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Plastic Deformation of Metals and Related Properties

1.1 INTRODUCTION

Metal forming is the backbone of modern manufacturing industry besides being a major industry in itself. Throughout the world hundreds of million tons of metals go through metal forming processes every year. As much as 15–20% of GDP of industrialized nations comes from metal forming industry. Besides, it fulfils a social cause by providing job opportunities to millions of workers. Metal forming industry, in general, is a bulk producer of semi-finished and finished goods and this is one reason that it is viable to undertake large scale research and development projects because even a small saving per ton adds up to huge sums.

In metal forming processes, the product shapes are produced by plastic deformation. Hence it is important to know the plastic flow properties of metals and alloys for optimizing the processes. Also the resulting component properties depend upon the intensity and the conditions of plastic deformation during forming.

Many forming processes produce raw materials for other processes which in turn produce finished or semi-finished products. For example, steel plants produce sheet metal which is used by automobile industry to manufacture components of automobiles and their bodies. In fact sheet metal is used by a number of manufacturers for producing a large variety of household and industrial products. Similarly billets produced by steel plants are used by re-rolling mills for rolling into products like angles, channels, bars etc. Bars may be further used for manufacturing forgings, wires, bright bars and machined products. Similarly the manufacturers of rivets, screws, bolts and nuts buy wire from wire manufacturers and process them further. Therefore, the producers of semi-finished materials such as sheet metal, bar stock and wires, etc. have to consider that they produce such properties in their products which are required by down stream industry engaged in further processing of these products. For example, deep drawability of sheet metal increases with increase in anisotropy ratio (*see Section* 1.9), therefore, rolling parameters such as finishing temperature, cold reduction etc, are adjusted to produce higher anisotropy ratio in the sheet metal which is to be used for deep drawing.

The properties of metals and alloys are highly influenced by their microstructure which may be modified or altered by alloying elements, by heating or heat treatment or by plastic deformation. For example, metals and alloys may be hardened by plastic deformation. It would, therefore, be helpful if we look at metals at the micro level.

1.2 BASIC STRUCTURE OF METALS AND ALLOYS

1.2.1 Grain Structure

The microstructure of solid metallic bodies consists of grains. Grains consist of unit cells in which atoms are arranged in a particular order. The cell structure repeats itself throughout the volume of the grain (Fig. 1.1). That is why the grains are also called crystallites. The structure is called lattice in which atoms are placed at lattice points. In metals, generally there is only one atom at a lattice point. There are many types of structures of unit cells for different materials, however, metals generally possess one of the following three cell structures.

(i)   Body centered cubic structure (BCC).
(ii)   Face centered cubic structure (FCC).
(iii)   Hexagonal closed packed structure (HCP).

The three cell structures are illustrated in Fig. 1.2. Some metals such as iron (Fe), cobalt (Co), titanium (Ti), etc. change their cell structure at different temperatures.
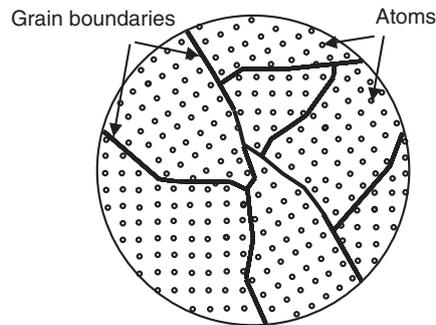

