Lecture 31

Surface defects
Strengthening mechanisms-Plastic deformation

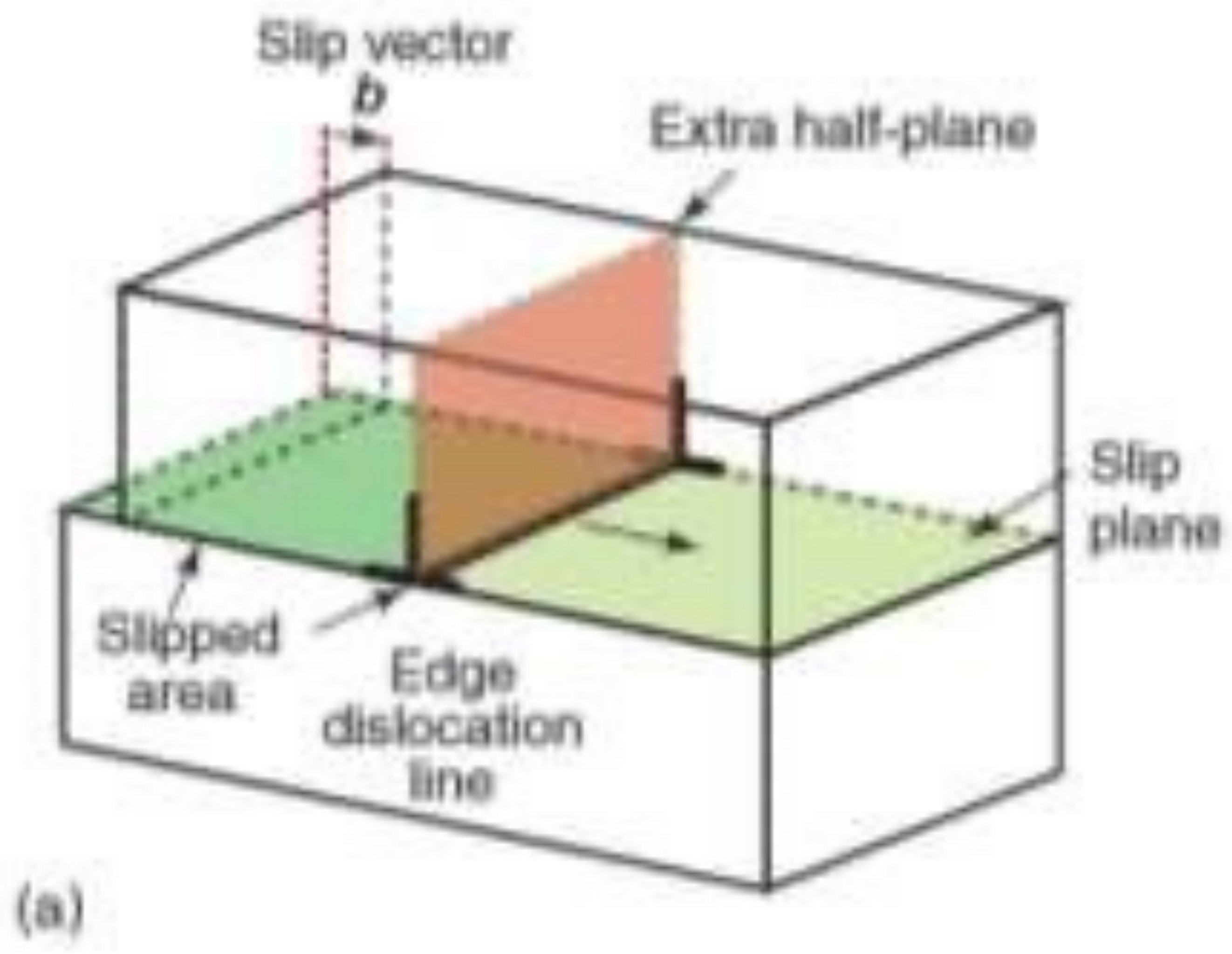
Prof. Divya Nayar
Department of Materials Science and Engineering
divyanayar@mse.iitd.ac.in

