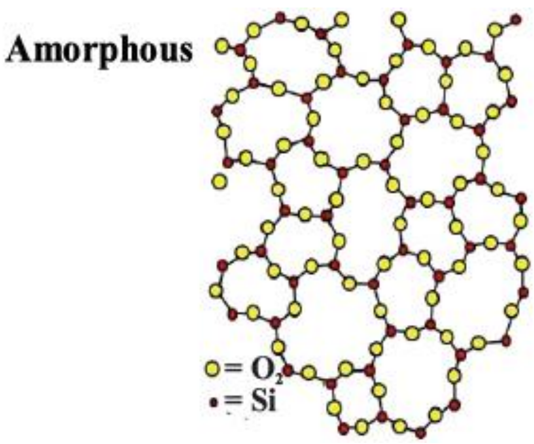
Crystalline solids are solid materials with atoms, ions, or molecules arranged in a highly ordered and repeating pattern extending in all three spatial dimensions. This regular arrangement gives crystalline solids well-defined geometric shapes and distinct physical properties.

Here are some common examples:

- Sodium Chloride (NaCl): Common table salt that forms cubic crystals.
- Diamond: A form of carbon with a highly ordered structure, known for its hardness.
- Quartz (SiO_2) is a common mineral found in sand with a hexagonal crystal structure.
- Metals: Many metals, such as iron, copper, and aluminum, crystallize in various lattice structures.
- Ice (H_2O): The solid form of water, which forms hexagonal crystals at lower temperatures.
- Sugar (Sucrose): Forms well-defined cubic crystals, commonly found in granulated sugar.

2. AMORPHOUS SOLIDS

Amorphous solids are materials that lack a long-range ordered structure, unlike crystalline solids. In amorphous solids, the arrangement of atoms or molecules is irregular and does not form a repeating pattern. This results in distinct physical properties compared to their crystalline counterparts.

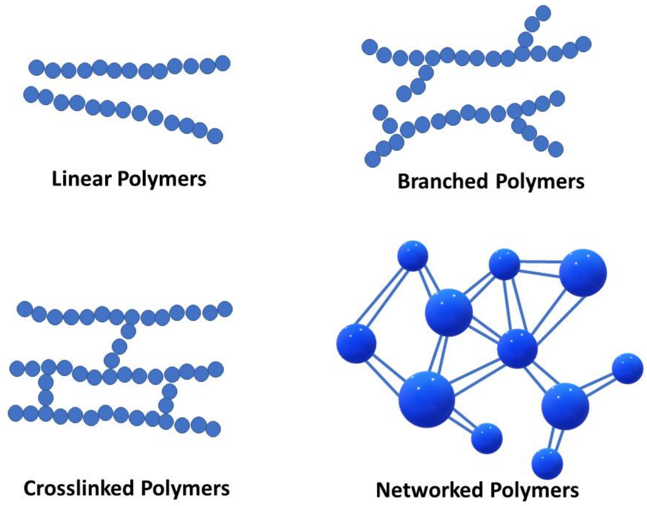


Common examples of amorphous solids include:

- Glass: Often used in windows and containers, glass is a classic example of an amorphous solid.
- Plastics: Many synthetic polymers are amorphous in nature.
- Gels: These materials can exhibit amorphous characteristics as well.

POLYMERIC SOLIDS

Polymeric solids are materials composed of long, repeating chains of molecules known as polymers. These polymers are formed through polymerization, where small molecules called monomers chemically bond to create a large, complex structure. The properties of polymeric solids depend on the nature of the polymer chains and the way they are organized.



Here are some common examples:

- Polyethylene: Widely used in plastic bags, bottles, and packaging materials.
- Polystyrene: Used in products like disposable cutlery, foam insulation, and packaging materials.
- Polyvinyl Chloride (PVC): Commonly found in pipes, vinyl flooring, and various plastic products.
- Polypropylene: Used in containers, automotive parts, and textiles.
- Polytetrafluoroethylene (PTFE): Known for its non-stick properties, often used in cookware and seals

Distinguish between structures of crystalline, glassy, amorphous, and polymeric solids:

Property	Crystalline Solids	Glassy Solids	Amorphous Solids	Polymeric Solids
Atomic Arrangement	Regular, Repeating pattern.	Random, short-range order.	Random, no long-range order.	Long chains or networks of repeating units.
Melting Point	Sharp, Specific temperature.	Gradual, over a range of temperature.	Gradual, over a range of temperatures.	Varies, typically lower than crystalline solids.
Rigidity	Very rigid and well-defined structure.	Rigid, but less than crystalline solids.	Not as rigid as crystalline solids.	Can be flexible or rigid.
Transparency	Can be transparent or translucent.	Transparent or opaque depending on composition.	Opaque.	Depending on structures, can be transparent or opaque.
Examples	Diamond, salt crystals, silicon.	Window glass, certain plastics, amorphous metals.	Rubber, some plastics, glass.	Polyethylene, PVC, nylon.

UNIT 21 PHYSICS OF SOLID

DEFORMATION:

Deformation refers to the modification of the shape or size of an object due to applied forces or a temperature change.

Deformation in one dimension:

STRESS:

Stress is the force applied to a material per unit area. It's a measure of how much an object deforms when an external force is applied.

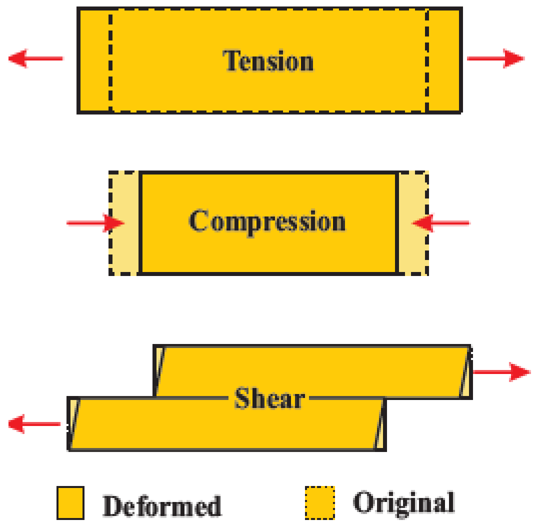
$$Stress(\sigma) = \frac{Force(F)}{Area(A)}$$

where:

σ is the stress,

F is the applied force, and

A is the cross-sectional area over which the force is applied.



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Stress is typically measured in units of ***Pascals (Pa)*** or Newtons per square meter **(N/m^2).**

There are different types of stress, including:

1. Tensile Stress: Occurs when a material is subjected to pulling or stretching forces.

2. Compressive Stress: Arises when a material is subjected to squeezing or compressive forces.

3. Shear Stress: Occurs when forces are applied parallel to the surface of a material, causing layers to slide against each other.

STRAIN:

In physics, strain is a measure of the deformation of a material in response to applied stress. It quantifies how much a material deforms relative to its original length or shape when subjected to external forces. Strain is defined as the change in length divided by the original length:

$$\boldsymbol{Strain\ (\varepsilon) = \frac{\Delta L}{L}}$$

where:

(ε) is the strain,

ΔL is the change in length, and

L is the original length of the material.

Strain is a dimensionless quantity, often expressed as a percentage or a ratio. There are different types of strain, including:

1. Tensile Strain: Occurs when a material is stretched.

2. Compressive Strain: Arises when a material is compressed.

3. Shear Strain: Results from forces that cause layers of material to slide past each other.

MECHANICAL PROPERTIES OF SOLIDS:

1. Young's modulus (modulus of elasticity)

Young's modulus, also known as the elastic modulus, is a measure of the stiffness of a material. It is the relationship between stress (force per unit area) and strain (deformation) in the elastic region of a material's behavior. The formula for Young's modulus (Y) is given by:

$$Y = \frac{Stress(\sigma)}{Strain(\varepsilon)}$$

Where stress

$$\sigma = \frac{F}{A}$$

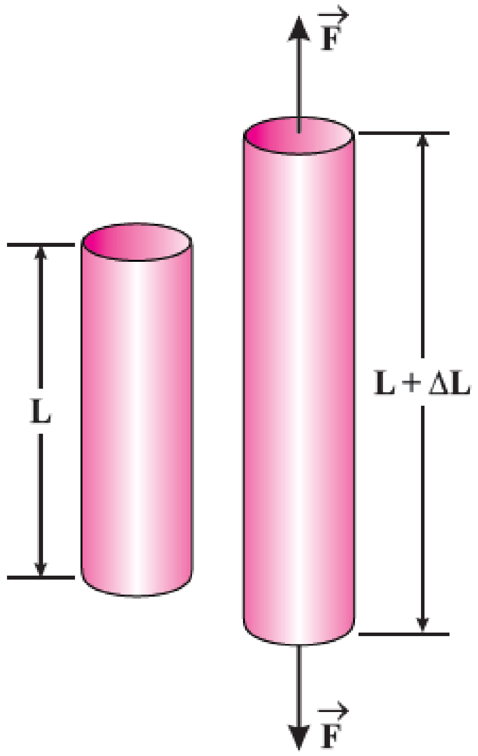
and (ε) is the strain.

$$\varepsilon = \frac{\Delta L}{L}$$

Now, we can write.

$$Y = \frac{\frac{F}{A}}{\frac{\Delta L}{L}}$$

$$Y = \frac{F}{A} \times \frac{L}{\Delta L}$$



KEY POINTS:

Units: Young's modulus is typically expressed in Pascal's (Pa).

Material Property: It is a fundamental property of materials that helps predict how they will deform under load.

High Value: Materials with a high Young's modulus (like steel) are stiffer and deform less under stress, while those with a low Young's modulus (like rubber) are more flexible.

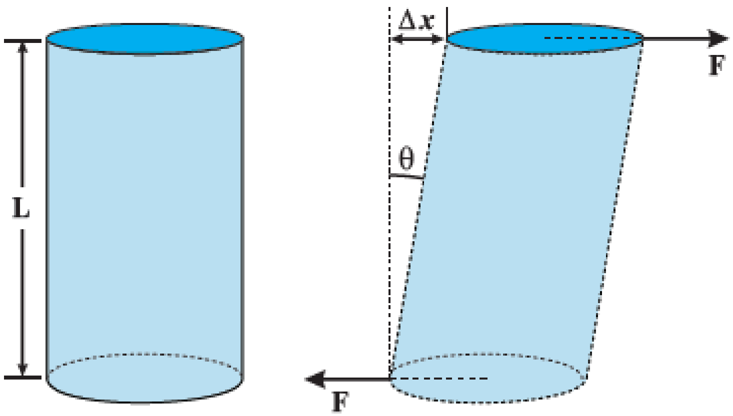
Elastic Limit: Young's modulus applies within the elastic limit of a material, meaning the material will return to its original shape after the stress is removed.

2. SHEAR MODULUS (MODULUS OF RIGIDITY)

The shear modulus, also known as the modulus of rigidity, is a measure of a material's response to shear stress. It measures how much a material deforms when a shear force is applied. The shear modulus (G) is defined as the ratio of shear stress to shear strain:

$$G = \frac{\text{Shear Stress}}{\text{Shear Strain}}$$

Consider a rigid body as shown in the figure. A tangential force (F) is applied to twist it.



The shear stress is F/A and the shear strain is $\Delta X/L$. The shear modulus is given as.

$$G = \frac{F/A}{\Delta X/L}$$

$$G = \frac{F\ L}{\Delta X\ \ A}$$

Shear Modulus Unit

The SI unit of shear modulus is Pascal (Pa)

Key Points:

Units: Shear modulus is typically expressed in Pascals (Pa) or Gigapascals (GPa).

Material Property: It indicates how resistant a material is to shear deformation. A high shear modulus means the material is stiff and does not deform easily under shear stress, while a low shear modulus indicates a more flexible material.

3. BULK MODULUS (MODULUS OF COMPRESSIBILITY)

The bulk modulus is a measure of a material's resistance to uniform compression. It quantifies how incompressible a substance is under pressure. Mathematically, it is defined as the ratio of the change in pressure to the fractional change in volume:

$$B = -\left(\frac{\Delta P}{\frac{\Delta V}{V}}\right)$$

where:

B is the bulk modulus,

V is the original volume,

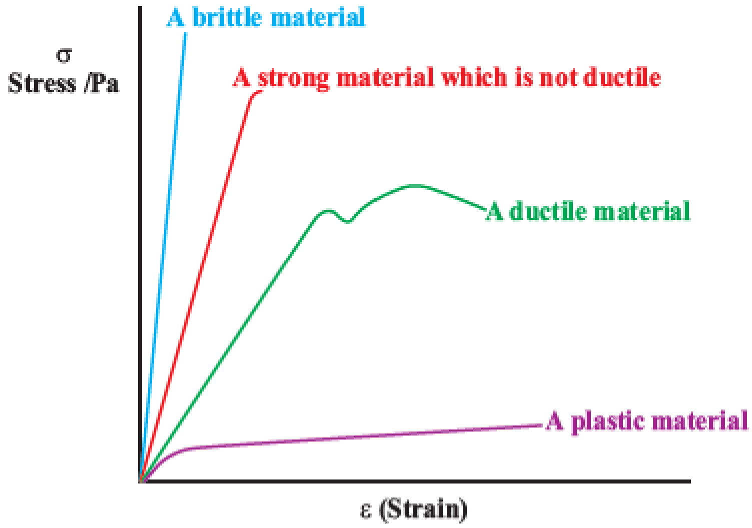
ΔP is the change in pressure,

ΔV is the volume change.

A higher bulk modulus indicates that the material is less compressible. This property is important in materials science, engineering, and geophysics, helping to understand how materials behave under different stress conditions.

Force-Extension graph:

A force-extension graph illustrates the relationship between the force applied (stress) to a material (like a spring or elastic material) and the extension (strain) it experiences.



1. Linear Region:

In the initial part of the graph, the relationship is linear, following Hooke's Law

$$F = kx$$

where F is the force, k is the spring constant, and x is the extension. The slope of this linear section represents the stiffness of the material.

2. Elastic Limit:

Beyond a certain point, the graph may start to curve. This indicates that the material is approaching its elastic limit the maximum extent to which it can be deformed and still return to its original shape.

3. Plastic Deformation:

If the force continues to increase past the elastic limit, the material may undergo plastic deformation. In this case, the graph may become non-linear and not return to its original shape after the force is removed.

4. Fracture Point:

Eventually, a point is reached where the material can no longer withstand the force, leading to failure (fracture). This is usually represented as the end of the curve.

Electrical properties of solids:

Resistivity:

Resistivity (ρ) is the resistance of a material to the flow of electric current per unit length and unit cross-sectional area.

It is a property of a material that describes how strongly it resists the flow of electric current. It is an intrinsic property, meaning it depends on the type of material rather than its shape or size.

Resistivity is measured in ohm-meters (Ω m).

Conductivity:

Conductivity refers to the ability of a material to allow the flow of electric current.

Temperature Coefficient of resistivity:

The temperature coefficient of resistance is defined as the change in electrical resistance of a substance with respect to a per-degree rise in temperature. When the temperature increases, the process of electron collision becomes rapid and faster. As a result, the resistance will increase with the rise in temperature of the conductor.

The quantity of charge carriers' n, the number of charge carriers per unit volume, can be found from the measurement of the Hall Effect. Its SI unit is m^{-3}.

ENERGY BANDS IN SOLIDS:

In solids, energy bands refer to ranges of energy levels that electrons can occupy, due to the interaction between atoms in the crystal structure. When atoms come together to form a solid, the individual energy levels of electrons in each atom overlap and spread out, creating continuous ranges or "bands" of allowed energy states. These energy bands are crucial for understanding the electrical properties of materials.

1. Valence band:

- The valence band is the highest range of energy levels that electrons occupy under normal conditions.
- Electrons in the valence band are generally bound to atoms and are not free to move easily.
- In insulators and semiconductors, the valence band is fully occupied, while in conductors, it overlaps with the conduction band or is only partially filled, allowing some electron movement.

2. Conduction band

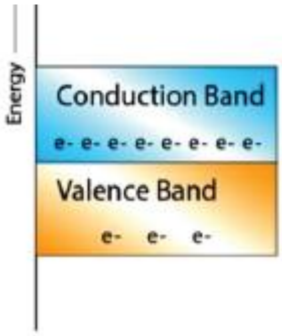
- The conduction band is the range of energy levels where electrons can move freely and conduct electric current.
- Electrons in the conduction band are free from atomic binding forces and can move throughout the material, contributing to electrical conduction.
- In conductors, the conduction band overlaps with the valence band, making it easy for electrons to move. There is a gap between insulators and semiconductors, requiring additional energy for electrons to jump to the conduction band.

