UNIT 16

......Physics of Solids......

After studying this chapter the students will be able to:

- distinguish between the structure of crystalline, glassy, amorphous and polymeric solids.
- describe that deformation in solids is caused by a force and that in one dimension, the deformation can be tensile or compressive.
- describe the behaviour of springs in terms of load-extension, Hooke's law and the spring constant.
- define and use the terms Young's modulus, bulk modulus and shear modulus.
- demonstrate knowledge of the force-extension graphs for typical ductile, brittle and polymeric materials.
- become familiar of ultimate tensile stress, elastic deformation and plastic deformation of a material.
- describe the idea about energy bands in solids.
- classify insulators, conductors, semiconductors on the basis of energy bands.
- become familiar with the behaviour of superconductors and their potential uses.
- distinguish between dia, para and ferro magnetic materials.
- describe the concepts of magnetic domains in a material.
- explain the Curie point.
- classify hard and soft ferromagnetic substances.
- describe hysteresis loss.
- synthesise from hysteresis loop how magnetic field strength varies with magnetizing current.

Materials have specific uses depending upon their characteristics and properties, such as, hardness, brittleness, ductility, malleability, conductivity etc. What makes steel hard, lead soft, iron magnetic, and copper electrically conducting? It depends upon the structure – the particular order and bonding of atoms in a material.

This clue has made it possible to design and creates materials with new and unusual properties for use in modern technology.

A solid consists of atoms or clusters of atoms arranged in close proximity. The physical structure of a solid and its properties are closely related to the scheme of arrangement of atoms within the solid.

In crystals the arrangement of atoms is regular and periodic. The concepts of lattice and unit cell help us in understanding the atomic arrangement in crystals.

The crystal structures are analyzed using x-ray diffraction technique invented by Max von Laue and extensively employed by Bragg. The real crystals have imperfections of different kinds. The study of crystal geometry helps us to understand the diverse behavior of solids in their mechanical, metallurgical, electrical, magnetic and optical properties. The imperfections in real crystals can be controlled and suitably altered to improve the selected physical properties of the material.

For your Information

Magnetic-levitation is an application where superconductors perform extremely well. Transport vehicles such as trains can be made to "float" on strong superconducting magnets, virtually eliminating friction between the train and its tracks. It can attain an incredible speed of 361 mph (581 kph). On the other hand conventional electromagnets waste much of the electrical energy as heat.

16.1 CLASSIFICATION OF SOLIDS

On the basis of atomic arrangement solids may be classified into three categories, namely crystals, polycrystalline solids and amorphous solids.

1. Crystals

In a crystalline solid, the particles (ion, molecule or atoms) are arranged in definite geometric pattern in the three dimensional network. This is known as long range order. This arrangement repeats periodically over the entire crystal. Due to this arrangement, they have short range as well as long range order.

Crystals have smooth faces and straight edges. When a crystal is broken, it cleaves along certain preferred directions. X-ray diffraction studies have shown that in crystals the constituent atoms are arranged in a regular periodic pattern in three dimensions. The arrangement of atoms in specific relation to each other is called order.

In crystals the order exists in the immediate neighborhood of a given atoms as well as over large distance corresponding to several layers of atoms. Therefore, crystals possess both short range order and long range order.

Quartz, Sucrose (sugar), diamond and rock salt (NaCl) are examples of solids that occur as large size single crystals.

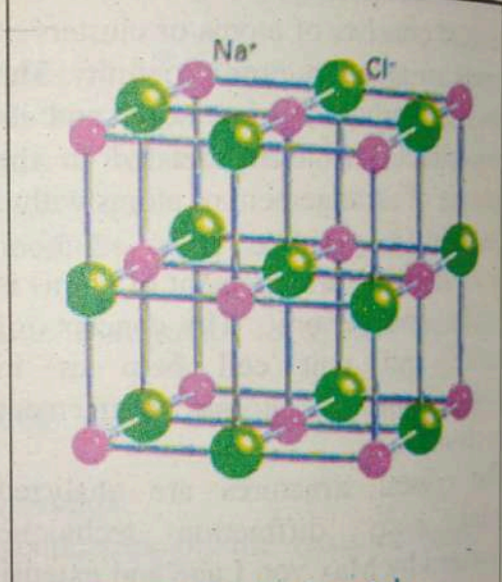
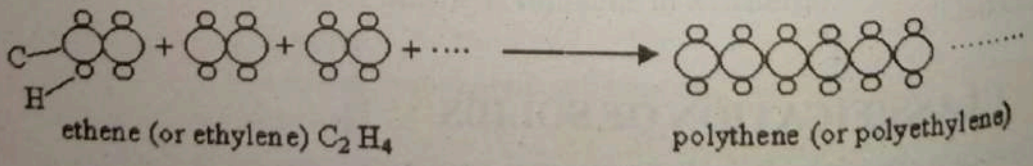


Figure 16.1: Nacl crystal

2. Polycrystalline solids

Polycrystalline is a material made up of *many small single crystals* (also called crystallites or grains).



Polycrystalline solids consist of fine grains, having a size of 10^3 to 10^4A°, separated by well define boundaries and oriented in different directions. Each such grain is a single crystal of an irregular shape. Since the grains are oriented haphazardly, a polycrystalline material is isotropic and exhibits the same properties in all directions. Majority of the natural solids have polycrystalline structure. Metals are examples of polycrystalline solids.

In these solids the ordered regions, vary in size and orientation with respect to one another.

These regions are called as grains (domain) and are separated from one another by grain boundaries. The atomic order can vary from one domain to the next. The grains are usually 100 nm - 100 microns in diameter.

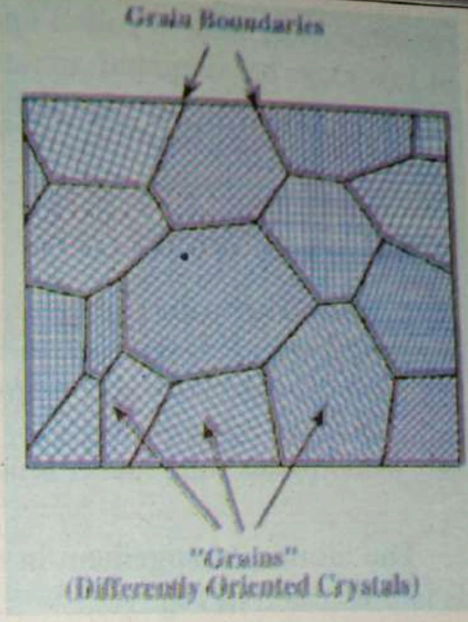


Figure 16.2: crystal grains

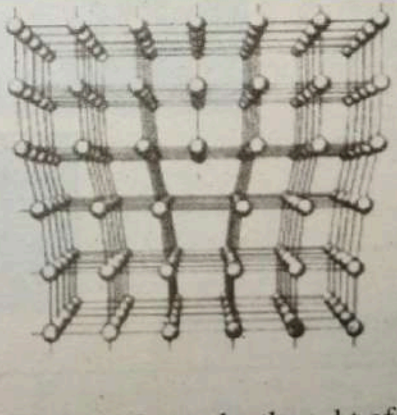
3. Amorphous Solids

Amorphous (Non-crystalline) solid is composed of randomly orientated atoms, ions, or molecules that do not form defined patterns or lattice structures.

So in amorphous solids the arrangement of atoms is random. These are the substance whose constituent particles don't possess a regular orderly arrangement. In an amorphous solid, the particles are arranged in a regular manner up to a small region only. This is called short range order. So, in these solids, the particles are not in regular arrangement and possess only short range order and have irregular shape.

Some liquids when cooled become more and more viscous and then rigid, retaining random atom characteristic

For your information



Although metals can be thought of as polycrystalline, the structure is by no means perfect. For example there are dislocations and point defects where atomic bonding is mis-matched.

distribution. This state is called undercooled liquid or amorphous solid. Some of the metals may be prepared in amorphous solid form by rapid cooling from molten state. Glass, rubber and polymers are examples of amorphous substances.

Do you know?

- Amorphous solids glass and plastics are very useful materials and are widely used in construction, house ware, laboratory ware, etc.
- Amorphous silica is one of the best materials for converting sunlight into electricity (photovoltaic).
- Amorphous solid rubber is used in making tyres, shoes soles etc.