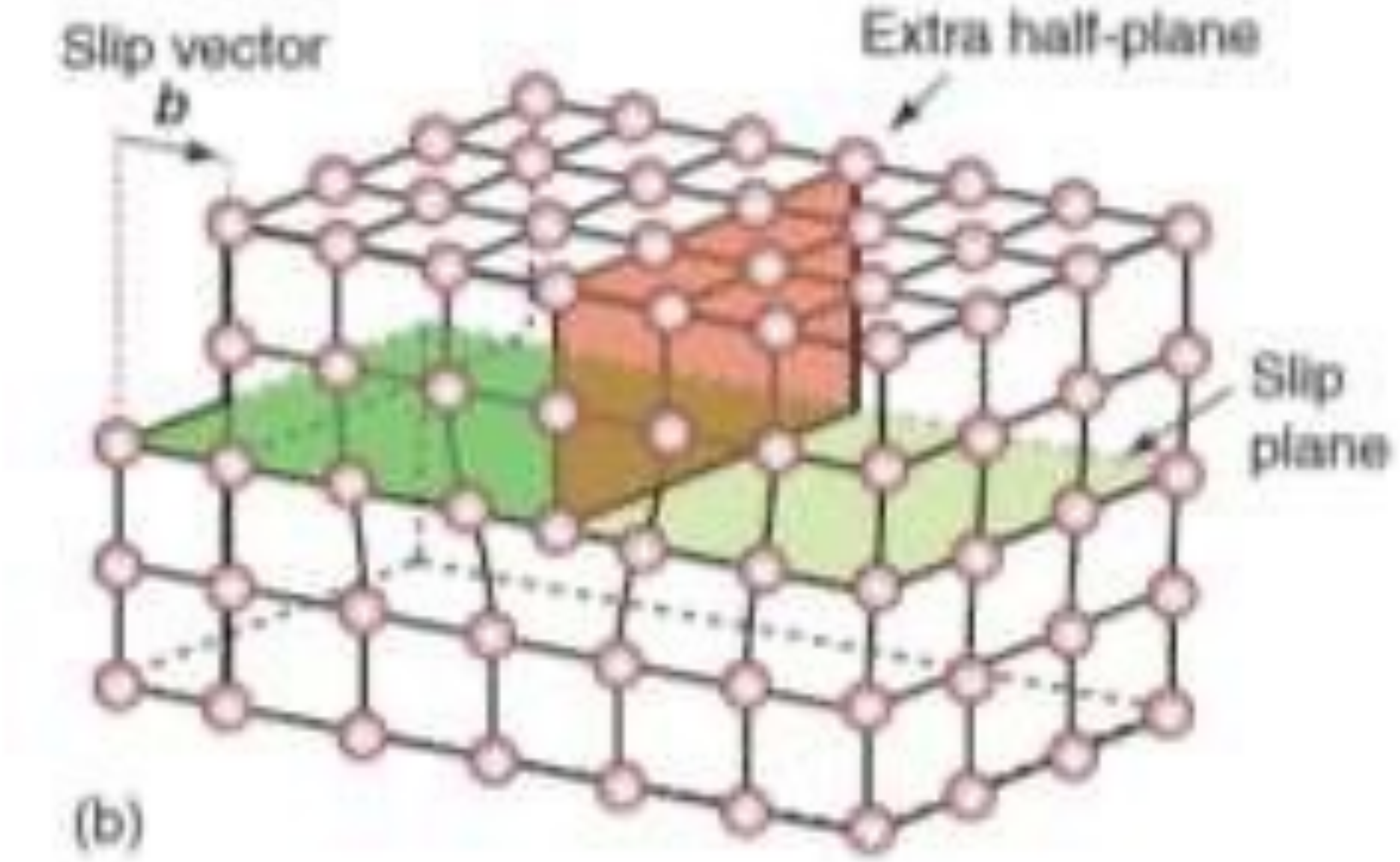
Recap…

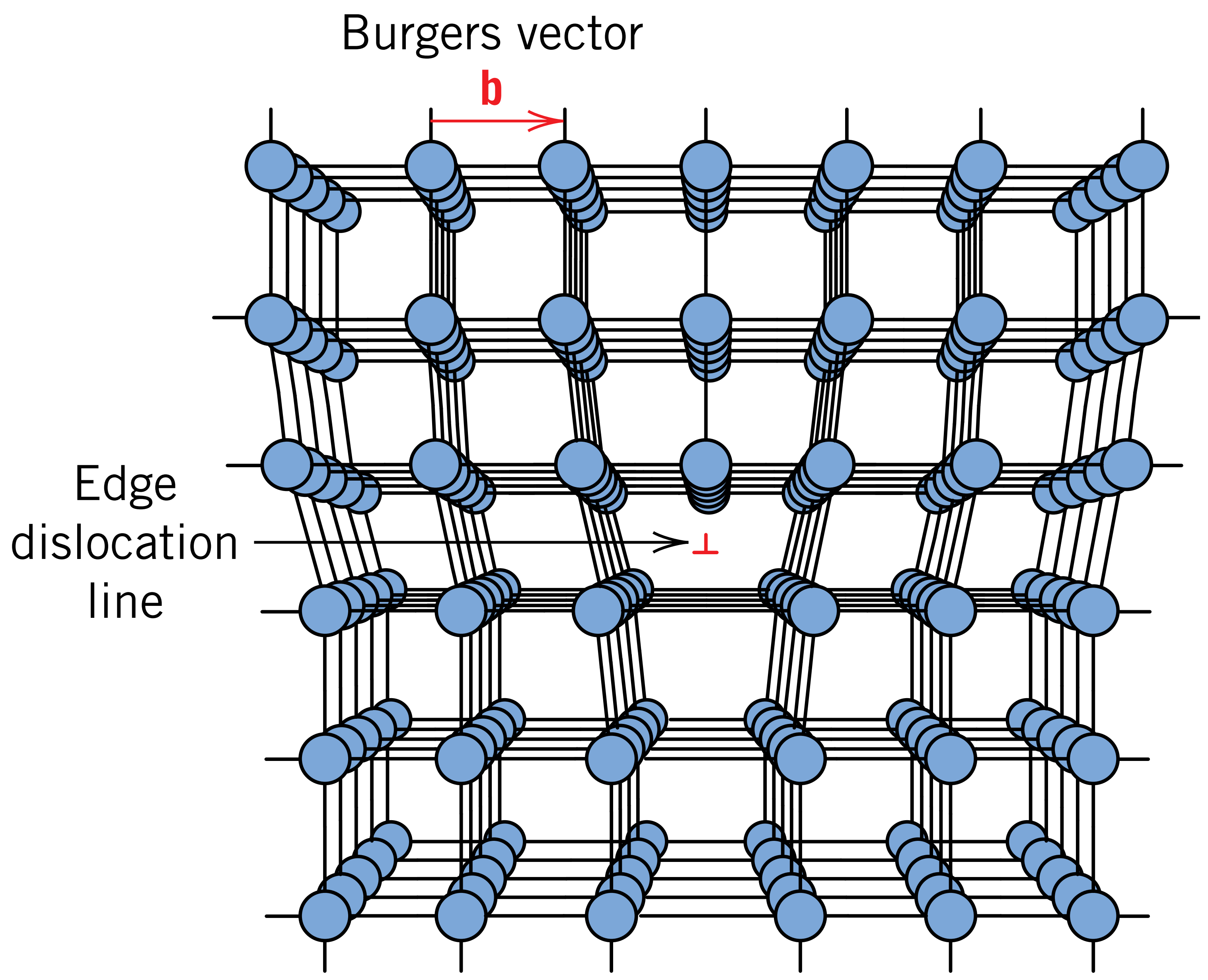
- Defects in solids
- Line defect: Disclocations
- Slip: Edge dislocation

Dislocation

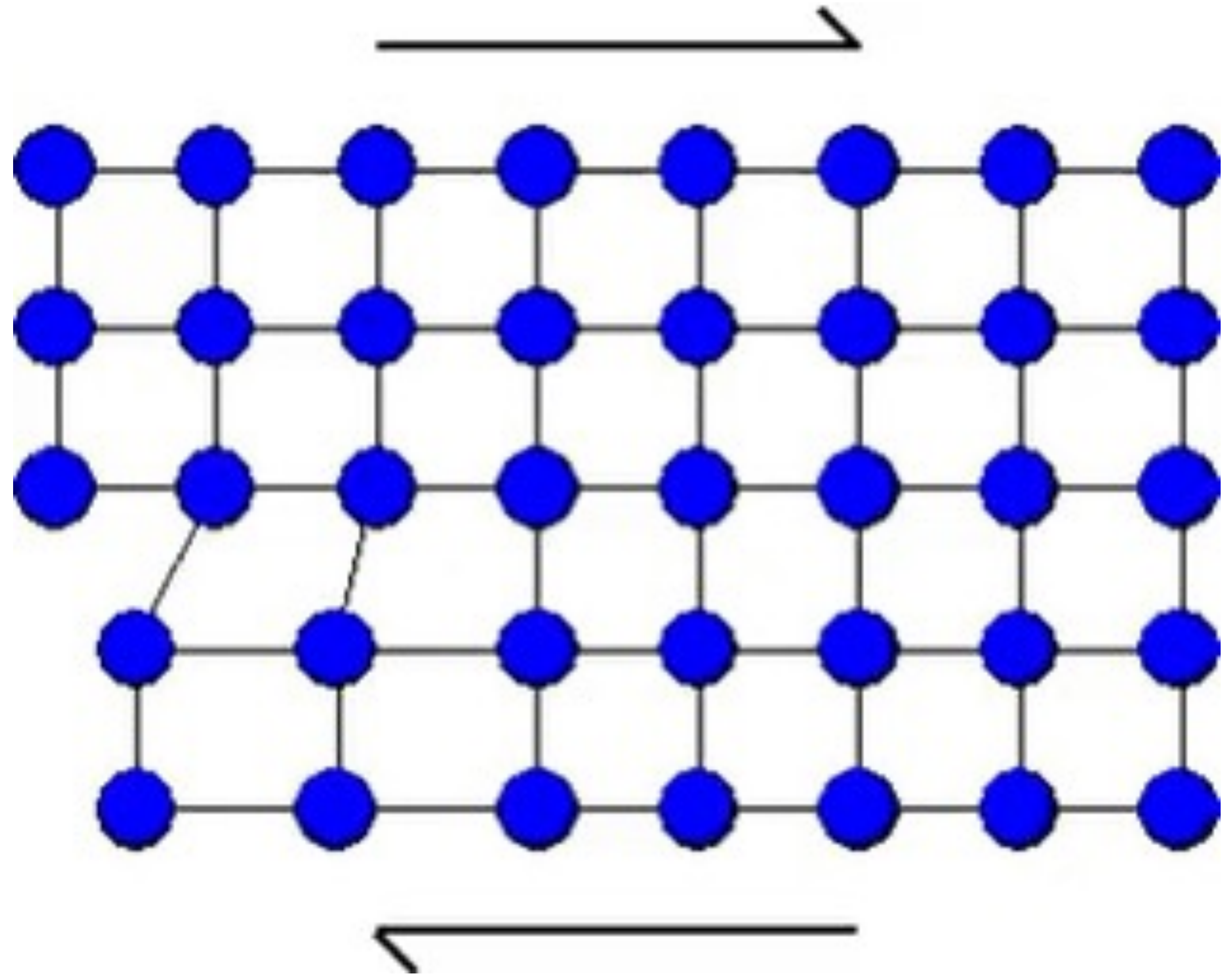
Motion of dislocation in a slip plane is called glide





