ME 254: Materials Engineering

Chapter 7: Dislocations and Strengthening Mechanisms

1st Semester 1435-1436 (Fall 2014)

Dr. Hamad F. Alharbi, harbihf@ksu.edu.sa

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Outline

DISLOCATIONS AND PLASTIC DEFORMATION

7.2 Basic Concepts
7.3 Characteristics of Dislocations
7.4 Slip Systems
7.5 Slip in Single Crystals
7.6 Plastic Deformation of Polycrystalline Materials
~~7.7 Deformation by Twinning~~

STRENGTHENING MECHANISMS IN METALS

7.8 Strengthening by Grain Size Reduction
7.9 Solid-Solution Strengthening
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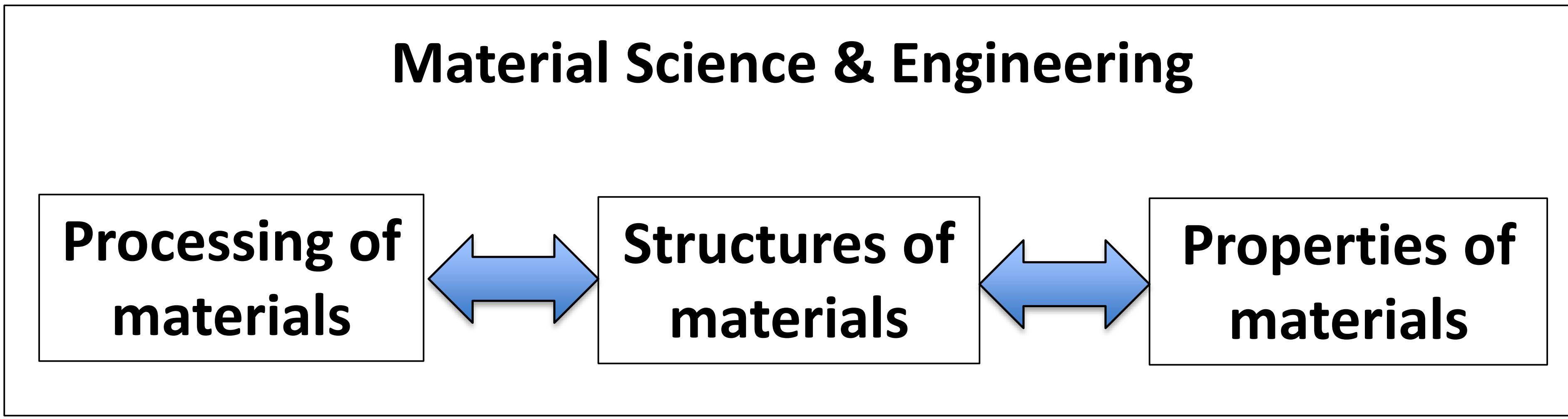
RECOVERY, RECRYSTALLIZATION, AND GRAIN GROWTH

7.11 Recovery
7.12 Recrystallization

Why do we need to study dislocations?

From Chapter 1:

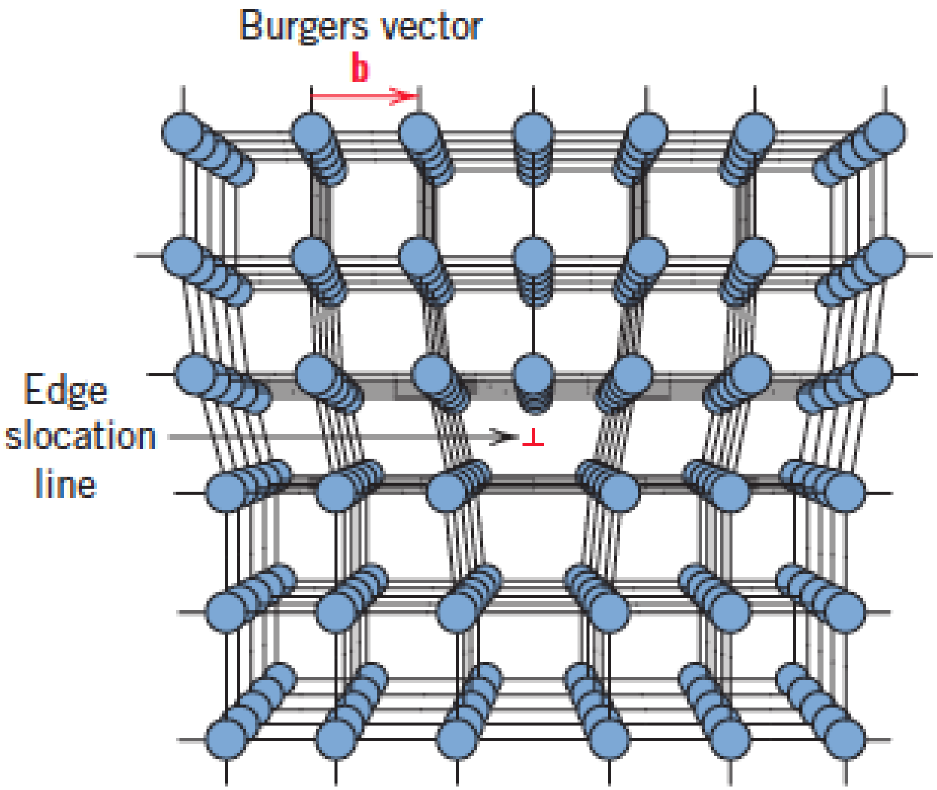


Most of the mechanical (plastic) properties of metals depend strongly on dislocations.

From Chapter 4:

Line defects: dislocations

Dislocation is a linear crystalline defect around which there is atomic misalignment (localized lattice distortion).

