

PY2N20

**Material Properties and
Phase Diagrams**

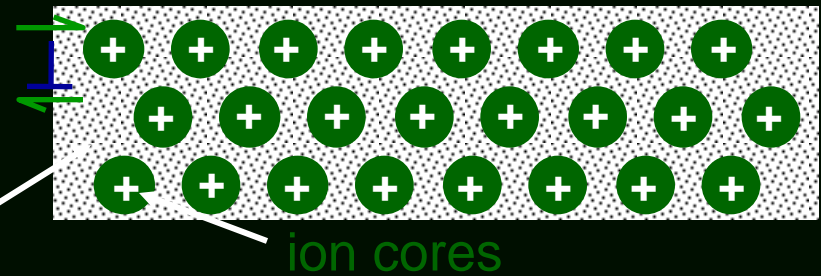
Lecture 3

P. Stamenov, PhD

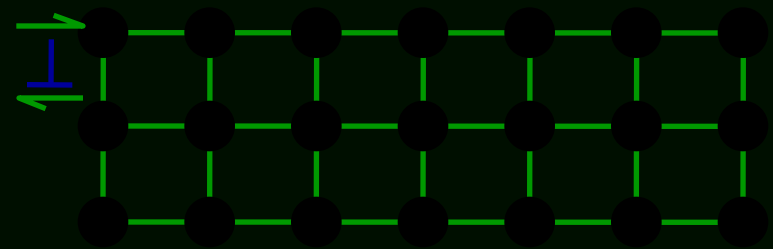
School of Physics, TCD

Dislocations & Materials Classes

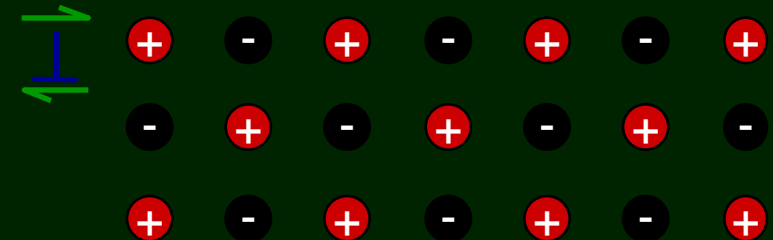
- Metals: Disl. motion easier.
 - non-directional bonding
 - close-packed directionsfor slip.
electron cloud



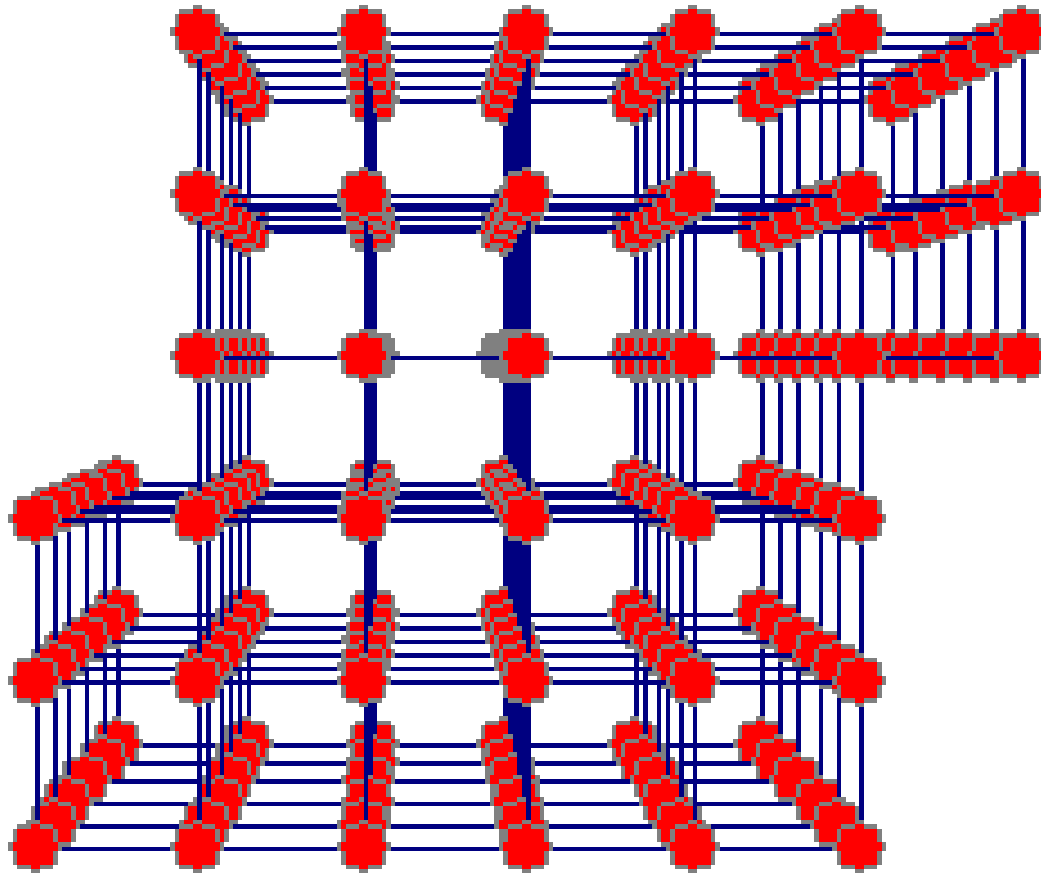
- Covalent Ceramics (Si, diamond): Motion hard.
 - directional (angular) bonding