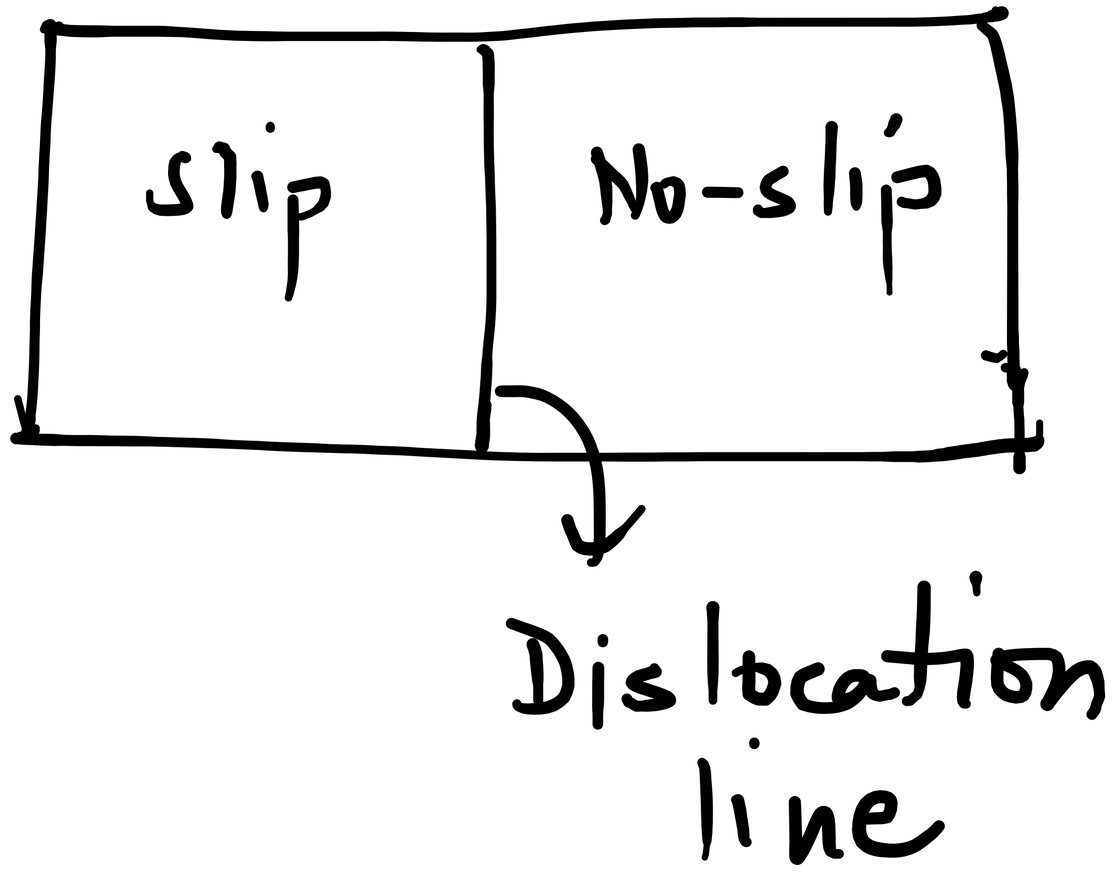


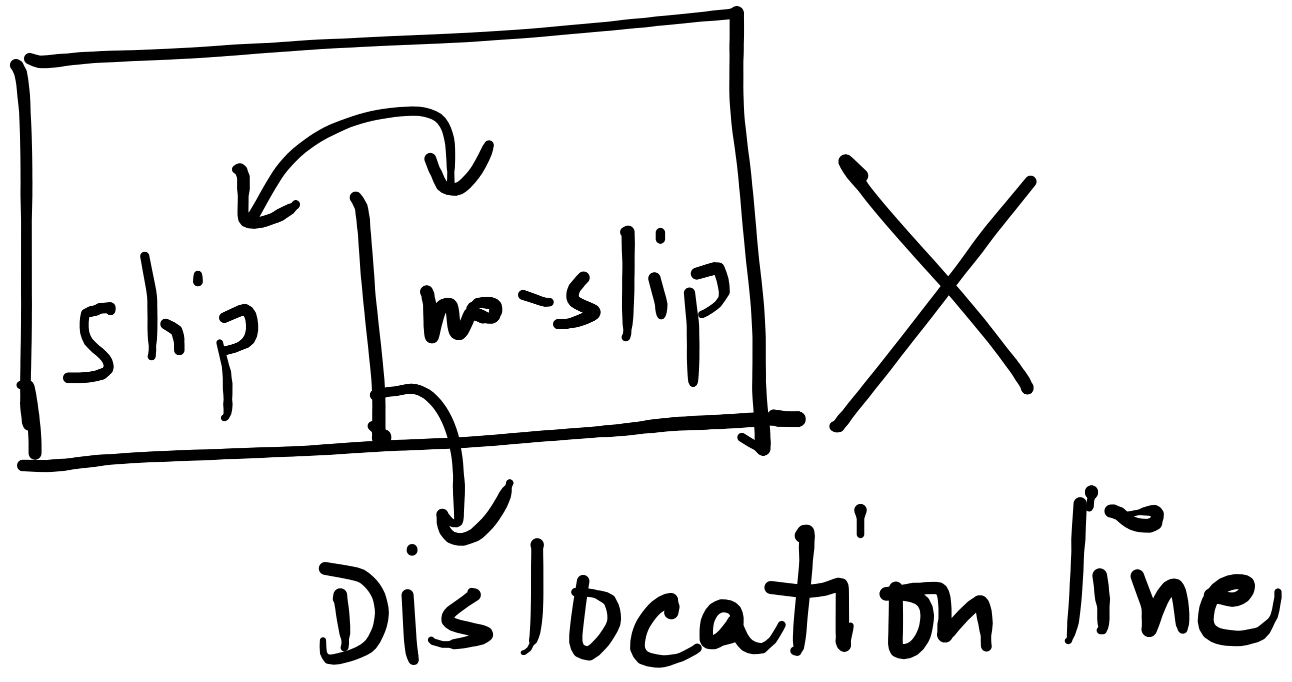
Glide

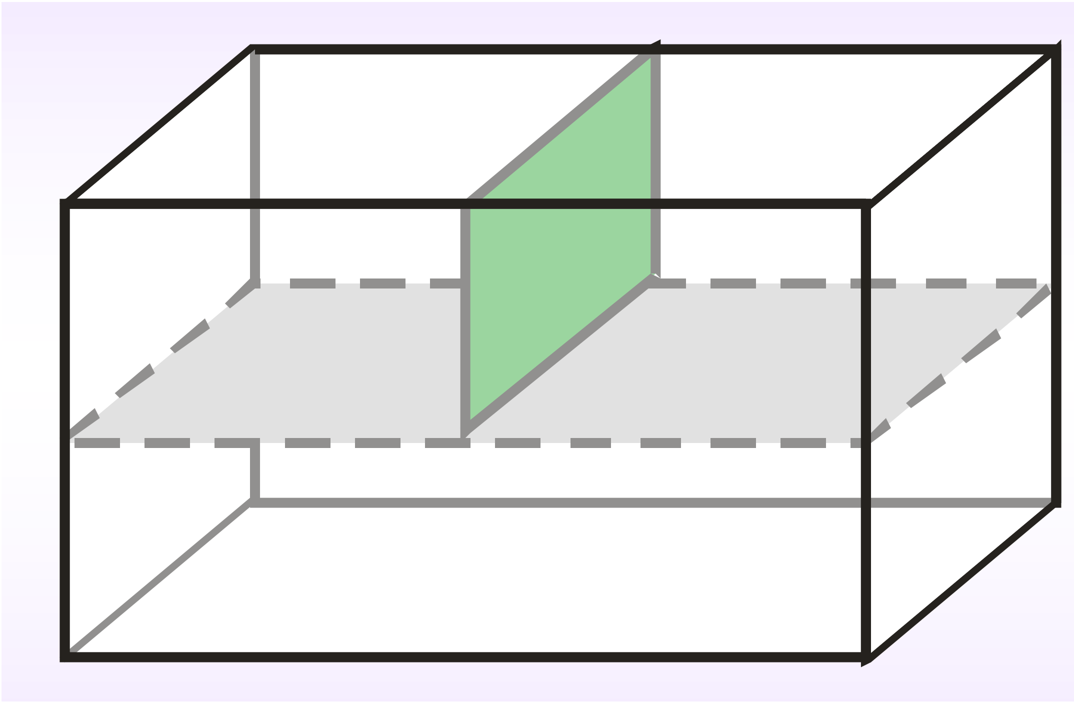


Surface Defects

Interfacial defects are boundaries that have two dimensions and normally separate regions of the materials that have different crystal structures and/or crystallographic orientations