The atomic arrangement in two dimensions in cases of the three classes of solids is illustrated in Fig. 16.3

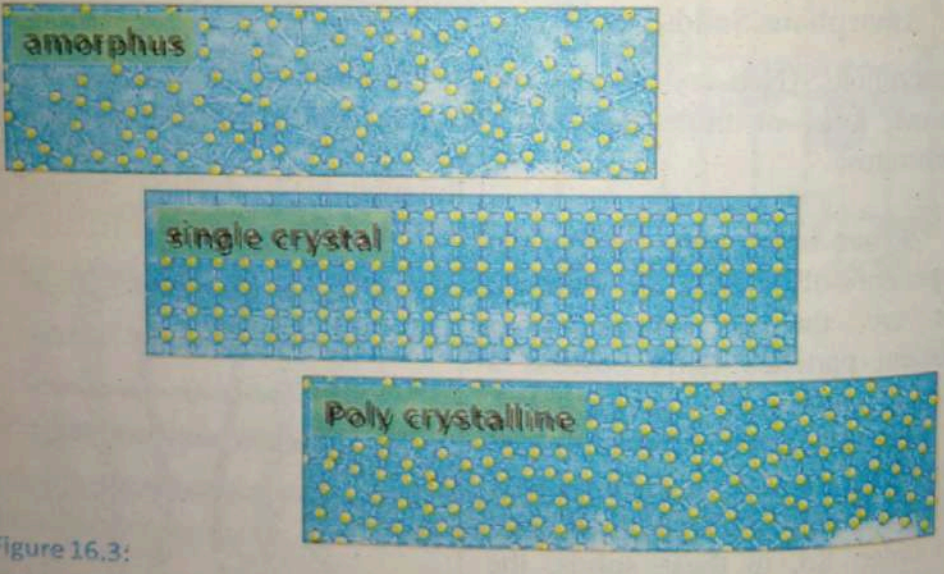


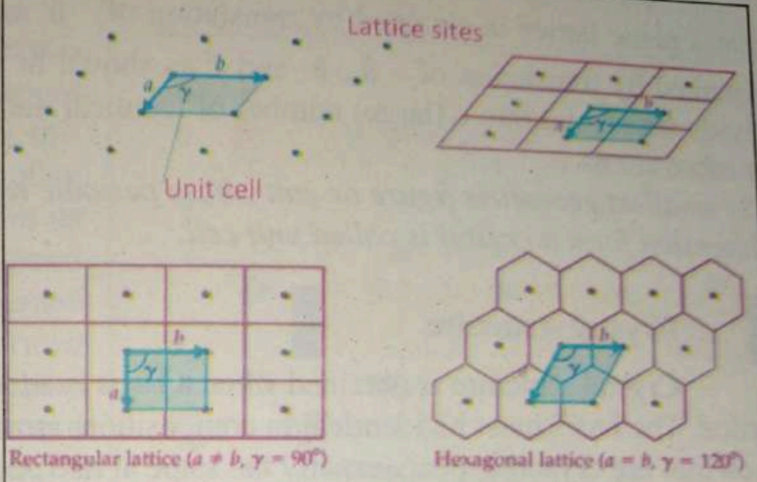
Figure 16.3:

X-ray investigations show that the crystals are composed of atoms (or group of atoms) held in an orderly three-dimensional array. The array may be viewed as produced when the group of atoms, henceforth called a basis or unit, is repeated at regular intervals along all directions in the crystal. The regular and periodic arrangement of the basis is the basic feature of crystals. Geometrical analysis of crystal structure is made by referring to an imaginary array of points in space. It is conventional to represent the periodicity by replacing the basis with a point.

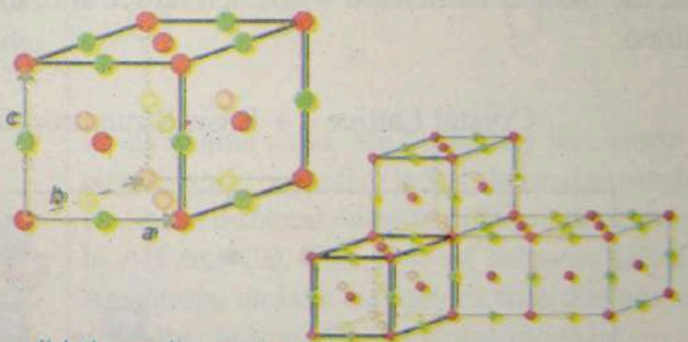
The collection of infinite number of points in a periodic arrangement is called a lattice.

A point is a dimension less and shapeless entity. Therefore, a lattice is merely an imaginary geometrical framework. The space lattice is a skeleton upon which crystal structure is built by placing atoms on or near the lattice points. Therefore, the study of crystal structure becomes simpler when it is represented by a space lattice. The points which are forming a lattice are called lattice sites.

The distance between the consecutive neighbours sites is called lattice constant. When we assign direction to these lattice constant, they become lattice translation vectors.



(a)two dimensional lattice points with each having an identical environment.



(b) three dimensional lattice

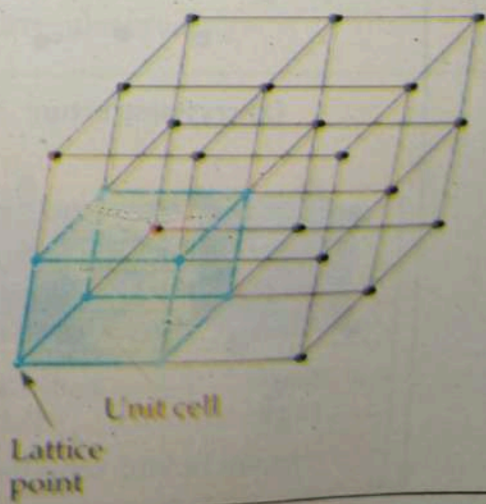


Figure 16.4(c) :unit cell

The two dimensional arrangements of lattice is shown in fig:. which shows that a plane lattice is obtained by translation of $\vec{a}$ and $\vec{b}$ and a space lattice is obtained by translation of $\vec{a}$, $\vec{b}$ and $\vec{c}$ as shown in fig16.4(a): It is possible to divide the crystal into a (large) number of identical unit cells, each containing one or more atoms.

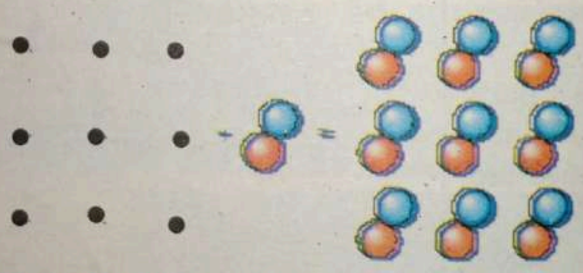
The smallest geometric figure or unit whose periodic repetition in two or three dimension form a crystal is called unit cell.

Crystal structure

Crystal structure is obtained when a basis is added at each point in the lattice. The basis must be identical in composition, arrangement and orientation such that the crystal appears exactly the same at one point as it does at other equivalent points. Fig.16.5(a) shows the basis consisting of a group of two atoms.

When the basis is associated with each lattice site, the crystal structure is obtained.

Crystal Lattice + Basis Structure= Crystal



(a):crystal structure

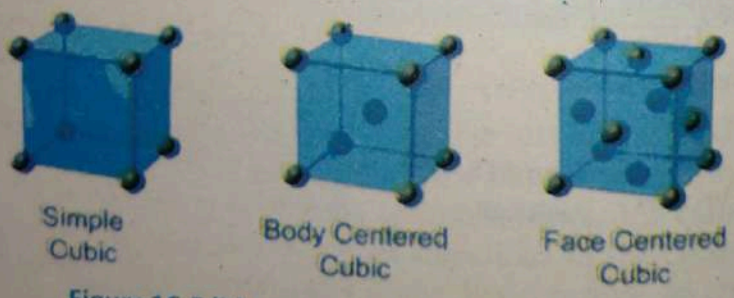


Figure 16.5 (b): some unit cells

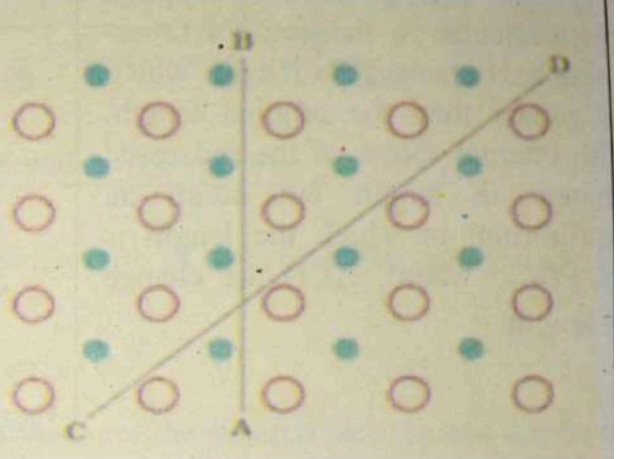
16.2 ELASTIC MODULI

When an external force is applied on the object, it changes its shape or size. Generally this deformation is small and often temporary. If an object regains its original shape when external force is removed it is called elastic. If it remains in deformed state it is called plastic. There are three types of deformations and corresponding three elastic moduli. The deforming force is expressed in terms of stress and the deformation is expressed in terms of strain. For elastic solids, the ratio of stress to strain is constant and it is called elastic modulus. That is

$$\text{Elastic modulus} = \frac{\text{Stress}}{\text{Strain}}$$

This is known as Hooke's law. There are three elastic moduli: Young's modulus (Y), Shear or Rigidity modulus (S) and Bulk modulus (B).