Fig. 1.1. Grain structure

Body Centered Cubic Structure: The structure consists of one atom at each of the eight corners of a cubical element and one atom at the center of the cube in Fig. 1.2(*a*). Metals with this structure are chromium (Cr), hafnium (Hf) at temperatures greater than 1975°C, iron (Fe) except at temperatures 911°C to 1392°C, molybdenum (Mo), niobium (Nb), tantalum (Ta), titanium (Ti) at temperatures greater than 882°C and tungsten (W), etc.
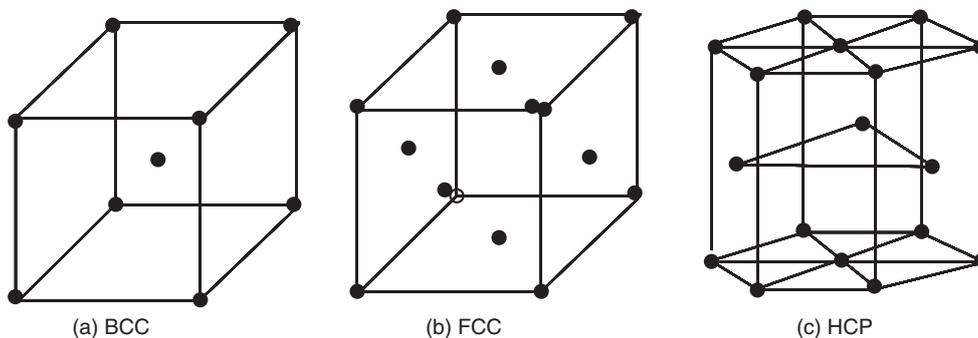

(a) BCC   (b) FCC   (c) HCP

Fig. 1.2. Cell structures of metals

Face Centered Cubic Structure: In this structure there is an atom at each of the eight corners of the cubical element and there is an atom in the middle of each face of the cube as shown in Fig. 1.2(*b*). Metals with this structure are aluminum (Al), cobalt at temperature greater than 1120°C, copper (Cu), gold (Au), iron (Fe) between temperatures 911°C–1392°C, lead (Pb), nickel (Ni), silver (Ag), platinum (Pt), etc.

Hexagonal Closed Packed Structure: In this cell structure there is an atom at each corner of a hexagonal prismatic element, besides, there are three atoms symmetrically placed between the two end faces as shown in Fig. 1.2(*c*) and one atom each at center of the flat end faces. Metals with this structure are beryllium (Be), cobalt at temperatures less than 1120°C, magnesium (Mg), zinc (Zn), titanium (Ti) at temperatures less than 882°C, etc.

1.2.2   Lattice Defects

Ideally there should not be any defect in lattice structure, however, imperfections and defects may occur due to alloying elements, plastic deformation, grain boundaries, etc. The lattice structure generally contains following types of defects which are illustrated in Fig. 1.3.

(i)   Point defects or imperfections.
(ii)   Line defects which are also called dislocations.
(iii)   Surface defects—grain boundaries.

Point defects are caused by various reasons such as (i) absence of an atom from a lattice point, (ii) an atom getting to a site which is not a lattice point, (iii) an atom of a different element (alloy) substituting an atom of parent metal, etc. Point defects disturb the natural arrangement of atoms in its vicinity and consequently atoms surrounding the point defect are either stretched apart or are pushed too close. This gives rise to additional pull or push among the atoms.
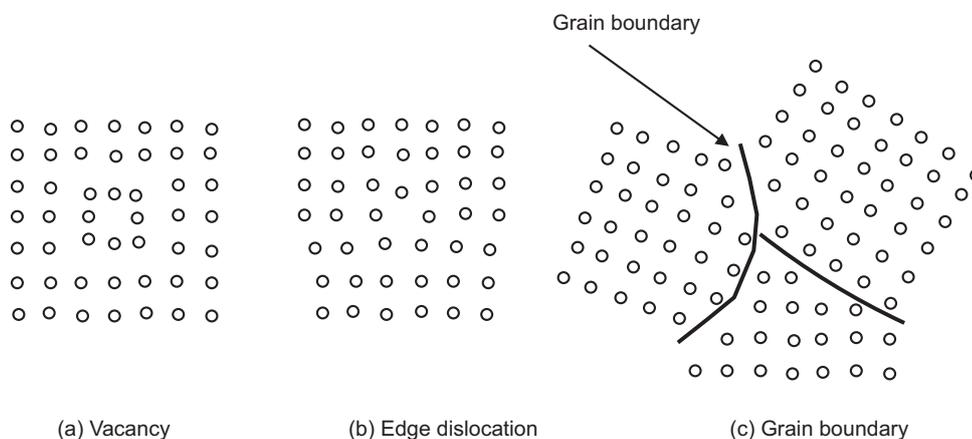

(a) Vacancy   (b) Edge dislocation   (c) Grain boundary

Fig. 1.3. Imperfections in lattice structure

The type and concentration of these imperfections or defects greatly influence the properties of metals and alloys. The defects may also be induced or controlled by alloying, heat treatment or plastic deformation in order to obtain a change in the mechanical properties.

Line defects or dislocations are important for plastic deformations. The following two types of dislocations are observed.

4   Fundamentals of Metal Forming Processes

 (i)   Edge dislocations.
(ii)   Screw dislocations.

These are illustrated (Fig. 1.4). The figure also shows how these defects travel through the lattice when subjected to shear forces. The dislocations travel from one layer of atoms to another as the shear stresses increase. Slipping of all the atoms simultaneously would take enormous forces which is not explained by much lower yield strength of metals. A dislocation may be obstructed in its movement by atoms of alloying elements or point defects, by stationary dislocations and grain boundaries or by other defects. More force is then required to overcome the obstruction. Sometimes, the ends of a dislocation may get pinned down, in such a case, increase in applied shear force results in curving of the line defect (Fig. 1.5). With further increase in stress the dislocation may get curved inward, ultimately transforming into a ring dislocation and a new dislocation at the initial points. Thus this becomes a source of production of dislocations. Plastic deformation creates a large number of dislocations. Higher the dislocation density in the material, higher is the resistance to movement of dislocations and hence higher forces are required for plastic deformation. This explains the increase in strength during plastic deformation, which is called strain hardening or work hardening.
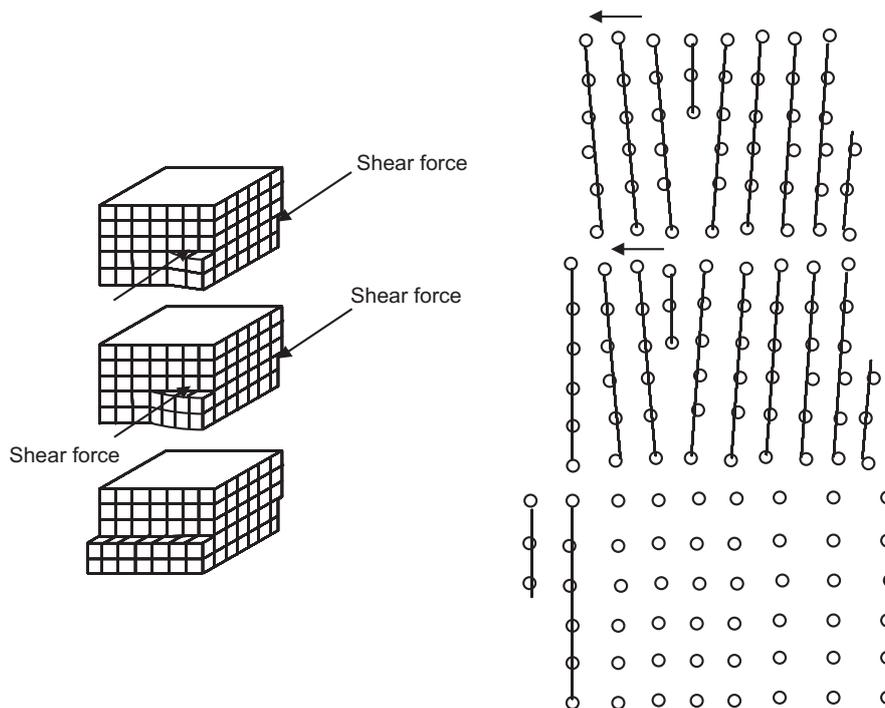
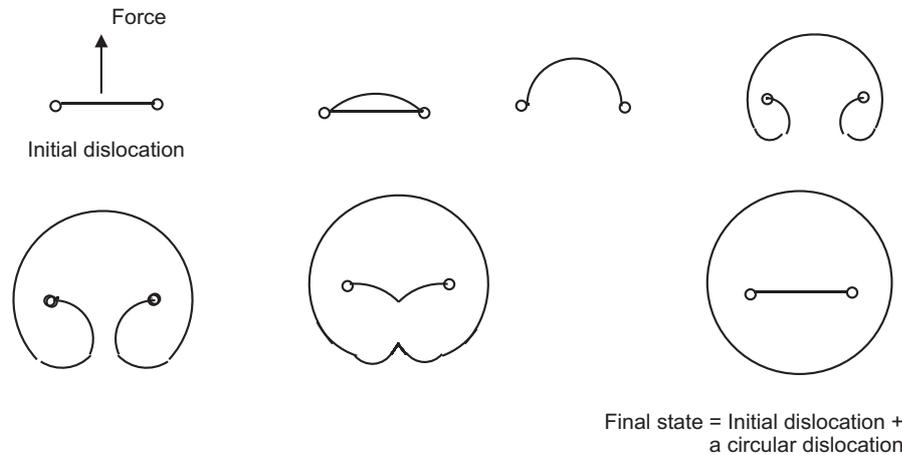**Fig. 1.4.** Dislocations and their movement

Fig. 1.5. Generation of dislocation

Surface defects are the irregular arrangement of atoms at the grain boundaries. In a grain the atoms are arranged in particular order, however, the directions of the arrangement are different in neighbouring grains. The boundaries are irregularly shaped with the effect that at some places atoms are too far apart while at other places they are too close than the normal distance, thus giving rise to tensile and compressive forces. These defects also cause restriction to movement of dislocations. In a structure with small grains the dislocations can move only a small distance before encountering an obstacle, i.e. grain boundary. Therefore, a metal is stronger when it has small grains structure than when it has a large grain structure.

1.3   FORMING PROPERTIES OF METALS AND ALLOYS

Most of the metal forming processes require a combination of material properties for their successful operation. For example, for deep drawing of sheet metal, one of the requirements is that the material should be ductile. However, lead is quite ductile at room temperature but lead sheet is not that suitable for drawing into cups in the way steel cups are drawn. The material properties which are of importance for metal forming are listed below.

1. Yield strength/flow stress.
2. Ductility.
3. Strain hardening.
4. Strain rate sensitivity.
5. Effect of temperature on yield strength and ductility.
6. Effect of hydrostatic pressure on yield strength and ductility.
7. Instability and fracture strength.

1.4   TESTING FOR YIELD STRENGTH / FLOW STRESS

1.4.1   Tensile Test

For determination of yield strength or flow stress, one or more of the following three basic tests are conducted.

 (i)   Tension test.
 (ii)   Compression test.
(iii)   Torsion test.

Most of us are quite conversant with the simple tension test which is the most common and is conducted to determine the yield strength, ultimate tensile strength, percent elongation and fracture strength of metals. Figures 1.6 and 1.7 show typical stress-strain curves obtained in tension tests on two different alloys. Figure 1.6 is obtained for a low carbon steel or mild steel test specimen and Fig. 1.7 is obtained for an aluminium alloy test specimen. In these two diagrams the stress and strain are defined as given below.

Stress = Force/Original area of cross-section of specimen.

Strain = Change in length/original length of specimen.

In case of mild steel, for loading up to point *A* (Fig. 1.6), there is a straight line or linear relationship between stress and strain. That is why the point *A* is also called *proportional limit*. Thereafter, the relationship between stress and strain is nonlinear up to a point *B* which is very near to *A*. Also up to the point *B* the deformations are largely elastic and on unloading the specimen regains the original dimensions. But beyond the point *B* the metal yields, it suffers plastic deformation. This is indicated by a sudden bend in the curve. Most of the strain after this point is plastic strain which is not recovered on unloading. The value of stress at *B* is called *upper yield strength* and point *B* is called *upper yield point*.
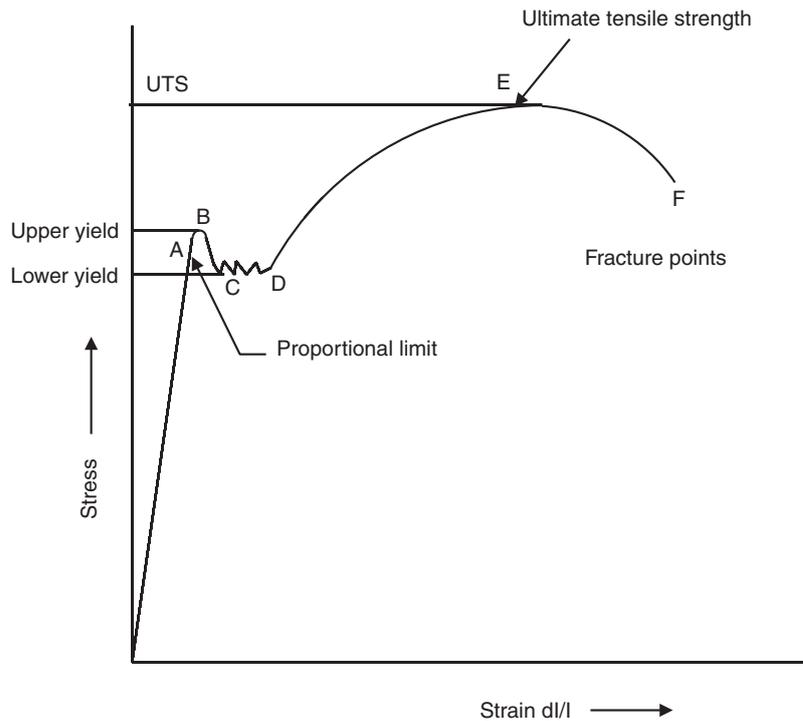

Fig. 1.6. A typical stress-strain curve for mild steel

With further increase in strain (beyond *B*) the stress may fall a bit to a lower level at *C* (Fig. 1.6). This is due to formation of Lüder bands. With increase in tension, localized plastic flow takes place in a narrow band with boundary planes inclined at a certain angle with the axis of test specimen. Consequently the load falls a bit. However, due to strain hardening of the material in the band, the load again increases till another Lüder band appears in the test piece.

This goes on till the whole specimen is full of Lüder bands. Thus between the points *C* and *D* the stress is oscillating between two narrow limits. This occurs in alloys having interstitial solid solution structure like low carbon steels. The stress at the point *C* is called *lower yield strength.*

However with further increase in strain beyond the point *D*, when the test piece is full of Lüder bands, the load or stress again starts increasing. The distinction between the two yields may disappear with strain hardening and only a small kink may remain on the stress strain curve. Some authors prefer to take stress value at *C* as the flow stress at the yield point, however, the data given in material standards generally refers to upper yield point.

After the point *D* the stress-strain curve moves upwards, however, with further deformation, its slope gradually decreases to zero at the point *E* which is the highest point on the curve. After *E* the curve goes down. Before the point *E*, increase in strain increases the load on the specimen due to strain hardening. Even after the point *E*, the strain hardening is still there but at some point the area of cross section of the test piece starts decreasing much faster and a neck formation starts, with the result, the force that the test piece can bear decreases continuously with further deformation resulting in an unstable condition. After some elongation in the neck, the specimen fractures at the point *F*. Since we have defined stress as force divided by original area of cross section the stress value thus calculated also decreases after *E*, however, if we take true stress, as explained below, it will be much higher.

The stress at the point *E* is known as *ultimate tensile strength*. At point *E* the actual area of cross section is smaller than the original area of cross-section. In order to obtain realistic values of material strength, we must plot *true stress-true strain* curve which is discussed in the next section.

Most of the nonferrous metals and alloys do not show the sudden bend or kink in their stress strain curve like the one we get for low carbon steel as described above. Instead there is a gradual transition from elastic to plastic state (Fig. 1.7). In such cases, the yield strength may be taken at the point of intersection of tangents to elastic and plastic lines [9].
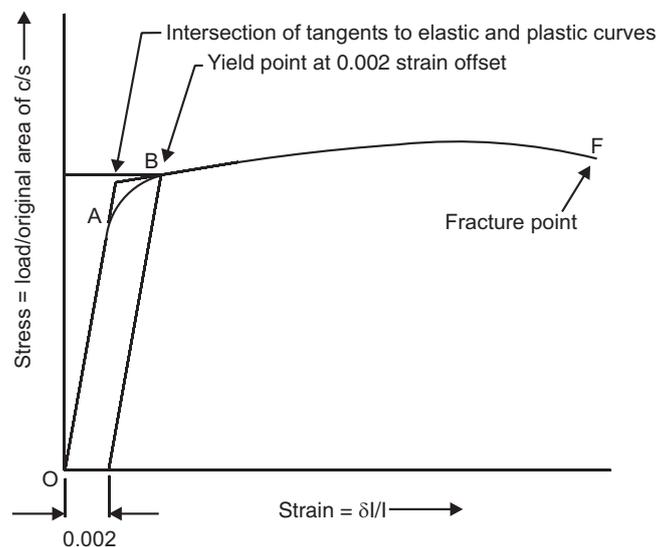

Fig. 1.7. A typical stress-strain curve for aluminum

However the change from elastic to plastic state is very gradual, the point of intersection is rather ambiguous. Different values may be obtained if tangents are drawn at different points. Therefore, an offset yield point is obtained at a strain of 0.002 (0.2%). A straight line is drawn parallel to initial portion of stress-strain curve at the strain value of 0.002 and the point where it intersects the stress-strain curve is taken as yield point.

1.4.2   True Stress-True Strain

The curves of Figs. 1.6 and 1.7 are drawn with the stress defined as load divided by *original* area of cross-section and the longitudinal strain is defined as $\delta l/l_0$, where l_0 is the original length of test specimen. The curves would look very much different if we use true stress on ordinate and true strain on abscissa. The *true stress* and *true strain* are defined below.

$$\text{True stress} \; = \; \frac{\textit{Force applied on the specimen}}{\textit{Current area of cross-section}} \tag{1.1}$$

For true strain, let us take that a specimen of length l is elongated by 'δl'. The differential strain $d\varepsilon$ becomes

$$d\varepsilon \; = \; \frac{\delta l}{l} \tag{1.2}$$

The true strain in the specimen which has been elongated from the initial length l_0 to final length l is obtained by integrating the above equation.

$$\text{True strain} \quad \varepsilon \; = \; \int_{l_0}^{l} \frac{\delta l}{l} \; = \; \log_e (l/l_0) \tag{1.3}$$

The expression for true strain may also be written as below.

$$\log_e (l/l_0) \; = \; \log_e (1 + \delta l /l_0)$$
$$= \; \log_e (1 + E) \tag{1.4}$$

where

$$E \text{ is the engineering strain} \; = \; \delta l/l_0 \tag{1.5}$$

For accurate calculations, the true stress-true strain curve for the metal should be drawn to determine the yield strength. Figure 1.6 redrawn on true stress-true strain axes would look like the one shown in Fig. 1.8. Also there are standard specifications for the shape and dimensions of test specimen, which should be adapted in order to obtain meaningful results. Besides, in all above type of tests the following factors should also be noted.

    (i)   Temperature at which the test is conducted.
    (ii)   The strain rate during the test.
    (iii)   Accuracy of load measuring instrument.
    (iv)   Accuracy of instrument which measures elongation.
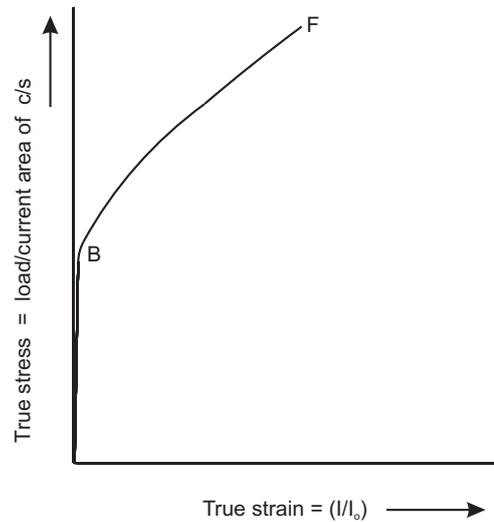
Fig. 1.8. True stress-true strain curve for tensile test

Example 1.1

A mild steel rectangular specimen of length 100 mm is extended to 120 mm. Neglecting the elastic deformation and taking that material is isotropic, determine the true strains in length, width and thickness directions.

Solution

Let ε_l, ε_w, and ε_t be the true strains in length, width and thickness directions respectively.

True strain along the length $\varepsilon_l = \ln(120/100) = 0.1823$

Also, in plastic deformation the change in volume is zero. Therefore,

$$\varepsilon_l + \varepsilon_w + \varepsilon_t = 0$$

Since material is isotropic $\quad \varepsilon_w = \varepsilon_t$

Hence $\quad \varepsilon_w = \varepsilon_t = -\varepsilon_l/2 = -0.09115$

The three strains are 0.1823, – 0.09115 and – 0.09115.

Example 1.2

Determine the true strains in length, width and thickness directions of a sheet metal test specimen if it is elongated to 130 % of its original length. The anisotropy ratio $\varepsilon_w/\varepsilon_t = 1.5$. Also determine the per cent decrease in area of cross-section.

Solution

The longitudinal strain $\quad \varepsilon_l = \log_e(130/100) = 0.2623$

From incompressibility condition $\quad \varepsilon_l + \varepsilon_w + \varepsilon_t = 0$

and also we are given that $\quad \varepsilon_w/\varepsilon_t = 1.5$

Therefore,

$$\varepsilon_t = -\ 0.2623/2.5 = -\ 0.1049$$

and $\varepsilon_w = -\ 0.1573$

Let 'a' be area of cross-section and 'l' the length. The volume V of the specimen is given by,

$$V = a.l$$

The differential change in the volume is given as,

$$dV = a.dl + l.da$$

In plastic deformations the volume does not change. Hence, $dV = 0$, and hence

$$da/a = -\ dl\ /\ l$$

∴   Change in area of cross-section $= -\ 30\ \%$

1.5   FACTORS THAT AFFECT THE YIELD STRENGTH

In metal forming, particularly in hot forming many metallurgical processes may take place concurrently. These include strain hardening, recovery, re-crystallization, etc. All these factors affect the yield strength. Therefore, it is important to know the extent of effect of each of these factors. The yield strength of a metal or alloy is affected by following factors.

   (i)   Strain hardening.
  (ii)   Strain rate.
 (iii)   Temperature of metal and microstructure.
 (iv)   Hydrostatic pressure.

1.5.1   Strain Hardening

To understand the effect of strain hardening let us again consider the tension test curve shown below in Fig. 1.9.

In this figure the test piece is loaded beyond the yield point up to a point P. The test piece is then unloaded. The elastic deformation recovers via the unloading curve PR which is more or less parallel to AO. It is generally taken that there is no change in Young's modulus during plastic deformation. The line PR depicts elastic recovery. Out of the total strain OS corresponding to the point P, the part RS is the elastic recovery. The part OR which is not recovered is the plastic strain suffered by the test specimen.

Now if we reload the same test piece, it nearly follows the line RP. There is, however, some deviation due to hysteresis which is very small, and the yielding now occurs at the point P. Further loading of the test piece beyond P gives the same stress-strain curve as we would have obtained if there were no unloading. This shows that after suffering a plastic strain represented by OR, the yield strength of metal has increased from point B to point P (or σ_{o1} to σ_{o2}). This is called strain hardening or work hardening.