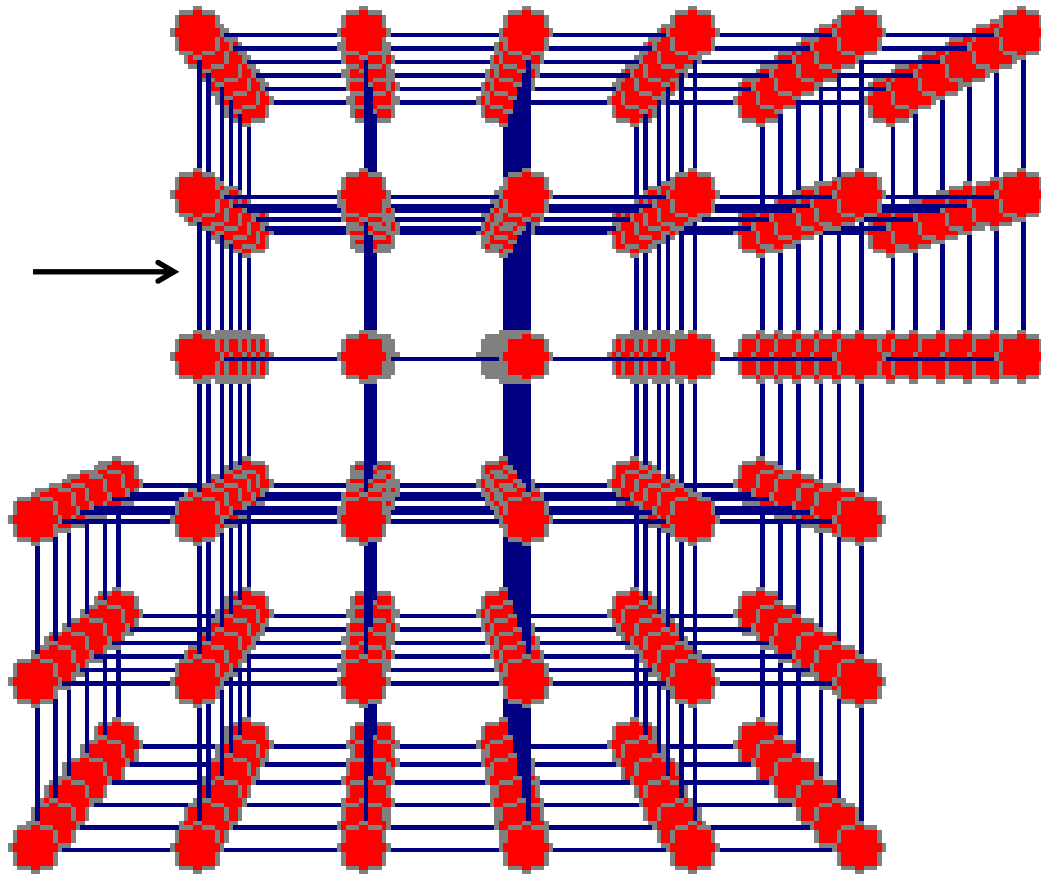
- Ionic Ceramics (NaCl): Motion hard.
 - need to avoid ++ and -- neighbors.



Edge Dislocation Motion



'Slip' – in the direction of the Burgers vector



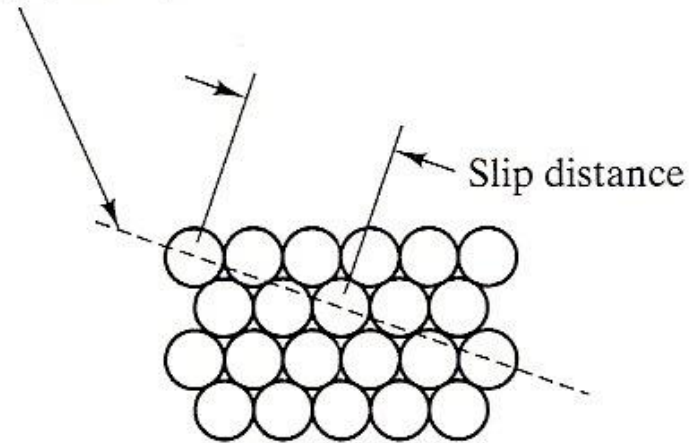
Slip System

- For movement of dislocations there is
 - Preferred plane
 - Plane with highest packing density
 - Preferred direction
 - Direction with highest linear packing density

Slip plane + slip direction = slip system

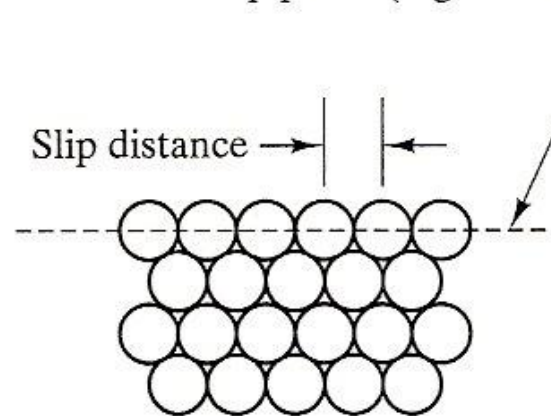
Slip Distance and Atomic Density

Slip plane (low atomic density)



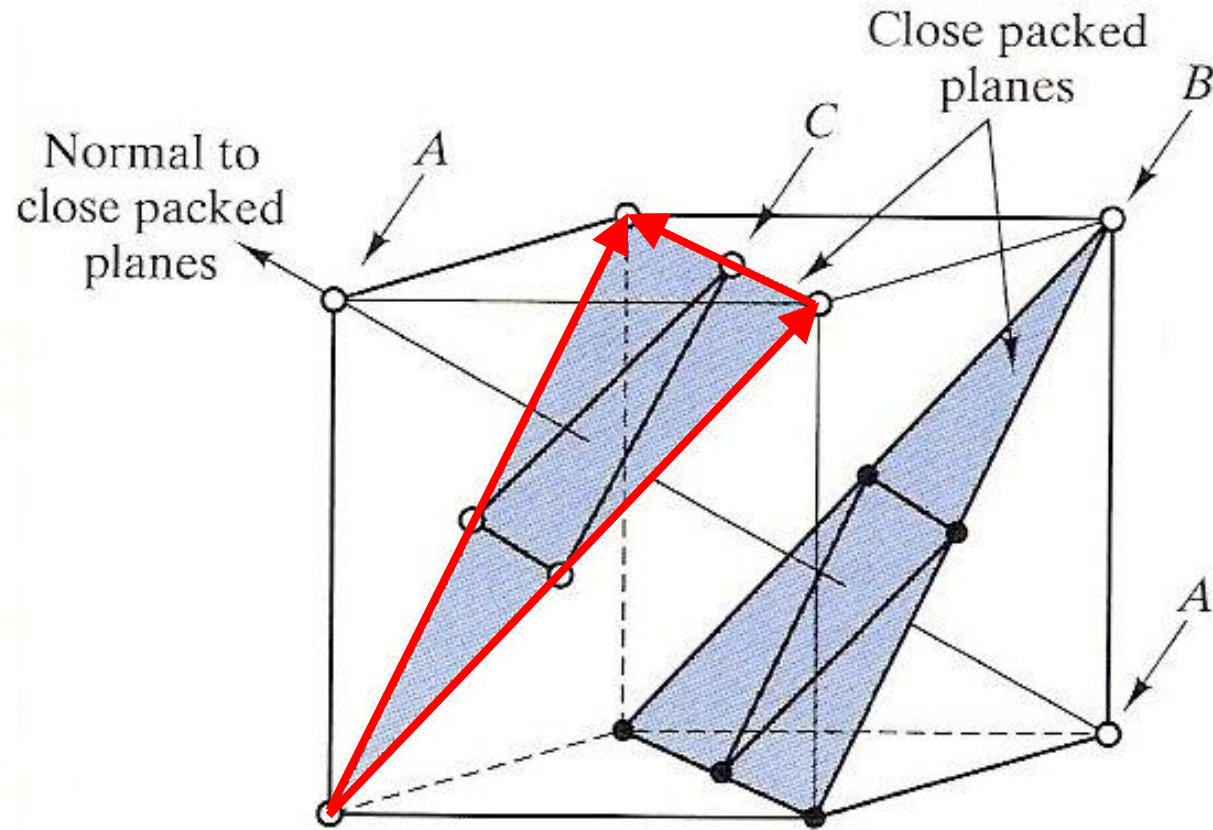
(a)

Slip plane (high atomic density)



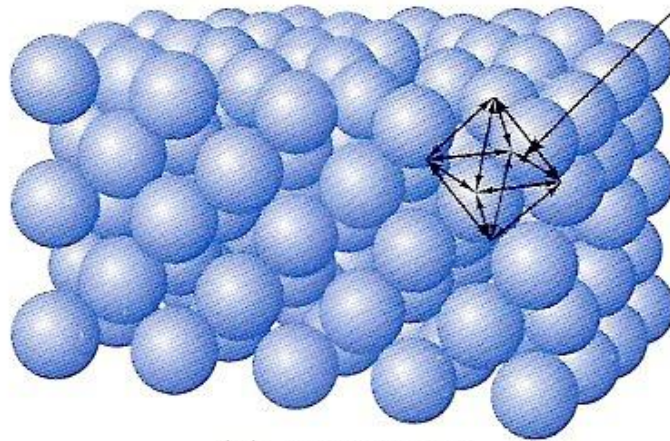
(b)

Slip Systems in FCC



(c) Face-centered cubic

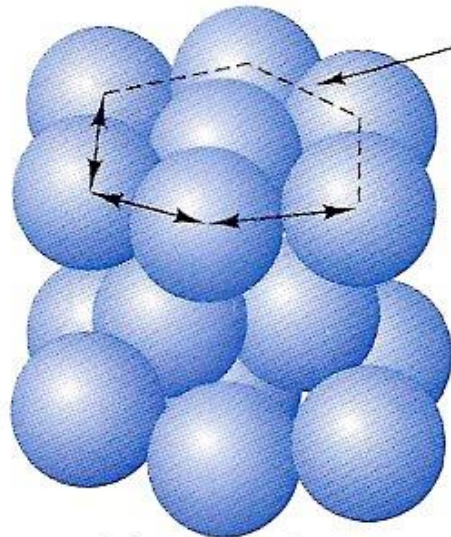
Slip planes in FCC and HCP



(a) Aluminum

$$\{111\}\langle 1\bar{1}0\rangle =$$

$(111)[1\bar{1}0]$	$(111)[\bar{1}01]$	$(111)[01\bar{1}]$
$(11\bar{1})[1\bar{1}0]$	$(11\bar{1})[101]$	$(11\bar{1})[011]$
$(1\bar{1}1)[110]$	$(1\bar{1}1)[10\bar{1}]$	$(1\bar{1}1)[011]$
$(\bar{1}11)[110]$	$(\bar{1}11)[101]$	$(\bar{1}11)[01\bar{1}]$



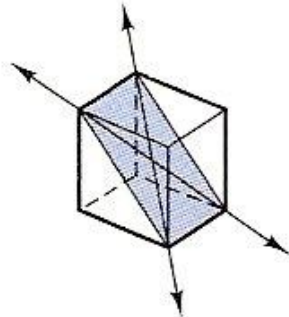
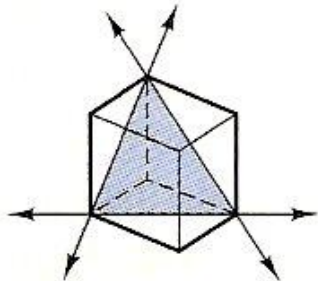
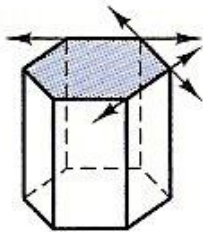
(b) Magnesium

$$(0001)\langle 11\bar{2}0\rangle =$$

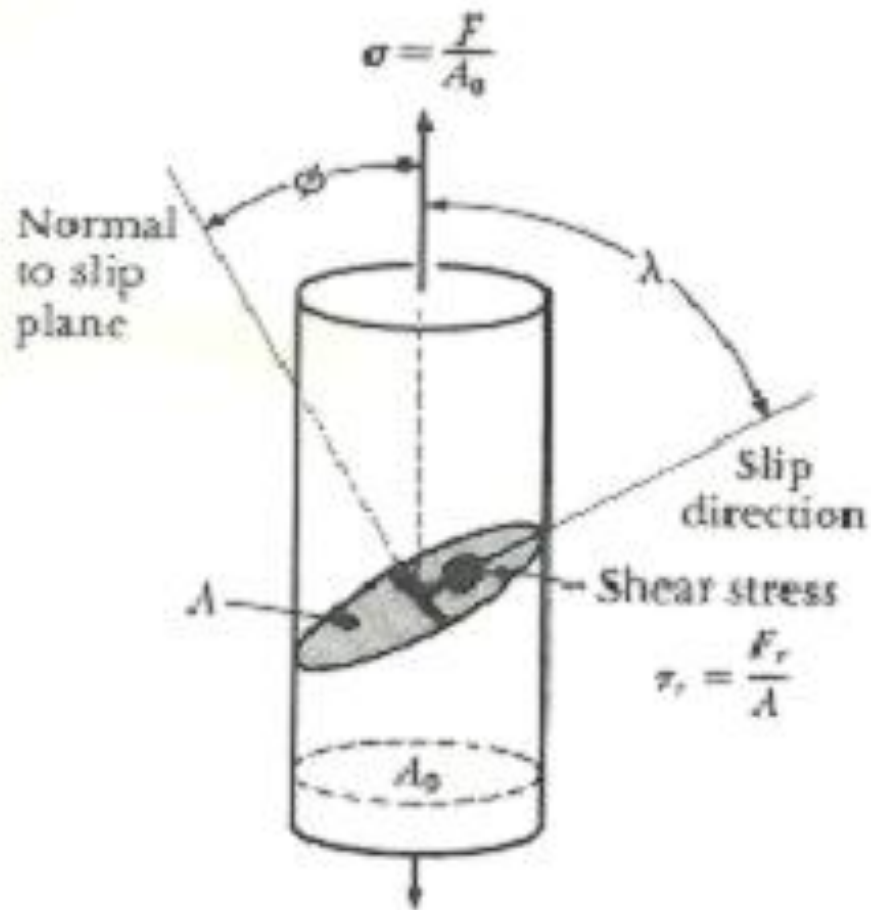
$(0001)[11\bar{2}0]$	$(0001)[1\bar{2}10]$	$(0001)[\bar{2}110]$
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Major Slip Systems

Table 6.9 Major Slip Systems in the Common Metal Structures

Crystal structure	Slip plane	Slip direction	Number of slip systems	Unit-cell geometry	Examples
bcc	{110}	$\langle \bar{1}11 \rangle$	$6 \times 2 = 12$		α -Fe, Mo, W
fcc	{111}	$\langle \bar{1}\bar{1}0 \rangle$	$4 \times 3 = 12$		Al, Cu, γ -Fe, Ni
hcp	(0001)	$\langle 11\bar{2}0 \rangle$	$1 \times 3 = 3$		Cd, Mg, α -Ti, Zn

Resolved Sheer Stress



crystal

Schmid's Equation for the resolved shear stress (τ_r)

$$\tau_r = \frac{F_r}{A}$$

where

$$F_r = F \cos \lambda$$

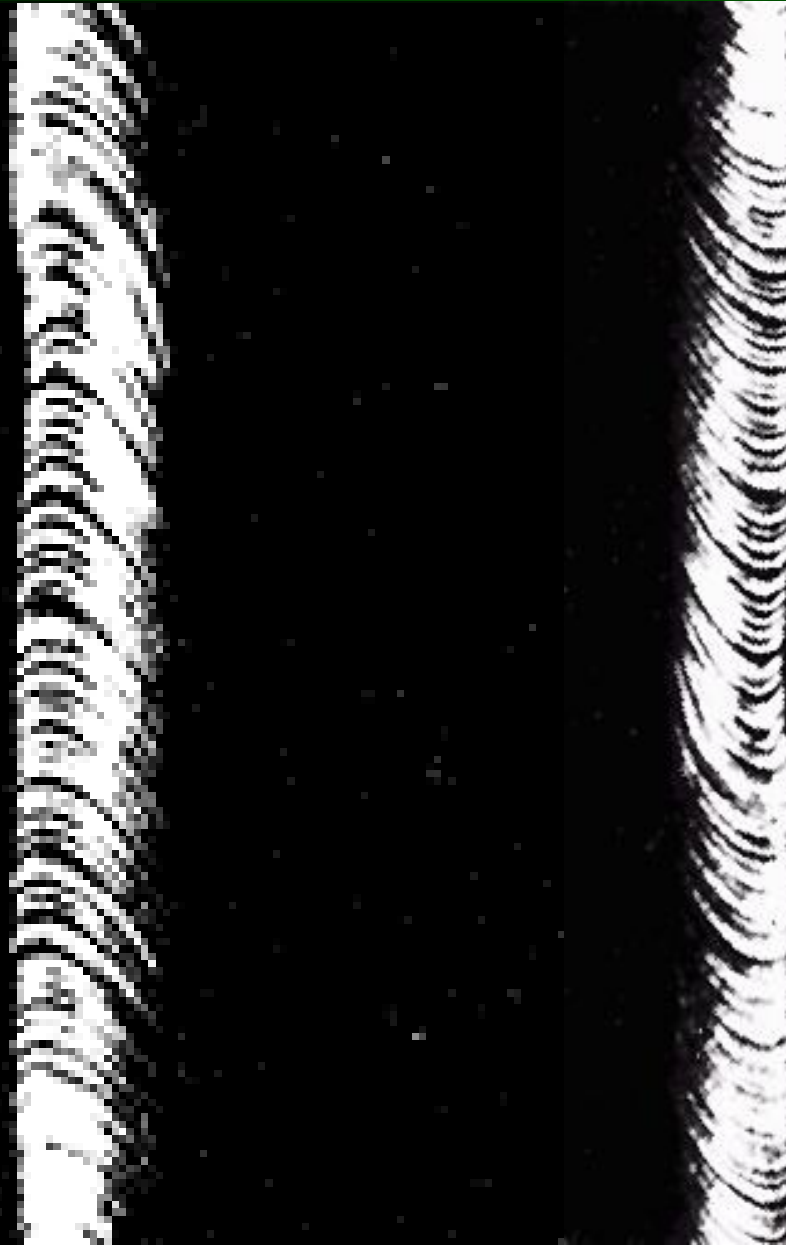
$$\sigma = \frac{F}{A_o}$$

$$A = \frac{A_o}{\cos \phi}$$

gives

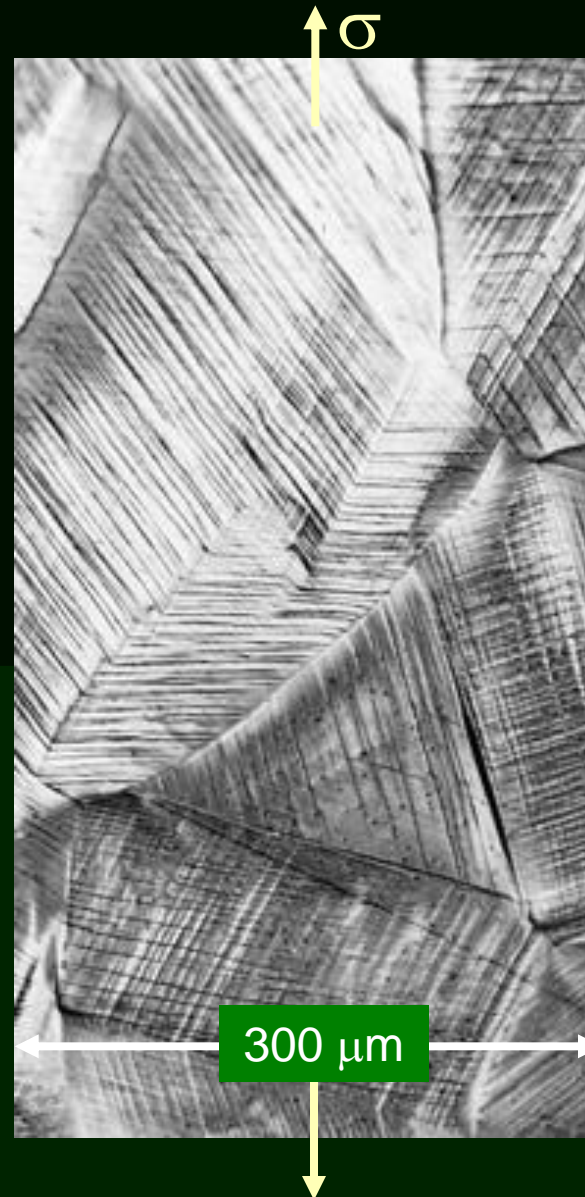
$$\tau_r = \sigma \cos \phi \cos \lambda$$

Slip in a Zinc single crystal



Slip Motion in Polycrystals

- Stronger - grain boundaries pin deformations
- Slip planes & directions (λ , ϕ) change from one crystal to another.
- τ_R will vary from one crystallite to another.
- The crystallite with the largest τ_R yields first.
- Other (less favorably oriented) crystals yield later.

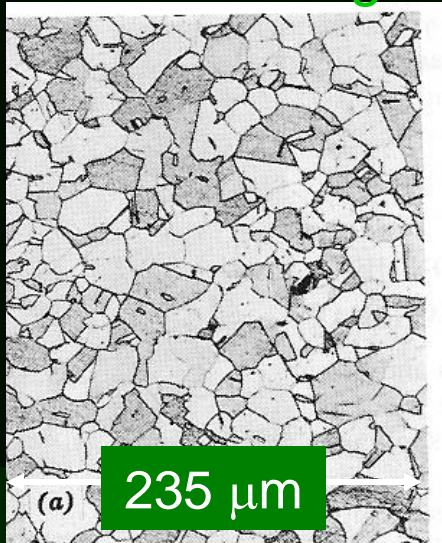


Adapted from Fig. 7.10, *Callister 7e*.
(Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

Anisotropy in σ_y

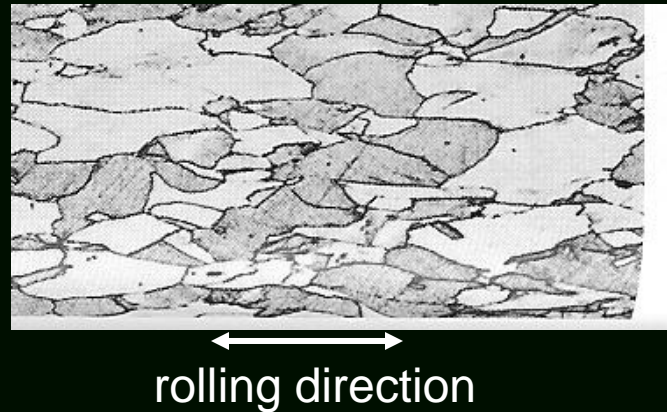
- Can be induced by rolling a polycrystalline metal

- before rolling



- isotropic
since grains are
approx. spherical
& randomly
oriented.

- after rolling



- anisotropic
since rolling affects grain
orientation and shape.

Adapted from Fig. 7.11,
Callister 7e. (Fig. 7.11 is from
W.G. Moffatt, G.W. Pearsall,
and J. Wulff, *The Structure
and Properties of Materials*,
Vol. I, *Structure*, p. 140, John
Wiley and Sons, New York,
1964.)

Generation of line defects

- Dislocations are often formed by the agglomeration of points defects which reduces the energy of the system.
- Point defects can be generated by stresses during processing.
 - For example, a large temperature gradient in a sample can create thermoplastic stress.
 - In a sample composed of different materials with different coefficients of expansion.
 - In a material where one or more of the constituents are volatile.

Generation of line defects

- Large concentrations of substitutional impurities can also create stress as the atoms are different sizes to the host atom.
 - The effect of the stress is to reduce the energy required to break bonds and form vacancies.
- Ion implantation will also create vacancies and defects which can coalesce to form extended defects or even amorphous layers.
- Other types of radiation damage.

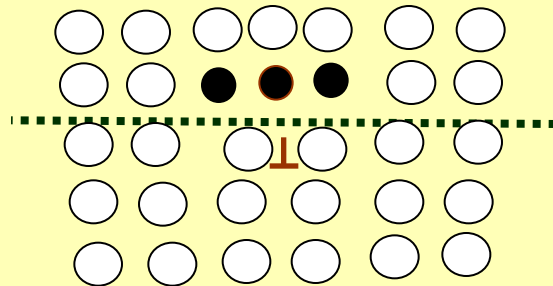
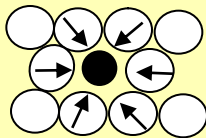
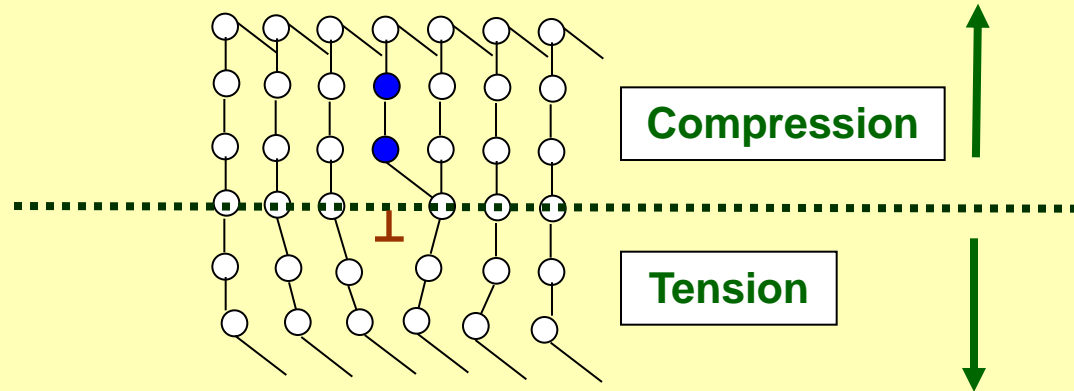
Significance of Dislocations

- In metals slip explains why the strength of metals is much lower than the value predicted from the metallic bond.
- Deform a bar by causing slip
 - Only a fraction of the metallic bonds need to be broken at any one time.
- In addition slip provides ductility.
 - If no dislocations were present, for example an iron bar would be brittle, especially when 'tortured in the wrong direction' and metals could not be worked into various shapes.
 - Ultimate resilience and strength is still found in single crystals – jet turbine blades are nowadays essentially single crystalline.

Solid Solution Strengthening

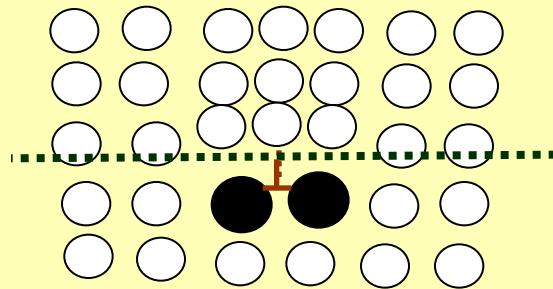
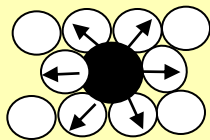
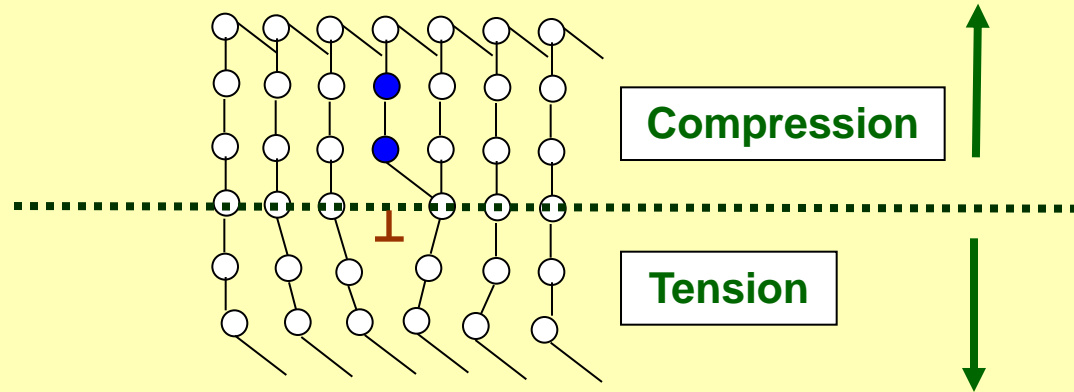
- Alloys are stronger
 - The lattice strain field allows for interactions between the dislocations and the impurity atoms.
 - The solute atoms tend to segregate around the dislocations to reduce the overall strain energy.
 - Thus the applied stress must be greater to initiate and move the dislocation.
 - Can be governed by both size and electron affinity of the solute atoms.

Solid Solution Strengthening



Partial cancellation
of dislocation lattice
strain distribution by
the impurities.

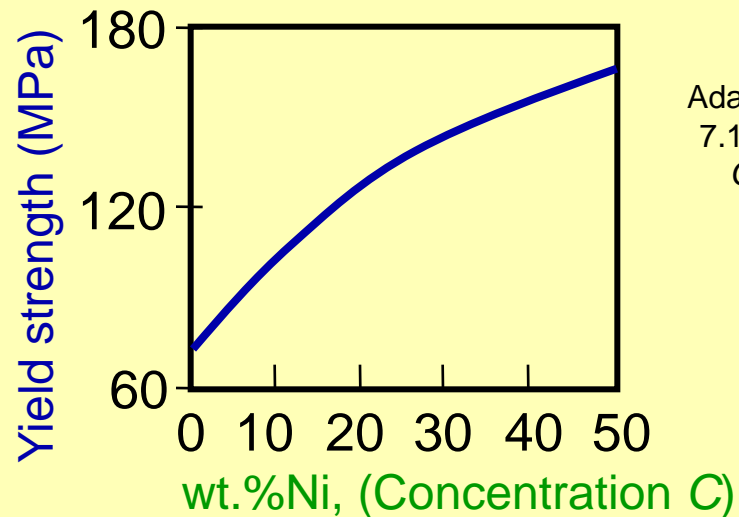
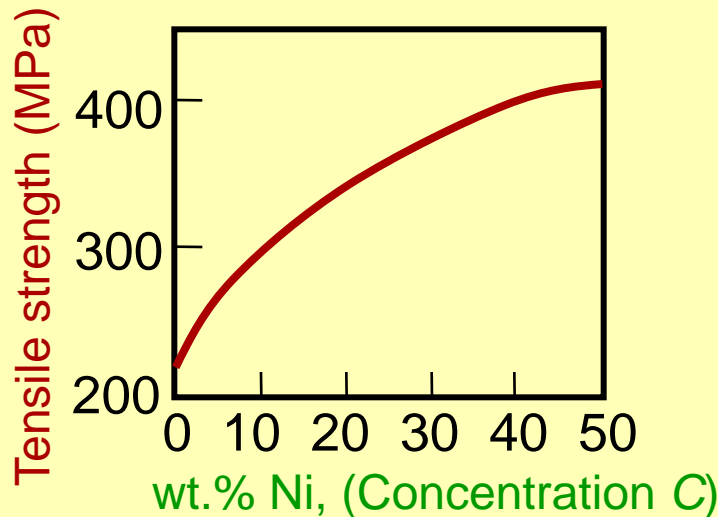
Solid Solution Strengthening



Partial cancellation
of dislocation lattice
strain distribution by
the impurities.

Example: Solid Solution Strengthening in Copper

- Tensile strength & yield strength increase with wt% Ni.



Adapted from Fig. 7.16 (a) and (b), Callister 7e.

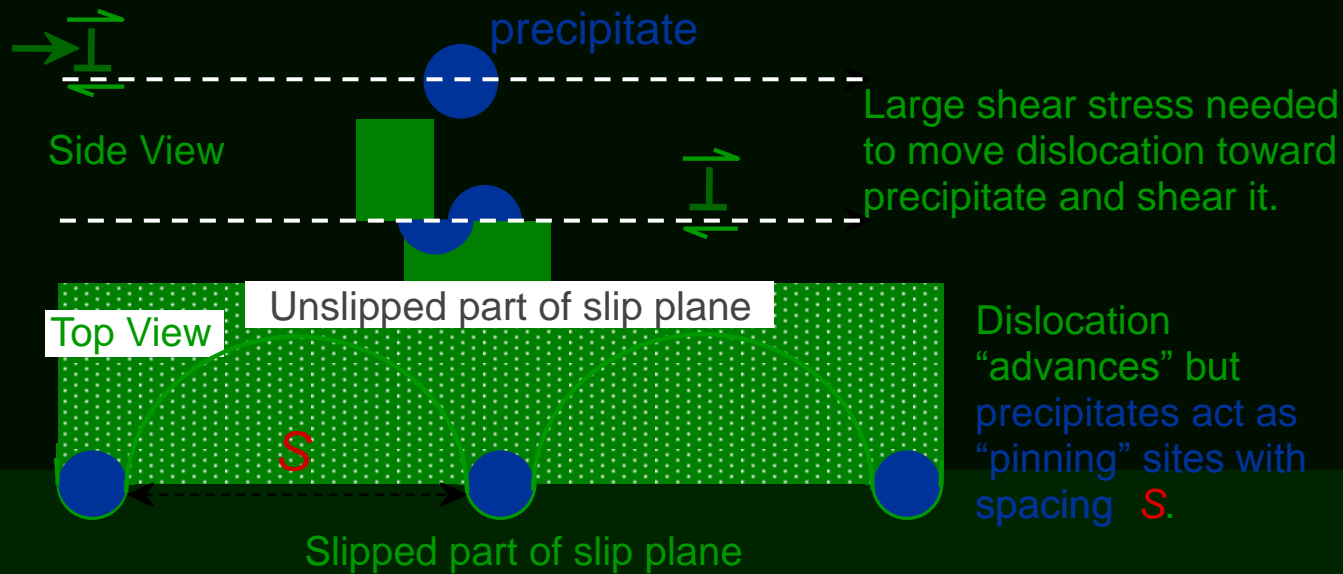
- Empirical relation:

$$\sigma_y \sim C^{1/2}$$

- Alloying increases σ_y and *TS, YS, etc.* – all will be defined accurately later.

Precipitation Strengthening

- Hard precipitates are difficult to shear
Examples: Ceramics in metals (SiC in Iron or Aluminum).



- Result:

$$\sigma_y \sim \frac{1}{S}$$

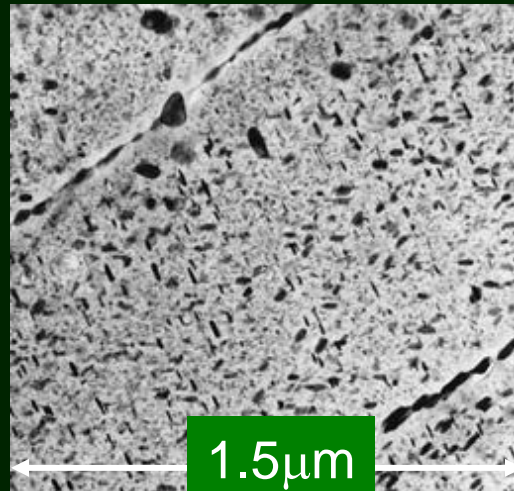
Applications of Precipitation Strengthening

- Internal wing structure on Boeing 767



Adapted from chapter-opening photograph, Chapter 11, *Callister 5e* (courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

- Aluminum is strengthened with precipitates formed by alloying.



Adapted from Fig. 11.26, *Callister 7e*. (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Strengthening by Grain Size Reduction

- The grain size of a metal will influence its properties.
- Adjacent grains will normally have different crystal orientations – always, only a small number of grains would be aligned along a slip direction.
- The grain boundary will act as a barrier to dislocation movement as;
 1. The dislocation will have to change its direction as it passes between two grains of different orientations and so it become more difficult as the mis-orientation increases.
 2. The atomic disorder at the GB will result in a discontinuity of the slip planes from one grain to another.

Grain Size Reduction

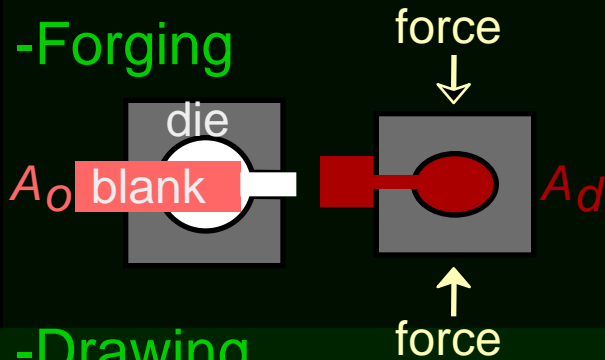
Thus a sample with small grains will have a larger GB surface area to impede dislocation motion. For many metals the *Hall-Petch* equation indicates how the yield strength (σ_y) varies with grain size according to

$$\sigma_y = \sigma_0 + k.d^{-\frac{1}{2}}$$

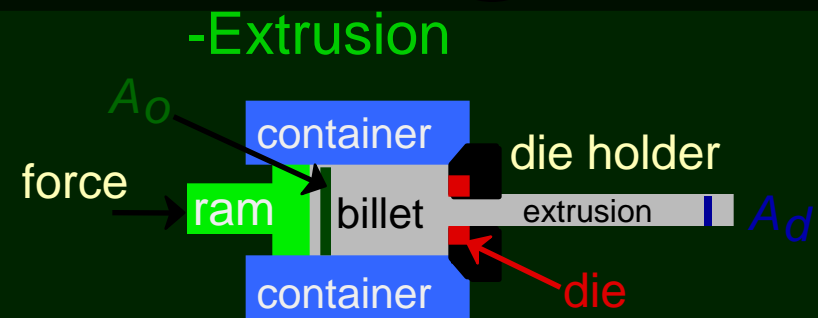
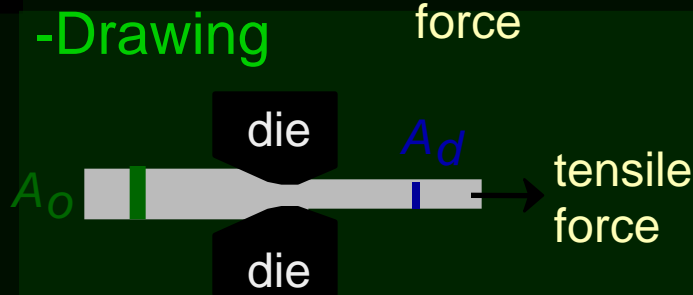
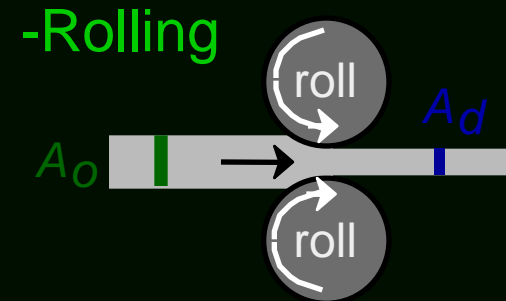
where d is the average grain size.

Cold Working - Examples

- Room temperature deformation.
- Common forming operations change the cross sectional area:



Adapted from Fig. 11.8, Callister 7e.



Cold Working

- Deformation of metal at a temperature \ll melting temperature
 - Reduces grain size
 - Increase number of dislocations
 - Dislocation – dislocation interactions are (on average) repulsive
- Measured as percent cold work (A_o, A_d is x-sectional area before, after deformation)

$$\% CW = \left(\frac{A_o - A_d}{A_o} \right) \times 100$$