Do you know?



In crystalline solid, the properties like electrical conductance, refractive index, thermal expansion, etc., have different value in different directions as in AB and CD. This type of behavior is called Anisotropy and the substances with this property are called Anisotropic. A crystalline solid gives a clean surface after cleavage with knife rather than an irregular breakage.

Material	Young modulus Y(Pa)	Bulk modulus B(Pa)	Shear modulus S(Pa)
Aluminium	7×10^{10}	7.5×10^{10}	2.5×10^{10}
Brass	9×10^{10}	6×10^{10}	3.5×10^{10}
Copper	11×10^{10}	14×10^{10}	4.4×10^{10}
Crown glass	6×10^{10}	5×10^{10}	2.5×10^{10}
Iron	21×10^{10}	16×10^{10}	7.7×10^{10}
Lead	1.6×10^{10}	4.1×10^{10}	0.6×10^{10}
Nickel	21×10^{10}	17×10^{10}	7.8×10^{10}
Steel	20×10^{10}	16×10^{10}	7.5×10^{10}

16.2.1 Young's Modulus

The change in the length due to deforming force is described by Young's modulus. Consider a rod of length L having cross-sectional area A as shown in Fig16.6. If it is clamped at one end and a force is applied perpendicular to the area of cross-section, it changes its length, which is greater than the original length. The internal forces of the rod resist change in length but attain an equilibrium in which the length is $(L+\Delta L)$, where, ΔL is the change in length.

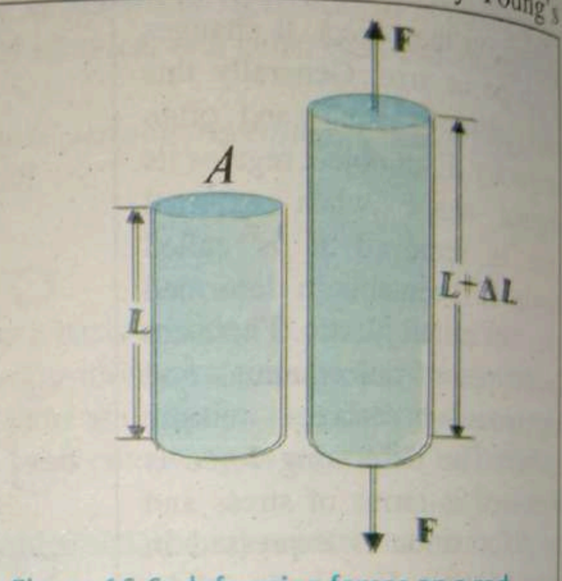


Figure 16.6: deforming forces on a rod

The ratio of the magnitude of external force F to the area of cross-section A is called as tensile stress. Where

$$\text{Tensile stress} = \frac{F}{A} \qquad ...(16.1)$$

The ratio of the change in length to the original length is called as tensile strain. And

$$\text{Tensile strain} = \frac{\Delta L}{L} \qquad ...(16.2)$$

Young's modulus is defined as the ratio of tensile stress to tensile strain.

$$Y = \frac{\text{Tensile stress}}{\text{Tensile strain}} = \frac{F / A}{\Delta L / L} \qquad ...(16.3)$$

Its SI unit is N/m^2.

The Hooke's law is valid within the elastic limit and for small strains. When the metal rod is subjected to increasing deforming force, the relation between stress and strain is as shown in Fig. 16.6.

16.2.2 Shear or Rigidity Modulus

When an object is subjected to a force tangential to one of its faces while the opposite face is held fixed there occurs a deformation (Fig16.7).

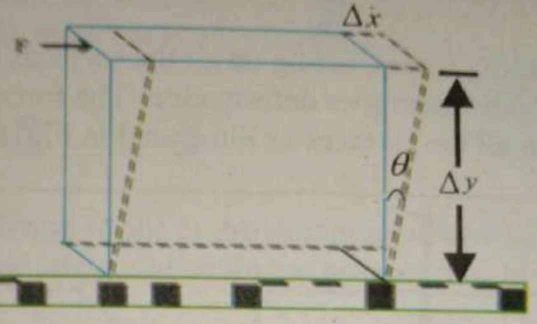


Figure 16.7: tangential deforming force on a box

The shear stress is defined as the ratio of tangential deforming force F to the area A of the face being sheared, i.e.

$$\text{Shear stress} = \frac{F}{A} \qquad \text{...(1)}$$

The shear strain is the ratio of displacement of the sheared face Δx and the fixed face y.

$$\text{Shear strain} = \frac{\text{displacement of Sheared face}}{\text{displacement of fixed face}}$$

$$= \frac{\Delta x}{y} \qquad \text{...(2)}$$

It may be described in terms of angle θ, which is called as angle of shear. Hence

$$\tan\theta = \frac{\Delta x}{y} \qquad \text{...(16.4)}$$

When the angle is small,

$$\tan\theta \approx \theta \qquad \text{...(16.5)}$$

The shear modulus is defined as the ratio of shear stress to the shear strain.

$$S = \frac{\text{shear stress}}{\text{shear strain}} = \frac{F/A}{\Delta x/y} \qquad \text{...(16.6)}$$

$$= \frac{F/A}{\tan\theta} \approx \frac{F}{A\theta} \qquad \text{...(16.7)}$$

16.2.3 Bulk Modulus

When deforming forces, acting on all the surfaces of a body, are at right angles, the body undergoes deformation. The forces are distributed uniformly on all the surfaces as illustrated in Fig16.8.

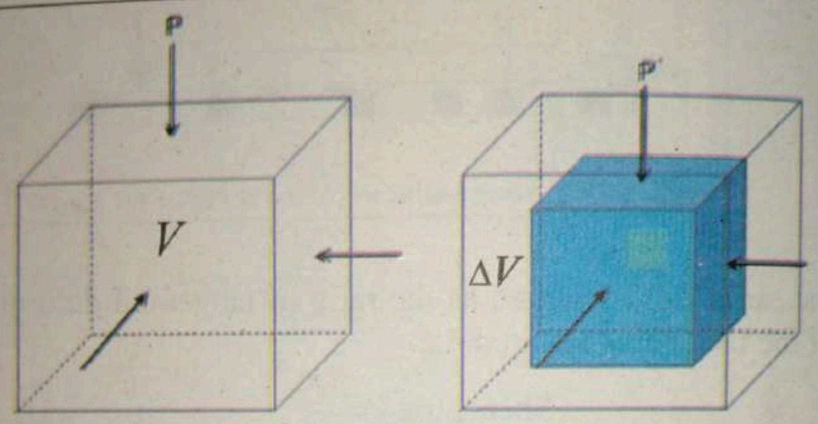


Figure 16.8: change in volume *V* of a box

In this case there is a change in the volume and not in the shape. The volume stress is the ratio of magnitude of the normal force *F* to the area *A*. Therefore

$$\text{Bulk or Volume stress} = \frac{F}{A}$$

In case of fluids it is called as pressure

$$\Delta P = \frac{F}{A}$$

The ratio of change in volume ΔV and original volume V is the volume strain. Where

$$\text{Volume strain} = -\frac{\Delta V}{V} \qquad ...(16.8)$$

The bulk modulus is defined as the ratio of volume stress to volume strain. Therefore,

$$B = \frac{\text{Volume stress}}{\text{Volume strain}} = \frac{F / A}{(-\Delta V / V)}$$

$$= \frac{\Delta P}{(-\Delta V / V)} \qquad ...(16.9)$$

The negative sign is inserted because increase in pressure cause decrease in volume. The value of bulk modulus is always taken as positive.

