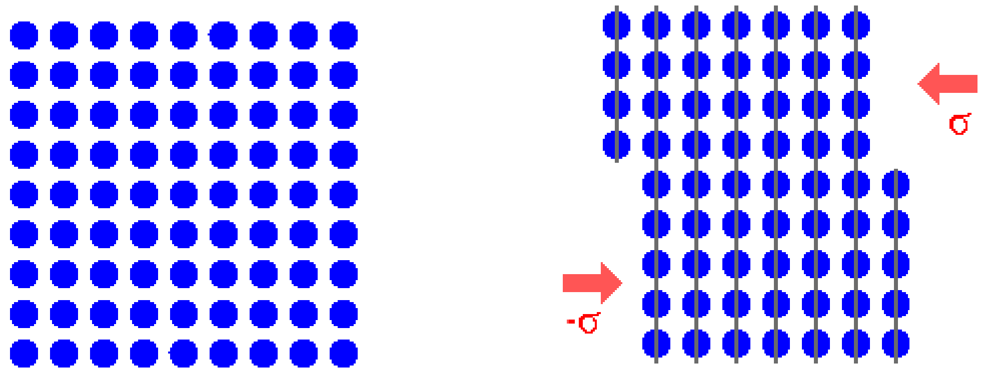
Dislocations and Strengthening Mechanisms

Introduction:

- Why metals could be plastically deformed?
- Why the plastic deformation properties could be changed to a very large degree by forging without changing the chemical composition?
- Why plastic deformation occurs at stresses that are much smaller than the theoretical strength of perfect crystals?



Plastic deformation – the force to break all bonds in the slip plane is much higher than the force needed to cause the deformation. Why?

These questions can be answered based on the idea proposed in 1934 by Taylor, Orowan and Polyani:

Plastic deformation is due to the motion of a large number of dislocations.

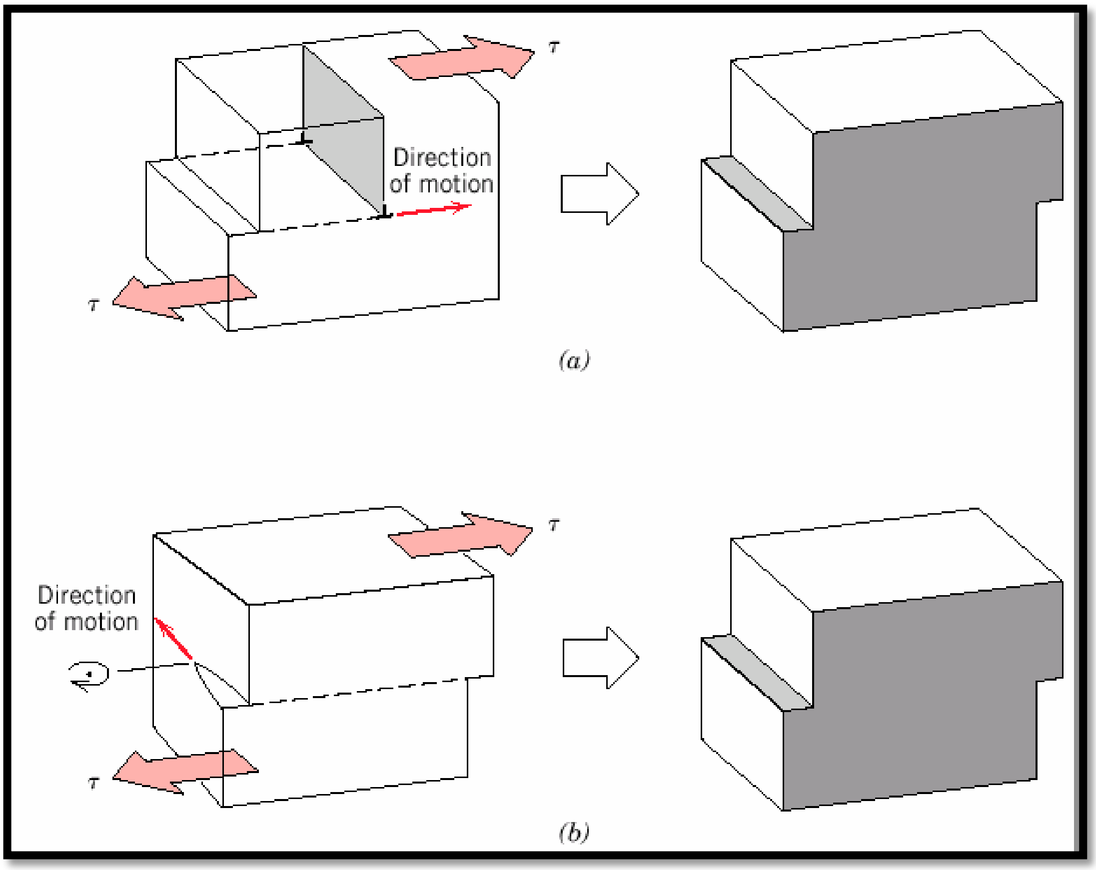
Dislocations allow deformation at much lower stress

than in a perfect crystal:

- If the top half of the crystal is slipping one plane at a time then only a small fraction of the bonds are broken at any given time and this would require a much smaller force.
- The propagation of one dislocation across the plane causes the top half of the crystal to move (**to slip**) with respect to the bottom half but we do not have to break all the bonds across the middle plane simultaneously (which would require a very large force).

The slip plane – the crystallographic plane of dislocation motion.

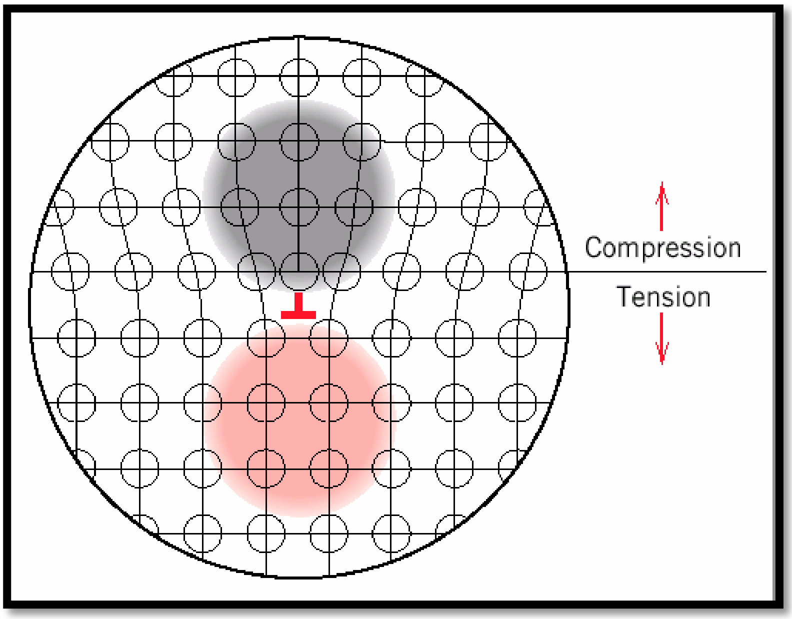
Direction of the dislocation motion



A: **Edge dislocation line moves parallel to applied stress**
B: **Screw dislocation line moves perpendicular to applied stress**

For mixed dislocations, direction of motion is in between parallel and perpendicular to the applied shear stress

Strain field around dislocations



- **Dislocations have strain fields arising from distortions at their cores - strain drops radially with distance from the dislocation core**.
- **Edge dislocations introduce compressive, tensile, and shear lattice strains, screw dislocations introduce shear strain only.**

- **dislocation density** - the total dislocation length per unit volume or the number of dislocations intersecting a unit area.
- Dislocation densities can vary from 10^5 cm^{-2} in carefully grown metal crystals to 10^{12} cm^{-2} in heavily deformed metals.
- The number of dislocations increases dramatically during plastic deformation.

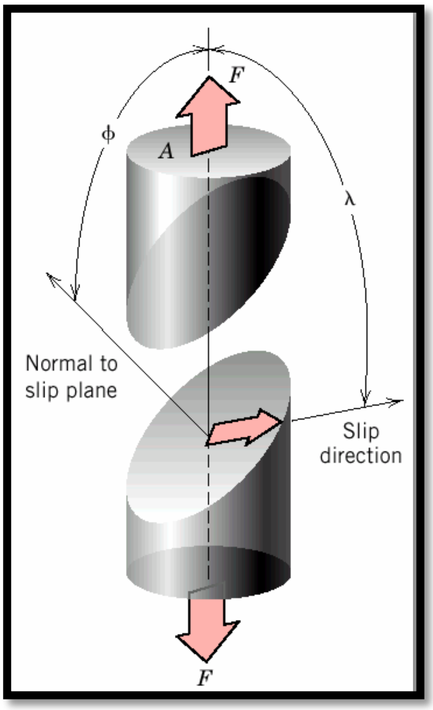
Slip Systems

- In single crystals there are preferred planes where dislocations move (**slip planes**).
- Within the slip planes there are preferred crystallographic directions for dislocation movement (**slip directions**).
- The set of slip planes and directions constitute **slip systems**.
- **The slip planes and directions are those of highest packing density.**

- Since the distance between atoms is shorter than the average, the distance perpendicular to the plane has to be longer than average.
- Being relatively far apart, the planes can slip more easily relatively to each other.
- BCC and FCC crystals have more slip systems as compared to HCP, there are more ways for dislocation to propagate ⇒ FCC and BCC crystals are more ductile than HCP crystals.

Slip in single crystals

Dislocations move in particular directions on particular planes (the slip system) in response to shear stresses applied along these planes and directions ⇒ we need to determine how the applied stress is **resolved** onto the slip systems.



Resolved shear stress, τ_R, (which produces plastic deformation) that result from application of a simple tensile stress, σ .

$$\tau = \sigma \cos\phi \cos\lambda$$

- When the resolved shear stress becomes sufficiently large, the crystal will start to yield (dislocations start to move along the most favorably oriented slip system).
- The onset of yielding corresponds to the yield stress, σ_y .
- The minimum shear stress required to initiate slip is termed the critical resolved shear stress:

$$\tau_{CRSS} = \sigma_y (\cos\phi \cos\lambda)_{MAX}$$

$$\sigma_y = \frac{\tau_{CRSS}}{(\cos\phi \cos\lambda)_{MAX}}$$

- Maximum value of ($\cos\phi \cos\lambda$) corresponds to $\phi = \lambda = 45^o \Rightarrow \cos\phi \cos\lambda = 0.5 \Rightarrow \sigma_y = 2\tau_{CRSS}$
- Slip will occur first in slip systems oriented close to these angles ($\phi = \lambda = 45^o$) with respect to the applied stress

Plastic deformation of polycrystalline materials

□ Slip directions vary from crystal to crystal ⇒ Some grains are unfavorably oriented with respect to the applied stress (i.e. $\cos\phi \cos\lambda$ low)

□ Even those grains for which $\cos\phi \cos\lambda$ is high may be limited in deformation by adjacent grains which cannot deform so easily

□ Dislocations cannot easily cross grain boundaries because of changes in direction of slip plane and atomic disorder at grain boundaries

- As a result, polycrystalline metals are stronger than single crystals (the exception is the perfect single crystal without any defects, as in whiskers)