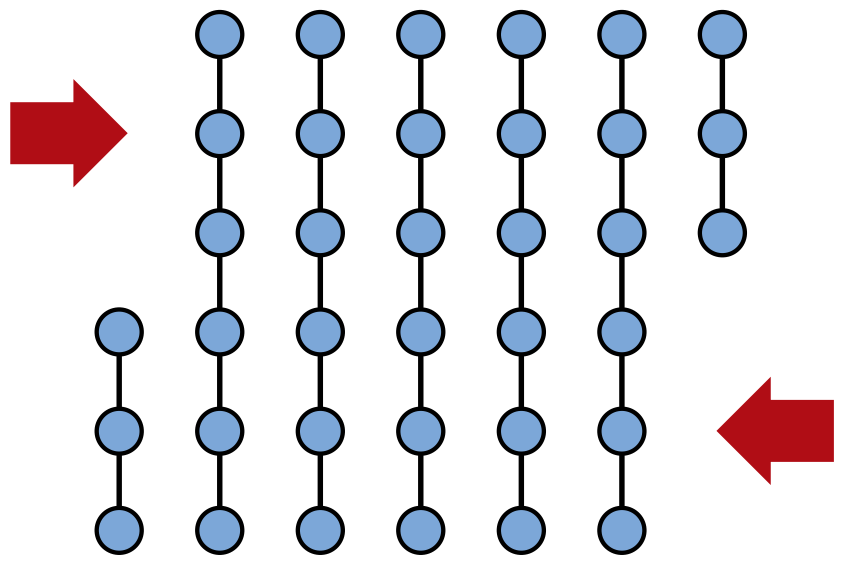




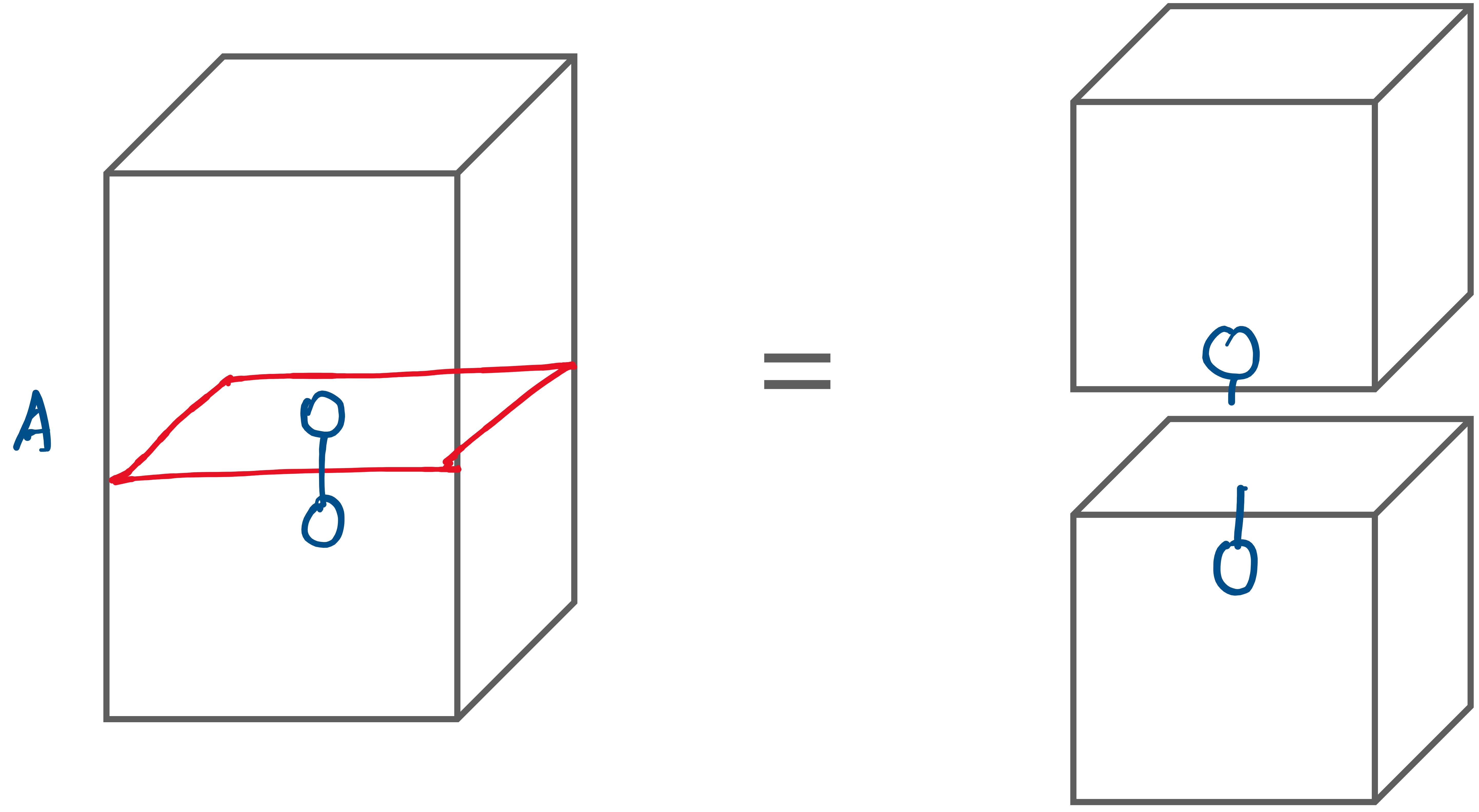


- The dislocation cannot end abruptly inside a crystal. It can end on:
  - Free surfaces (external)
  - Grain boundaries (internal)
  - Other dislocations (nodes)
  - Itself (continuous loop)

- **Free surface:** One boundary is the external surface, along which the dislocation line terminates.
- The bonds of these surface atoms that are not satisfied give rise to a surface energy, expressed in units of energy per unit area (J/m^2).