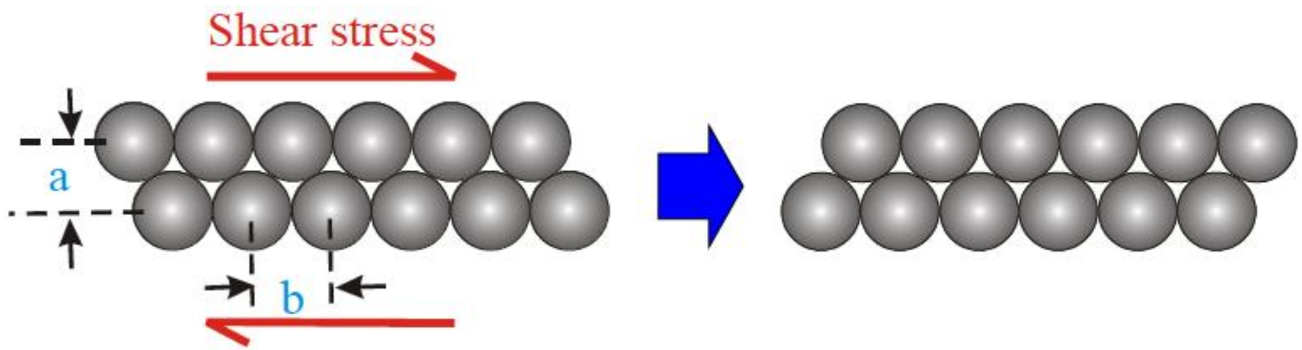


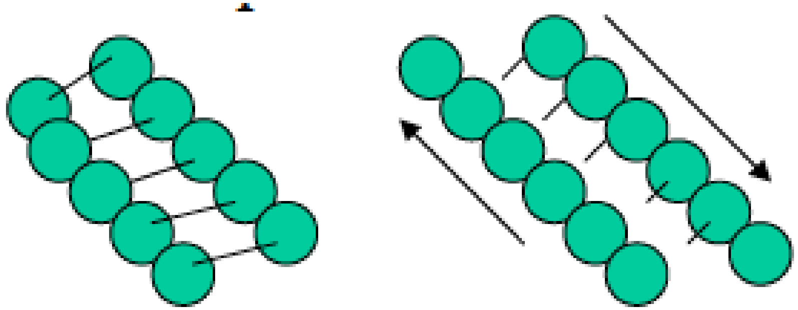
1. Edge dislocations
2. Screw dislocations
3. Mixed dislocations

Basis of presence of dislocations:

Actual strength of materials is 2-to-4 orders of magnitude less than theoretical strength