16.3 HOOKE'S LAW

Stress and strain take different forms in the situations shown in the Fig. (16.9). For small deformations the stress and strain are proportional to each other. This is known as Hooke's law.

Thus,

$$\text{stress} \propto \text{strain}$$

$$\text{stress} = k \times (\text{strain}) \quad \ldots(16.10)$$

Where, k is the proportionality constant and is known as modulus of elasticity. Hooke's law is an empirical law and is found to be valid for most materials. However, there are some materials which do not exhibits this linear relationship

16.3.1 STRESS-STRAIN CURVE

Engineering stress and strain are usually measured using a machine that strains the material at a fixed linear rate and records the stress.

The applied stress is gradually increased in steps and the change in length is noted. These values are then plotted on a graph .A typical graph for a metal is shown in Fig16.9. The stress-strain curves vary from material to material. These curves help us to understand how a given material deforms with increasing loads. From the graph, we can see that in the region between O to A, the curve is linear. In this region, Hooke's law is obeyed. The body regains its original dimensions when the applied force is removed. In this region, the solid behaves as an elastic body. In the region from A to B, stress and strain are not proportional. Nevertheless, the body still returns to its original dimension when the load is removed. The point B in the curve is known as yield point (also known as elastic limit) and the corresponding stress is known as yield strength (S_y) of the material. If the load is increased further, the stress developed exceeds the yield strength and strain increases rapidly even for a small change in the stress. The region of the plasticity is represented by the portion of the curve between B and C. Where point C in the fig16.9: shows the ultimate tensile strength (S_u) of the material. If the stress is increased beyond point C, the material is said to be permanently changed, and the body does not regain its original dimension. In this case, even when the stress is zero, the strain is not zero. This type of deformation is called plastic deformation. At point D the material cannot be stretched further and smallest increase in stress can result in breaking the sample.

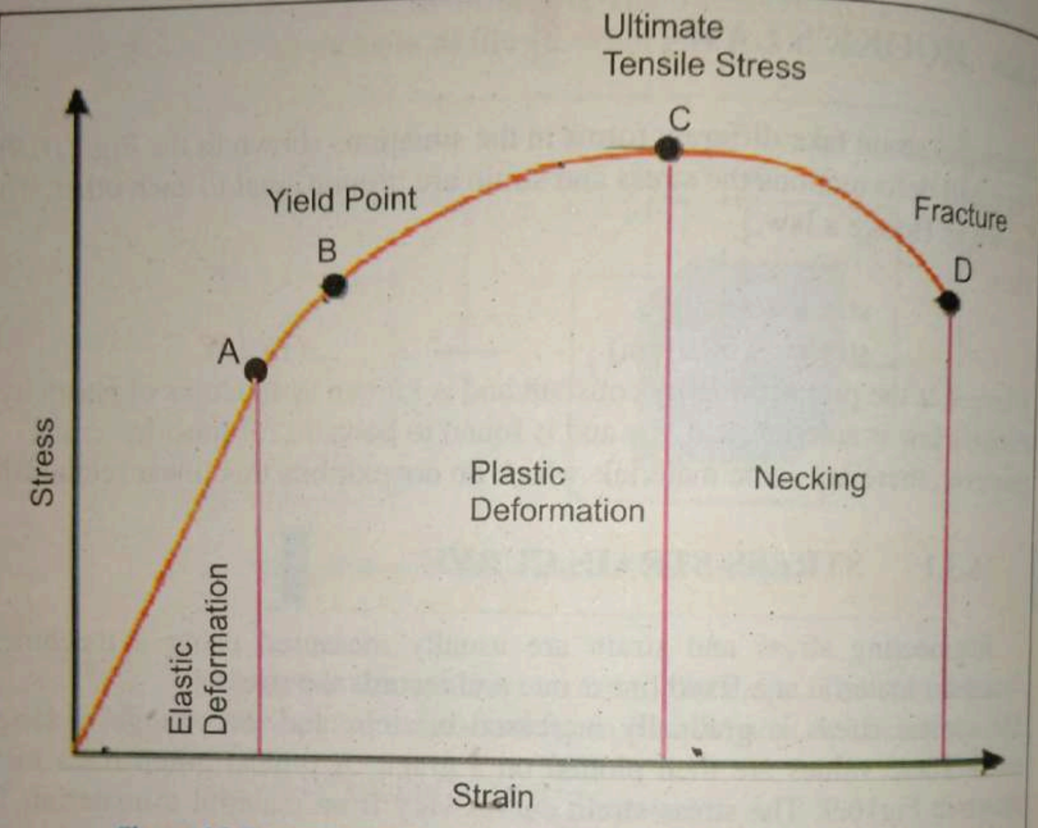


Figure 16.9: stress strain curve

If the ultimate strength and fracture points C and D are close, the material is said to be brittle. If they are far apart, the material is said to be ductile.

Example 16.1

A force of 500N is applied to one end of a cylindrical steel rod of diameter 50cm. What is the tensile stress?

Solution:

$$\text{Since Stress} = \frac{\text{force}}{\text{area}} = \frac{500}{\pi(25\times10^{-2})^2}$$

$$\text{Stress} = 2.5 \times 10^5\ \text{Nm}^{-2}$$

Thus the tensile stress in the rod is

$2.5 \times 10^5\ \text{Nm}^{-2}$

Example 16.2

In an experiment to measure Young's modulus, a load of 500Kg hanging from a steel wire 2.4m long, of cross section 16cm^2,was found to stretch the wire .30cm from its un-stretched length. What is (a) the stress? (b) the strain (c) the value of Young's modulus for the steel of which the wire is composed?

Solution:

Stretching in wire = x = .30cm = 3×10^{-3}m

Cross section of wire =A= .16cm^2 = 1.6×10^{-5}m^2

(a) $$\text{Stress}=\frac{F}{A}=\frac{5000}{1.6\times10^{-5}m^2}=3.1\times10^{8}\,\text{Nm}^{-2}$$

(b) $$Strain=\frac{x}{L}=\frac{3.0\times10^{-3}}{2.4}=1.25\times10^{-3}$$

(c) Young's Modulus $$y=\frac{\text{Stress}}{\text{Strain}}=\frac{3.1\times10^{8}}{1.25\times10^{-3}}=2.48\times10^{11}\,\text{Nm}^{-2}$$

16.4 Mechanical properties of solids

The mechanical properties of a material are those properties that involve a reaction to an applied load. The mechanical properties of metals determine the range of usefulness of a material and establish the service life that can be expected. Mechanical properties are also used to help classify and identify material. The most common properties considered are strength, ductility, hardness, impact resistance, and fracture toughness.

1. **Strength**: The general ability of a material to withstand an applied force.
2. **Hardness** : Hardness is a measure of how easily a material can be scratched or indented. Hard materials are often also very brittle - this means they have a low resistance to impact. Well known hard materials include diamond and hardened high carbon steels.
3. **Brittleness**: A material that has a tendency to break easily or suddenly without any extension first. Good examples are Cast iron, concrete, high carbon steels, ceramics, and some polymers such as urea formaldehyde (UF).
4. **Toughness**: A material that absorbs impact (sudden forces or shocks such as hammer blows) well is tough - this is the opposite to brittleness. [units for toughness are energy per unit area - J/m²]

5. **Plasticity**: The materials which deform permanently when small forces are applied show plasticity. Plasticine and clay are good examples.
6. **Elasticity**: The ability of a material to return to its original form after a load has been applied and removed. Good examples include rubber, mild steel and some plastics such as nylon.
7. **Stiffness**: The ability to resist bending.
8. **Ductility**: The ability to be drawn out into a thin wire or threads. It is a measure of how easily a material can be worked. Good examples are gold, copper, titanium, wrought iron, low carbon steels and brass. It also provides an indication of how visible overload damage to a component might become before the component fractures. Ductility is also used a quality control measure to assess the level of impurities and proper processing of a material.

The conventional measures of ductility are the engineering strain at fracture (usually called the elongation) and the reduction of area at fracture. Both of these properties are obtained by fitting the specimen back together after fracture and measuring the change in length and cross-sectional area.