Surface energy



No. of bonds broken = n_B

No. of atoms per unit area on the surface = n_A

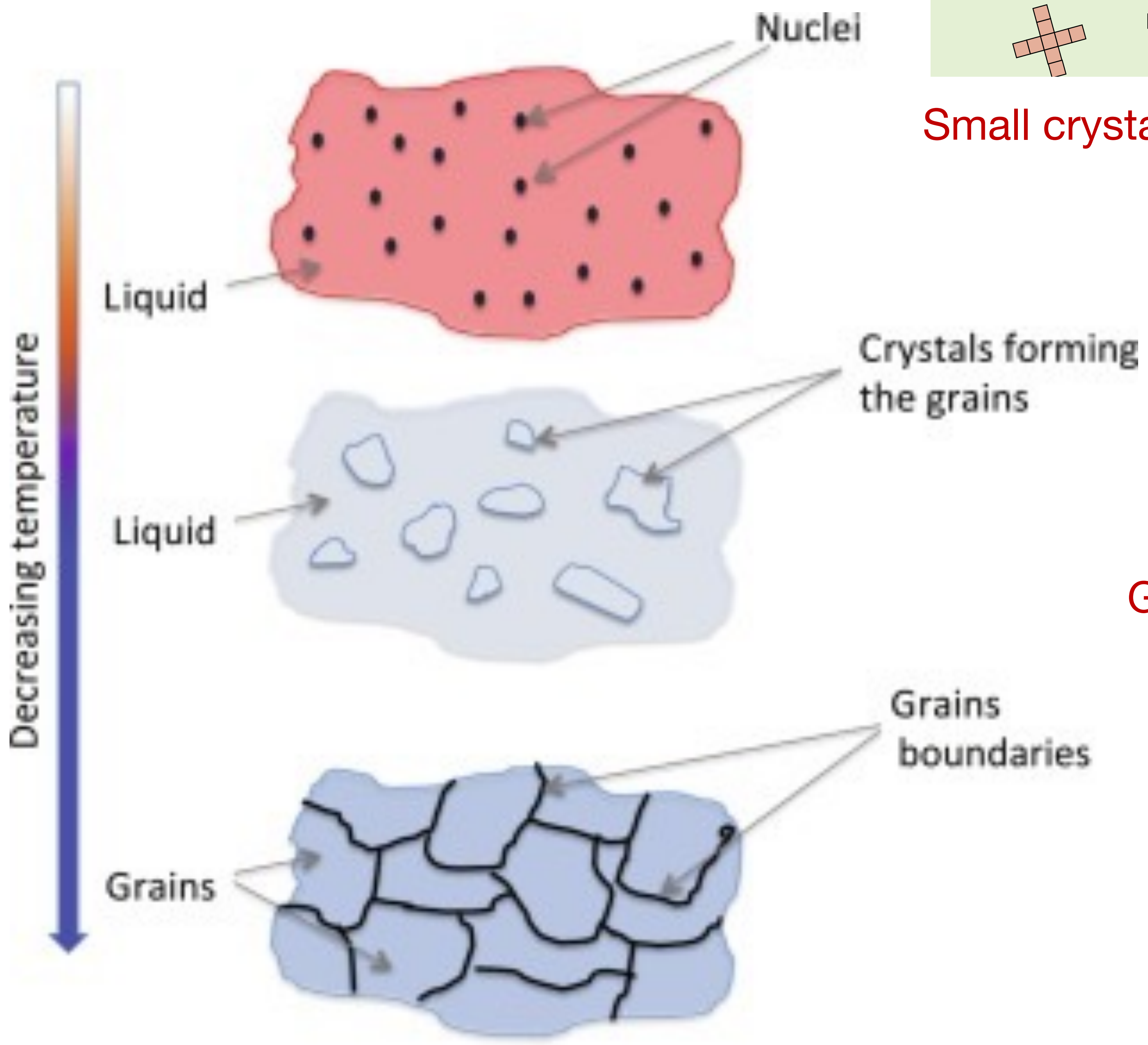
Bond energy per bond = ε

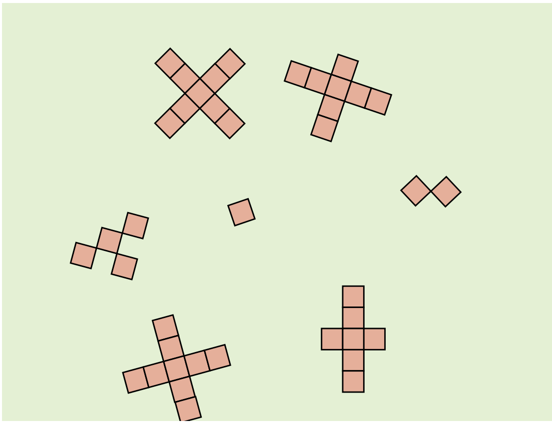
Surface energy, γ =

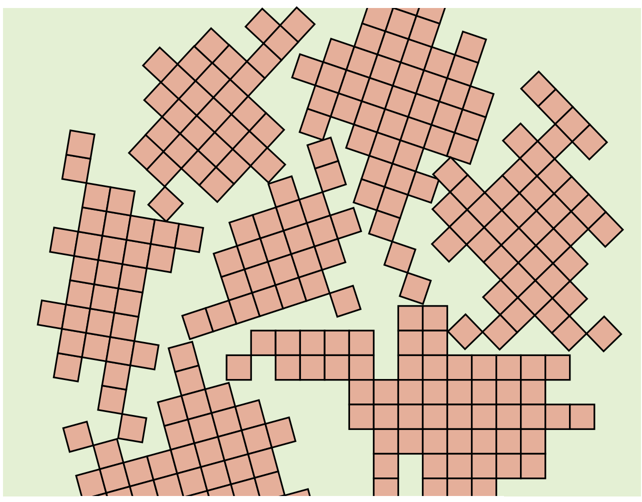
$$\frac{A\, n_A \cdot n_B \cdot \varepsilon}{2A} = \frac{n_A n_B \varepsilon}{2}$$

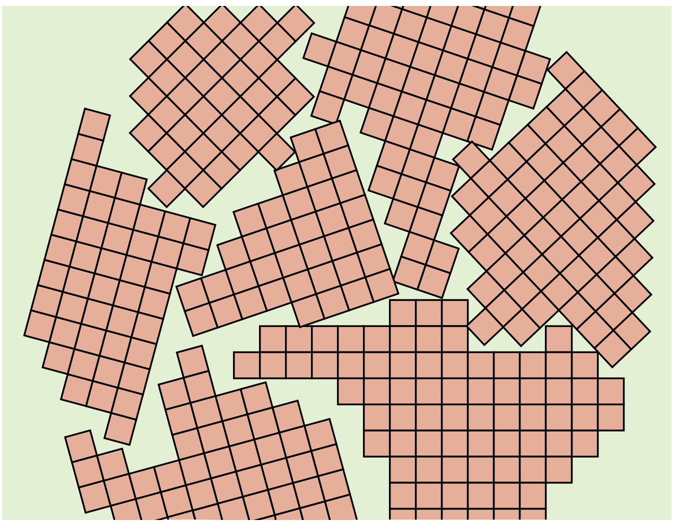
surface area generated

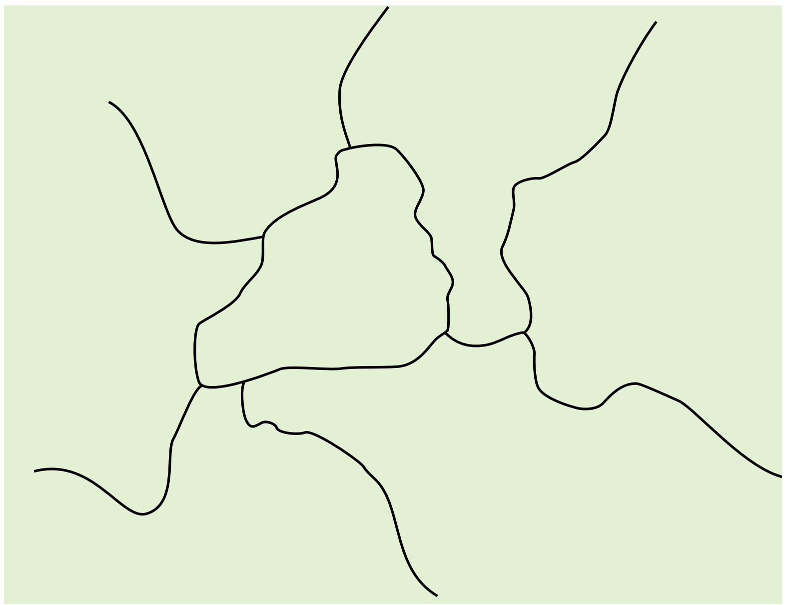
Grains and grain boundaries




Small crystallite nuclei


Growth of crystallites or Grains

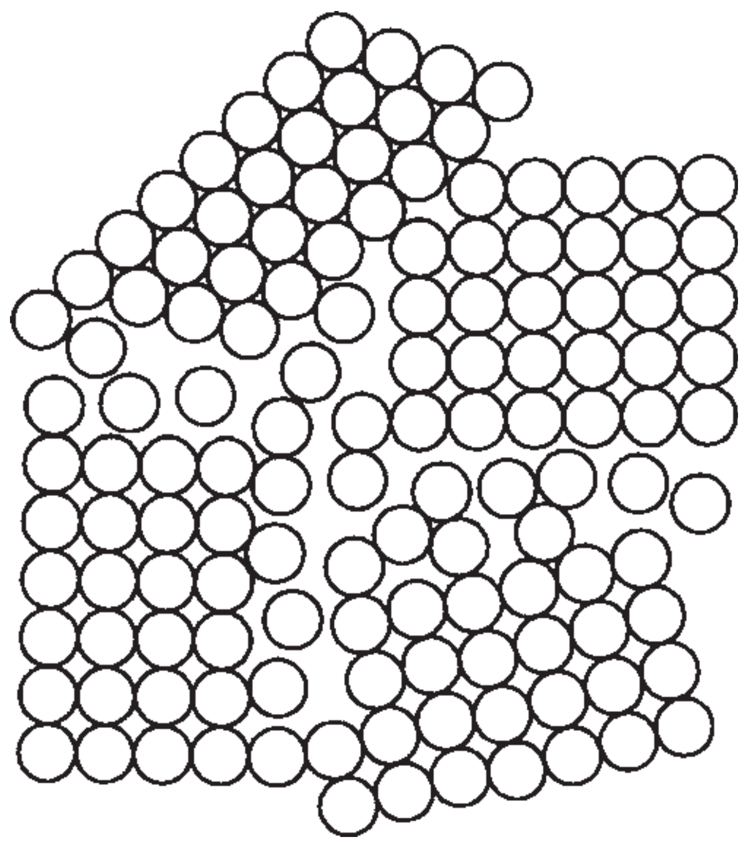

Upon completion of solidification, grains having irregular shapes have formed.

