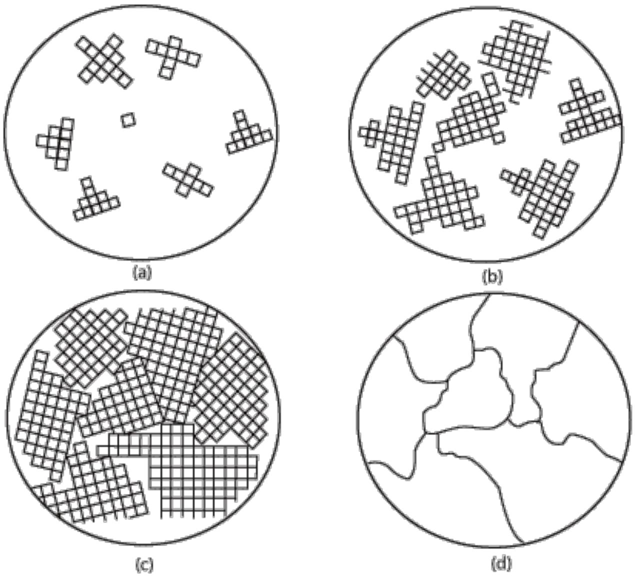
Properties of Materials: Plasticity

1. Crystalline materials.



Most engineering metals are poly crystalline material. Process (a)-(d) shows the metal solidification. (a) is nucleation of crystallites; (b) is crystal growth; (c) the irregular grains form as crystals grow together; (d) different grains touch each other to form grain boundaries. Mark grain and grain boundaries in (d). In one metal material, each grain has the same atom packing but with different orientations.

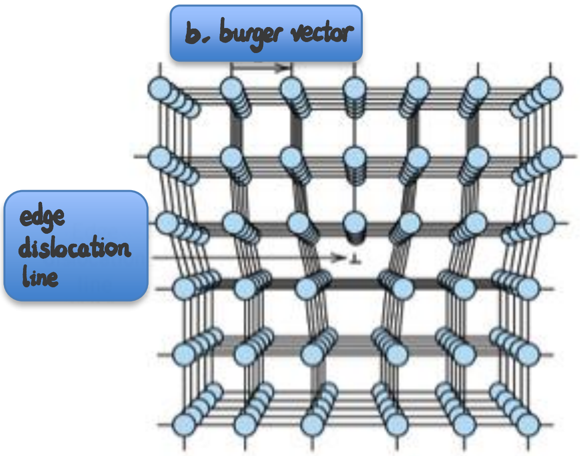
2. Plastic deformation and dislocation.

In reality when crystalline materials plastically deform, the bonds on the atom plane do not break altogether at the same time to shear, which requires a very **low/high** shear stress. Instead, dislocations act as the carrier of plastic deformation.

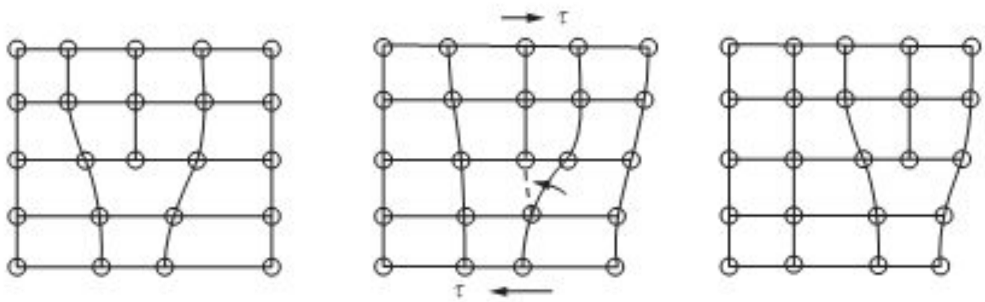
There are two different extremes of dislocations: edge dislocation (symbol: ⊥) and screw dislocation (symbol: s). An edge dislocation has its Burgers vector perpendicular to the dislocation line. Edge dislocations are easiest to visualise as an extra half-plane of atoms inserted into the crystal. A screw dislocation is more complex - the Burgers vector is parallel to the dislocation line.

Materials are full of defects. For edge dislocation (figure below), the block contains an extra half-plane of atoms with its lower edge lying along the line ⊥ - ⊥. This line is called the __edge dislocation line__. The burgers vector is the __slip__ step that this dislocation will create as it moves through a crystal lattice.

Mark the Burgers vector, edge dislocation line and the extra half plane associated with the edge dislocation in the figure below:



Dislocations move in response to an external stress. As soon as a __critical__ shear stress is reached, the dislocation starts moving and deformation is no longer __elastic__ but __plastic__, because the dislocation **will**/**will not** move back when the stress is removed. Dislocation motion is analogous to the caterpillar movement model. The caterpillar forms a hump with its position and movement corresponding to those of __extra half-plane__ (bonds break __sequentially__) in the dislocation model.



3. Dislocation motion and classes of materials

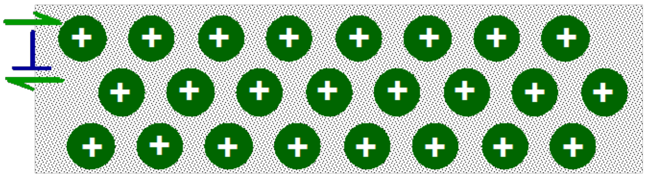
Metals: dislocation motion **easy/hard**

- **directional/non-directional bond**;

- close-packed directions for slip

Therefore, **soft (relatively to ceramics)/hard**, **ductile/brittle**.

Typical materials: Al, Ag, Cu.

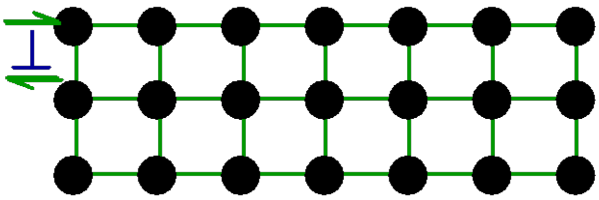


Covalent ceramic: dislocation motion **easy/hard**

- **directional/non directional bond**
- almost no dislocation motion

Therefore, **soft/hard** **ductile/brittle**

Typical materials: diamond, Si.

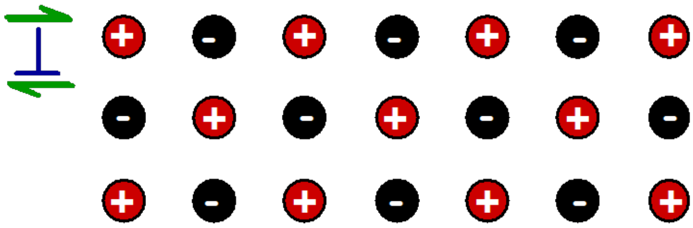


Ionic ceramic: dislocation motion **easy/hard**

- **directional/non-directional** but need to avoid ++ and – - neighbours.

Therefore, **soft/hard** **ductile/brittle (under tension)**.

Typical materials: MgCl, SiC.



4. Definitions for slip systems.

Slip plane- crystallographic plane on which the dislocation moves

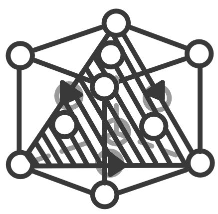
Slip direction – crystallographic direction in the slip plane along which the dislocation moves

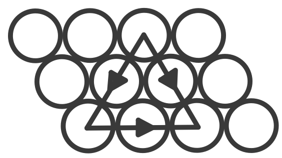
Slip system – slip plane + slip direction (the direction MUST lie in the plane)

Slip step – the atomic displacement left in the crystal by the dislocation.

5. Slip systems for different crystal packing

FCC close packed planes {1 1 1} and close packed directions <1 1 0>. Mark one plane and one direction in an FCC unit cell.





Compare the ductility of Cu (fcc), α-Fe (bcc) and Mg (hcp) at room temperature.

Cu > α-Fe > Mg

--- Cu: fcc structure with {111} packed planes and <110> packed directions. 12 slip systems at room temperature.

--- α-Fe : bcc structure with only closed packed directions. **Few/Many** slip systems but hard to activate (bonds more directional).

--- Mg: hcp stucture with closed packed planes and closed packed directions. Very few slip systems which are partly only activated at elevated temperatures.

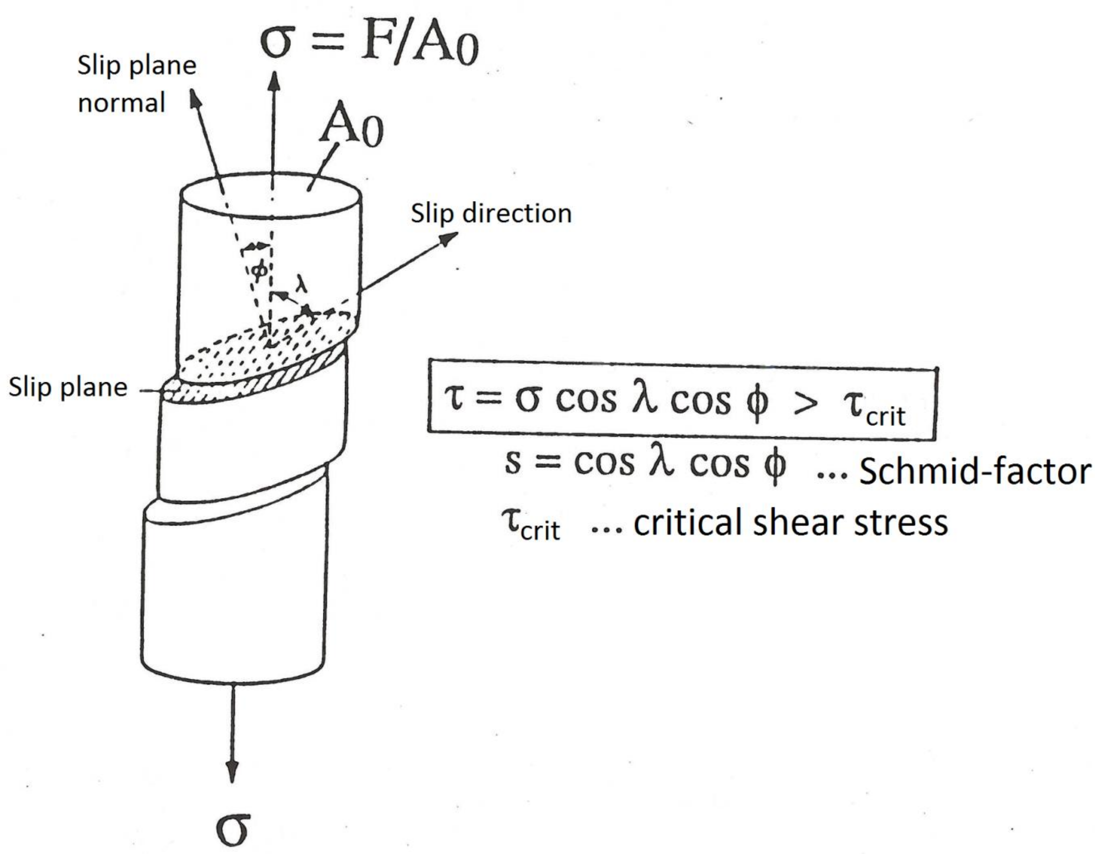
6. Schmid factor (for single crystals)

Schmidt factor is used to decide which slip systems will be active in single crystal materials under certain stress.

a. For τ of any slip systems > τ_{crit}, the slip system(s) will be active.

b. For the biggest absolute value of Schmid factor, the slip system(s) will be active first.

See more examples in the tutorial questions.



Taylor factor is used for polycrystals to account for their higher strength.

7. Strengthening mechanisms.

- **Solid solution strengthening -** introduction of solute atoms into matrix to form alloy with host elements

Tow types of solid solution strengthening:

- Substitutional solid solution in which the added atoms have similar size as the host atoms and replace the host atom positions in the material, e.g. Al in Ti;

- Interstitial solid solution in which much smaller atoms are added to the host atoms and fit into a gap between the host atoms. e.g. oxygen in Ti.

Dislocation motion is hindered by the interaction of the stress - strain field of the dislocations with the respective distortions caused by the solute atoms.

Fill in the different solid solution in the big figure below. Mark the dislocation stress-strain field in the insert figure, which side is compressive field and which side is tensile field.

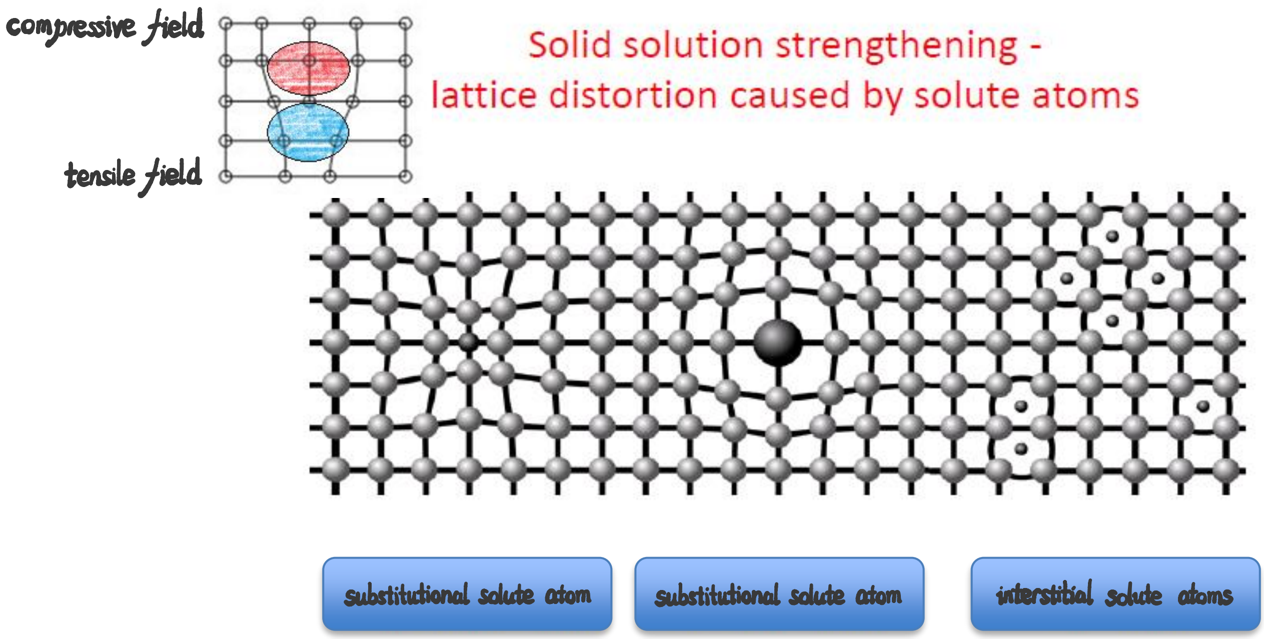


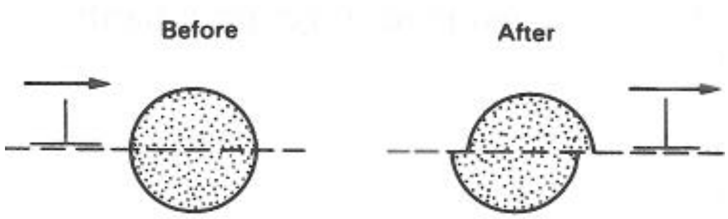
Image courtesy ESA IMPRESS

Strength vs. ductility: As a general rule, in the same alloy system, increasing the strength, by whatever means, will decrease the ductility. (With one exception---grain refinement!)

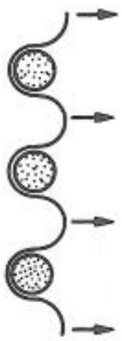
- **Precipitation strengthening**- formation or introduction of particles (second phase precipitates) into the metal matrix and the dislocation will interact with them.

Two different kinds of interaction:

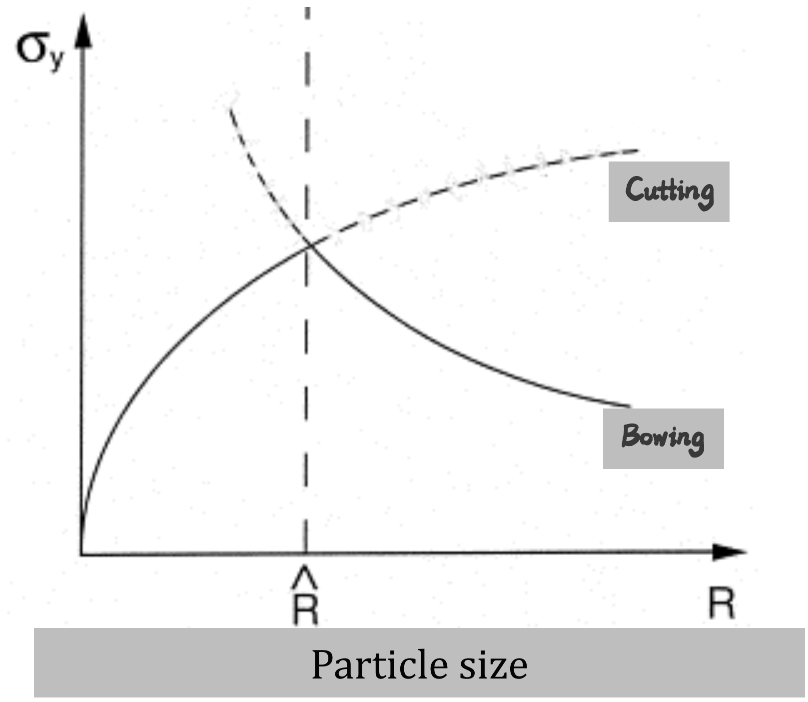
- Cutting: Large shear stress required to move a dislocation through a hard precipitate. Numerous, closely - spaced, $\boxed{\textbf{small}}$/**large** particles must be cut by dislocations (boundary type!).



- Bowing: Precipitates 'pin' dislocations and the shear stress required to move the dislocation increases. Fewer, wider-spaced, **small**/$\boxed{\textbf{large}}$ particles can be bowed-around by dislocations.

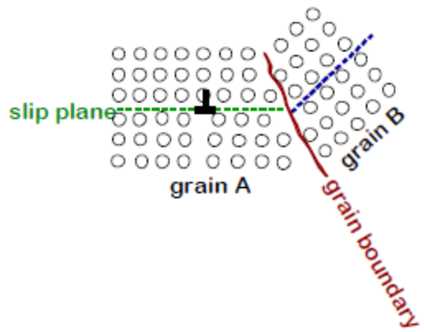


To sum up, $\boxed{\textbf{smaller}}$/**bigger**, more $\boxed{\textbf{closely-spaced}}$/**widely spaced** particles are easier to cut; and **smaller**/$\boxed{\textbf{bigger}}$ more **closely-spaced**/$\boxed{\textbf{widely spaced}}$ particles are easier to bow around, which would give an optimised particle size for Precipitation strengthening. Mark the curve for cutting and bowing.



- **Grain size strengthening**: reduction of grain size and related increase of grain boundary area will increase the material strength.

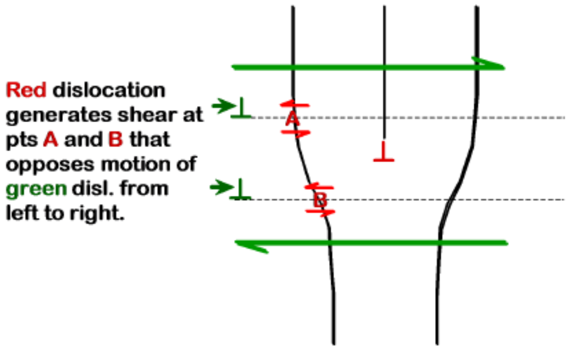
  Grain boundaries are barriers to slip. At grain boundaries, dislocations have to change direction; grain boundaries are regions of disordered leading to discontinuity in slip planes.



Hall-petch equation indicates the strength is inversely proportional to the inverse square root of grain size.

$$\boxed{\sigma_{yield} = \sigma_0 + k_y d^{-1/2}}$$

- **Work hardening**: cold work increases dislocation density interacting with each other. Dislocations generate stress which hinders other dislocations.



Common forming operations change the cross sectional area, such as rolling, forging, drawing and extrusion.

The amount of cold work usually expressed in terms of change in cross section area. Write the equation below:

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

Impact of cold work: As cold work percentage increases, yield strength increases, tensile strength increases, ductility decreases.

Heat treatment can be used to improve the ductility of the materials afterwards, but meanwhile, the strength will be decreased. More details will be taught in the second year.