– Basis of presence of dislocations





Sliding of planes

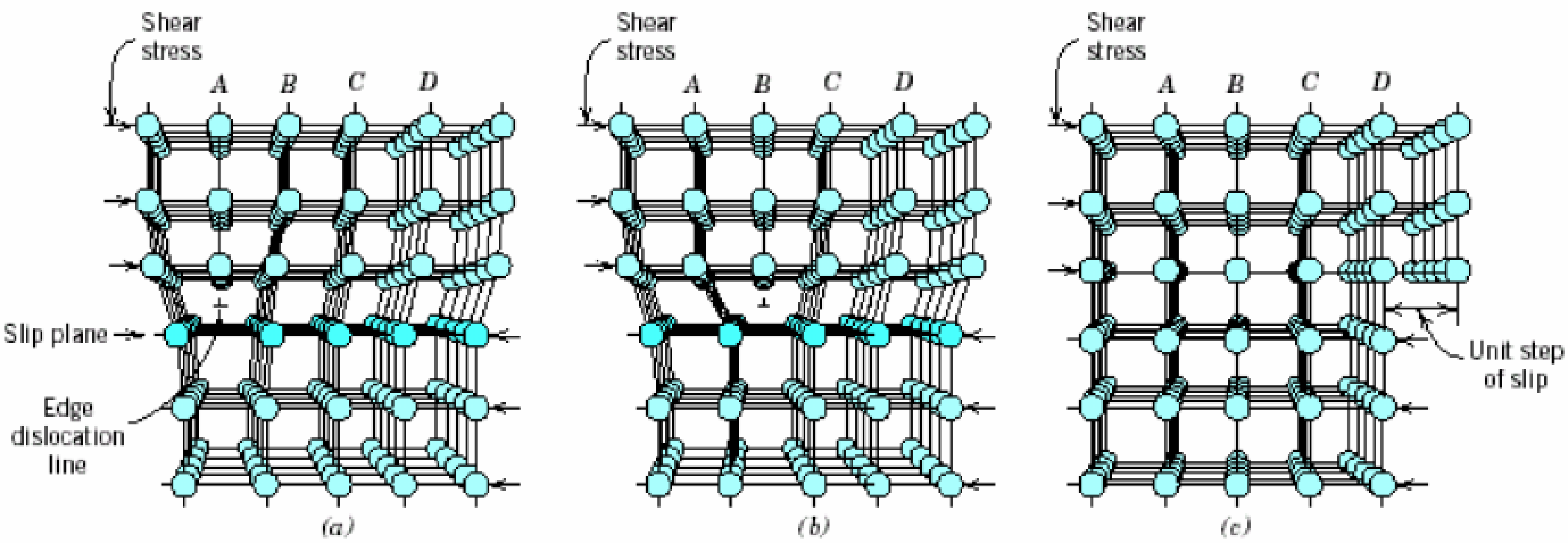
1900

Plastic deformation happens by sliding of planes of atoms

>>> Breaking of all interatomic bonds between planes

>>> which would require a tremendous external stresses

Cont'd: Basis of presence of dislocations: In 1930s



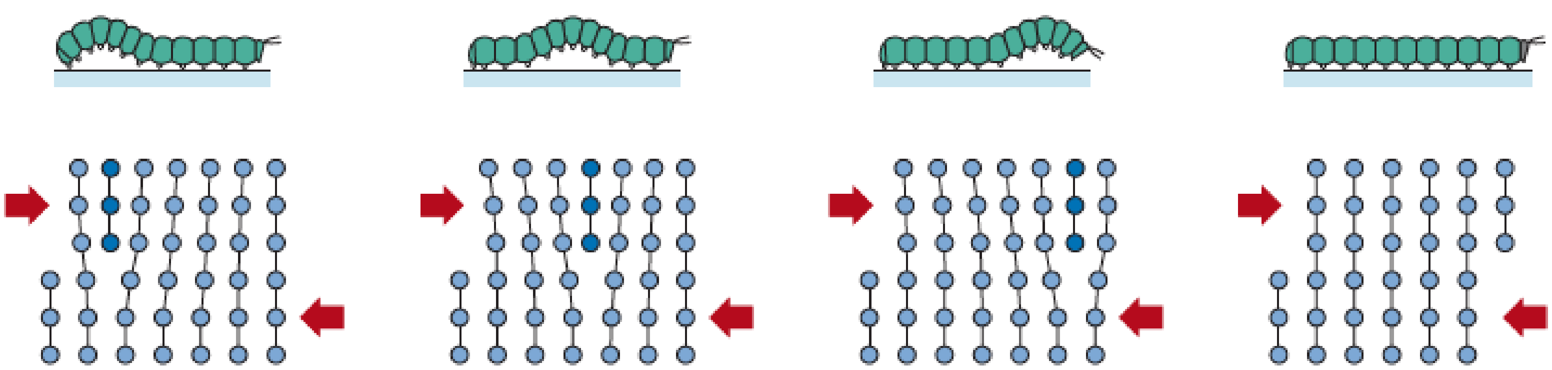
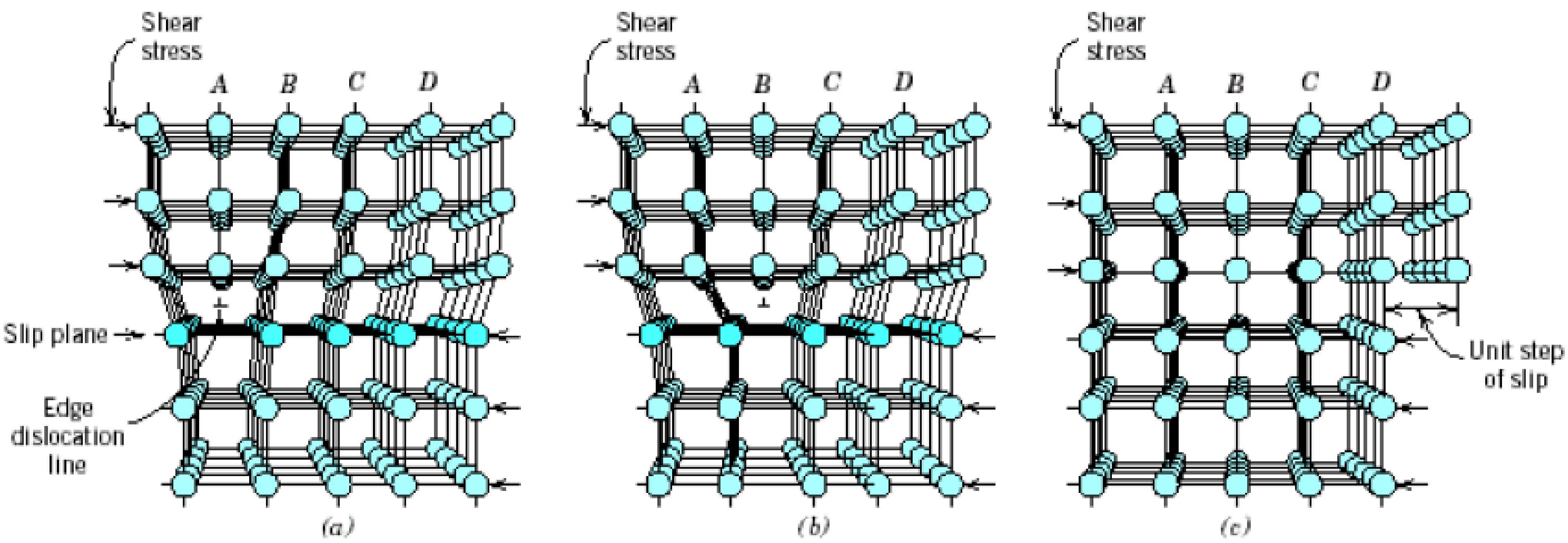


Figure 7.3 Representation of the analogy between caterpillar and dislocation motion.

Cont'd: Basis of presence of dislocations: **In 1930s**



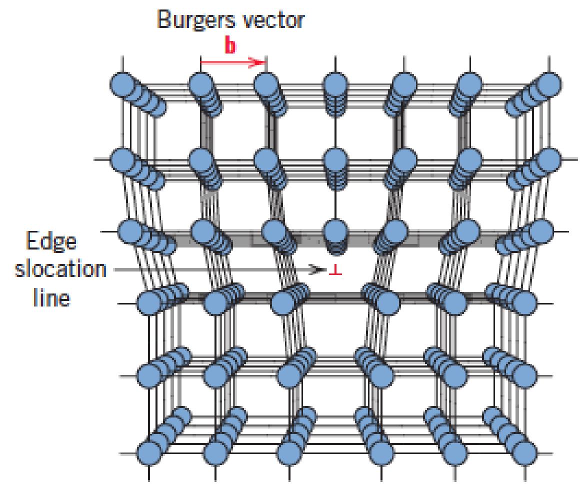
Large variation between predicted (theoretical) strength and actual (measured) strength was used to account for presence of dislocations by Taylor, Polanyi, and Orowan in 1934.