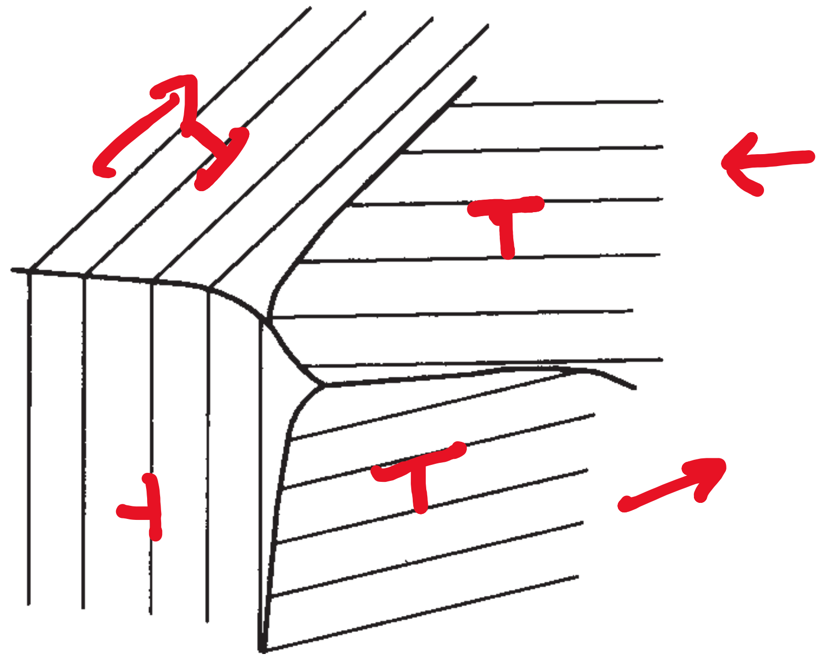

The grain structure as it would appear under the microscope; dark lines are the grain boundaries.

- Polycrystalline materials, the crystallographic orientations of the individual grains are totally random.
- each grain may be anisotropic, a specimen composed of the grain aggregate behaves isotropically.

Grain boundaries

Boundary separating two small grains or crystals having different crystallographic orientations in polycrystalline materials



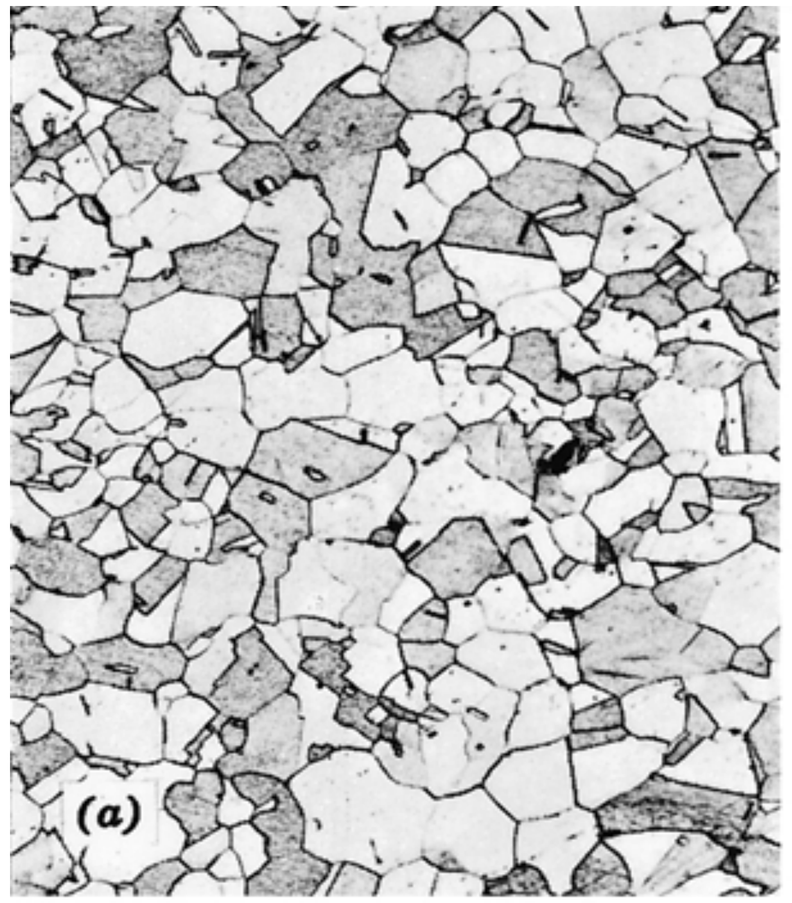


- There is some atomic mismatch in a transition from the crystalline orientation of one grain to that of an adjacent one.
- Various degrees of crystallographic misalignment between adjacent grains are possible

(a) When this orientation mismatch is slight, less than 10 degrees, then the term *small*- (or *low*-) *angle grain boundary* is used

(b) When the orientation difference is greater than 10 to15°, the grain boundaries are also known as *high angle boundaries*.

- Planes in grain do not cross the grain boundaries.
- Half-planes do not cross grain boundaries and thus, dislocation line ends on the grain boundary.
- Dislocations are stopped by a grain boundary and pile up against it.



Before plastic deformation

The deformation has produced elongated grains

During plastic deformation:

- grain boundaries usually do not come apart or open up.
- each individual grain is constrained, to some degree, in the shape it may assume by its neighboring grains.

Stacking Faults

- **Planar surface imperfections** created by a fault (or error) in the stacking sequence of atomic planes in crystals.
- There is no change in the orientation of the crystal across the stacking fault
- Long-range structure is not affected.
- The number of nearest neighbours in the faulted region remains 12 as in the perfect regions of the crystal
- But the second nearest neighbour bonds in the faulted region are not of the correct type for the FCC crystal.
- Hence, a small surface energy is associated with the stacking fault, in the range 0.01–0.05 J m^{-2} (10–50 erg/cm^2)

FCC

A
B
C
A
B
C
C plane is missing
A
B
C
A
B
C

A
B
C
A
B
C
FCC
HCP
A
B
Stacking fault plane
HCP
A
B
FCC
C
A
B
C
FCC

Twin boundaries

Mirror lattice symmetry

- A *twin boundary* is a special type of grain boundary across which there is a specific mirror lattice symmetry; that is, atoms on one side of the boundary are located in mirror-image positions of the atoms on the other side.
- Applied mechanical shear forces (mechanical twins), and also during annealing heat treatments following deformation (annealing twins)

Perfect FCC structure

A
B
C
A
B
C
A
B
C
A
B
C

A
B
C
A
B
C
B
A
C
B
A

"Twin boundary" → g.b.

↑
Mirror plane

Summary of the defects

1. 1-D defect: dislocation (slip, edge/screw/mixed disclocation, glide)
2. 2-D defect: free surface, grain boundaries, stacking faults, twin boundaries

Food for thought…

Blacksmith and his forge

Why Blacksmith hammers the weapon to make it strong?

Dislocation motion and strengthening mechanisms

Strengthening mechanisms (in single-phase metals)

Plastic deformation depends *on the ability of dislocations to move*

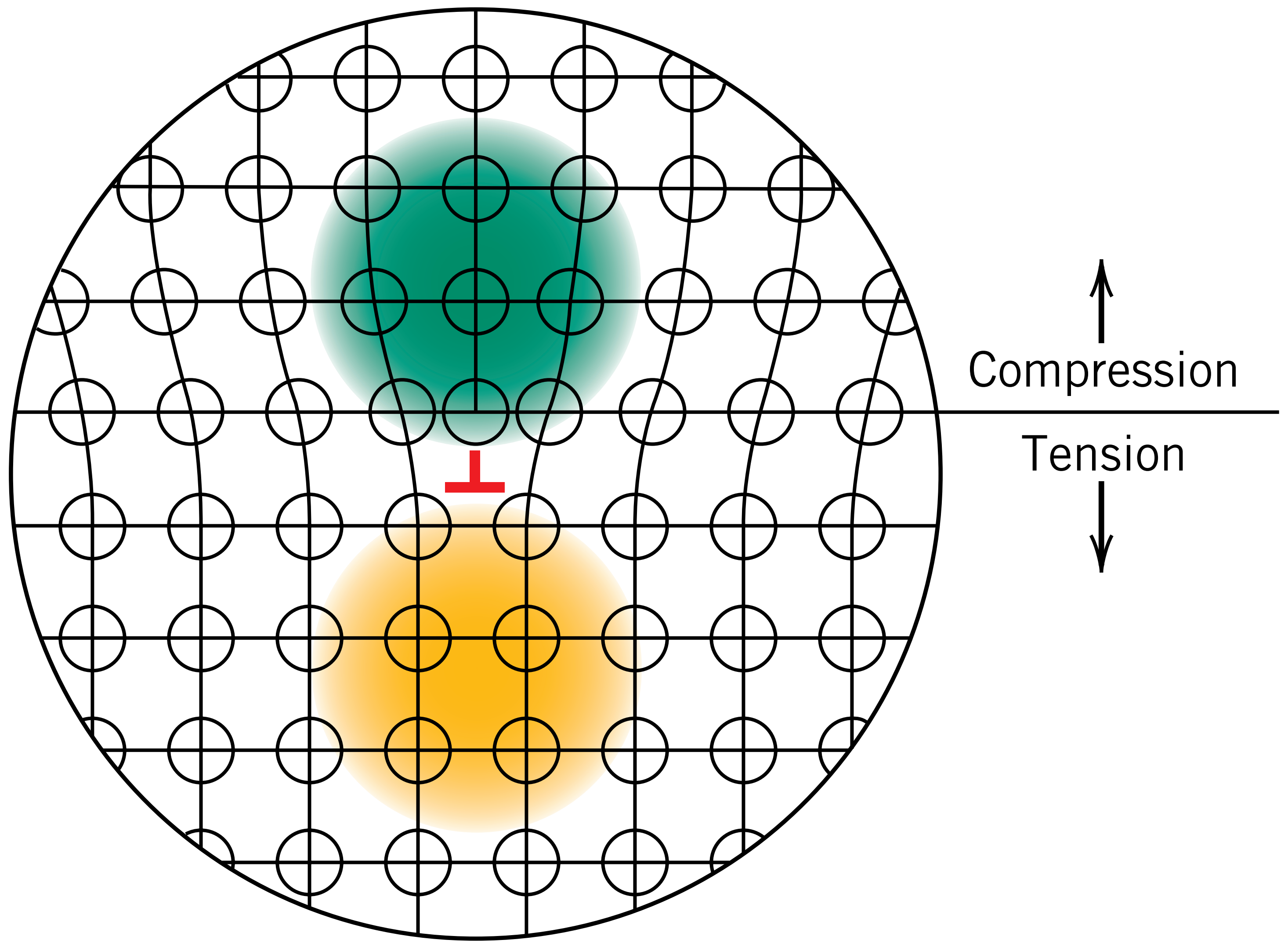
Restricting or hindering dislocation motion renders a material stronger.