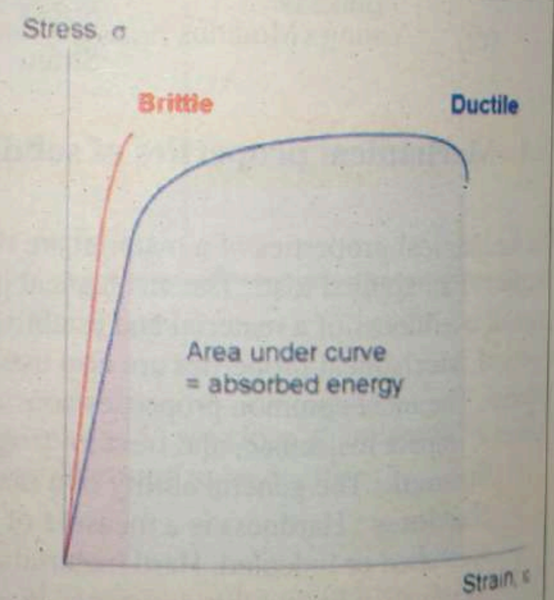


Figure 16.10: Stress-strain curves for brittle and ductile materials. Brittle materials fracture at low strains and absorb little energy. Conversely, ductile materials fail after significant plastic strain (deformation) and absorb more energy.

16.4.1 Strain energy

When a body is loaded without exceeding elastic limit, it changes its dimensions. When the load is removed, it regains its original dimensions. For the period of time it has remained loaded, it stores energy in itself and this energy is called elastic strain energy.

The work done when a wire is stretched results in energy being stored in it, called strain energy.

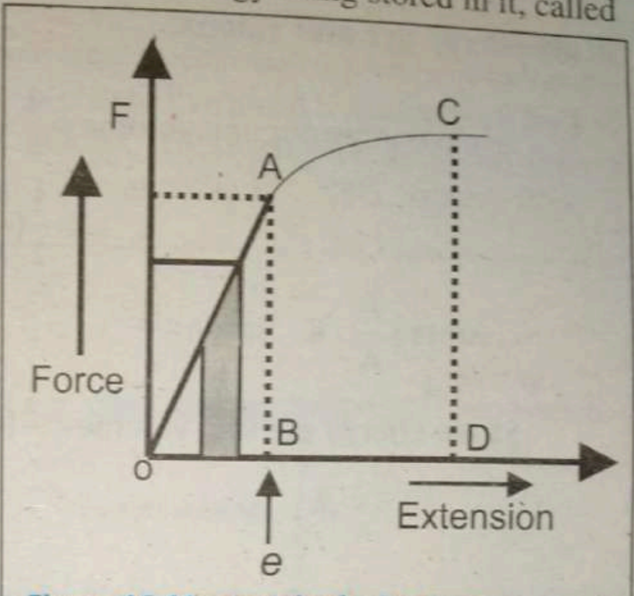


Figure 16.11: stretched wire curve

The above graph of force against extension has the same shape as the corresponding stress against strain graph.

The force varies from 0 at the start to F at the end when the wire is stretched by an amount e.

Therefore:

Work done on the wire during stretching = (average force) × (extension)

$$= \frac{1}{2}Fe \text{ =area of shaded strip} \qquad ...(16.11)$$

The diagram shows that F is not constant during the extension. However, though the strip has to be drawn quite wide for clarity, we can imagine it to be as thin as we wish, and the thinner it is, the smaller the change in F over the correspondingly small extension.

Total work done while producing extension Δe in the string:
=area of triangle OAB

$$\text{Strain energy} = \frac{1}{2}\text{base}\times\text{height} = \frac{1}{2}(\text{OB})(\text{AB}) \qquad ...(16.12)$$

$$\text{Strain energy } = \frac{1}{2}F \times e \qquad ...(16.13)$$

Strain energy per unit volume

$$\text{Strain energy per unit volume} = \frac{1}{2}\frac{F\times e}{A\ell}$$

$$= \frac{1}{2}\left(\frac{F}{A}\times\frac{e}{\ell}\right) \qquad \ldots(16.14)$$

$$\therefore \text{stress} = \frac{F}{A} \quad \& \quad \text{strain} = \frac{e}{\ell}$$

$$\text{Strain energy per unit volume} = \frac{1}{2}(\text{stress}\times\text{strain})$$

This is the area under the stress-strain graph.

16.5 ENERGY BAND THEORY

When atoms bond together to become molecules their energy levels merge and split-this results in the splitting of spectral lines in molecular spectra. In a solid this process takes place between large numbers of atoms, and the energy levels divide into bands of closely spaced levels with large energy gaps between the bands. There is a space between these energy bands which cannot be occupied by electrons these are called forbidden energy gap or forbidden energy states. So electron in an atom can only occupy certain discrete energy states which are called permissible energy states

The energy band structure of solids can explain many of their electrical and optical properties. Fig:16.12 a: shows two energy bands, the upper band is called the conduction band in which the electrons are forced to move. In this band electrons move freely and therefore can conduct electric current through solids. It may be either empty or partially filled with electrons.
The lower energy band is called valence band, in which the electrons are tightly bound to their atoms and are not free to move about.

INSULATOR

In an insulating material the outer electrons are all shared between atoms to form bonds, so they are not available as charge carriers (the inner electrons are, of course, tightly bound to individual atoms). These valence electrons have a range of allowed energies which form a "valence band". This valence band is completely filled, so there are no vacant allowed energy levels which would allow the electrons to gain energy from an applied electric field and move from an occupied state in one atom to an empty state in another. There is another allowed energy band above the valence band and if electrons could somehow get into this empty band they could skip from atom to atom through the structure. Thermal vibration might give individual electrons energy boosts, but the energy gap is much greater than the typical size of these thermal excitations so the material is an insulator.

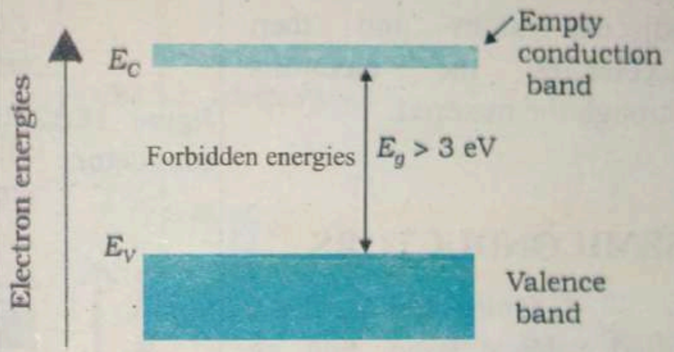


Figure 16.12 (a) : Energy band structure for an insulator

Typical thermal excitation = $kT = 0.025$eV

Thermal excitation is a random process, so electrons will sometimes get energy boosts a lot greater than kT, but the band gap in an insulator is so great that the probability of an electron jumping into the conduction band and becoming a useful charge carrier is virtually zero. In the valence band the electrons are unable to gain energy from an applied electrical field as there are no vacant energy levels for them to jump into. This explains the extremely high resistivity and low conductivity of many insulators.

CONDUCTORS

In a conducting material the energy levels of [illegible]nt atoms [illegible] to form bands that overlap. The top of the valenc[illegible] the b[illegible] conduction band. This means that electrons i[illegible] to vacant energy levels in the partially filled conduction band. In practice this means that an applied electric field (e.g. created by a cell connected across the conductor) supplies the tiny amount of energy needed to move electrons from one atom to a vacant state in the conduction band of an adjacent atom and then accelerates the electrons through the material.

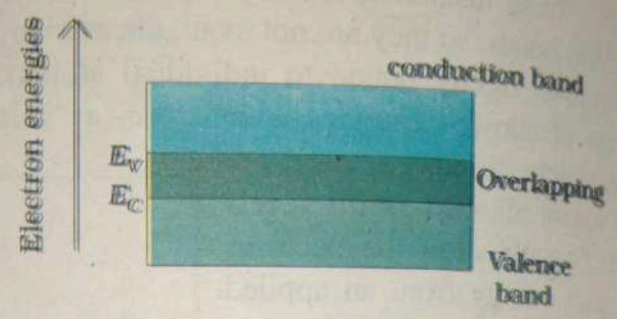


Figure 16.12 (b): Energy band structure for a conductor.

SEMICONDUCTORS

A semiconductor has a filled valence band, and an empty conduction band, just like an insulator. In fact, all semiconductors are insulators at very low temperatures. The band gap, however, is much smaller than in materials that are insulators at room temperature. As a result, some electron will be thermally excited into the conduction band where they can move freely through the material. When this happens the electrons leave 'holes' in the valence band.

