

MID TERM SYLLABUS

Materials Science II

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DEPARTMENT OF PHYSIC, IUB, PAKISTAN

Course Outline

MATERIALS SCIENCE II

Imperfections in crystals. Impurities. Vacancies. Grain boundaries. Dislocations. Stacking faults. Frenkel and Schottky disorder. Electrons and holes. Color centres. Mechanical properties of metals. Polymers and ceramics. Elastic and plastic deformation. Fracture, creep and fatigue phenomena. Strengthening mechanism. Annealing. Effect of imperfections on the mechanical properties of materials. Modulation spectroscopy for optical properties in solids. Modulation techniques. Wavelength modulation. Temperature modulation. Stress modulation. piezo absorption and piezo-reflectance. Electric field modulation.

Books Recommended:

1. C.S.Barrett. Structure of Metals (McGraw-Hill).
2. A.V.Tobolsky. Properties and Structure of Polymers (John-Wiley and Sons).
3. F.C.Phillips. An Introduction to Crystallography (John-Wiley and Sons).
4. A.H.Cottrell. Theory of Dislocations in Crystals (Gordon and Breach).

Week#01

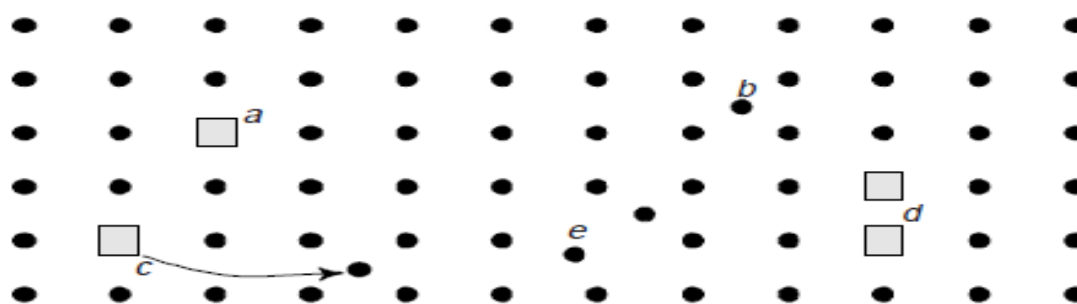
19. DEFECTS OR IMPERFECTIONS IN CRYSTALS

Up to now, we have described perfectly regular crystal structures, called *ideal* crystals and obtained by combining a basis with an infinite space lattice. In ideal crystals atoms were arranged in a regular way. However, the structure of real crystals differs from that of ideal ones. Real crystals always have certain defects or imperfections, and therefore, the arrangement of atoms in the volume of a crystal is far from being perfectly regular.

Natural crystals always contain defects, often in abundance, due to the uncontrolled conditions under which they were formed. The presence of defects which affect the colour can make these crystals valuable as gems, as in ruby (chromium replacing a small fraction of the aluminium in aluminium oxide : Al_2O_3). Crystal prepared in laboratory will also always contain defects, although considerable control may be exercised over their type, concentration, and distribution.

The importance of defects depends upon the material, type of defect, and properties which are being considered. Some properties, such as density and elastic constants, are proportional to the concentration of defects, and so a small defect concentration will have a very small effect on these. Other properties, e.g. the colour of an insulating crystal or the conductivity of a semiconductor crystal, may be much more sensitive to the presence of small number of defects. Indeed, while the term defect carries with it the connotation of undesirable qualities, defects are responsible for many of the important properties of materials and much of material science involves the study and engineering of defects so that solids will have desired properties. A defect free, i.e. ideal silicon crystal would be of little use in modern electronics; the use of silicon in electronic devices is dependent upon small concentrations of chemical impurities such as phosphorus and arsenic which give it desired properties. Some simple defects in a lattice are shown in Fig. 3.46.

There are some properties of materials such as stiffness, density and electrical conductivity which are termed structure—insensitive, are not affected by the presence of defects in crystals while there are many properties of greatest technical importance such as mechanical strength, ductility, crystal growth, magnetic



key:

- a* = vacancy (Schottky defect)
- b* = interstitial
- c* = vacancy—interstitial pair (Frenkel defect)
- d* = divacancy
- e* = split interstitial
- = vacant site

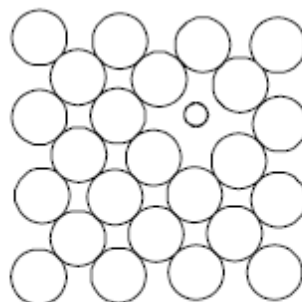
Fig. 3.46 Some simple defects in a lattice

hysteresis, dielectric strength, condition in semiconductors, which are termed structure sensitive are greatly affected by the relatively minor changes in crystal structure caused by defects or imperfections. Crystalline defects can be classified on the basis of their geometry as follows:

- (i) Point imperfections
- (ii) Line imperfections
- (iii) Surface and grain boundary imperfections
- (iv) Volume imperfections

The dimensions of a point defect are close to those of an interatomic space. With linear defects, their length is several orders of magnitude greater than the width. Surface defects have a small depth, while their width and length may be several orders larger. Volume defects (pores and cracks) may have substantial dimensions in all measurements, i.e. at least a few tens of Å. We will discuss only the first three crystalline imperfections.

(i) *Vacancies*: The simplest point defect is a vacancy. This refers to an empty (unoccupied) site of a crystal lattice, i.e. a missing atom or vacant atomic site [Fig. 3.47(a)] such defects may arise either from imperfect packing during original crystallisation or from thermal vibrations of the atoms at higher temperatures. In the latter case, when the thermal energy due to vibration is increased, there is always an increased probability that individual atoms will jump out of their positions of lowest energy. Each temperature has a



(a) Vacancy defect

corresponding equilibrium concentration of vacancies and interstitial atoms (an interstitial atom is an atom transferred from a site into an interstitial position). For instance, copper can contain 10^{-13} atomic percentage of vacancies at a temperature of $20-25^{\circ}\text{C}$ and as many as 0.01% at near the melting point (one vacancy per 10^4 atoms). For most crystals the said thermal energy is of the order of 1 eV per vacancy. The thermal vibrations of atoms increases with the rise in temperature. The vacancies may be single or two or more of them may condense into a di-vacancy or trivacancy. We must note that the atoms surrounding a vacancy tend to be closer together, thereby distorting the lattice planes. At thermal equilibrium, vacancies exist in a certain proportion in a crystal and thereby leading to an increase in randomness of the structure. At higher temperatures, vacancies have a higher concentration and can move from one site to another more frequently. Vacancies are the most important kind of point defects; they accelerate all processes associated with displacements of atoms: diffusion, powder sintering, etc.

Grain Boundaries

Engineering materials may be either polycrystalline or single crystal type. A polycrystalline alloy contains an enormous quantity of fine grains. Grain boundary imperfections are those surface imperfections which separate crystals or grains of different orientation in a polycrystalline aggregation during nucleation or crystallization. The shape of a grain is usually influenced by the presence of surrounding grains. The lattices

of adjacent grains are oriented at random and differently (Fig. 3.54) and a boundary between any two grains is essentially a transition layer of thickness of 1–5 nm. This layer may have a disordered arrangement of atoms, dislocation of clusters, and an elevated concentration of impurities. In grain boundaries the atomic packing is imperfect and between two adjacent grains, there is a transition zone that is not aligned with either grain (Fig. 3.55). As a result, we note that boundary atoms in such cases cannot have a perfect complement of surrounding atoms. The mismatch with orientation of the adjacent grain produces a less efficient packing of atoms along the boundary. Thus, the atoms along the boundary have a higher energy than those within the grains. The higher energy of the boundary atoms is also important for the nucleation of polymorphic phase changes. The boundary between two crystals which have different crystalline arrangements or different compositions, is called an *interphase* boundary or commonly called an *interface*.

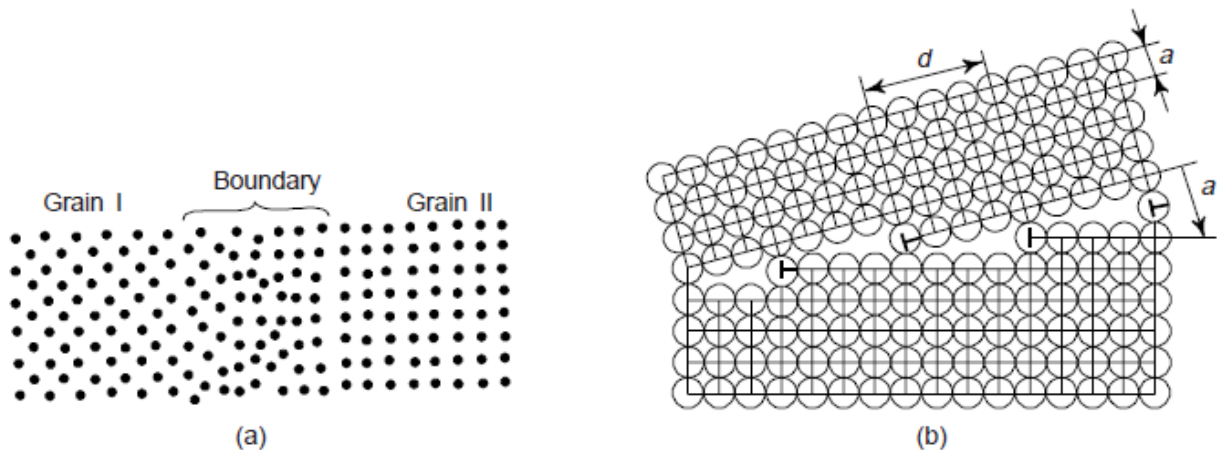


Fig. 3.54 Schemes of (a) high angle and (b) low-angle boundaries

The lower atomic packing along the boundary favours atomic diffusion. When the orientation difference between neighbouring grains is more than 10° – 15° , boundaries are called *high angle grain boundaries* (Fig. 3.54(a)). Each grain in turn consists of *subgrains or blocks*.

A subgrain is a portion of a crystal of a relatively regular structure. Subgrain boundaries are formed by walls of dislocations which divide a grain into a number of subgrains or blocks [Fig. 3.54(b)]. Angle of misorientation between adjacent subgrains are not large (not more than 5°), so that their boundaries are termed 'low angle'. Low angle boundaries can also serve as places of accumulation of impurities.

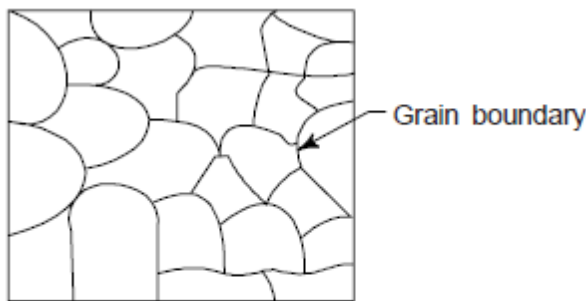


Fig. 3.55 Area of disorder at grain boundaries

Week#02

LINE DEFECTS OR DISLOCATIONS

Line imperfections are called dislocations. A linear disturbance, i.e. one dimensional imperfections in the geometrical sense of the atomic arrangement, which can very easily occur on the slip plane through the crystal, is known as dislocation. The most important kinds of linear defects are *edge* and *screw dislocation*. Both these types are formed in the process of their deformation. Both these defects are the most striking imperfections and are responsible for the useful property of ductility in metals, ceramics and crystalline polymers.

(i) *Edge Dislocation*: This type of dislocation is formed by adding an extra partial plane of atoms to the crystal [Fig. 3.48(a)]. An edge dislocation in its cross-section is essentially the edge of an 'extra' half-plane in the crystal lattice. The lattice around dislocation is elastically distorted.

Figure 3.49(a) shows a cross-section of a crystal where atoms (shown by dots) arranged in a perfect orderly manner. When an extra half plane is inserted from the top, the displacement of atoms is shown in Fig. 3.49(b). We note from Fig. 3.49(b) that top and bottom of the crystal above and below the line XY appears perfect. When the extra half plane is inserted from the top, the defects so produced is represented by \perp (inverted tee) and if the extra half plane is inserted from the bottom, the defects so produced is represented by T (Tee).

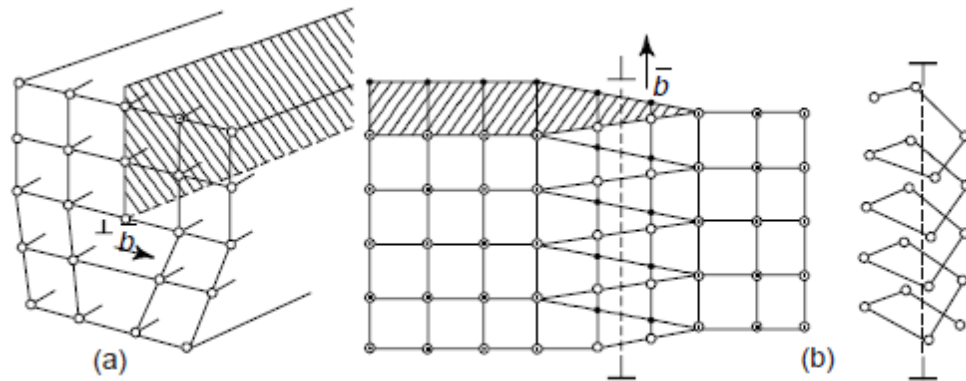


Fig. 3.48 Schemes of (a) edge dislocation (b) screw dislocation

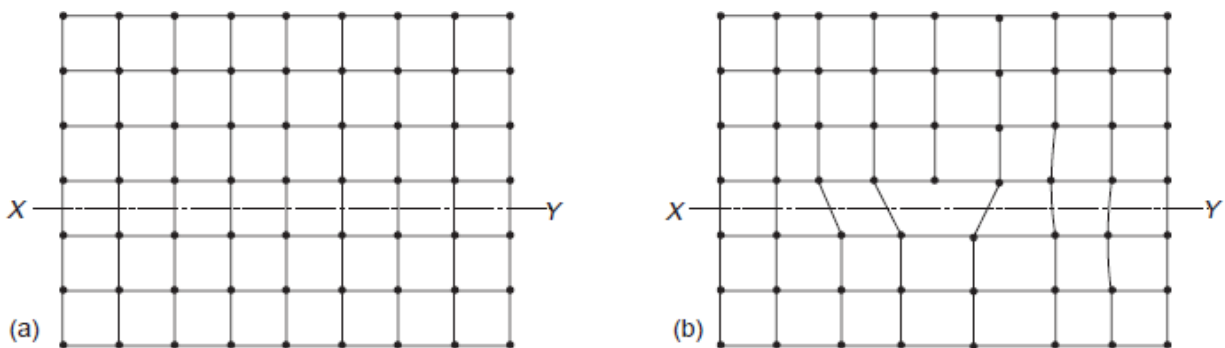


Fig. 3.49 Edge dislocation caused by an extra partial plane of atoms in the crystal

Near the dislocation, the distortion in the crystal is due to the presence of zones of compression and tension in the crystal lattice. The lattice above the line of dislocation is in a state of compression, whereas below this line, it is in tension. We must note that the dislocation line is a region of higher energy than the rest of the crystal.

The criterion of distortion is what is called the *Burgers vector*. It can be determined if a closed contour is drawn around a zone in an ideal crystal by passing from one site to another as shown in Fig. 3.50(a) and then the procedure is repeated a zone in a real crystal containing a dislocation. As may be seen from Fig. 3.50(b), the contour described in real crystal turns out to be unclosed. The vector required for the closing the contour is the Burgers vector. The Burgers vector of an edge dislocation is equal to the interatomic space and perpendicular to the dislocation line.

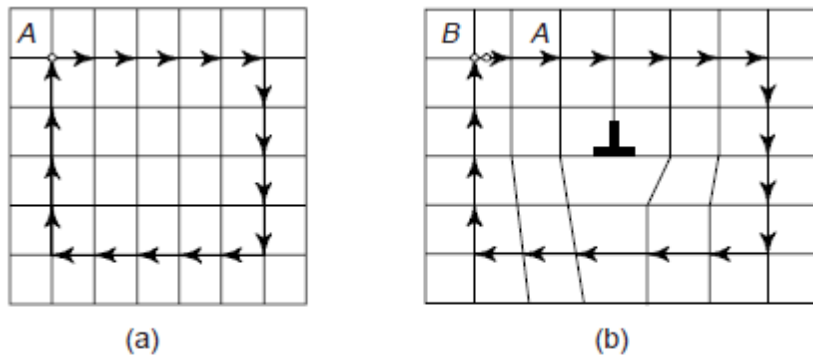


Fig. 3.50 Determination of Burgers vector (BA)

(ii) *Screw Dislocation*: The formation of screw dislocation is shown in Fig. 3.48(b). In this, the atoms are displaced in two separate planes perpendicular to each other. An isomeric view of a perfect crystal is shown in Fig. 3.51(a). The displacement of atoms in the region ABC is shown in Fig. 3.51(b). The arrangement of atoms in screw dislocations appear like that of a screw or a helical surface.

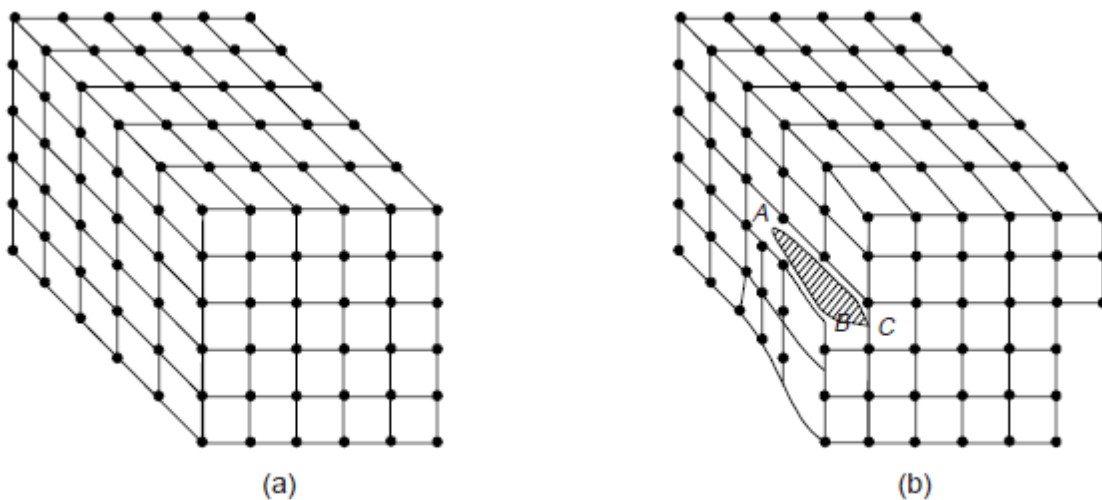


Fig. 3.51 Scheme of screw dislocation

A screw dislocation does not exhibit climb motion.

The following effects of screw dislocation are of great importance.

- (i) Probably, the force required to form and move a screw dislocation is somewhat greater than that required to initiate an edge dislocation.
- (ii) Without breaking the continuity of the lattice, the plastic deformation is possible under low stress.
- (iii) Screw dislocation causes distortion of the crystal lattice for a considerable distance from the centre of the line and takes the form of spiral distortion of the planes. We must remember that the dislocations of both types, i.e., combinations of edge and screw, are closely associated with the crystallization as well as deformation.

The total length of all dislocation lines in a unit of volume is called the *dislocation density*. It may be equal to $10^4 - 10^5 \text{ cm}^{-2}$ in semiconductor crystals and $10^6 - 10^8 \text{ cm}^{-2}$ in annealed metals. After cold plastic deformation, the dislocation density may rise up to $10^{11} - 10^{12} \text{ cm}^{-2}$. Attempts to raise the dislocation density above 10^{12} cm^{-2} end quickly in cracking and failure of the metal. Dislocation appear on crystallization; their density may then be quite high and they influence substantially the properties of materials. Along with other defects, dislocations participate in phase transformations and recrystallization and may serve as nuclei for

precipitation of a secondary phase from solid solution. The rate of diffusion along dislocation lines is several orders of magnitude greater than that through a crystal lattice without defects. Dislocations serve as places for concentration of impurity atoms, especially of interstitial impurities, since this decreases lattice distortions. Impurity atoms can concentrate around dislocations and form the *Cottrell atmospheres* which impede dislocation movement and strengthen the metal.

