3.3 Strengthening Methods

To meet the challenges of advanced technologies, new materials are need to be developed. The new and conventional materials desire their strengthening and hardening so as to withstand varying functional conditions. The behavior of a solid depends on its chemical composition, mechanical properties and thermal processing. Heat treatment, casting, hot-working, sintering, etc., are the thermal processes that influence the mechanical properties by changing grain sizes and phases. Accumulation of dislocations during plastic deformation also adds to the strength of a metal. Various strengthening and hardening mechanisms are

a) Strain hardening

b) Precipitation hardening (Age hardening)

c) Dispersion hardening

d) Solid-solution hardening

Cold Working

Working means processing or operations regarding fabrication of metals to some desired shapes. These processes may be rolling, forging, embossing, etc. When the processes are carried out below the re crystallization temperature ($0.3T_m$ to $0.5T_m$), these are known as cold working processes.

The advantages during cold working is given below:

i) Increase in the hardness

ii) Increase in the yield and ultimate strengths

iii) Decrease in ductility

iv) Slight decrease in density

v) Decrease in electrical conductivity

vi) Distortion in the microstructure of metals

vii) Formation of crystal defects

viii) Improved surface finish

ix) Closer dimensional tolerances

x) High mechanical energy required to cause plastic deformation

xi) Raising of re crystallization temperature of metals

The amount of cold working is expressed as percent of cold work. This indicates the percent reduction of thickness, or reduction in area of this metal. The percent cold working may be determined from

$$\%CW = \frac{t_o - t_d}{t_0} \times 100$$

or

$$\%CW = \frac{A_0 - A_d}{A_0} \times 100$$

Where t_o and A_o are the initial thickness and cross-sectional area; t_d and A_d are thickness and cross-sectional area after deformation, respectively. The effect of cold working on the hardness of some materials is shown in the figure below.

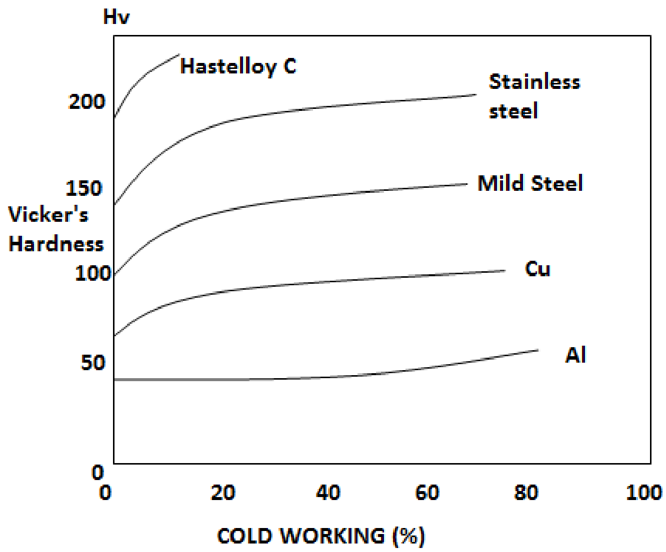

Fig 3.3.1 cold working

It indicates that the hardness increases with increasing cold working. Increase in tensile strength with a corresponding reduction in elongation due to enhancing amount of working in mild steel is depicted in figure below. The defects induced due to cold working is removed or minimized by ***annealing*** a heat treatment process.

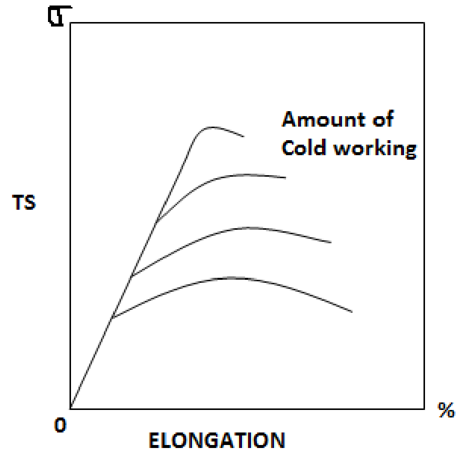

Fig 3.3.2 Annealing

Strain Hardening (Work Hardening)

Strain hardening (or work hardening) is a phenomenon in which steeply rising tensile stress-strain behavior is noticed after yielding. During strain hardening in ductile materials, an increase in stress is needed to produce further strain in the plastic region. Each increment of strain strengthens and hardens the material so that a larger stress is needed for further straining (deforming) of material. The stress-strain behavior during this phenomenon is shown in Figure below. Initially, the slope of curve is upward which gradually lowers down. The increasing stresses $\sigma_4 > \sigma_3 > \sigma_2 > \sigma_1$ are required to cause increasing strains $\varepsilon_4 > \varepsilon_3 > \varepsilon_2 > \varepsilon_1$.

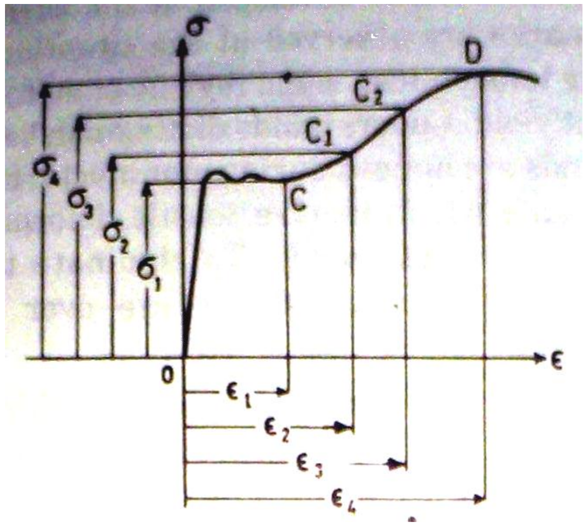

Fig.3.3.3 Strain hardening showing ever increasing stress required to cause increasing strain during CD part of stress-strain curve.

Mechanism of the Process

Strain hardening cannot occur if any one of the following situations are not present.

1. Dislocations
2. Obstacles and
3. Back stresses

Strain hardening is mainly accounted for by dislocations and their interactions. We shall first study the case of interaction of like and unlike dislocations existing on the same plane. If the Burgers vector of these dislocations is the same, the net effect will be annihilation of dislocations. Hence, no strain hardening will be produced in the material.

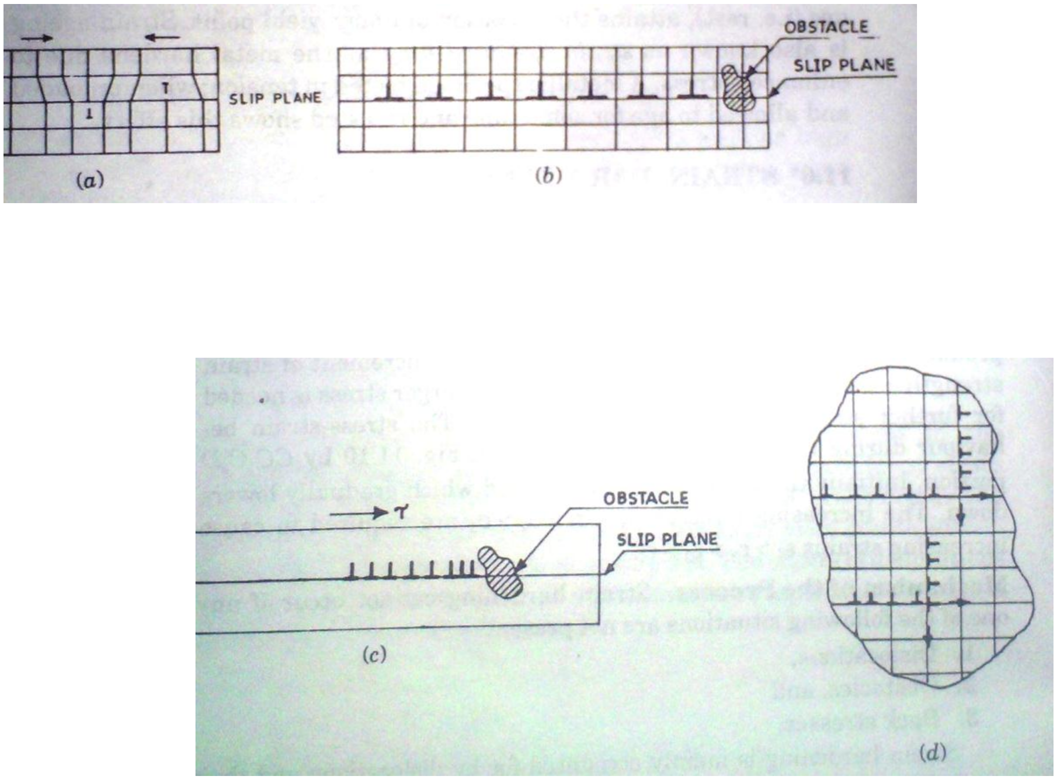

Fig 3.3.4 Mechanism of strain hardening showing (a) like and unlike dislocations annihilating each other (b) like dislocations on the same slip plane (c) crowded dislocations stopped by an obstacle, and (d) collision of dislocations on intersecting planes.

Consider the case of similar dislocations (Fig. b above). If for any reason, similar dislocations approach each other, they interact in such a way that the stress and strain field will cause increased strain energy. When these like dislocations lying on the same slip plane, move under the influence of shear stress τ, they are encountered by an obstacle lying within the material. The obstacle may be natural or manmade. Cementite in steel and oxides in non-ferrous metals are the examples of natural obstacles. Grain boundaries and other imperfections are manmade obstacles. The dislocations are stopped by the obstacle which they cannot break or by-pass and hence get crowded (Fig. c above). Now a back stress sets-up. The entire slip on that place is brought to halt. To produce further slip, τ has to be increased to overcome the obstacle. Stress required to move a dislocation in stress field of dislocation density ρ_d is given by

$$\tau = \tau_o + \lambda\sqrt{\rho_d}$$

where, τ_o is the stress to move dislocation with zero dislocation density and λ is a constant.

Initially, the slope of the curve CC_1C_2D is upwards. In due course of loading, it slops down when obstacle becomes weaker and dislocations move gradually. It is an indication of diminishing strain hardening.

In above discussion, we considered dislocations on a single slip plane. As there are several slip planes in most of the crystals, the dislocations interact on these intersecting slip planes and hinder the movement of each other. Consequently, they accumulate within the material and result into strain-hardening.

Effect of strain-hardening:Cubic crystals strain harden more than hexagonal crystals. Hexagonal crystals have only one set of slip planes whereas the cubic crystals have several slip planes. These are prone to multiple slip. Polycrystals have higher rate of strain hardening than the single crystal. It is because the dislocations find additional obstacles in the form of crystal boundaries.

Strain hardening occurs in all the metals and ceramics. To a material scientist, this phenomenon is good and bad both. It is useful in that this is a material strengthening method. It is not useful in a process like rolling of thin metal sheet where yield strength rises to a limit which is difficult to work. Rolling can proceed further by annealing the metal to remove accumulated dislocations.