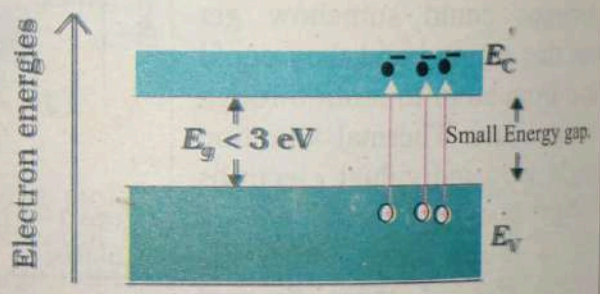


Figure 16.12 (c): Energy band structure for a semiconductor

These holes behave just like positive charge carriers and can also move through the material. When a potential difference is connected across a semiconductor, holes and electrons drift in opposite directions and both contribute to the current that flows. The concentration of charge carriers in a typical semiconductor at room temperature is about 10^{21} m^{-3}. The concentration of charge carriers in a metal is about ten million times greater; as their conductivity is in between conductors and insulators so these substances are called semiconductors.

16.6 Superconductors

A superconductor is a material that can conduct electricity or transport electrons from one atom to another with no resistance.

This means no heat, sound or any other form of energy would be released from the material when it has reached "critical temperature" (T_c), or the temperature at which the material becomes superconductive. Unfortunately, most materials must be in an extremely low energy state (very cold) in order to become superconductive. The resistance of a superconductor is zero, since there are no heat losses for currents through them; they are used in magnets needing high currents, such as in MRI machines, and it does not offer resistance to transmission line. In the past decade, tremendous advances have been made in producing materials that become superconductors at relatively high temperatures. There is hope that room temperature superconductors may someday be manufactured.

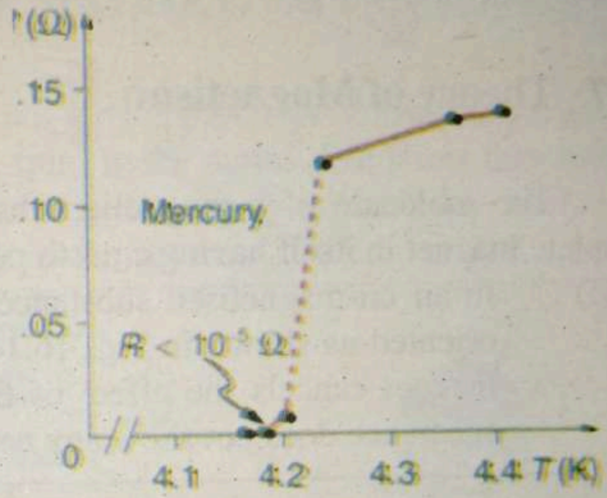


Figure 16.13: A graph of resistivity versus temperature for a superconductor shows a sharp transition to zero at the critical temperature Tc.

High temperature superconductors have verifiable Tc greater than 125 K, well above the easily achieved 77-K temperature of liquid nitrogen.

The temperature at which and below which a material becomes a superconductor is said to be its critical temperature, denoted by T_c.

Certain other elements were also found to become superconductors, but all had T_c less than 10 K, which are expensive to maintain. In 1986, a ceramic compound was found to have T_c of 35 K. It looked as if much higher critical temperatures could be possible, and by early 1988 another ceramic (thallium, calcium, barium, copper, and oxygen) had been found to have $T_c = 125$ K. The first commercial use of a high temperature superconductor is in an electronic filter for cellular phones.

High-temperature superconductors are used in experimental apparatus. The search is on for even higher T_c superconductors, many of complex and exotic copper oxide ceramics, sometimes including strontium, mercury, or yttrium as well as barium, calcium, and other elements. Room temperature (about 293 K) would be ideal, but any temperature close to room temperature is relatively cheap to produce and maintain.

16.7 Theory of Magnetism

The molecule of a magnetic substance (where magnetized or not) is a complete magnet in itself having a north pole and a south pole of equal strength.

(i) In an un-magnetised substance, the molecular magnets are randomly oriented as shown in Fig. 16.14 (a). The north pole of one molecular magnet cancels the effect of the south pole of the other so that the substance does not show any net magnetism.

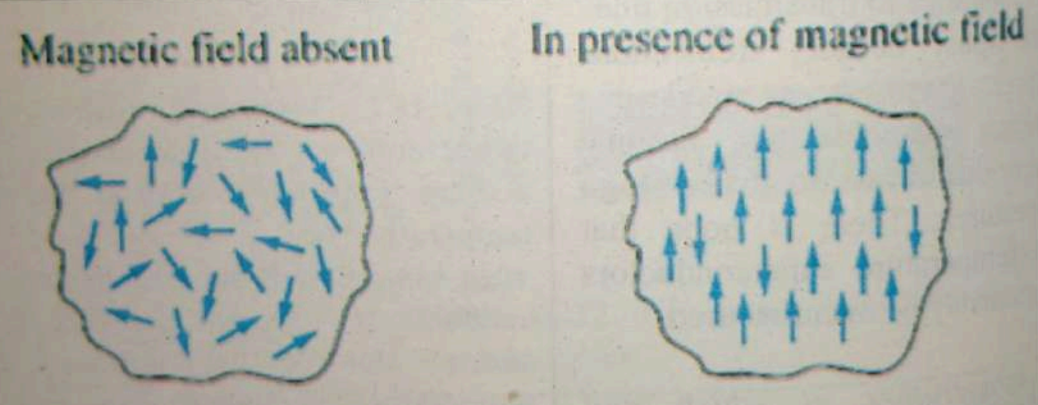


Figure 16.14: (a) (b)

(ii) When a magnetising force is applied to the substance, the molecular magnets are turned and tend to align in the same direction with N-pole of one molecular magnet facing the S-pole of other as shown in Fig.16.14 (b). The result is that magnetic field of the molecular magnets aid each other and two definite N and S-pole are developed near the ends of the specimen; the strength of the two poles being equal. Hence the substance gets magnetised.

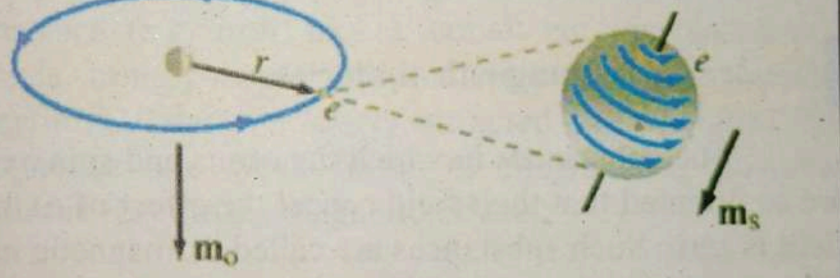
(iii) The extent of magnetisation of the substance depends upon the extent of alignment of molecular magnets. When all the molecular magnets are fully aligned, the substance is said to be saturated with magnetism.

(iv) When a magnetised substance (or a magnet) is heated, the molecular magnets acquire kinetic energy and some of them loss their arrangement. For this reason, a magnet loses some magnetism on heating.

16.8 MODERN VIEW ABOUT MAGNETISM

According to modern view, the magnetic properties of a substance are due to the motions of electrons (orbital and spin) in the atoms. We know that an atom consists of central nucleus with electrons revolving around the nucleus in different orbits. This motion of electrons is called orbital motion [Fig16.15(a).].

The electrons also rotate around their own axis. This motion of electrons is called spin motion [Fig16.15(b)].



(a) Orbiting electron (b) Spinning electron

Figure 16.15:

Due to these two motions, each atom is equivalent to a current loop i.e. each atom behaves as a magnetic dipole.

1. In the un-magnetised substances, the magnetic dipoles are randomly oriented so that magnetic fields mutually cancel. When the substance is magnetized, the magnetic dipoles are aligned in the same direction. Hence the substance shows net magnetism.
2. Since the revolving and spinning electrons in each atoms cause magnetism, no substance is non-magnetic.
3. It is important to note that spinning motion of electrons in particular is responsible for magnetism of a substance.

16.8.1 CLASSIFICATION OF MAGNETIC MATERIALS

We can classify materials into three categories *viz.* diamagnetic, paramagnetic and ferromagnetic. The behaviour of these three classes of substances is different in an external magnetic field.

1. Paramagnetic material

In these substances the orbital and spin axis of the electrons in an atom are so oriented that their field support each other and the atom behaves like a tiny magnet. These substances are called paramagnetic materials.

When a paramagnetic substance (e.g. aluminium, antimony etc.) is placed in a magnetic field, the substance is weakly magnetized in the direction of the applied field. Therefore, a paramagnetic substance is weakly attracted by a strong magnet.

2. Diamagnetic materials

The substances in which the orbits and spin axis of the electron in an atom are so oriented that their field cancel the effect of each other so that their resultant field is zero. Such substances are called diamagnetic materials.

When a diamagnetic substance (e.g. copper, zinc, bismuth etc.) is placed in a magnetic field, the substance is weakly magnetized in a direction opposite to that of the applied field. Therefore, a diamagnetic substance is weakly repelled by a strong magnet.

3. Ferromagnetic Materials

In these substances the individual atoms act like tiny magnets. The interaction between these tiny atomic magnets is so strong that it line up parallel to each other even when no external magnetic fields is present. Such substances are called ferromagnetic materials. These tiny magnets are called magnetic domains. The size of these domains is very small of the order of millimeters or less but large enough to contain atoms from 10^{12} to 10^{16}. Each domain acts like a small magnet with its own north and South Pole. The coupling or interaction between the neighboring tiny magnets is reduced by increasing the temperature of a substance. The temperature at which a ferromagnetic material becomes paramagnetic is called its curie temperature.

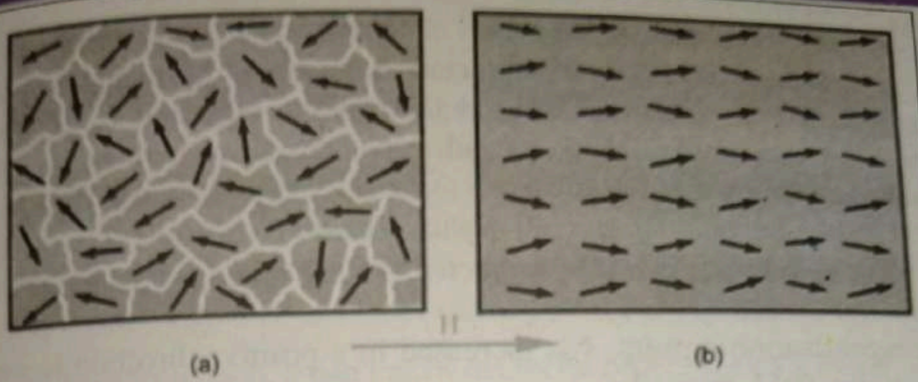


Figure 16.16: (a) a piece of ferromagnetic material which is not magnetised, where the domain poles are not aligned; (b) the domain poles aligned with an external magnetising force (H).

When a ferromagnetic substance (e.g. iron, nickel, cobalt etc.) is placed in a magnetic field, the substance is strongly magnetised in the direction of the applied field. Therefore, ferromagnetic material is strongly attracted by a magnet. The diamagnetism and paramagnetism are weak forms of magnetism. However, ferromagnetic substances exhibit very strong magnetic effects.

16.9 MAGNETIC HYSTERESIS

Hysteresis loop

When an electric current is passed through a coil of wire, the coil acts like a bar magnet with a north pole at one end and a south pole at the other. In other words, it acts like an electromagnet. If a bar of soft iron is placed inside the coil, the strength of the electromagnet is much increased. This is because the piece of soft iron is itself converted into a magnet by the effect of the current in the coil. The Magnetic Flux Density is a measure of the amount of magnetic flux in a unit area perpendicular to the direction of magnetic flow, or the amount of magnetism induced in a substance placed in the magnetic field. Magnetic field strength (H) is the amount of magnetizing force. The intensity of the Magnetic Flux Density, (B), is affected by the intensity of the Magnetic Field, (H) the quantities of the substance and the intervening media between the source of the magnetic field and the substance.

The relationship between magnetic field strength and magnetic flux density is:

$$B = H \times \mu_o$$

When a magnetic material is subjected to a cycle of magnetism (i.e. it is magnetised first in one direction and then in the other), it is found that flux density B in the material lags behind the applied magnetizing force H. This phenomenon is known as hysteresis.

The phenomenon of lagging of flux density (B) behind the magnetizing force (H) in a magnetic material subjected to cycle of magnetization is known as magnetic hysteresis.

If the magnetization current, *I* is increased in a positive direction to some value the magnetic field strength H increases linearly with *I* and the flux density B will also increase as shown by the curve from point O to point a as it heads towards saturation. Now if the magnetizing current in the coil is reduced to zero the magnetic field around the core reduces to zero but the magnetic flux does not reach zero due to the residual magnetism present within the core and this is shown on the curve from point a to point b. Fig.16.17

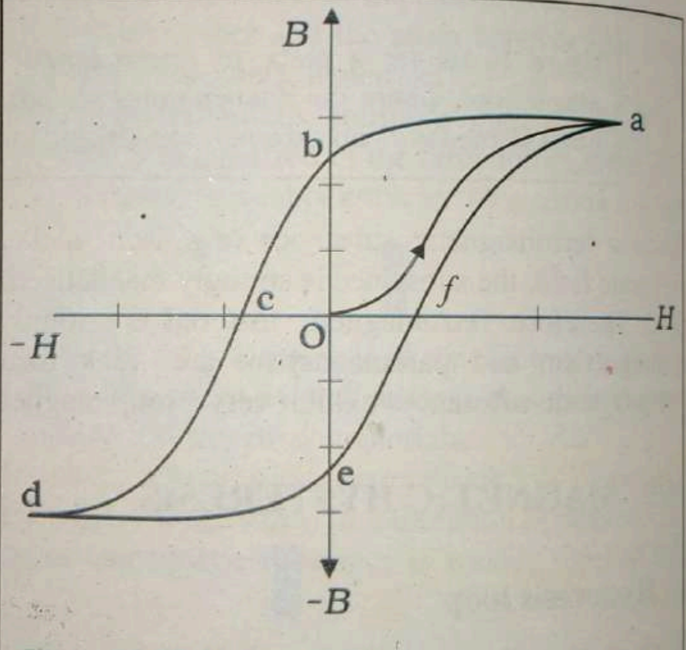


Figure 16.17: hysteresis loop

To reduce the flux density at point b to zero we need to reverse the current flowing through the coil. The magnetizing force which must be applied to null the residual flux density is called a "Coercive Force". This coercive force reverses the magnetic field re-arranging the molecular magnets until the core becomes un-magnetized at point c. An increase in the reverse current causes the core to be magnetized in the opposite direction and increasing this magnetization current will cause the core to reach saturation but in the opposite direction, point d on the curve. If the magnetizing current is reduced again to zero the residual magnetism present in the core will be equal to the previous value but in reverse at point e. Again reversing the magnetizing current flowing through the coil this time into a positive direction will cause the magnetic flux to reach zero, point f on the curve and as before increasing the magnetization current further in a positive direction will cause the core to reach saturation at point a. Then the B-H curve follows the path of a-b-c-d-e-f-a as the magnetizing current flowing through the coil alternates between a positive and negative value such as the cycle of an AC voltage. This path is called a Magnetic Hysteresis Loop. Thus when a magnetic material is subjected to one cycle of magnetization, B always lags behind H so that the resultant B-H curve forms a closed loop, called hysteresis loop.

From the hysteresis loop, a number of magnetic properties of a material are

1. **Retentivity** - It is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation.
2. **Residual Magnetism or Residual Flux** - the magnetic flux density that remains in a material when the magnetizing force is zero.
3. **Coercive Force** - The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero.
4. **Reluctance** - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.

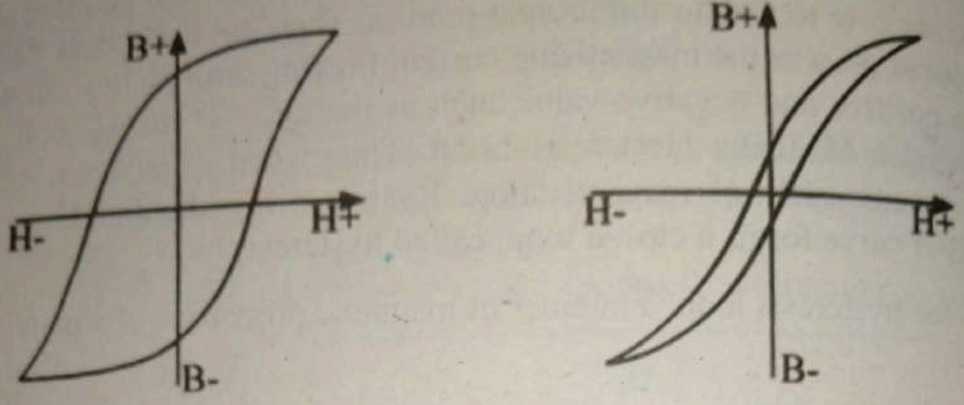
16.9.1 Magnetic Hysteresis Loops for Soft and Hard Materials

- **Soft magnetic materials:**

Soft ferromagnetic materials such as iron or silicon steel have very narrow magnetic hysteresis loops resulting in very small amounts of residual magnetism making them ideal for use in relays, solenoids and transformers as they can be easily magnetised and de-magnetised.

Since a coercive force must be applied to overcome this residual magnetism, work must be done in closing the hysteresis loop with the energy being used being dissipated as heat in the magnetic material. This heat is known as hysteresis loss, the amount of loss depends on the material's value of coercive force.

By adding silicon, to iron a material with a very small coercive force can be made, such materials typically contain 5% silicon and have very narrow hysteresis loop (figure 16.18b).



(a) (b)

Figure 16.18: (a) the hysteresis loop for hard magnetic material suitable for permanent magnet; (b) the hysteresis loop for soft magnetic material suitable for a transformer core.

Materials with narrow hysteresis loops are easily magnetised and de-magnetised and known as soft magnetic materials.

Magnetic Hysteresis results in the dissipation of wasted energy in the form of heat with the energy wasted being in proportion to the area of the magnetic hysteresis loop. Hysteresis losses will always be a problem in AC transformers where the current is constantly changing direction and thus the magnetic poles in the core will cause losses because they constantly reverse direction

Hard magnetic materials:

In order to create a permanent magnet, a material with a very fat hysteresis loop may be used (figure 16.18a). Such materials, once magnetised, are very difficult to demagnetise and when the magnetising force is removed a substantial magnetic flux density remains. These materials are known as hard magnetic materials. Its examples are Tungsten steel, Cunife, Cobalt rare earth 1, Sintered ferrite 3, and Sintered alnico 8 etc.,

Materials with fat hysteresis loops are difficult to de-magnetise and magnetic flux density remains even magnetising force is removed are known as hard magnetic materials.

Key points

- In a crystalline solid, the particles (ion, molecule or atoms) are arranged in definite geometric pattern in the three dimensional network. This is known as long range order.
- Polycrystalline is a material made up of *many small single crystals* (also called crystallites or grains). Metals are examples of polycrystalline solids.
- Amorphous (Non-crystalline) Solid is composed of randomly orientated atoms, ions, or molecules that do not form defined patterns or lattice structures.
- Geometrical analysis of crystal structure is made by referring to an imaginary array of points in space.
- *The collection of infinite number of points in a periodic arrangement is called a lattice.*
- *The smallest geometric figure or unit whose periodic repetition in two or three dimension form a crystal is called unit cell.*
- Crystal structure is obtained when a basis is added at each point in the lattice.
- The ratio of stress to strain is constant and it is called elastic modulus
- The ratio of the magnitude of external force F to the area of cross-section A is called as tensile stress.
- Young's modulus is defined as the ratio of tensile stress to tensile strain.
- The shear stress is defined as the ratio of tangential deforming force F to the area A of the face being sheared.
- The bulk modulus is defined as the ratio of volume stress to volume strain.
- For small deformations the stress and strain are proportional to each other. This is known as Hooke's law.
- Hardness is a measure of how easily a material can be scratched or indented.
- A material that has a tendency to break easily is called brittle.

- Stiffness is the ability to resist bending.
- The work done when a wire is stretched results in energy being stored in it, called strain energy.
- According to band theory of solids the energy level in an atom can be divided into two main bands namely conductions band and valance band
- *A superconductor is a material that can conduct electricity or transport electrons from one atom to another with no resistance.*
- According to modern view, the magnetic properties of a substance are due to the motions of electrons (orbital and spin) in the atoms
- Magnetic materials are classified into three categories *viz.* diamagnetic, paramagnetic and ferromagnetic.
- When a magnetic material is subjected to a cycle of magnetism, it is found that flux density B in the material lags behind the applied magnetizing force H. This phenomenon is known as hysteresis.

Exercise ?

Multiple choice questions:

Each of the following questions is followed by four answers. Select the correct answer in each case.

1. A wire is stretched to double of its length. Its strain is
   (a) 2 (b) 1 (c) 0 (d) 0.5
2. Which of the modulus of elasticity is involved in compressing a rod to decrease its length?
   (a). young's modulus (b). Bulk modulus
   (c). Modulus of elasticity (d). none of the above
3. Which one is Ferromagnetic in nature?
   (a) Soft iron (b) Nickle
   (c) Copper (d) None of these
4. If both the length and radius of the rod are doubled, then the modulus of elasticity will
   (a) increase (b) decrease
   (c) remains the same (d) doubled
5. Curie temperature is a point where
   (a) diamagnetism changes to paramagnetism
   (b) paramagnetism changes to diamagnetism
   (c) ferromagnetism changes to paramagnetism
   (d) paramagnetism changes to ferromagnetism
6. A cable breaks if stretched by more than 2mm. it is cut into two equal parts. How much either part can be stretched without breaking?
   (a) 25 m (b) 1mm (c) 2mm (d) 0.5m

Conceptual questions

1. Evaluate the importance of strength and stiffness in a design context.
2. Discuss the superconductivity of a conductor with the help of a curve.
3. Distinguish between crystalline, amorphous and polymer solids.

4. Define unit cell, basis and space lattice.
5. Differentiate between paramagnetic diamagnetic and ferromagnetic materials with suitable examples..
6. Distinguish between soft and hard substance by drawing its curves.
7. Explain Hook's Law and Modulus of Elasticity.
8. Is there any difference in the length of a 20 meter steel girder when standing vertically and horizontally?
9. Steel reinforcing is used in concrete beams to prevent cracking. Explain where the steel reinforcing should be placed in a concrete beam?
10. (a) What is meant by the elastic limit of a material.
    (b) In what way does a material behave if it obeys Hook's Law?
11. Cast-iron beams are used in bridge and building construction. The lower part of the beam is thicker than the upper part. Why is it better for the lower part of the beam to be thicker than the upper part? Given reasons for your answer including reference to the tensile and compressive strength.

Comprehensive questions

1. Explain the differences between tensile and compressive forces and how they affect equilibrium within a structure.
2. Draw and describe a stress/strain graph and identify the elastic region, plastic flow region, yield stress and ultimate tensile stress.
3. Describe the valence band, conduction band and forbidden energy gap with the help of energy level diagram.
4. Discuss the superconductivity of a conductor with the help of a curve.
5. Describe the mechanical properties of solids?
6. Describe Hysteresis loop for a ferromagnetic materials by drawing its curve for iron.
7. Explain strain energy in a deformed wire by drawing its graph.

Numerical Problems

1. A 1.50cm length of pianos wire with a diameter of 0.25cm is stretched by attaching a 10kg mass to one end. How far is the wire stretched?

(1.5×10^{-4}m)

2. A cable has a length of 12m and is stretched by 1.2×10^{-4}m when a stress of 8.0×10^{8} Nm^{-2} is applied. What is the strain energy per unit volume in the cable when the stress is applied?

(4×10^{3} Jm^{-3})

3. A cylindrical steel rod 0.50m long and 1cm in radius is subjected to a tensile force of 1×10^{4} N.

(a) What is the tensile stress?

(b) What is tensile strain?

(c) By what amount does the rod stretch?

((a) 0.31×10^{8} Nm^{-2} (b) 1.6×10^{-4} (c) 0.8×10^{-4}m)

4. A cable has an un-stretched length of 12m and it stretches by 1.2×10^{-4}m when a stress of 6.4×10^{8} Nm^{-2} is applied. What is the strain energy per unit volume in the cable when this stress is applied? (3.2×10^{3} Jm^{-3})

5. Young's Modulus for a particular wood is 1×10^{10} Nm^{-2}. A wooden chair has four legs each of length 42cm and cross sectional area 2×10^{-3}m^2. Hamza has a mass of 100Kg.

(a) What is the stress on each leg of the chair when Hamza stands on the chair?

(b) By what amount do the chair legs shrink when Hamza stands on the chair?

((a) 5×10^{5} [illegible] (b) 2.1×10^{-5}m)

6. A force of 1.5×10^4N causes a strain of 1.4×10^{-4} in a steel cable of cross-sectional area 4.8×10^{-4}m^2.

(a)What is the Young's Modulus of the steel cable?

(b) The stress strain graph is linear for this cable. Calculate the strain energy per unit volume stored in the cable when the cable has a strain of 1×10^{-4}.

((a) 2.2×10^{11}Nm^{-2}, (b) 1.5×10^3Jm^{-3})