The effect of dislocations is especially pronounced on the strength of crystals. The experimentally measured yield strength of metals turns out to be the only one-thousandth of its theoretical value, the loss being mainly attributed to the effect of mobile dislocations. By increasing substantially the dislocation density and decreasing the dislocation mobility, the strength of a metal can be raised several times compared with its strength in the annealed state. Faultless pieces of metals (in particular, long and thin 'whiskers' obtained by crystallization from the gaseous phase) exhibit a strength approaching the theoretical value (Fig. 3.52).

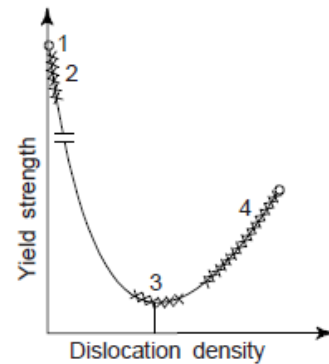


Fig. 3.52 Effect of dislocation density on yield strength: 1—a perfect faultless crystal; 2—faultless 'whisker' crystals; 3—annealed metals; 4—metals with an elevated stacking fault density after treatment.

Dislocations have certain geometrical characteristics, e.g. (i) The vectorial sum of the Burgers vectors of dislocations meeting at a point called the node must be zero, analogous to Kirchhoff's law for electrical currents meeting at a junction and (ii) A dislocation line cannot end abruptly within the crystal. It either ends at a node or at the surface. Alternatively, a dislocation line can close on itself as a loop.

Dislocations have distortional energy associated with them, as is evident from the compressive and the tensile strains around an edge dislocation or the shear strains around a screw dislocation. As a first approximation, one can take these strains to be elastic strains. The elastic strain energy E per unit length of a dislocation of Burgers vector b can be expressed approximately by

$$E \approx \frac{\mu b^2}{2} \quad (9)$$

Here μ is the shear modulus of the crystals. For BCC iron ($a = 2.87 \text{ \AA}$), E is of the order $2.5 \times 10^{-9} \text{ J-m}^{-1}$.

In real crystals, the dislocations can be classified as *full* and *partial* dislocations. For a *partial dislocation*, the Burgers vector is a fraction of a lattice translation, whereas for a *full dislocation*, the Burgers vector is an integral multiple of a lattice translation. From relation (9), it is obvious that the elastic strain energy of a dislocation is proportional to the square of the Burgers vector, dislocations tend to have as small a Burgers vector as possible.

Week#03

(iii) *Frenkel Defect*: Whenever a missing atom, which is responsible for vacancy occupies an interstitial site (responsible for interstitial defect) as shown in Fig. 3.47(c), the defect caused is known as Frenkel defect. Obviously, Frenkel defect is a combination of vacancy and interstitial defects. These defects are less in number because energy is required to force an ion into new position. This type of imperfection is more common in ionic crystals, because the positive ions, being smaller in size, get lodged easily in the interstitial positions.

(iv) *Schottky Defect*: These imperfections are similar to vacancies. This defect is caused, whenever a pair of positive and negative ions is missing from a crystal [Fig. 3.47(e)]. This type of imperfection maintains a charge neutrality. Closed-packed structures have fewer interstitialcies and Frenkel defects than vacancies and Schottky defects, as additional energy is required to force the atoms in their new positions.

Mechanical Properties of Metals

1. INTRODUCTION

In determining the fabrication and possible practical applications, the mechanical properties of materials, their strength, rigidity and ductility are of vital importance. The important mechanical properties of materials are: *elasticity, plasticity, strength, ductility, hardness, brittleness, toughness, stiffness, resilience, malleability, fatigue, creep*, etc. The complete specifications of mechanical properties and composition of various materials have been standardised by BIS. Materials exhibit a wide range of mechanical properties ranging, e.g., from the ductility of pure copper to the hardness of diamond and most surprising elastic behaviour of rubber. There are several materials behave quite differently when stressed in different ways, e.g. steel and wood are stronger in tension whereas cast iron, cement and bricks are much stronger in compression. Obviously, stresses can produce a shape change and may also cause a material to break or fracture. For materials which have to withstand high temperatures, the melting point is also of importance.

The combination of high yield strength and good fracture toughness or ductility makes steel an excellent structural material. Modern high strength low alloy (HSLA) steels have a very fine grain size around 10 micro-meters which provides both high strength and good crack growth resistance or fracture toughness.

In addition to mechanical properties of materials, the following properties are also important for an engineer, to enable him in selecting suitable metals for various jobs:

(i) *Physical Properties*: These properties of materials include shape, size, colour, lusters, specific gravity, porosity, structure, finish, etc.

(ii) *Technological Properties*: We may note that all the technical properties of a metal are essentially its mechanical properties, which include properties like malleability, machinability, weldability, formability or workability, castability, etc.

(iii) *Thermal Properties*: Specific heat, thermal conductivity, thermal expansion, latent heat, thermal stresses, thermal shock, etc. fall under thermal properties of materials.

(iv) *Electrical Properties*: These include conductivity, resistivity, relative capacity, dielectric strength, etc.

(v) *Chemical Properties*: These properties include atomic weight, equivalent weight molecular weight, atomic number, acidity, alkalinity, chemical composition, corrosion, etc.

In this chapter, we shall discuss mechanical and technological properties. Other properties will be discussed in subsequent chapters. Initially, we present a brief review of some definitions of common mechanical properties.

2. COMMON TERMS

(i) **Isotropy:** A body is said to be isotropic if its physical properties are not dependent upon the direction in the body along which they are measured, e.g. a polycrystalline material in which the grains or crystals are randomly oriented behaves isotropically, i.e. its properties are independent of direction. Aluminium, steels and cast irons have random distribution of crystals. When a solid material is subjected to a force and if it withstand applied force, then such a material is of interest to engineers from design point of view. There are many solid materials which behave elastically when subjected to a load or force. By this it is meant that the solid material deforms when subjected to force, i.e. loaded, but returns to its original condition when the force is removed. A body displaying isotropy has only one refractive index, one dielectric constant and so on. R. Hooke studied the elastic behaviour of metals and formulated a law, now known as Hooke's law. When a specimen of length l and cross-sectional area A is loaded with a tensile strength P , the length increases by an amount δl , which is termed as *elongation*. On further increasing the load, the elongation also increases upto a certain limit (Fig. 8.1).

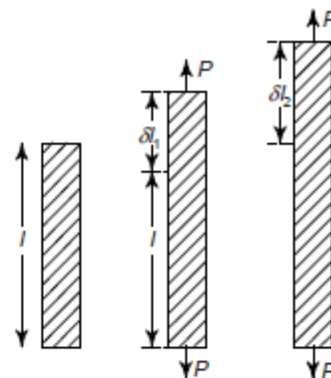


Fig. 8.1 Effect of axial tensile load on a specimen

(ii) **Anisotropy:** The quality of variation of a physical property with the direction in a body along which the property is measured, e.g., the resistivity of certain single crystals measured with the electric field along a particular crystallographic direction may be higher than along directions perpendicular to it. Thus such crystals are anisotropic with respect to resistivity. Obviously, anisotropy is a state having different properties in different directions. Various composite materials, aggregates of polycrystals with a preferred orientation, wood, laminated plastics, etc. are few examples showing high anisotropy.

(iii) **Elasticity:** It is the property of a material which enables it to regain its original shape and size after deformation within the *elastic limit*. However, in nature no material is perfectly elastic, i.e., a certain limit exists for every material beyond which it will not be able to regain its original shape and size. This limit is termed as *elastic limit*. Materials with high elastic limit are called as more elastic than the others. This property is always desirable in metals used in machine tools and other structural constituents. Steel and rubber are amongst the common examples of materials having elasticity. Elasticity of solids has its origin in the existence and stability of interatomic and intermolecular bondings, i.e. rubber and steel.

(iv) **Plasticity:** It is the ability of material to be permanently deformed (without fracture) even after the load is removed. To some extent all materials are plastic. This property of a material, which is extreme opposite of elasticity, is of importance in deciding manufacturing processes like forming, shaping, extruding operations etc. Metals possess more plasticity at high temperatures. Usually, plasticity of a material increases with increase in temperature and this is important in deciding the further operations.

The plasticity of a metal depends upon its nature and the environmental conditions, i.e., whether the metal is shaped red hot or in cold. Materials such as clay, lead are plastic at room temperature. Steel is plastic at bright red hot and hence shaped when hot. This property finds its use in forming, shaping and extruding operations of metals.

Plastic deformation takes place only after the elastic range has been exceeded. A general expression of plastic action would involve the time rate of strain since in the plastic state materials can deform under constant sustained stress. It would also involve the concept of limit of deformation before rupture. Evidences of plastic action in structural materials are called *yield*, *plastic flow* and *creep*.

As stated above, plasticity is important in forming, shaping and extruding operations. Some materials are shaped cold, e.g. the deep drawing of the sheets, several materials particularly metals are shaped hot, e.g. the rolling of the structural steel shapes and the forging of certain material parts. Clay, lead etc. are the materials, which are plastic at room temperatures. Figure 8.2 shows elastic and plastic region of materials in a graph applied load vs. strain.

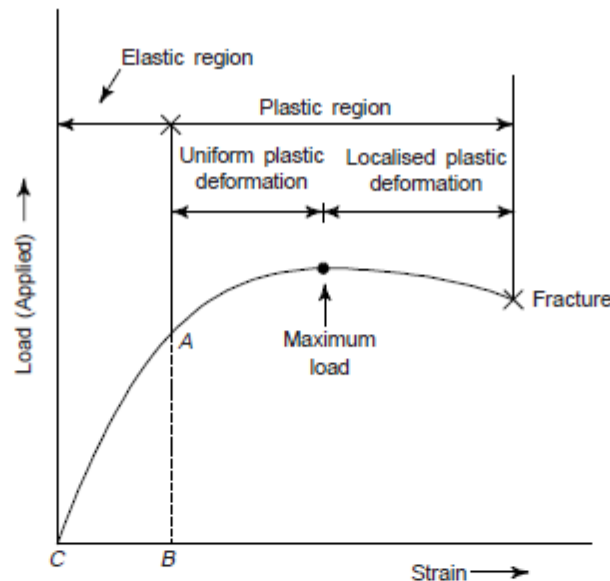


Fig. 8.2 Elastic and plastic regions of materials

(v) **Ductility:** It is defined as the property of a metal by virtue of which it can be drawn into wires or elongated before rupture takes place. It is the deformation produced in a material at the breaking point and measured by the percentage of elongation and the percentage of reduction in area before rupture of test piece. Its value is expressed as elongation, i.e., percentage elongation is most widely used to measure ductility. The term percentage elongation is the maximum increase in the length expressed as percentage of original length. Mathematically, one can express percentage elongation as

$$\begin{aligned}\text{Percentage elongation} &= \frac{\text{Increase in length}}{\text{Original length}} \times 100 \\ &= [(l_f - l_o)/l_o] \times 100\end{aligned}$$

Similarly, the term percentage reduction of cross-sectional area is the maximum decrease in cross-sectional area. Mathematically, one can express the percentage reduction in cross-sectional area

$$\begin{aligned}&= \frac{\text{Decrease in cross-sectional area}}{\text{Original cross-section area}} \times 100 \\ &= [(A_o - A_f)/A_o] \times 100\end{aligned}$$

In the above relations l and A represent the length and area of cross-section respectively, f and o are respectively the suffixes to denote final and original values.

Ductility commonly referred to in tensile test, which is strain at fracture. The unit of Ductility is same as that of strain. As stated above, the valuable information about ductility of a material is obtained from the form of test curves and by the percentage elongation and percentage reduction in the area of test piece at the neck. Ductility is a measure of the amount of permanent deformation that has occurred when the material reaches its breaking point.

We can see that brittle materials, e.g., cast irons show little or no plastic deformation before fracture, i.e. they are not ductile. A little consideration shows that a metal with a good percentage of elongation or reduction in cross-sectional area explains its high ductility. Metals with more than 15% elongation are considered as ductile. Metals with 5 to 15% elongation are considered of intermediate ductility. However, the metals with less than 5% elongation are considered as brittle ones. Brittle materials such as cast irons

show little or no plastic deformation before fracture, i.e. they are not ductile. Copper is a ductile material, show considerable plastic flow due to high ductility before fracture. One can draw wires due to this property. Ductility of glass is high when hot and hence drawn in various shapes in hot condition. The order of ductility for few common metals is as under:

1. Gold, 2. Platinum, 3. Silver, 4. Iron, 5. Copper, 6. Aluminium, 7. Nickel, 8. Zinc, 9. Tin and 10. Lead.

Ductility is an important property of a material which governs its ability to be deformed in processes, e.g. drawing, rolling and forging. Adequate ductility ensures that the material during these processes will not fracture. There is an associated property by virtue of which sheets can be rolled from material is called 'malleability'.

We must note that for any given material, the strength and ductility are inversely proportional to each other. Any treatment which increases strength, decreases the ductility. Ductility and strength, both are appreciably affected by temperature.

(vi) *Strength*: It may be defined as the capacity of material by virtue of which it can withstands or support an external force or load with rupture. It is expressed as force per unit area of cross-section. This is most important property of a metal, which plays a decisive role in designing various structures and components.

A material has to withstand different types of load, e.g. tensile, compressive and shear load. Accordingly, one may broadly classify strength into following two categories:

- (a) Depending upon the value of stress, the strengths of a metal may be elastic or plastic.
- (b) Depending upon the nature of stress, the strengths of a metal may be tensile, compressive, shear, bending and torsional. Now, we study all these types of strengths.

Ultimate strength: It is the load required to fracture a unit cross-section of material.

Elastic Strength: It is the value of strength corresponding to transition from elastic to plastic range, i.e. when material changes its behaviour from elastic range to plastic range. One cannot measure it accurately. This is known as ideal stress value and used to define elastic strength of a material.

Plastic strength: It is the value of strength of the material which corresponds to plastic range and rupture. It is also termed as ultimate strength. In actual practice, a specimen is subjected to a stress which is always less than the working stress. The ratio of ultimate stress to the working stress of a metal is termed as *factor of safety* or factor of ignorance. This greatly depends upon the nature of loads or stresses. Usually, the following values of factor of safety are generally kept for various loads.

Dead load	4 or 5
Live load	6
Alternating kind of load	8 to 12
Shock loading	12 to 15

One adopts the lower value of factor of safety by ensuring the metal to be without any defect, which is done through 'non destructive' tests. In determining the reliability of the design, the factor of safety is of great importance.

Tensile Strength: It is the maximum tensile stress which a material is capable of developing when subjected to loading upto rupture. Mathematically,

$$\text{Tensile stress} = \frac{\text{Maximum tensile load}}{\text{Original cross-sectional area}}$$

The tensile stress is expressed in N/mm^2 or MN/m^2 . In actual practice, a given specimen is always subjected to a tensile stress less than the working tensile stress. Tensile strength is obtained from the following relation

$$\text{Tensile strength} = \frac{\text{Maximum Force in kg}}{\text{Original area in sq. cm}}$$

Week#04

Tensile strength is the ultimate strength in tension and corresponds to the maximum load in a tension test. It is measured by the highest point on the conventional stress-strain curve. This strength provides the basic design information on the material's acceptance in engineering tests. In ductile materials the load drops after the ultimate load because of necking and this indicates the plastic instability. For working stresses, the ultimate tensile strength is a logical basis in brittle materials. We may note that like yield strength, tensile strength is used with a factor of safety.

Compressive Strength

For a metal, the compressive strength is the value of load applied to break it off by crushing. Mathematically,

$$\text{Compressive Stress} = \frac{\text{Maximum compressive load}}{\text{Original cross-sectional area}}$$

Compressive stress is also expressed in N/mm^2 or MN/m^2 . In actual practice, a given specimen is also subjected to a compressive stress less than the working compressive stress.

Shear Strength

The shear strength of a metal is the value of load applied tangentially to shear it off across the resisting section. Mathematically, we can express,

$$\text{Shear Stress} = \frac{\text{Maximum tangential load}}{\text{Original cross-sectional area}}$$

It is also expressed in N/mm^2 or MN/m^2 . We must note that in actual practice, the given specimen is also subjected to shear stress less than the working shear stress.

Bending Strength

For a metal, it is that value of load which can break the metal off by bending it across the resisting section. Mathematically,

$$\text{Bending Stress} = \frac{\text{Maximum bending load}}{\text{Original cross-sectional area}}$$

This is also expressed in N/mm^2 or MN/m^2 . In practice, the given specimen is also subjected to bending stress less than the working bending stress.

Torsional Strength

For a metal, the torsional strength is that value of load applied to break the metal by twisting across the resisting section. Mathematically,

$$\text{Torsional stress} = \frac{\text{Maximum twisting load}}{\text{Original cross-sectional area}}$$

This is also expressed in N/mm^2 or MN/m^2 . In practice, the given specimen is also subjected to torsional stress less than the working torsional stress.

(vii) *Stress and Strain*: Stress is defined as the force per unit area and strain as the fractional change in length, area or volume. Obviously, this is the resistance of the body to deformation due to the application of external force.

Stress describes the intensity of a force that acts on a unit area. Its unit is N/mm^2 or N/m^2 which is called Pascal in SI and denoted by Pa. When the force acting over an area is uniformly distributed, we have

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

In several cases, such uniformly distributed loads are not present and therefore stress is non-uniform. This is why, the stress is always referred to a point and in a body the stress varies from point to point over any section. If P is the total load acting on the original cross-sectional area A_0 , then normal stress,

$$\sigma = \frac{P}{A_0} \quad (1)$$

Obviously, stress is the intensity of internal force. The stress is said to be *normal* if load P is normal to the surface and *tangential* or shearing, if load is tangential to this surface. The normal or direct (tensile or compressive) stress is produced over a section when force is acting normal to the section. If the force is acting away from the section, the stress is tensile, if it is acting towards the section the section is compressive.

In general, the stress at any point will have six components and its nature is different than that of force and area both. In fact, stress at a point is a *tensor quantity* and needs the following specifications for complete specification: (i) magnitude (ii) plane passing through the point, on which stress is being defined and (iii) the direction in which stress is acting.

Strain is the deformation produced per unit length of a body due to the effect of stress on it. It is the ratio of the change in length of the specimen to its original length. If L is the original length of the sample and l is the change in length, then

$$\text{longitudinal strain, } \epsilon = \frac{l}{L} \quad (2)$$

Strain is simply a ratio and has no unit and it is a dimensionless quantity. Depending upon the type of load, strain can be *lateral strain* or *shear strain*.

As there are different types of stresses, there are different types of strains, e.g. (i) *tensile strain* (ii) *compressive strain*, (iii) *shear or transverse strain* and (iv) *volumetric strain*. The strain associated with the change in length is called the *elongation strain* (l/L). Similarly $\Delta V/V$ is the volume strain where V is the volume. When there is a change in shape and no change in volume, corresponding strain is called *shear strain*. The shear strain is measured by the angle. The behaviour of a material within the elastic limit is the same under compression as under tension.

Corresponding to *elastic and plastic* properties of materials, we have two classes of strain:

- (a) *Elastic Strain*: It is the change in dimension of a body when it is subjected to a load. This is reversible phenomenon, i.e., elastic strain disappears after the applied load is removed. This is proportional to the stress applied.

(b) *Plastic Strain*: This is the permanent change in the body when subjected to a load. The change remains even after the applied load is removed.