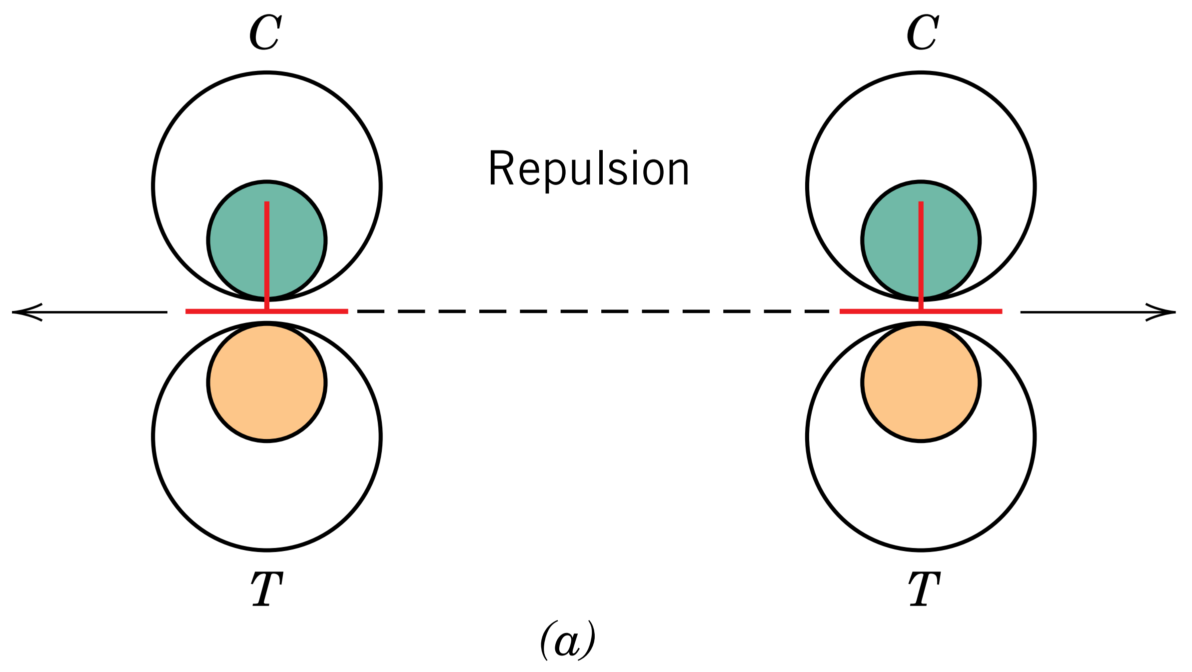
- Grain size reduction
- Strain hardening
- Solid solution hardening
- Precipitation hardening

Lattice strain

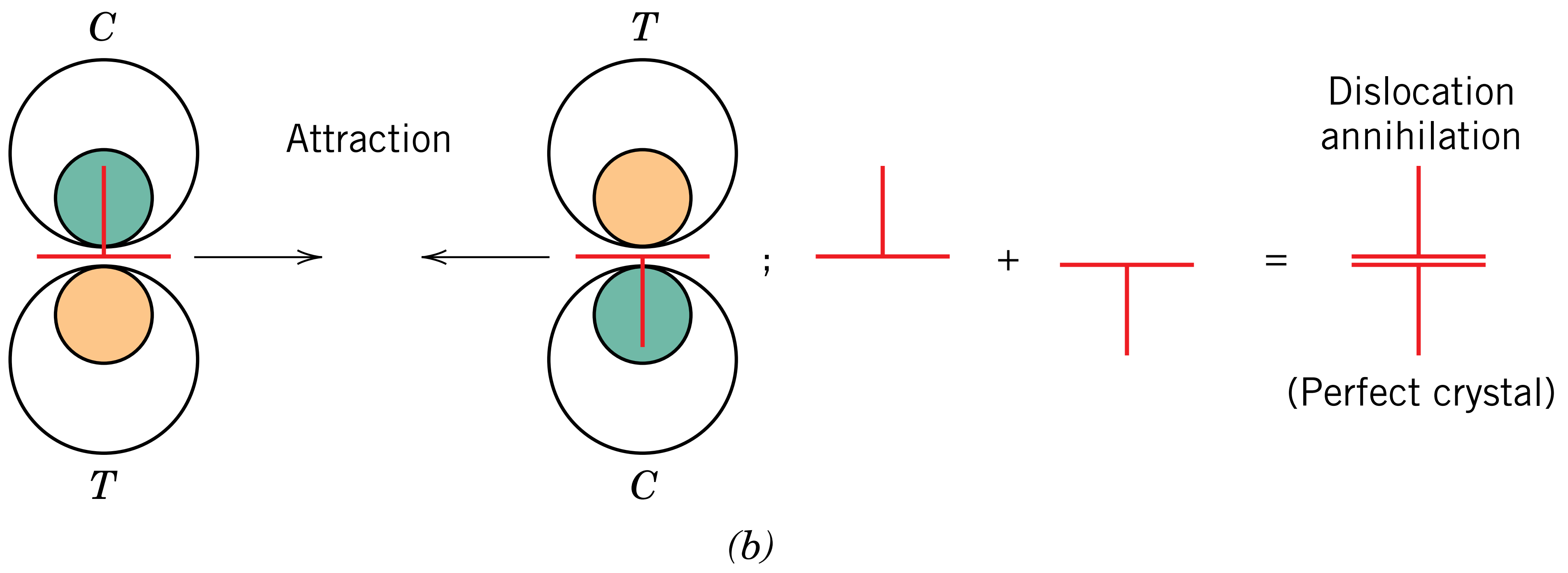
Characteristic of Dislocations

- **Strain energy:** When metals are plastically deformed, some fraction of the deformation energy is retained internally
- Dislocations cause atomic lattice distortion that imposes compressive, tensile, shear strains on neighbouring atoms. e.g. atoms immediately above and adjacent to the dislocation line are squeezed together.
- These lattice distortions may be considered to be strain fields that radiate from the dislocation line. The strains extend into the surrounding atoms, and their magnitude decreases with radial distance from the dislocation.