3. Forbidden Band (Band Gap):

The band gap is the energy difference between the top of the valence band and the bottom of the conduction band. This gap plays a crucial role in determining the electrical properties of the material.

TYPES OF SOLIDS BASED ON ENERGY BANDS:

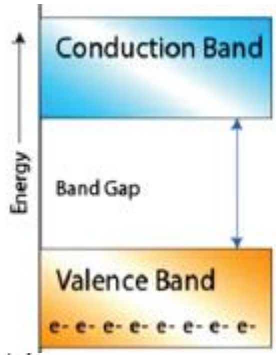
Conductors (e.g., metals):



In conductors, the valence band overlaps with the conduction band, or the conduction band is partially filled, allowing electrons to move freely.

Example: Copper (Cu), Silver (Ag), and Gold (Au) are good conductors because their conduction bands have free electrons that allow easy current flow.

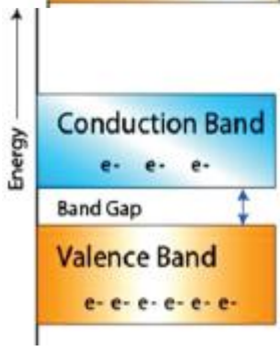
Insulators (e.g., rubber, glass):



In insulators, there is a large band gap between the valence band and the conduction band. Electrons in the valence band cannot gain enough energy to move to the conduction band, so the material does not conduct electricity.

Example: Diamond and rubber have a wide band gap, which makes them poor conductors of electricity.

Semiconductors (e.g., silicon, germanium):



Semiconductors have a small band gap, meaning electrons can be excited from the valence band to the conduction band with small amounts of energy (e.g., heat or light).

Example: Silicon (Si) and Germanium (Ge) are common semiconductors, and their conductivity can be controlled by doping (adding impurities to the material).

SUPERCONDUCTORS:

Superconductivity was discovered by Dutch physicist **Heike Kamerlingh Onnes** in 1911. He made this discovery while studying the electrical properties of mercury at very low temperatures. When he cooled mercury to 4.2 Kelvin (just above absolute zero) using liquid helium, he observed that its electrical resistance suddenly dropped to zero. This meant that the mercury could conduct electricity without any loss of energy. This is an astonishing and groundbreaking phenomenon that came to be known as **superconductivity**.

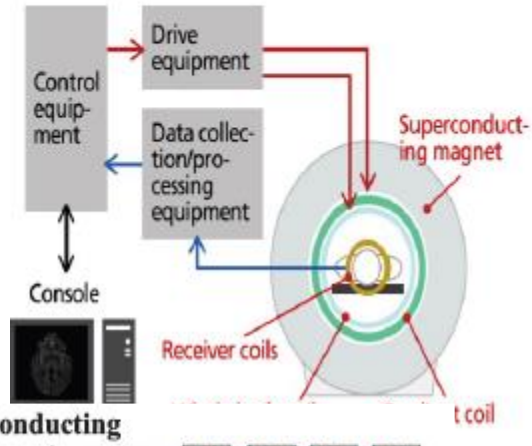
A **superconductor** is a material that, when cooled below a certain critical temperature, exhibits **zero electrical resistance** and **expels magnetic fields** (a phenomenon known as the Meissner effect). In this superconducting state, electric current can flow through the material indefinitely without any loss of energy, making superconductors highly efficient conductors of electricity.

Superconductor Applications:

1. Magnetic Resonance Imaging:

MRI stands for Magnetic Resonance Imaging. It is a medical imaging technique used to create detailed images of the inside of the human body. MRI uses strong magnetic fields, radio waves, and a computer to generate images of organs, tissues, and other structures.

Working:

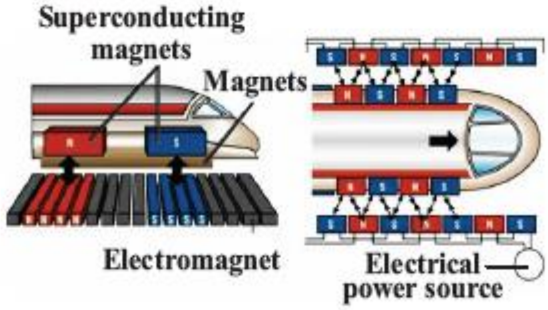


Magnetic Field: Superconductor coils generate a strong magnetic field that aligns hydrogen atoms in the body.

Radio Waves: Radiofrequency pulses are applied, causing the aligned hydrogen atoms to produce signals.

Detection: The MRI scanner detects these signals, and a computer processes them to create detailed images.

2. Maglev (Magnetic Levitation) train system:



A Maglev (Magnetic Levitation) train system is a high-speed transportation technology that uses magnetic forces to lift, propel, and guide trains over a track. Unlike conventional trains, which run on wheels, maglev trains float above the tracks, eliminating friction. Here are some key features and aspects of the system:

How Maglev Works

1. Levitation: The train is lifted off the track by magnetic forces, which are typically created by superconducting magnets or electromagnetic systems.
2. Propulsion: The train is propelled forward using a linear motor system that relies on magnetic fields.
3. Guidance: Magnetic forces also keep the train centered on the track, ensuring stability.

3. Small electric motors

Superconducting motors are advanced electrical motors that leverage superconducting materials to achieve extremely high efficiency, compact size, and powerful performance. These materials exhibit zero electrical resistance when cooled below a critical temperature, which significantly reduces energy losses and allows for stronger magnetic fields.

KEY FEATURE

Precision Instruments:

Superconducting motors can be used m prec1s10n instruments where high efficiency and low noise are critical.

Medical Devices:

Compact, efficient motors for medical devices such as MRI machines, which already use superconducting magnets.

Aerospace:
High-efficiency, lightweight motors for aerospace applications, where every gram of weight saved is crucial.
Robotics:
Small, powerful motors for advanced robotic applications requiring precise control and high power output.

4. Super Conductivity and Super Computers:

Superconducting components can improve the performance of supercomputers in several ways as:
Superconducting qubits:
These are the basic building blocks of quantum computers, which are able to perform calculations at speeds that are exponentially faster than classical computers. Superconducting qubits can maintain their quantum states for long periods of time, allowing for complex computations to be performed.
Faster processing speeds:
Super conducting components can process information at much faster speeds than traditional electronic components, resulting in faster computing times and the ability to handle larger datasets.
Lower power consumption:
Super conducting circuits require less power to operate than traditional electronic circuits, reducing energy costs and making them more environmentally friendly.
Improved reliability:
Superconducting components are less prone to errors and can operate for longer periods without failure, resulting in more reliable and efficient supercomputers.
However, the use of superconducting components in supercomputers is still in the experimental stage and faces several challenges.

Magnetic properties of solids:

The magnetic properties of solids arise from the behavior of their electrons, particularly the alignment of electron spins and orbital motion in the presence of a magnetic field. These properties are fundamental to understanding the behavior of materials in various fields, from electronics to materials science.

Classification of Magnetic Materials

Based on their response to a magnetic field, solids can be classified into the following categories:

1. Paramagnetic Materials

- **Description**: Weakly attracted to a magnetic field.
- **Cause**: Presence of unpaired electrons with magnetic moments that align weakly with the external field.
- **Examples**: Aluminum, magnesium, platinum.

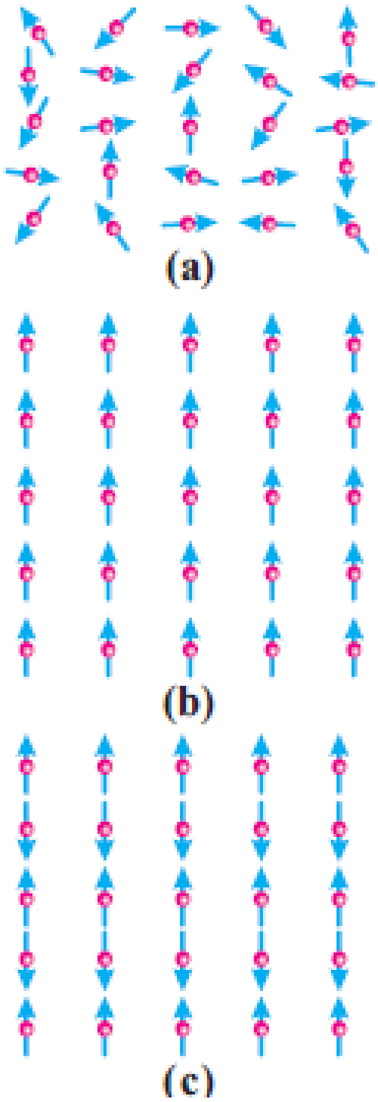
2. Ferromagnetic Materials

- **Description**: Strongly attracted to a magnetic field and can retain magnetism.

- **Cause**: Unpaired electrons align in the same direction due to exchange interactions, creating domains with strong magnetic moments.
- **Examples**: Iron, cobalt, nickel.

3. Diamagnetic Materials

- **Description**: Weakly repelled by a magnetic field.
- **Cause**: Arises from the orbital motion of electrons. The magnetic moments cancel each other out, resulting in no net magnetic moment.
- **Examples**: Copper, bismuth, gold, quartz.



Magnetic domain

The magnetic domain theory, proposed by Weiss in 1907, explains that ferromagnetic materials consist of tiny regions called magnetic domains, each with aligned atomic magnetic moments. Initially, these domains are randomly oriented, resulting in weak magnetization. When exposed to a strong external magnetic field, the domains align with the field, creating strong magnetization. Ferromagnetic materials retain their aligned domains even after the field is removed, making them ideal for permanent magnets. The theory also contrasts paramagnetic (randomly oriented), ferromagnetic (perfectly ordered), and antiferromagnetic (perfectly anti-ordered) materials.

Curie Temperature and Curie's Law:

Curie Point/Temperature: The temperature above which magnetic materials lose their magnetic properties. The weakening of magnetic properties occurs due to increased thermal agitation. Pierre Curie, a French physicist, proposed laws about magnetic properties and temperature changes in 1895.

Curie's Law:

In a paramagnetic material, magnetization (M) is directly proportional to the applied magnetic field (H): $M \propto H$.

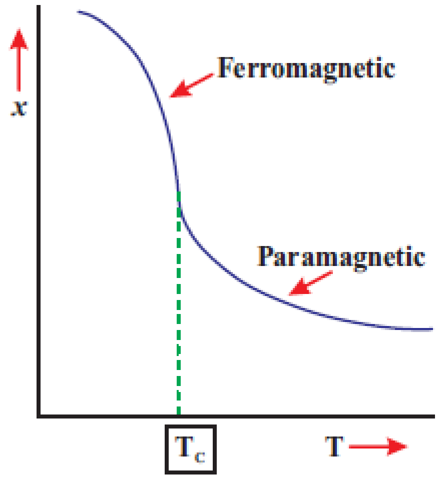
When heated, the magnetization becomes inversely proportional to temperature (T):

$$M = \frac{C \times H}{T}$$

where C is the material's Curie constant.

Curie Temperature and Magnetic Properties:

- Magnetic Susceptibility (χ\chi): Inversely proportional to absolute temperature (T) as per the formula $\chi = C/T$, where C is a constant.
- Iron Example: At 770°C (Curie temperature for iron), iron atoms act like tiny magnets and align to form a magnetic material.
- Ferromagnetic Materials: Magnetic domains align to strengthen the magnetic field. Example: Pure iron.
- Anti-Ferromagnetic Materials: Atomic magnets align in opposite directions, canceling each other's fields.
- Graph Interpretation: The plot shows the magnetic susceptibility decreasing with increasing temperature above the Curie point (T_c). This trend is observed across ferromagnetic, paramagnetic, and anti-ferromagnetic materials.



Hard and Soft Ferromagnetic Substances:

1. Hard Ferromagnetic Materials:

- Examples: Neodymium, samarium cobalt, and alnico.
- Characteristics: High coercivity, making them ideal for permanent magnets in stable magnetic fields.
- Applications: Speakers, generators, and other devices requiring stable magnetic properties.

2. Soft Ferromagnetic Materials:

- Examples: Iron, nickel, and cobalt.
- Characteristics: Low coercivity, making them easy to magnetize and demagnetize. Their microstructure (fine-grained vs. coarse-grained) affects their properties.
- Applications: Used in transformers, inductors, and rotating armatures that require rapid changes in magnetic fields.

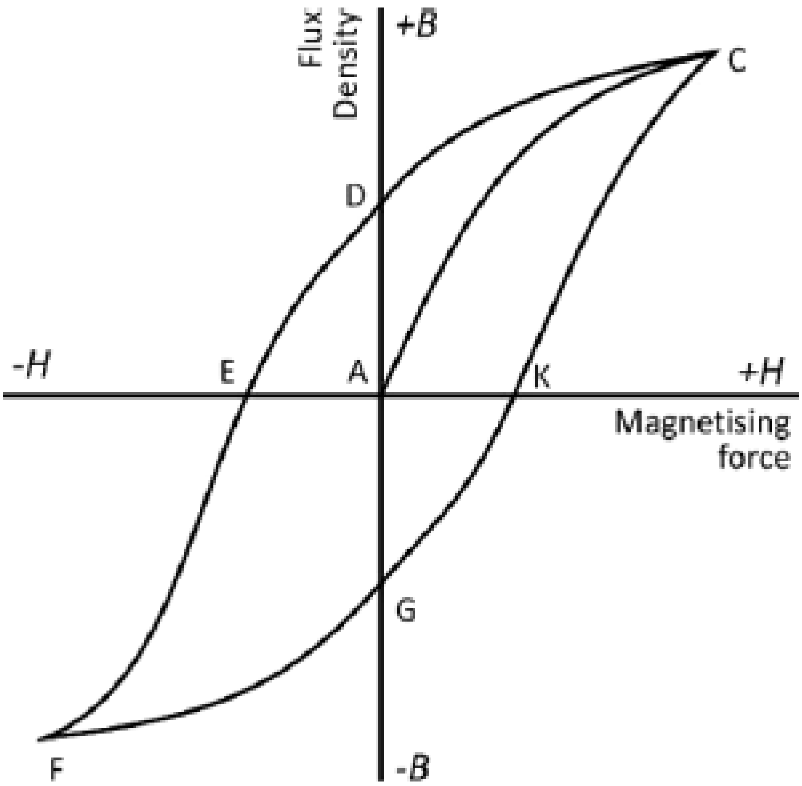
Hard ferromagnetic materials are suitable for permanent magnets, while soft ferromagnetic materials are preferred for applications involving rapid changes in magnetic fields.

HYSTERESIS LOSS:

Hysteresis loss refers to the energy lost as heat in a magnetic material when it is subjected to a cyclic process of magnetization and demagnetization. It occurs due to the lag between the changes in the magnetic field (applied magnetizing force) and the resulting magnetic flux density in the material. This lag is caused by the internal friction of the magnetic domains as they realign with the changing magnetic field.

1 HYSTERESIS LOOP:

When a magnetic material is subjected to a cycle of magnetization, a hysteresis loop (a B-H curve) is formed, representing the relationship between magnetic flux density (B) and magnetizing force (H). The area enclosed by this loop corresponds to the energy lost during the cycle.



2. Variation of Magnetic Field Strength with Magnetizing Current:

The horizontal axis of the hysteresis loop represents the magnetizing current or applied magnetic field strength. The vertical axis represents the resulting magnetization of the material.

3. Magnetizing and Demagnetizing:

When the magnetizing current increases, the material gets magnetized, and the magnetic field strength goes up, shown on the right side of the hysteresis loop.

When the magnetizing current decreases, the material may not fully demagnetize, and the magnetic field strength remains at a certain level, shown on the descending left side of the loop.

4. Understanding the Loop:

The width of the hysteresis loop indicates energy loss (hysteresis loss) during magnetization and demagnetization cycles.

The shape of the loop provides information about the material's magnetic properties, such as coercivity and remanence.

HYSTERESIS LOOP FOR PERMANENT AND TEMPORARY MAGNETS:

Hysteresis is especially marked in materials of high residual magnetism, such as hardened steel. In most cases, hysteresis is a necessity as it causes dissipation of heat, waste of energy, and vibration due to changes in polarity and rotation of element magnets in the material.

Hysteresis loops for hard steel, wrought iron, cast steel, and alloyed sheet steel are shown in Figure