The amount of elongation, expressed as a percentage of the original gauge length is called as the percentage elongation:

$$\text{Percentage elongation} = \frac{\text{Final length} - \text{Initial length}}{\text{Initial length}} \times 100$$

(viii) *Hooke's Law*: In 1678, Robert Hooke, for the first time stated that *within elastic limits, stress is proportional to strain*, i.e.

$$\text{Stress} = \text{a constant} \times \text{strain}$$

The ratio of stress to strain is a constant characteristic of a material, and this proportionality constant is called *modulus of the material*. It differs from material to material and for different nature of stresses. When the stress applied is *tensile or compressive*, the constant is called *Young's modulus of elasticity*. The slope of stress-strain diagram upto the limit of proportionality is called *Young's Modulus of elasticity* (Y or E) (Fig. 8.2).

$$\therefore Y \text{ or } E = \frac{\text{Stress}}{\text{Strain}} = \frac{\sigma}{\epsilon} = \text{constant} \quad (3)$$

When the shear stress (τ) and strain (γ) are used, it is called *modulus of rigidity* (G). It is given by

$$\tau = G\gamma \quad (4)$$

G is also called shear modulus. G and E are related as

$$G = \frac{E}{2} (1 + \nu) \quad (5)$$

where ν is Poisson's ratio.

For volumetric stresses and strains, the constant is called bulk modulus (K). The relation between K and E is

$$K = \frac{E}{3(1 - 2\nu)} \quad (6)$$

In Table 8.2 we list the values of Y , G and ν (Poisson's ratio) of few polycrystalline solids at room temperature. Nature of the bond and melting point, T_m ($^{\circ}\text{C}$) are also given. We must note that the single crystal values can differ widely from polycrystalline solids, depending on the direction.

Table 8.2 Young's modulus (Y or E), shear modulus (G), poisson ratio (ν) of some polycrystalline solids. Melting point (T_m) and type of bond are also given

Material	Y or E ($\times 10^{10}$ N/m ²)	G ($\times 10^{10}$ N/m ²)	ν	$T_m(^{\circ}\text{C})$	Bond
Aluminium	7.0	2.4	0.34	660	Metallic
α -Fe	20.7	8.3	0.29	1538	Metallic
Cu	12	4.5	0.34	1084.5	Metallic
Ag	7.2	2.9	0.38	960.5	Metallic
Pb	1.6	0.6	0.45	327.4	Metallic
Tungsten	41	15.2	0.30	3370	Metallic
Si	11	—	—	1420	Covalent
Alumina	40	—	0.23	2050	Covalent + ionic
Magnesia	31	—	0.19	2900	Covalent + ionic
Polystyrene	0.3	—	0.33	100	Vander Waal

Poisson's Ratio (ν)

When a specimen is stressed by a uniaxial force, it is strained in the direction of the force and also in a direction perpendicular to the direction of the force. The strain in the direction of force is called longitudinal strain and that perpendicular to it as lateral strain. The relationship existing between the lateral strain and axial strain is called Poisson's ratio (ν):

$$\text{Poisson's ratio } (\nu) = \frac{\text{Lateral strain}}{\text{Longitudinal strain}} = \frac{l}{m} = \nu \text{ (constant)}$$

Poisson's ratio is an important elastic constant and its value is different for different materials. For most engineering structural materials its value is usually between 0.3 and 0.6. The relation between E , G and ν is

$$\nu = \frac{E}{2G} - 1 \quad (7)$$

Stress-Strain Relation

The stress and strain relation is commonly shown by means of a stress-strain diagram. These diagrams are obtained by drawing a graph or curve from the data obtained in a tensile test, in which an increasing tensile stress is applied to a specimen (Fig. 8.1). There are resulting changes in length which can be observed and recorded by strain measuring devices. Stress-strain for different engineering materials are shown in Fig. 8.3.

In the case of ductile materials, at the beginning of the test, the material extends elastically. The strain (both longitudinal and lateral) at first increases proportionally to the stress and the sample or specimen

returns to its original length on removal of the stress. The limit of proportionality (stress \propto strain) is the stage upto which the specimen, i.e., material obeys Hooke's law perfectly (Fig. 8.3(a)).

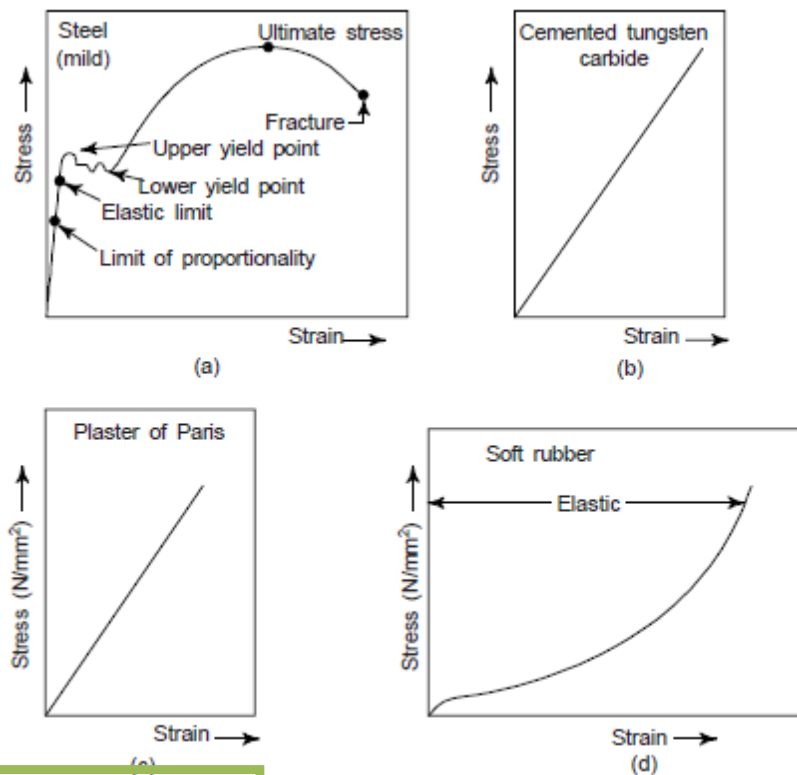


Fig. 8.3 Stress-strain curve for different engineering materials

Week#05

On further increasing the applied stress, i.e., beyond the elastic limit, it produces plastic deformation so that a permanent extension remains even after the removal of the applied load, i.e. stress. The resultant strain, in this stage begins to increase more quickly than the corresponding stress and continues to increase till the *yield point* is reached. We must note that at the yield point the material suddenly stretches.

The ratio of applied load to original cross-sectional area is called the *normal stress* and this continues to increase with elongation, due to work hardening or strain hardening, until the tensile stress is maximum. This is the value of stress at maximum load and one can calculate it by dividing the maximum load by the original cross-sectional area. This stress is called *ultimate tensile stress* (Fig. 8.3(a)).

From Fig. 8.3(a) it is evident that at a certain value of load the strain continues at slow rate without any further stress or loading. This phenomenon of slow extension increasing with time, at constant stress, is termed *creep*. A neck begins to develop at this point, along the length of the specimen and further plastic deformation is localized within the neck. The cross-sectional area decreases in proportion to the increasing length during elastic elongation. We must note that the volume of the test bar, i.e. specimen remains constant. Figure 8.3(a) is a stress-strain diagram for mild steel. This diagram clearly shows the limit of proportionality, elastic limit, yield point, ultimate tensile stress and fracture stress at the breaking points. We note that this diagram shows a well-defined yield point.

Poorly defined yield point as in the case of brittle materials is shown in Fig 8.4. For the determination of the yield strength in such materials, following the general practice, one has to draw a straight line parallel to the elastic portion of the stress-strain curve at a pre-determined strain ordinate value (say 0.1%). The point at which this line intersects the stress vs. strain curve is the yield point at off-set and called the yield strength at 0.1% or 0.2% of set strain.

In case of hard steels and non-ferrous metals stress is specified corresponding to a definite amount of permanent elongation. This stress is termed as the proof stress. We must note that the proof stress is applied for 15 seconds and, when removed, the specimen should not lengthen permanently beyond 0.1%. The method of finding the proof stress from the stress-strain curve is shown in Fig. 8.4.

Stress vs. strain curves also help to explain the properties of ductile materials. We find that, greater the angle of inclination of the line of

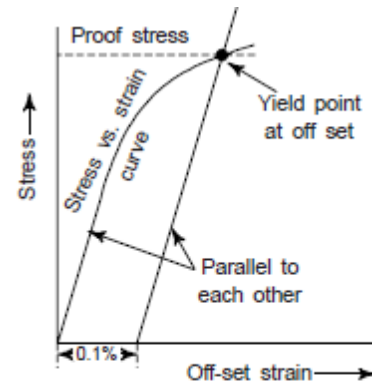


Fig. 8.4 Stress vs. strain curve for a brittle material

stress vs. strain proportionality to the ordinates, the more elastic is that metal. A higher yield point reveals greater hardness of the metal. A higher value of the maximum stress point shows that the metal is a stronger one. Similarly, the toughness and brittleness of metal are indicated by the distance from the ordinates of the breaking stress or load point. The metal is more brittle when the distance is shorter. Stress vs. strain curves for ferrous and non-ferrous materials are shown in Fig. 8.5. We find that brittle materials show little or no permanent deformation prior to fracture. Some metals and magnesium oxide exhibit brittle behaviour (Fig. 8.5). Prior to fracture, the small elongation reveals that the material gives no indication of impending fracture and brittle fracture usually occurs rapidly. It is reported that this is often accompanied by loud noise.