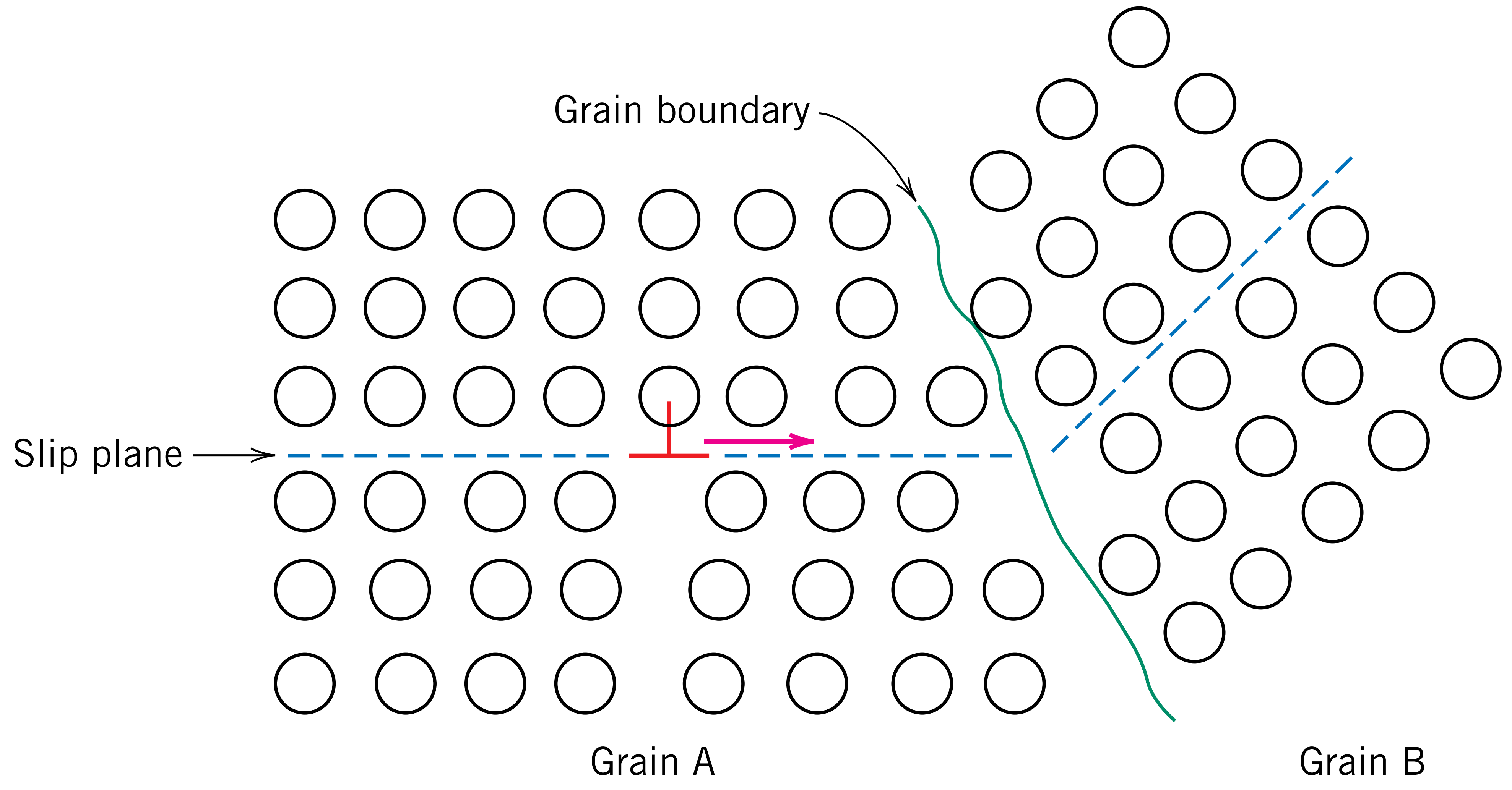
Two edge dislocations of the same sign and lying on the same slip plane exert a repulsive force on each other;



Edge dislocations of opposite sign and lying on the same slip plane exert an attractive force on each other.

Grain size reduction

The size of the grains, or average grain diameter, in a polycrystalline metal influences the mechanical properties



- *The grain boundary acts as a barrier to dislocation motion for two reasons:*
  - Since the two grains are of different orientations, a dislocation passing into grain B will have to change its direction of motion; this becomes more difficult as the crystallographic misorientation increases.
  - The atomic disorder within a grain boundary region will result in a discontinuity of slip planes from one grain into the other.

- High-angle grain boundaries: dislocations tend to “pile up” (or back up) at grain boundaries.
- A fine-grained material (one that has small grains) is harder and stronger: greater total grain boundary area to impede dislocation motion.
- grain size which determines the average distance from a dislocation source to the grain boundary
- The smaller is the grain size, the more frequent is the pile up of dislocations.

Larger the grain size→ distance of dislocation from g.b. is higher→ less piling up of dislocations→ plastic deformation is easy

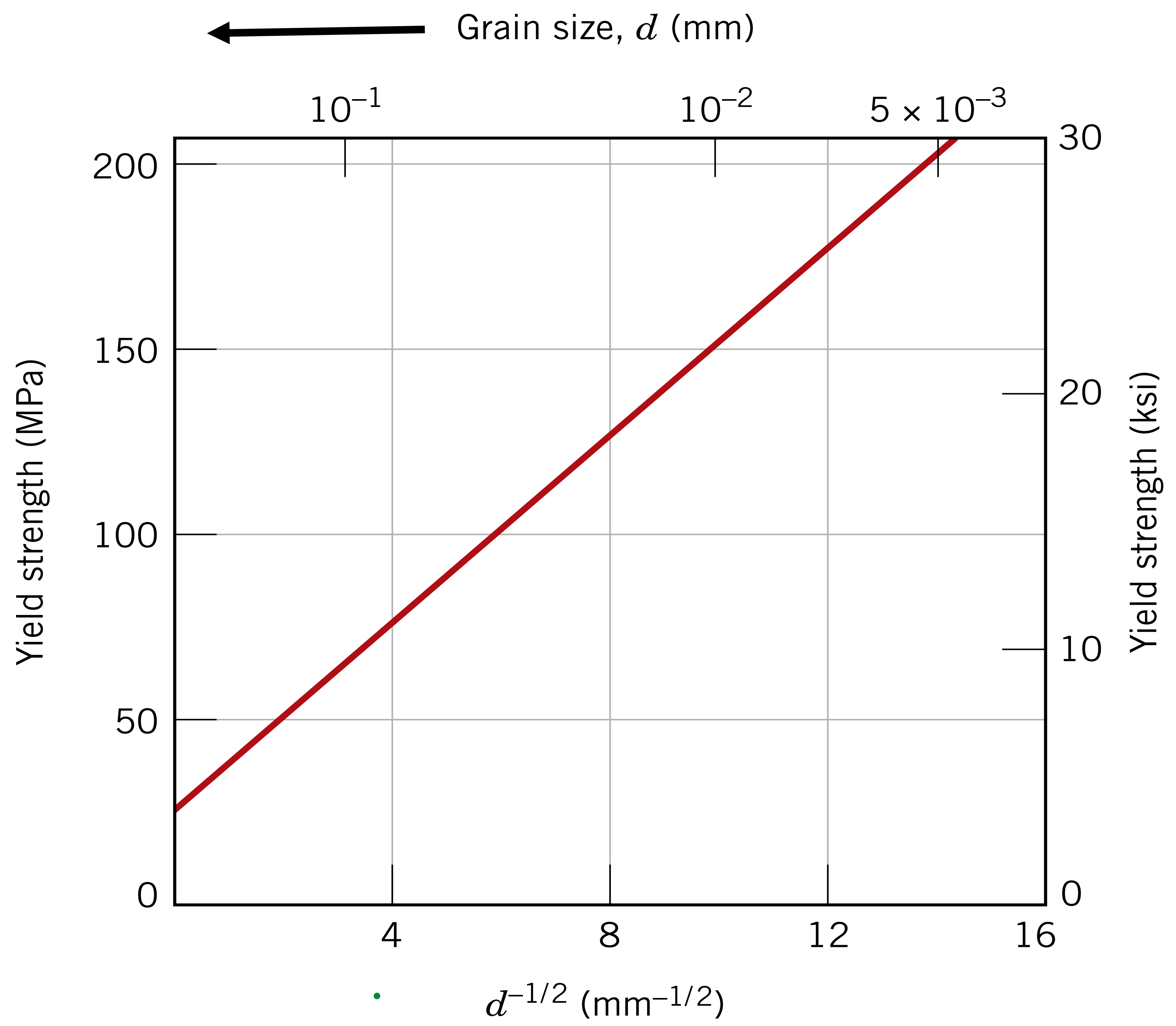
Hall-Petch equation

Dependence of yield strength on grain size

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

d: average grain diameter
k_y: constant for a material
σ_0: yield stress for crystal of same material with no grain boundaries

[Not valid for both very large (coarse) grain and extremely fine grain polycrystalline materials]



The influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy.