

Module-6

Dislocations and Strengthening Mechanisms

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- 1) Dislocations & Plastic deformation and Mechanisms of plastic deformation in metals
- 2) Strengthening mechanisms in metals
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Plastic deformation – Dislocations

- Permanent plastic deformation is due to shear process – atoms change their neighbors.
- Inter-atomic forces and crystal structure plays an important role during plastic deformation.
- Cumulative movement of dislocations leads to gross plastic deformation.
- Edge dislocation move by slip and climb, while screw dislocation move by slip and cross-slip.
- During their movement, dislocations tend to interact. The interaction is very complex because of number of dislocations moving over many slip systems in different directions.

Plastic deformation – Dislocations (contd...)

- Dislocations moving on parallel planes may annihilate each other, resulting in either vacancies or interstitials.
- Dislocations moving on non-parallel planes hinder each other's movement by producing sharp breaks – jog (break out of slip plane), kink (break in slip plane)
- Other hindrances to dislocation motion – interstitial and substitutional atoms, foreign particles, grain boundaries, external grain surface, and change in structure due to phase change.
- Material strength can be increased by arresting dislocation motion.

Plastic deformation mechanisms - Slip

- Mainly two kinds: slip and twinning.
- Slip is prominent among the two. It involves sliding of blocks of crystal over other along slip planes.
- Slip occurs when shear stress applied exceeds a critical value.
- Slip occurs most readily in specific directions (slip directions) on certain crystallographic planes.
- Feasible combination of a slip plane together with a slip direction is considered as a slip system.
- During slip each atom usually moves same integral number of atomic distances along the slip plane.

Plastic deformation mechanisms – Slip (contd...)

- Extent of slip depends on many factors - external load and the corresponding value of shear stress produced by it, crystal structure, orientation of active slip planes with the direction of shearing stresses generated.
- Slip occurs when shear stress applied exceeds a critical value.
- For single crystal, Schmid defined critical shear stress as

$$\tau_R = \frac{P \cos \lambda}{A / \cos \phi} = \frac{P}{A} \cos \phi \cos \lambda = \sigma \cos \phi \cos \lambda$$

$$\Rightarrow m = \cos \phi \cos \lambda$$

Plastic deformation mechanisms – Slip (contd...)

- In a polycrystalline aggregate, individual grains provide a mutual geometrical constraint on one other, and this precludes plastic deformation at low applied stresses.
- Slip in polycrystalline material involves generation, movement and (re-)arrangement of dislocations.
- During deformation, mechanical integrity and coherency are maintained along the grain boundaries.
- A minimum of five independent slip systems must be operative for a polycrystalline solid to exhibit ductility and maintain grain boundary integrity – von Mises.
- On the other hand, crystal deform by twinning.

Slip systems

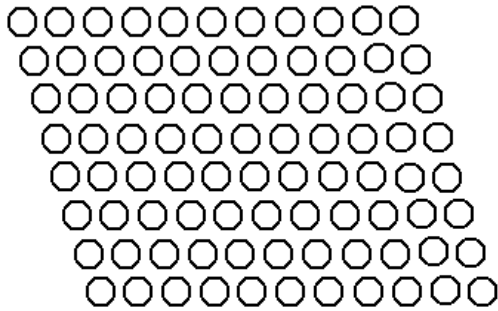
Crystal	Occurrence	Slip planes	Slip directions
FCC		{111}	<110>
BCC	More common Less common	{110} {112},{123}	<111>
HCP	More common Less common	Basal plane Prismatic & Pyramidal planes	Close packed directions
NaCl		{110}	<110>

Plastic deformation mechanisms – Twinning

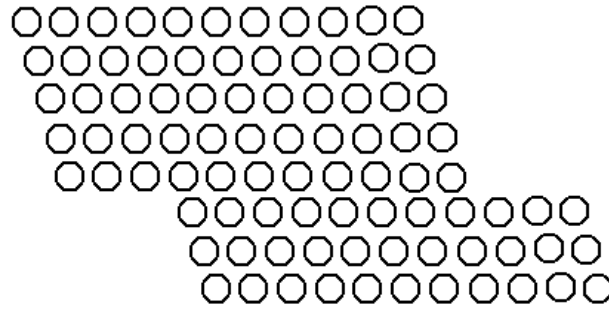
- It results when a portion of crystal takes up an orientation that is related to the orientation of the rest of the untwined lattice in a definite, symmetrical way.
- The important role of twinning in plastic deformation is that it causes changes in plane orientation so that further slip can occur.
- Twinning also occurs in a definite direction on a specific plane for each crystal structure.

Crystal	Example	Twin plane	Twin direction
FCC	Ag, Au, Cu	(111)	[112]
BCC	α -Fe, Ta	(112)	[111]
HCP	Zn, Cd, Mg, Ti	(10 $\bar{1}$ 2)	[$\bar{1}$ 011]

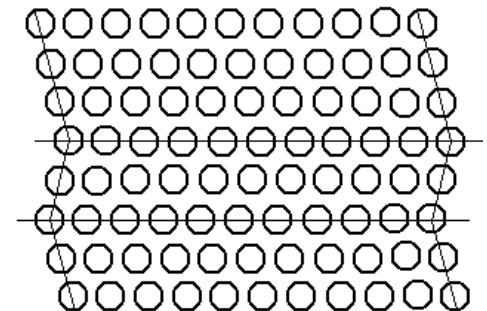
Slip Vs. Twinning



Undeformed Crystal



After Slip



After Twinning

	during/in slip	during/in twinning
Crystal orientation	Same above and below the slip plane	Differ across the twin plane
Size (in terms of inter-atomic distance)	Multiples	Fractions
Occurs on	Widely spread planes	Every plane of region involved
Time required	Milli seconds	Micro seconds
Occurrence	On many slip systems simultaneously	On a particular plane for each crystal

Strengthening mechanisms

- Material can be increased by hindering dislocation, which is responsible for plastic deformation.
- Different ways to hinder dislocation motion / Strengthening mechanisms:

in single-phase materials

- Grain size reduction
- Solid solution strengthening
- Strain hardening

in multi-phase materials

- Precipitation strengthening
- Dispersion strengthening
- Fiber strengthening
- Martensite strengthening

Strengthening by Grain size reduction

- It is based on the fact that dislocations will experience hindrances while trying to move from a grain into the next because of abrupt change in orientation of planes.
- Hindrances can be two types: forcible change of slip direction, and discontinuous slip plane.
- Smaller the grain size, often a dislocation encounters a hindrance. Yield strength of material will be increased.
- Yield strength is related to grain size (diameter, d) as Hall-Petch relation:

$$\sigma_y = \sigma_i + kd^{-1/2}$$

- Grain size can be tailored by controlled cooling or by plastic deformation followed by appropriate heat treatment.

Strengthening by Grain size reduction (contd...)

- Grain size reduction improves not only strength, but also the toughness of many alloys.
- If d is average grain diameter, S_v is grain boundary area per unit volume, N_L is mean number of intercepts of grain boundaries per unit length of test line, N_A is number of grains per unit area on a polished surface:

$$S_v = 2N_L \quad d = \frac{3}{S_v} = \frac{3}{2N_L} \quad d = \sqrt{\frac{6}{\pi N_A}}$$

- Grain size can also be measured by comparing the grains at a fixed magnification with standard grain size charts.
- Other method: Use of ASTM grain size number (Z). It is related to grain diameter, D (in mm) as follows:

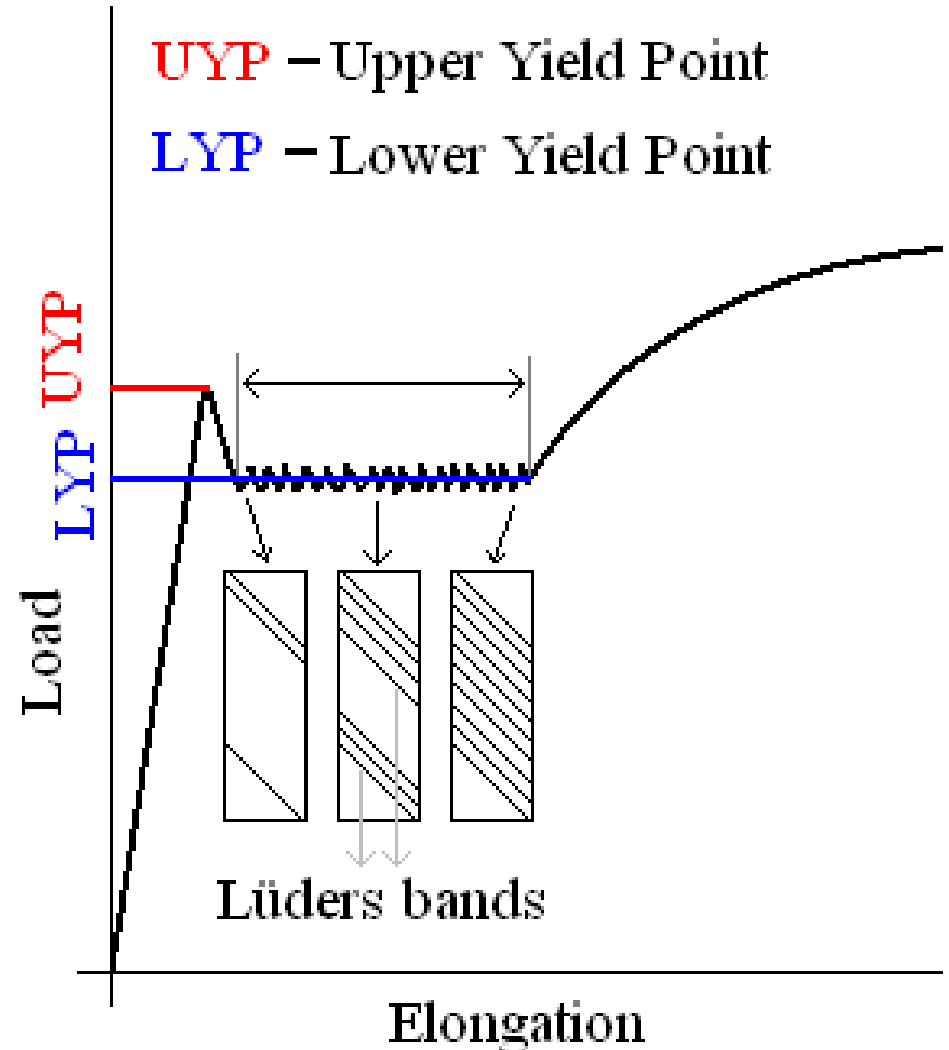
$$D = \frac{1}{100} \sqrt{\frac{645}{2^{G-1}}}$$

Solid solution strengthening

- Impure foreign atoms in a single phase material produces lattice strains which can anchor the dislocations.
- Effectiveness of this strengthening depends on two factors – size difference and volume fraction of solute.
- Solute atoms interact with dislocations in many ways:
 - elastic interaction
 - modulus interaction
 - stacking-fault interaction
 - electrical interaction
 - short-range order interaction
 - long-range order interaction
- Elastic, modulus, and long-range order interactions are of long-range i.e. they are relatively insensitive to temperature and continue to act about $0.6 T_m$.

Yield point phenomenon

- Localized, heterogeneous type of transition from elastic to plastic deformation marked by abrupt elastic-plastic transition – Yield point phenomenon.
- It characterizes that material needs higher stress to initiate plastic flow than to continue it.



Yield point phenomenon (contd...)

- The bands are called Lüders bands / Hartmann lines / stretcher stains, and generally are approximately 45° to the tensile axis.
- Occurrence of yield point is associated with presence of small amounts of interstitial or substitutional impurities. It's been found that either unlocking of dislocations by a high stress for the case of strong pinning or generation of new dislocations are the reasons for yield-point phenomenon.
- Magnitude of yield-point effect will depend on energy of interaction between solute atoms and dislocations and on the concentration of solute atoms at the dislocations.

Strain hardening

- Phenomenon where ductile metals become stronger and harder when they are deformed plastically is called strain hardening *or* work hardening.
- Increasing temperature lowers the rate of strain hardening. Hence materials are strain hardened at low temperatures, thus also called cold working.
- During plastic deformation, dislocation density increases. And thus their interaction with each other resulting in increase in yield stress.
- Dislocation density (ρ) and shear stress (τ) are related as follows:

$$\tau = \tau_0 + A\sqrt{\rho}$$

Strain hardening (contd...)

- During strain hardening, in addition to mechanical properties physical properties also changes:
 - a small decrease in density
 - an appreciable decrease in electrical conductivity
 - small increase in thermal coefficient of expansion
 - increased chemical reactivity (decrease in corrosion resistance).
- Deleterious effects of cold work can be removed by heating the material to suitable temperatures – Annealing. It restores the original properties into material. It consists of three stages – recovery, recrystallization and grain growth.
- In industry, alternate cycles of strain hardening and annealing are used to deform most metals to a very great extent.

Precipitation & Dispersion hardening

- Foreign particles can also obstruct movement of dislocations i.e. increases the strength of the material.
- Foreign particles can be introduced in two ways – precipitation and mixing-and-consolidation technique.
- Precipitation hardening is also called age hardening because strength increases with time.
- Requisite for precipitation hardening is that second phase must be soluble at an elevated temperature but precipitates upon quenching and aging at a lower temperature.

E.g.: Al-alloys, Cu-Be alloys, Mg-Al alloys, Cu-Sn alloys

- If aging occurs at room temperature – Natural aging
- If material need to be heated during aging – Artificial aging.

Precipitation & Dispersion hardening (contd...)

- In dispersion hardening, fine second particles are mixed with matrix powder, consolidated, and pressed in powder metallurgy techniques.
- For dispersion hardening, second phase need to have very low solubility at all temperatures.

E.g.: oxides, carbides, nitrides, borides, etc.

- Dislocation moving through matrix embedded with foreign particles can either cut through the particles *or* bend around and bypass them.
- Cutting of particles is easier for small particles which can be considered as segregated solute atoms. Effective strengthening is achieved in the bending process, when the particles are submicroscopic in size.

Precipitation & Dispersion hardening (contd...)

- Stress (τ) required to bend a dislocation is inversely proportional to the average interspacing (λ) of particles:

$$\tau = Gb/\lambda$$

- Interspacing (λ) of spherical particles: $\lambda = \frac{4(1-f)r}{3f}$
where r - particle radius, f - volume fraction

- Optimum strengthening occurs during aging once the right interspacing of particles is achieved.
 - Smaller the particles, dislocations can cut through them at lower stresses
 - larger the particles they will be distributed at wider distances.

Fiber strengthening

- Second phase can be introduced into matrix in fiber form too.
- Requisite for fiber strengthening:
 - Fiber material – high strength and high modulus
 - Matrix material – ductile and non-reactive with fiber material
 - E.g.: fiber material – Al_2O_3 , boron, graphite, metal, glass, etc.
 - matrix material – metals, polymers
- Mechanism of strengthening is different from other methods.
- Higher modulus fibers carry load, ductile matrix distributes load to fibers. Interface between matrix and fibers thus plays an important role.
- Strengthening analysis involves application of continuum, not dislocation concepts as in other methods of strengthening.

Fiber strengthening (contd...)

- To achieve any benefit from presence of fibers, critical fiber volume which must be exceeded for fiber strengthening to occur:

$$f_{critical} = \frac{\sigma_{mu} - \sigma'_m}{\sigma_{fu} - \sigma'_m}$$

where σ_{mu} – strength of strain hardened matrix, σ'_m – flow stress of matrix at a strain equal to fiber breaking stress, σ_{fu} – ultimate tensile strength of the fiber.

- Minimum volume fraction of fiber which must be exceeded to have real reinforcement:

$$f_{min} = \frac{\sigma_{mu} - \sigma'_m}{\sigma_{fu} + \sigma_{mu} - \sigma'_m}$$

Martensite strengthening

- This strengthening method is based on formation of martensitic phase from the retained high temperature phase at temperatures lower than the equilibrium invariant transformation temperature.
- Martensite forms as a result of shearing of lattices.
- Martensite platelets assume characteristic lenticular shape that minimizes the elastic distortion in the matrix. These platelets divide and subdivide the grains of the parent phase. Always touching but never crossing one another.
- Martensite platelets grow at very high speeds (1/3rd of sound speed) i.e. activation energy for growth is less. Thus volume fraction of martensite that exists is controlled by its nucleation rate.

Martensite strengthening (contd...)

- Martensite platelets attain their shape by two successive shear displacements - *first* displacement is a homogeneous shear throughout the plate which occurs parallel to a specific plane in the parent phase known as the habit plane, *second* displacement, the lesser of the two, can take place by one of two mechanisms: slip as in Fe-C Martensite or twinning as in Fe-Ni Martensite.
- Martensite formation occurs in many systems.
E.g.: Fe-C, Fe-Ni, Fe-Ni-C, Cu-Zn, Au-Cd, and even in pure metals like Li, Zr and Co. However, only the alloys based on Fe and C show a pronounced strengthening effect.
- High strength of Martensite is attributed to its characteristic twin structure and to high dislocation density. In Fe-C system, carbon atoms are also involved in strengthening.

Recovery

- Annealing relieves the stresses from cold working – three stages: recovery, recrystallization and grain growth.
- Recovery involves annihilation of point defects.
- Driving force for recovery is decrease in stored energy from cold work.
- During recovery, physical properties of the cold-worked material are restored without any observable change in microstructure.
- Recovery is first stage of annealing which takes place at low temperatures of annealing.
- There is some reduction, though not substantial, in dislocation density as well apart from formation of dislocation configurations with low strain energies.

Recrystallization

- This follows recovery during annealing of cold worked material. Driving force is stored energy during cold work.
- It involves replacement of cold-worked structure by a new set of strain-free, approximately equi-axed grains to replace all the deformed crystals.
- This process is characterized by recrystallization temperature which is defined as the temperature at which 50% of material recrystallizes in one hour time.
- The recrystallization temperature is strongly dependent on the purity of a material.
- Pure materials may recrystallizes around $0.3 T_m$, while impure materials may recrystallizes around $0.5-0.7 T_m$, where T_m is absolute melting temperature of the material.

Recrystallization laws

- A minimum amount of deformation is needed to cause recrystallization (R_x).
- Smaller the degree of deformation, higher will be the R_x temperature.
- The finer is the initial grain size; lower will be the R_x temperature.
- The larger the initial grain size, the greater degree of deformation is required to produce an equivalent R_x temperature.
- Greater the degree of deformation and lower the annealing temperature, the smaller will be the recrystallized grain size.
- The higher is the temperature of cold working, the less is the strain energy stored and thus R_x temperature is correspondingly higher.
- The R_x rate increases exponentially with temperature.

Grain growth

- Grain growth follows complete crystallization if the material is left at elevated temperatures.
- Grain growth does not need to be preceded by recovery and recrystallization; it may occur in all polycrystalline materials.
- In contrary to recovery and recrystallization, driving force for this process is reduction in grain boundary energy.
- Tendency for larger grains to grow at the expense of smaller grains is based on physics.
- In practical applications, grain growth is not desirable.
- Incorporation of impurity atoms and insoluble second phase particles are effective in retarding grain growth.
- Grain growth is very strongly dependent on temperature.