The values of *offset strain* (ϵ_0) have been standardized for different materials. ϵ_0 equal to 0.2% or 0.35% is often used. The yield strength determined by the offset method is always described as yield strength for an offset ϵ_0 . Commonly used offset values are given in Table 8.3

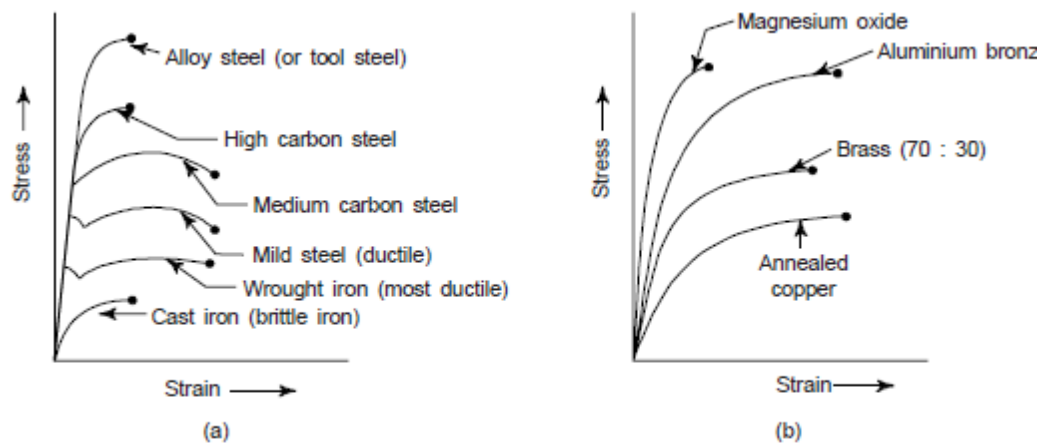


Fig. 8.5 Stress vs. strain curves (a) ferrous metals (b) non-ferrous metals

(ix) *Brittleness*: It may be defined as the property of a metal by virtue of which it will fracture without any appreciable deformation. This property is just opposite to the ductility of a metal. Few examples of brittle

materials are cast iron, glass and concrete. This property of metals find its importance for design of machine tools, which are subjected to sudden loads. Metals with less than 5% elongation are known to be brittle ones.

Table 8.3 Commonly used offset values (ASTM, E 6.35 T)

Material	Stress (type)	Offset strain ($\epsilon_0\%$)	Equivalent strain
Aluminium alloys	Tension and compression	0.20	0.0020
Brass and Bronze	Tension and compression	0.35	0.0035
Concrete	Tension	0.02	0.0002
Cast iron	Compression	0.05	0.0005
Steel	Tension or compression	0.20	0.0020
Wood	Compression	0.05	0.0005

(x) **Toughness:** It may be defined as the property of a metal by virtue of which it can absorb maximum energy before fracture takes place. It is the measurement of ultimate energy strength of material and is expressed as work units/unit volume, i.e. kg fm/m^3 . Toughness is also calculated in terms of area under stress-strain curve (Fig. 8.9(A)). We may note that the toughness is maximum under Fig. 8.7(a) (c). We may note that the total area under stress-strain curve is the work expended in deforming one m^3 of material until it fractures. This work is also termed as *modulus of toughness*. Tenacity and hardness of a metal are the measures of toughness. The toughness is approximately measured as the product of strength and elongation and these measurements are used for comparison purposes and termed as *merit number*.

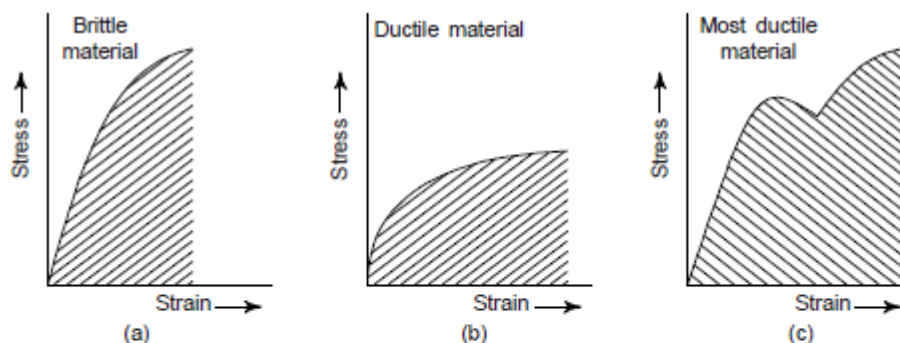


Fig. 8.9(a) Stress-strain curves

Toughness is the property of materials which enables a material to be twisted, bent or stretched under a high stress before rupture. The value of toughness falls with the rise in temperature.

Toughness is highly desirable property for structural and mechanical parts which have to withstand shock and vibration. Its importance lies in the selection of a material where the load increases beyond the elastic limit or yield point, e.g. power press punch and pneumatic hammer etc. Amongst the tough materials, few are: brass, mild steel, manganese and wrought. A ductile material with same strength as non-ductile material requires more energy for breaking and hence is more tough.

(xi) **Stiffness:** This may be defined as the property of a metal by virtue of which it resists deformation. Modulus of rigidity is the measure of stiffness. The term flexibility is quite opposite of stiffness. The materials which suffer less deformation under load have high degree of stiffness. We may note that the greater the stress required to produce a given strain, the stiffer is the material.

The stiffness of a metal is of great importance while selecting it for a number or a component of a machine or a structure. To make it clear, let us consider an example of two beams one of steel and other of aluminium. Both the beams are strong enough to carry the given load but aluminium beam will sag or deflect more than the mild steel beam. Obviously, the steel beam is stiffer than the aluminium beam. Stiffness is also used in graduating spring balance and spring controlled measuring instruments. Stiffness or flexibility is the function of dimensions, shape and characteristics of the material.

(xii) *Resilience*: This may be defined as the property of a metal by virtue of which it stores energy and resists shocks or impacts. It is measured by the amount of energy absorbed per unit volume, in stressing a material upto elastic limit. This property is of great importance in the selection of a material used for various types of springs.

The maximum energy which can be stored in a body upto elastic limit is termed as *proof resilience*. Proof resilience per unit volume is termed as *modulus of resilience*. Obviously, the energy stored per unit volume at elastic limit is modulus of resilience.

The annealed copper is not used for springs due to its very low elastic limit. However, the cold-worked copper has much high elastic limit (and resilience) and therefore it is used for springs. This shows that resilience is associated with high elastic limit. We may note that resilience is of importance for materials required to bear shocks and vibrations.

(xiii) *Endurance*: This is defined as the property of a metal by virtue of which it can withstand varying stresses (same or opposite nature). The maximum value of stress, which can be applied for an indefinite time without causing its failure, is termed as its *endurance limit*. For ordinary steel, the endurance limit is about half the tensile strength.

This property of a metal is of great importance in the design and production of parts in a reciprocating machine and components subjected to vibrations. It is always desirable to keep the working stress of a material well within the elastic limit.

Week#06

3. ATOMIC MODEL OF ELASTIC BEHAVIOUR

We have seen in chapter 4 that the potential energy of a pair of atoms and interatomic forces between them is a function of their distance of separation r . A general expression for the potential energy U is

$$U = -\frac{A}{r^n} + \frac{B}{r^m} \quad (15)$$

where A , B , n and m are constants and $m > n$. The negative term on the right of Eq. (15) is the attractive energy term. The potential energy term arises due to the mutual repulsion between the atoms at the close distances of approach. The net interatomic force F is

$$F = \frac{dU}{dr} \quad (16)$$

The potential energy, U is a minimum and the net interatomic force is at r_0 , i.e. the equilibrium distance of separation.

In order to decrease or increase the interatomic distance of separation starting from the equilibrium value r_0 to r , we have to apply an external force F_{app} equal in magnitude but opposite in sign to F at r ,

$$F_{app} = -F = \frac{dU}{dr} \quad (17)$$

From Fig. 8.10, to decrease the interatomic distance from r_0 to r' , a compressive force equal in magnitude to F' have to be applied. Further, to increase r_0 to r'' , a tensile force equal in magnitude to F'' have to be applied. From Fig. 8.10 it is evident that a tangent to the force-distance curve drawn at r_0 practically coincides with the curve over a small range of displacement on either side of r_0 . We can see that the strains in the elastic region for both brittle and ductile materials lie in the range of 0.001 to 0.005 and are, therefore, within this small range of displacement. Obviously, the negative of the slope of the force-distance curve at r_0 is proportional to the Young's modulus, Y of a material. Further, the curvature of the potential energy curve at r_0 is proportional to Y . Thus

$$Y = -\frac{dF}{dr} = \frac{d^2U}{dr^2} \quad (18)$$

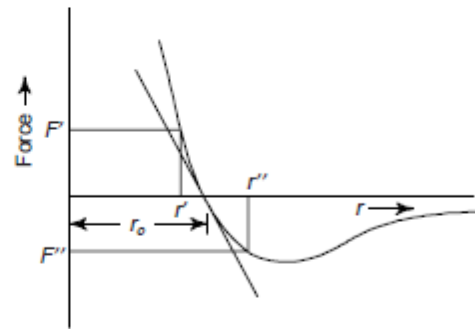


Fig. 8.10 The interatomic force-distance curve

We may note that materials with strong bonds have a deep potential energy well with a sharp curvature. Obviously, strong bonding results in large values for the elastic modulus. On the otherhand, the shallow potential well of the weakly bonded materials result in small values for the modulus Y of Li, Be, B and C (dia) in a row of the periodic table increase in that order

Element	Li	Be	B	C (dia)
Z (Atomic number)	3	4	5	6
Y (Young's Modulus) (GN/m ²)	11.5	289	440	1140

As we go down any given column of the periodic table, the covalent nature of the bonding decreases. We find that the elastic modulus shows a corresponding decrease. The elements of fourth column exhibit this trend.

Element	C (dia)	Si	Ge	Sn	Pb
Z	6	14	32	50	82
Y (GN/m ²)	1140	103	99	52	16

In a crystal, the interatomic distance, r varies with a corresponding variation in bond strength. This gives rise to *elastic anisotropy*, i.e., the elastic properties become a function of the crystal direction. We may note that the anisotropy is particularly evident in those materials which have two kinds of bonds. For, e.g., Y of graphite in a direction of crystal parallel to the sheets is 950 GN/m², which is much larger than that averaged over all directions, which is about 8 GN/m².

We may note that the transition metals have Y much higher than those of the alkali metals, as a result of the partial covalent character of their bonds. Metals of the first transition series have Y in the range of 200 GN/m². Y for metals of the second and the third transition series have higher values, reaching upto 600 GN/m².

The shear modulus G is related to the Young's modulus, Y through the Poisson's ratio ν , as

$$G = \frac{Y}{2(1 + \nu)} \quad (19)$$

5. FUNDAMENTAL MECHANICAL PROPERTIES

The following are the fundamental mechanical properties of materials:

- (i) Tensile Strength (ii) Hardness (iii) Impact Strength (iv) Fatigue and (v) Creep

We have already discussed about Tensile strength in section 2.

Hardness

This is the property of a material (metal) by virtue of it is able to resist abrasion, indentation (or penetration) and scratching by harder bodies. It is the resistance of a material to permanent deformation of the surface. In other words, one can define it as the resistance of the metal to penetration by an indenter. The hardness of a surface of the material is, of course, a direct result of interatomic forces acting on the surface of the material. We must note that hardness is not a fundamental property of a material, however, but rather a combined effect of compressive, elastic and plastic properties relative to the mode of penetration, shape of penetrator, etc. Hardness seems to bear a fairly constant relationship to the tensile strength of a given material and thus it can be used as a practical non-destructive test for an approximate idea of the value of that property and the state of the metal near the surface.

There are several methods of hardness testing, depending either on the direct thrust of some form of penetrator into the metal surface, or on the ploughing of the surface as a stylus is drawn across it under

a controlled load, or on the measurement of elastic rebound of an impacting hammer which possessing known energy. Measurements of hardness are the easiest to make and are widely used for industrial design and in research. All hardness tests are made on the surface or close to it. We may note that in mechanical tests the bulk of material is involved.

Brinell hardness number is the hardness index, calculated by pressing a hardened steel ball (indenter) into test specimen under standardised load. Brinell, Rockwell and Vickers hardness tests are used to determine hardness of metallic materials, to check quality level of products, for uniformity of samples of metals, for uniformity of results of heat treatment.

The Rockwell hardness is another index which is widely used by engineers. This index number is measured by the depth of penetration by a small indenter. By selecting different loads and shapes of indenter, different Rockwell scales have been developed. The value of Brinell hardness number is related to tensile strength and for two materials this is as shown in Fig. 8.11.

The mechanism of indentation in all indentation tests is that when the indenter is pressed into the surface under a static load, a large amount of plastic deformation takes place. The material thus deformed flows out in all directions. Sometimes the material in contact with the indenter produces a ridge around the impression as a result of plastic flow. Large amounts of plastic deformation are reported to be accompanied by large amounts of transient creep which vary with

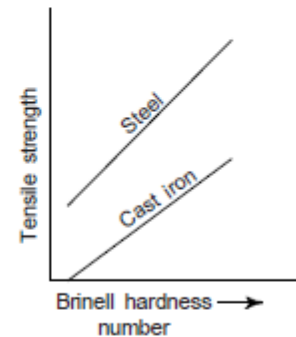


Fig. 8.11 Tensile strength versus Brinell hardness curves

the material and time of testing. We may note that the transient creep takes place rapidly at first and more slowly as it approaches its maximum. The time required for reaching maximum deformation for hard materials is short (~ few seconds) and for soft materials the time required to produce the desired indentation is quite long (~ few minutes). For minerals, hardness is expressed as resistance to abrasion which one mineral offers to another. Moh's scale has been developed for comparison of hardness. In order of increasing hardness, the following ten minerals are arranged: Talc, Gypsum, Calcite, Fluorite, Apatite, Orthoclase, Quartz, Topaz, Corundum and Diamond.

Sometimes, hardness is expressed in terms of macro-hardness and micro-hardness. The macro hardness of material relates to its resistance to larger volume displacements in plastic deformation, whereas micro-hardness is the hardness of the materials in microscopically small volumes e.g. in grain boundaries.

Hardness of materials is of importance for dies and punches, limit gauges, cutting tools, bearing surfaces etc. Softness of a material is opposite extreme of hardness. On heating all materials become soft.

Week#07

(iii) *Impact Strength*: The resistance of a material to fracture under dynamic loads is characterized by what is called the impact strength. Impact strength of a material is a complex characteristic which takes into account both the toughness and strength of a material. In S.I. units the impact strength is expressed in Mega Newtons per m^2 (MN/m^2). It is defined as the specific work required to fracture a test specimen with a stress concentrator (notch) in the mid when broken by a single blow of striker in pendulum-type impact testing machine:

$KC = K/S_0$ (where K is the work of the fracture and S_0 is the cross-sectional area of the specimen at the notch).

Impact strength is indicative of the toughness of the material, i.e. the ability of the material to absorb energy during plastic deformation. Obviously, brittleness of a material is an inverse function of its impact strength. Coarse grain structures and precipitation of brittle layers at the grain boundaries do not appreciably change the mechanical properties in static tension, but substantially reduce the impact strength.

Impact strength is affected by the rate of loading, temperature and presence of stress raisers in the material. It is also affected by variations in heat treatment, alloy content, sulphur and phosphorus content of the material.

Impact strength is determined by using the notch-bar impact tests on a pendulum-type impact testing machine. These results are used considerably in some industries to know shock-absorbing property of the material under the given variations. These results further help to study the effect of stress concentration and high velocity load application. Impact strength of a material varies with certain factors:

- (i) Impact strength increases if the dimensions of the specimen are increased.
- (ii) To some extent the velocity of impact also affects impact strength.
- (iii) When the sharpness of the notch increases, the impact strength of the material required to cause failure decreases.
- (iv) An indication about the type of the fracture that is likely to occur, i.e. ductile, brittle or ductile or brittle transition is provided by the temperature of the specimen under test.
- (v) The angle of notch also improves impact strength after certain values.

Impact strength is designated as KCU , KCV or KCT , where the first two letters are the symbol of impact strength and the letter U , V or T indicates the shape of the stress concentrator (notch): U-shaped with the radius of the notch $r_n = 1$ mm, V-shaped with $r_n = 0.25$ mm or T-shaped notch with a fatigue crack at its tip. The KCU index is the principal criterion of impact strength, whereas KCV and KCT indices are used only in special cases.

(iv) **Fatigue:** It is the failure of a material by fracture when subjected to a cyclic stress. Fatigue can occur at a stress whose amplitude is much smaller than the static load required to produce fracture. The maximum stress that a material can withstand without failure for a specific large number of cycles of stress is termed its *fatigue or endurance limit*. Fatigue is distinguished by three main features: (i) loss of strength (ii) loss of ductility and (iii) increased uncertainty in strength and service life.

Engineering materials are often subjected to fluctuating loads while in service. Few examples of components which are subjected to fluctuating loads or alternate stresses are: (i) aircraft wings subjected to turbulent air (ii) leaf springs bent to and fro (iii) connecting rods pushed and pulled in piston engines and (iv) some parts of compressors, pumps and turbines, etc. subjected to repeated loading and vibration. If a metal wire is bent to and fro several times, it ultimately breaks. Rotating and vibrating parts of machines as in aeroplanes are liable to undergo fatigue and cause accidents. About 80% of failure in engineering components takes place due to fatigue failure. Steel have generally a fatigue limit which is normally 0.4 to 0.5 times the tensile strength of the material. Due to the effect of inhomogeneities under repeated loading, fatigue results in brittle fracture with no gross deformation at the fracture. Obviously, fatigue fractures occur without any warning. They result in brittle fracture.

In all materials including metals, plastics, rubber and concrete, fatigue is an important form of behaviour. In addition to the above mentioned situations there are many other situations where fatigue failure will be very harmful. Under following conditions, the fatigue fracture progresses rapidly: (i) maximum tensile stress of sufficiently high value (ii) large vibrations or fluctuations in applied stress (iii) large number of cycles of applied stress and (iv) other variables which may change the conditions of failure such as stress concentration, over loading, corrosion, residual stresses, etc. Due to difficulty of recognizing fatigue conditions, fatigue failures comprise percentage of failures occurring in engineering. The point at which the curve flattens out is termed as the *fatigue limit* and is well below the normal yield stress. The fatigue strength is usually defined as the stress that produces failure in a given number of cycles usually 10^7 .

To avoid stress concentrations, rough surfaces and tensile residual stresses, fatigue specimens must be carefully prepared.

(v) **Creep:** It is essentially a slow rise of plastic deformation under the action of stresses below the yield strength of the material. A typical curve of deformation versus loading time is shown in Fig. 8.18. A creep curve usually consists of three portions corresponding to particular stages of creep. The first stage is the stage of what is called unstable, or transient creep (also called initial or primary creep). It features gradual decrease of the deformation rate to a definite constant value. The second stage is the stage of steady-state, or secondary creep and is characterized by a constant deformation rate. At the third stage (tertiary, or accelerated creep), the deformation rate increases upto failure. The third stage is, as a rule, short and should be avoided, since quick failure of parts is inevitable at this stage.

A physical explanation of the three stages of creep is as follows:

Primary Creep: This stage is mainly due to dislocation movement. The creep rate decreases with time and the effect of work hardening is more than that of the recovery process.

Secondary Creep: The rates of work hardening and recovery during this stage are equal, so the material creeps at a steady rate (minimum creep rate). Depending upon the state level and temperature, steady state creep may be essentially viscous or plastic in character. Structural observations reveals that polygonization is an important recovery process during secondary creep.

Tertiary Creep: Creep rate increases with time until fracture occurs in this stage. Tertiary creep can occur due to necking of the specimen or grain boundary sliding at high temperatures and this continues until specimen fractures.

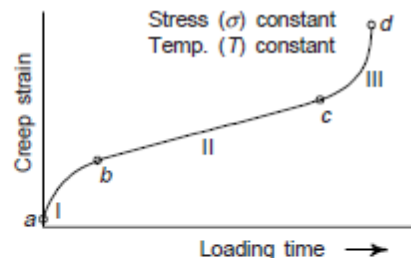


Fig. 8.18 Creep curve at constant temperature and stress: I-transient creep stage, II-steady stage creep stage and III-fracture stage

The development of each stage of creep depends on the temperature and stress. For the same stress, an increase of temperature shortens the time of the second stage and accelerates failure (Fig. 8.19(a)). An increase of stress at the constant temperature has a similar effect (Fig. 8.19(b)). One can obtain the maximum operating temperatures and stresses from creep data plotted in a suitable form. The phenomenon of creep is observable in metals, ionic and covalent crystals, the amorphous materials such as glasses and polymers. In polymers, the phenomenon of creep is important at room temperature, in alloys at 100°C, and in steel above 300°C.

Metals, generally, exhibit creep at high temperatures, whereas plastics, rubbers and similar amorphous materials are very temperature-sensitive to creep. A material subjected to a constant tensile load at an elevated temperature will *creep* and undergo a time dependent deformation.

The temperature and time dependence of creep deformation indicates that it is a *thermally activated process*. There are several atomic processes known to be responsible for creep in crystalline materials.

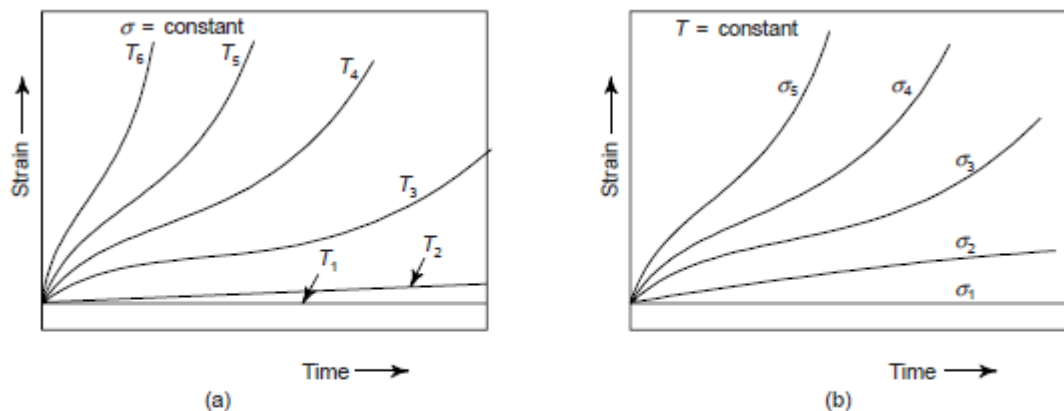


Fig. 8.19 Creep curves depending on (a) temperature (b) stress:

$$T_1 < T_2 < T_3 < T_4 < T_5 < T_6;$$

$$\sigma_1 < \sigma_2 < \sigma_3 < \sigma_4 < \sigma_5$$

Creep Curve Equations

One can consider creep curve to consist of a combination of two different creep processes, which occur after the sudden strain. These are: (i) transient creep having decreasing creep rate and (ii) viscous creep having constant rate. One can write the equation of curve with the help of following empirical equation,

$$l_t = l_o (1 + \beta t^{1/3}) \exp(kt)$$

where, $l_t \rightarrow$ length of the specimen at time t , $l_o \rightarrow$ length of specimen after sudden creep and β and k are constants. Setting $k = 0$, for transient creep, we have

$$l_t = l_o (1 + \beta t^{1/3})$$

$$\text{Now, change in length/unit time} = \frac{dl_t}{dt} = \frac{1}{3} l_o \beta t^{-2/3}$$

For viscous creep, setting $\beta = 0$, we have

$$l_t = l_o \exp(kt)$$

$$\text{Change in length/unit time} = \frac{dl_t}{dt} = k l_o \exp(kt) = k l_t$$

$$\text{or} \quad k = \frac{1}{l_t} \frac{dl_t}{dt} = \frac{\text{strain}}{\text{unit time}} = \text{strain rate}$$

Strain/unit time, i.e. k proceeds at constant rate. Obviously, the slope of viscous is constant. Creeps curves for sudden, transient and viscous creep are shown in Figure 8.20.

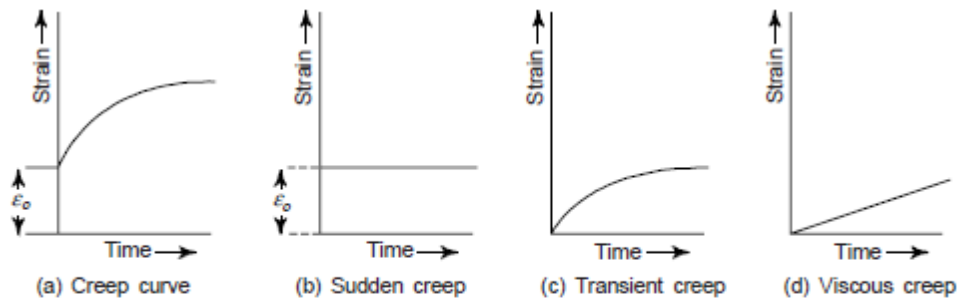


Fig. 8.20 Creep curve analysis. $\epsilon_0 \rightarrow$ instantaneous strain

Week#08

2. ELASTIC DEFORMATION

When subjected to a force or load, many solid materials behave elastically, i.e., the solid material deforms when loaded but returns to its original shape and size, i.e., position when unloaded. Such type of behaviour is common to metals, ceramics, rubbers and polymers. Elastic deformation in a solid can take place due to change in pressure, or by an application of force or load. We have read that elasticity has its origin in the forces between atoms of the solid, and therefore depends on both the chemical bonding and the structure of solid. However, the elastic properties of a material are independent of crystalline imperfections, e.g. vacancies and dislocations. Elastic deformation is illustrated in Fig. 11.1.

The deformation is said to be an *ideal deformation* which takes place instantaneously upon application of force or load and disappears completely on removal of the force or load. Such deformations in a solid materials obey *Hooke's law* (Stress & Strain). Strain related to this stress should not exceed more than one percent of the original length of the material. Elastic deformation in other non-crystalline materials such as rubber is a few hundred percent as compared to about one percent in metals. We may note that ideal deformation occurs with comparatively smaller deformation forces, i.e., such forces can keep working stresses within the elastic limit.

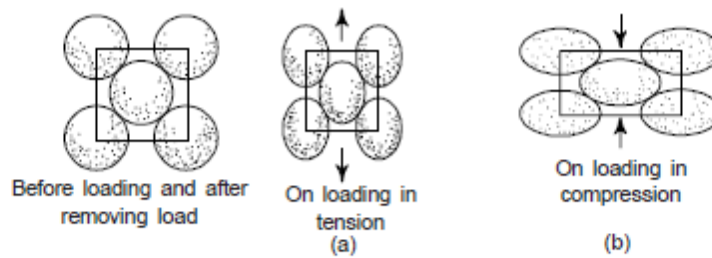


Fig. 11.1 Elastic deformation in a solid material

In engineering practice, material's crystal structures are also subjected to shearing loads. A shearing stress set up by the shearing load produces displacement of one plane of atoms relative to adjacent planes of atoms in a material (Fig. 11.2). Obviously, shear stress tends to slide each layer of atoms past the next. The modulus of elasticity does not apply directly to shear. However, shear stress bears a direct relationship to the elastic shear strain. Up to the limit of elastic displacement the shear strain is proportional to the shear stress.

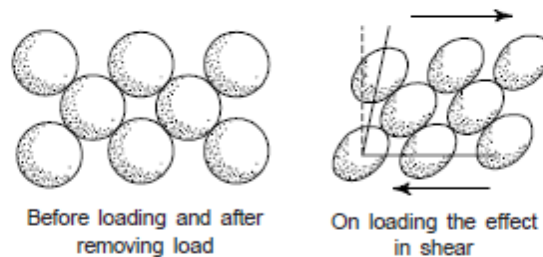


Fig. 11.2 Elastic shear strain (not to the scale)

There are many materials, where Hooke's law does not hold good for all engineering applications where deformation is large, i.e. for these materials, stress & strain, relationship is no longer applicable. Non-ferrous metals, mild steel, etc. are few examples which show *deviation from perfect elastic behaviour*.

3. PLASTIC DEFORMATION

For most metallic materials, elastic deformation persists only to strains of about 0.005. As the material is deformed beyond this point, Hooke's law ceases to be valid, i.e. stress is no longer proportional to strain, and *permanent, nonrecoverable, or plastic deformation* occurs. Figure 11.3 shows the tensile stress-strain behaviour into the plastic region for a typical metal. The proportional limit P , and the yield strength σ_y has been determined using the 0.002 strain offset method.

The transition from elastic to plastic is a gradual one for most metals; some curvature results at the onset of plastic deformation, which increases more rapidly with rising stress.

Plastic deformation can occur under tensile, compressive and torsional stresses. The rate of plastic deformation is controlled by applied stress, strain rate and temperature control.

The ability of metals to undergo plastic deformation is called *ductility*. In a plastic deformation of a metal, a change in shape occurs concurrently with changes in a number of metal properties; in particular, cold deforming increases the strength of a metal. The ductility of a metal ensures the structural strength of elements under a load and neutralizes the effect of stress concentrations. To

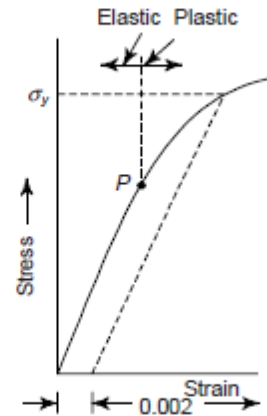


Fig. 11.3 Stress-strain behaviour for a metal showing elastic and plastic deformations

perform processes such as rolling, forging, extrusion, spinning, pressing, drawing, stamping, etc., plastic deformation is intentionally carried out. We may note that machinability and wear resistance are entirely dependent on the plasticity of the metals.

From an atomic perspective, plastic deformations are based on irreversible displacement of atoms through substantial distances from their equilibrium. Obviously, plastic deformation corresponds to the breaking of bonds with original atom neighbours and then reforming bonds with new neighbours as large number of atoms or molecules move relative to one another, upon removal of the stress they do not return to their original positions. Fig. 11.4 shows plastic deformation of a long range material. The mechanism of this deformation is different for crystalline and amorphous materials. For crystalline solids, deformation is accomplished by means of a process called *slip*, which involves the motion of dislocations. Plastic deformation in non-crystalline solids (as well as liquids) occurs by a *viscous flow mechanism*.

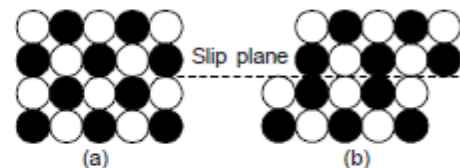


Fig. 11.4 Plastic deformation (a) Prior to deformation (b) After the passage of unit dislocation