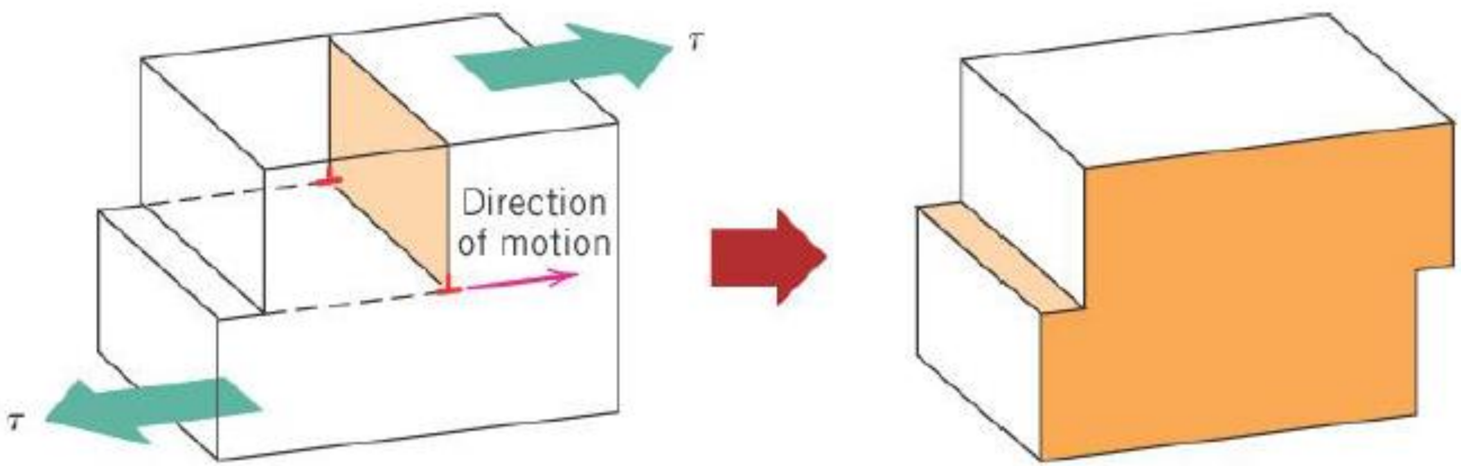
Dislocations allow for consecutive (rather than simultaneous) breakage of atomic bonds, requiring lower stress for onset of plastic deformation

Plastic deformation in metals

Plastic deformation corresponds to the motion of large numbers of dislocations (=slip)

<u>Slip</u>: The process of dislocation motion that produces plastic deformation.





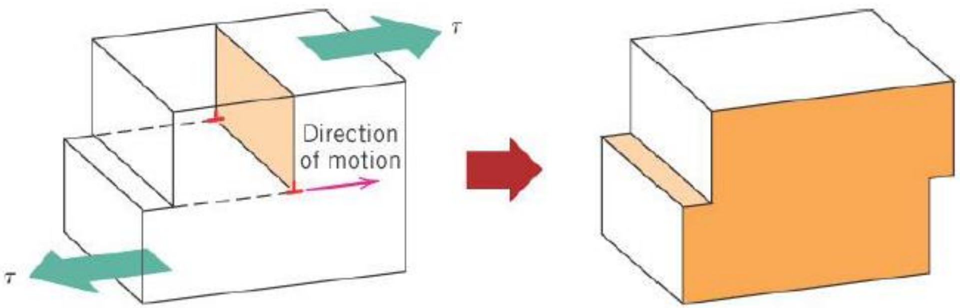
Dislocations:

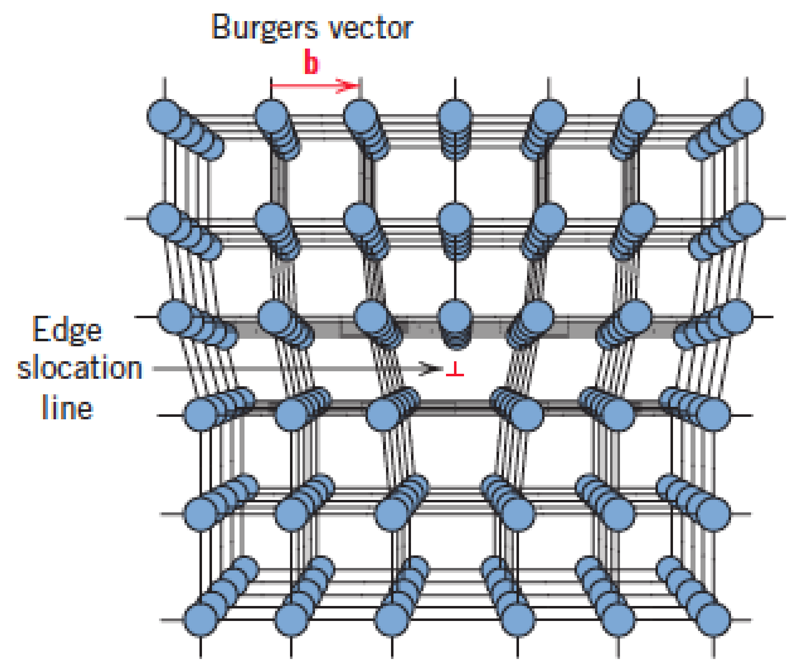
1. Edge dislocations
2. Screw dislocations
3. Mixed dislocations

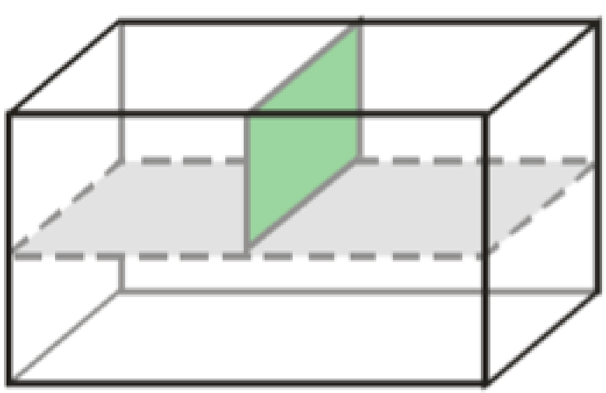
- ✓ Dislocation line
- ✓ Burger vector

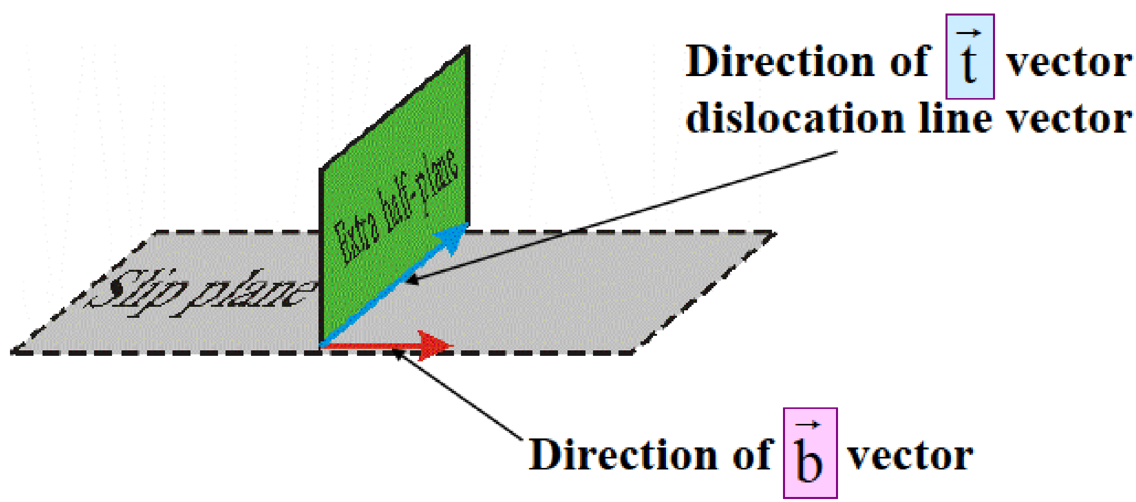
Dislocation line and Burger vector

Dislocation line. The line that extends along the end of the extra half-plane of atoms for an edge dislocation, and along the center of the spiral of a screw dislocation.



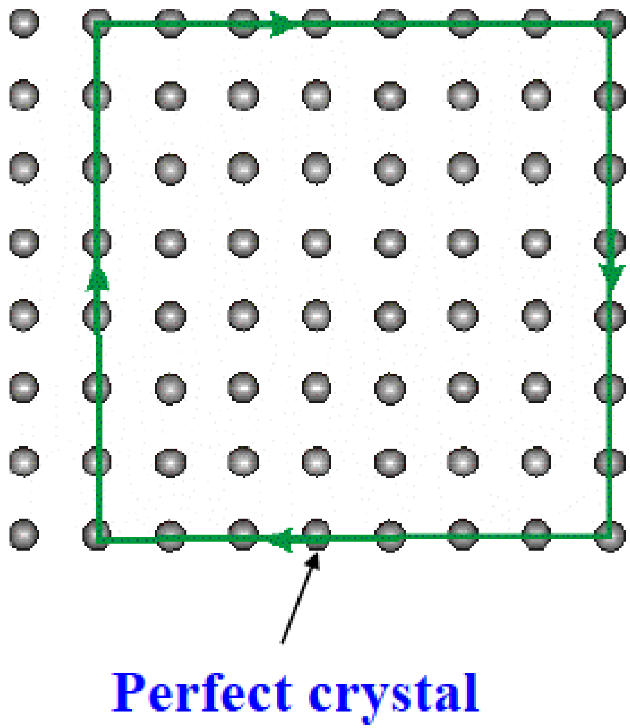


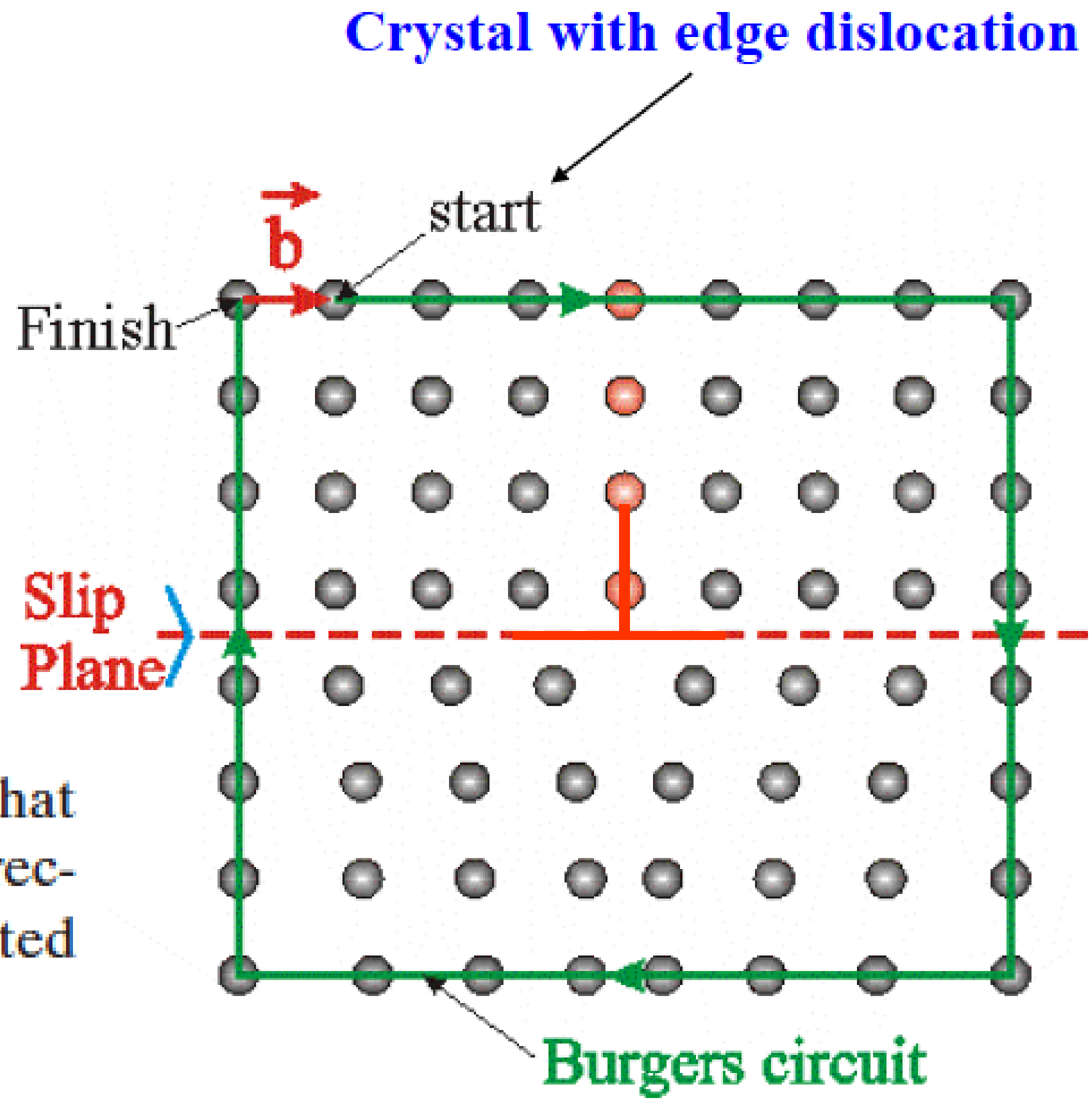




Burgers Vector

Edge dislocation

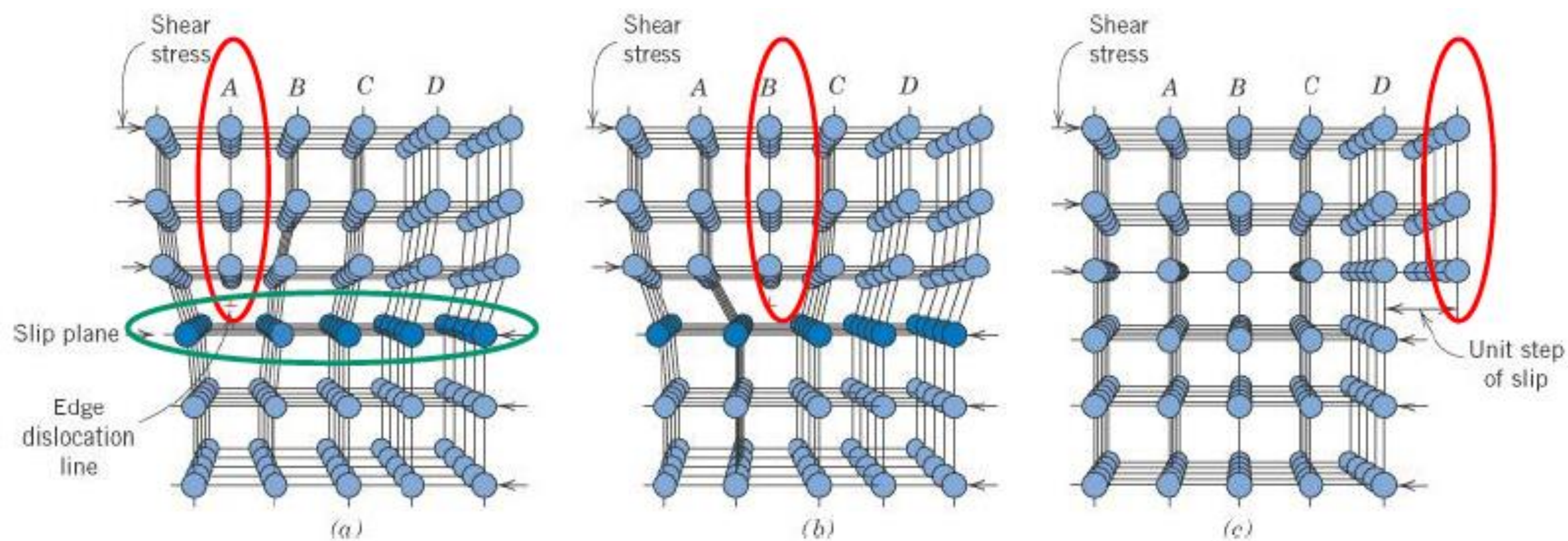


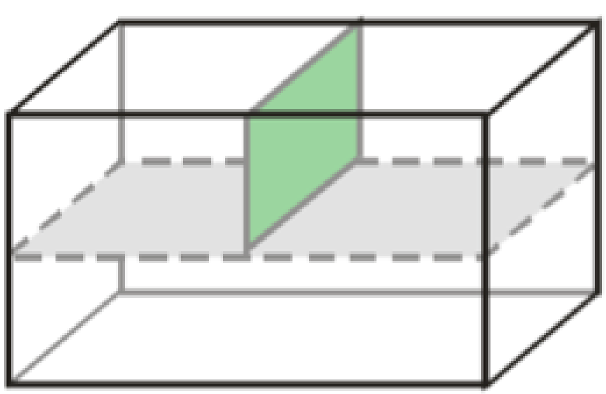


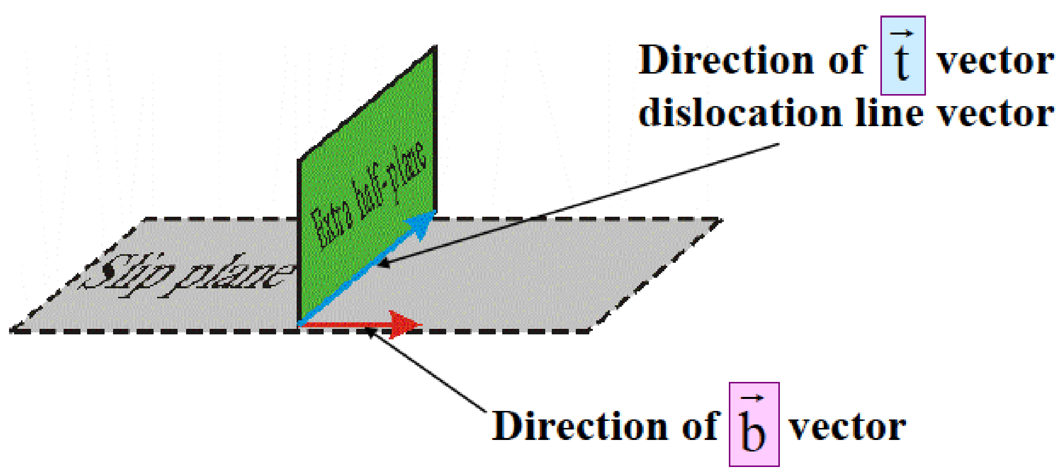
Burgers vector (b). A vector that denotes the magnitude and direction of lattice distortion associated with a dislocation.

1. Edge dislocations:

The burger vector is perpendicular to the dislocation line

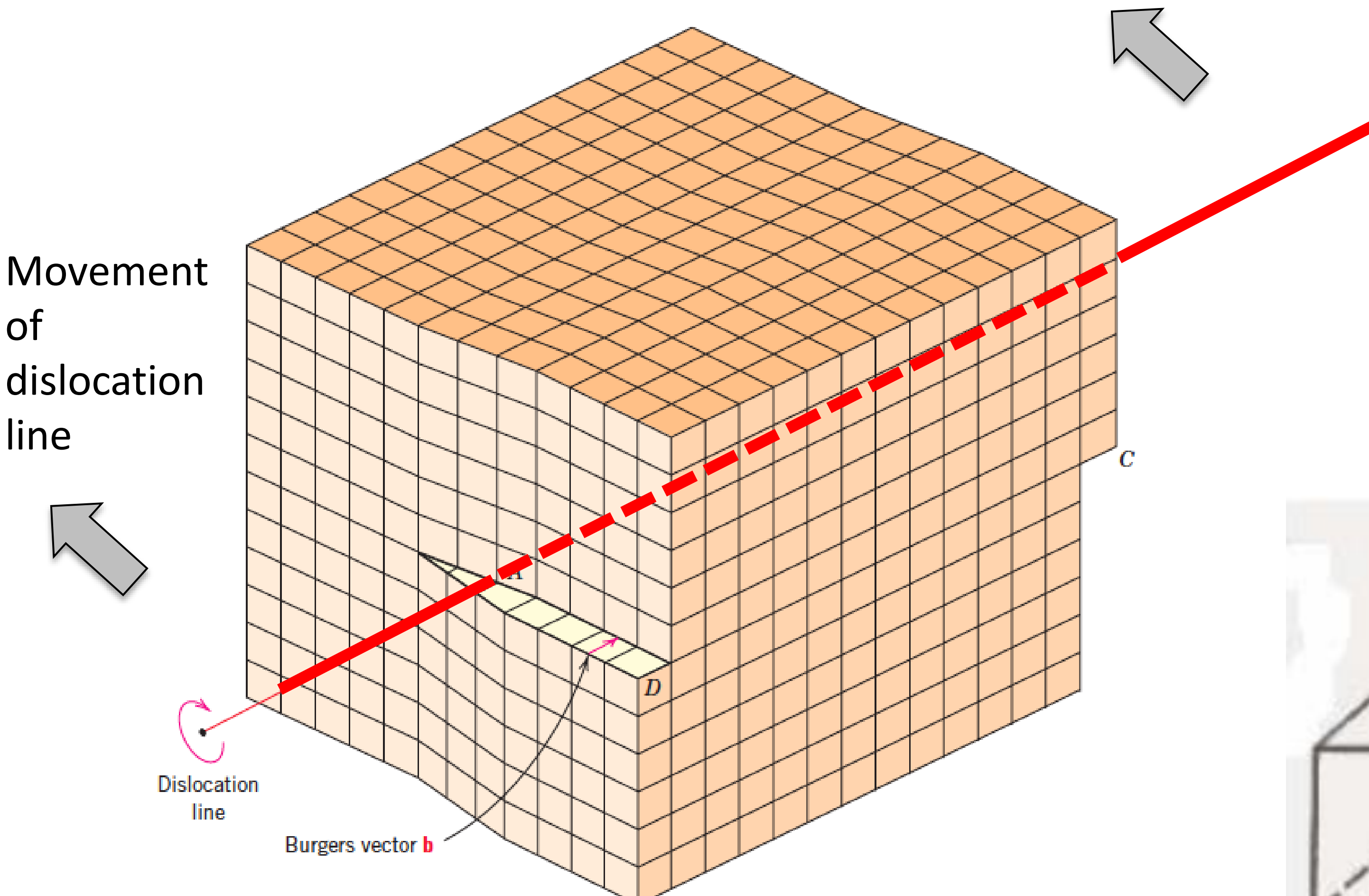


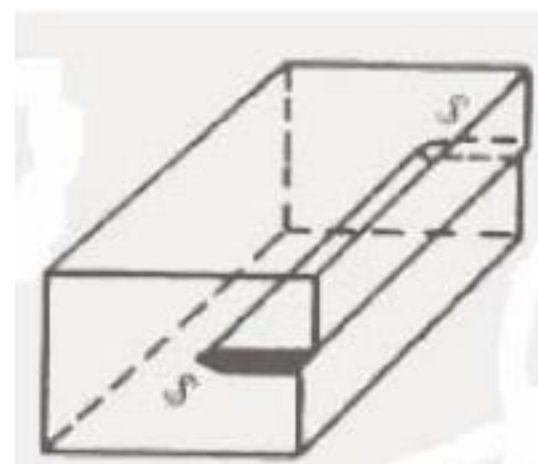




2. Screw dislocations:

The burger vector is parallel to the dislocation line

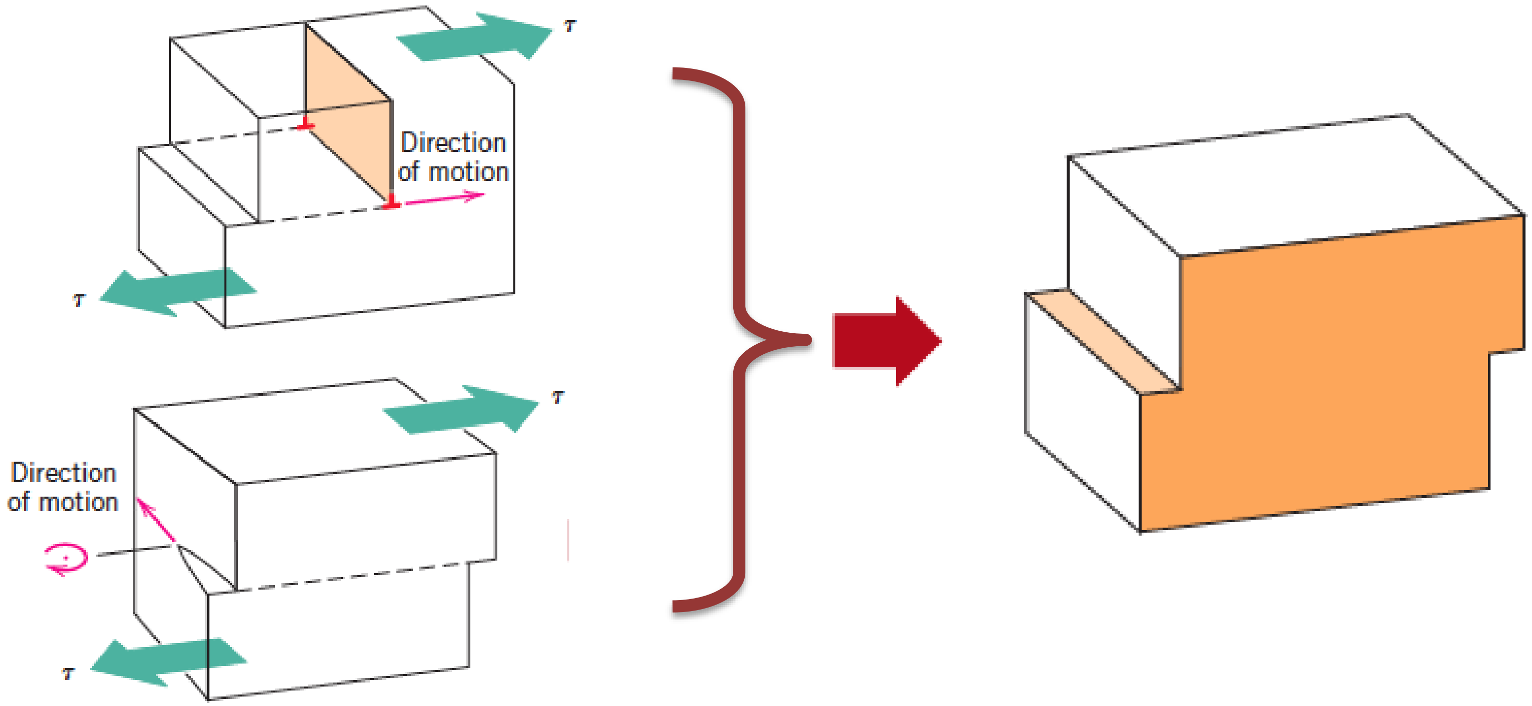




Geometric properties of dislocations

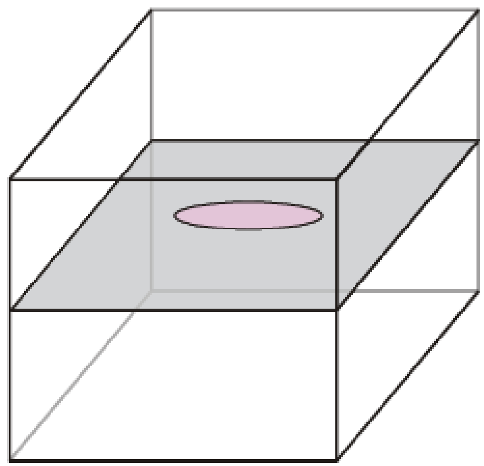
Edge

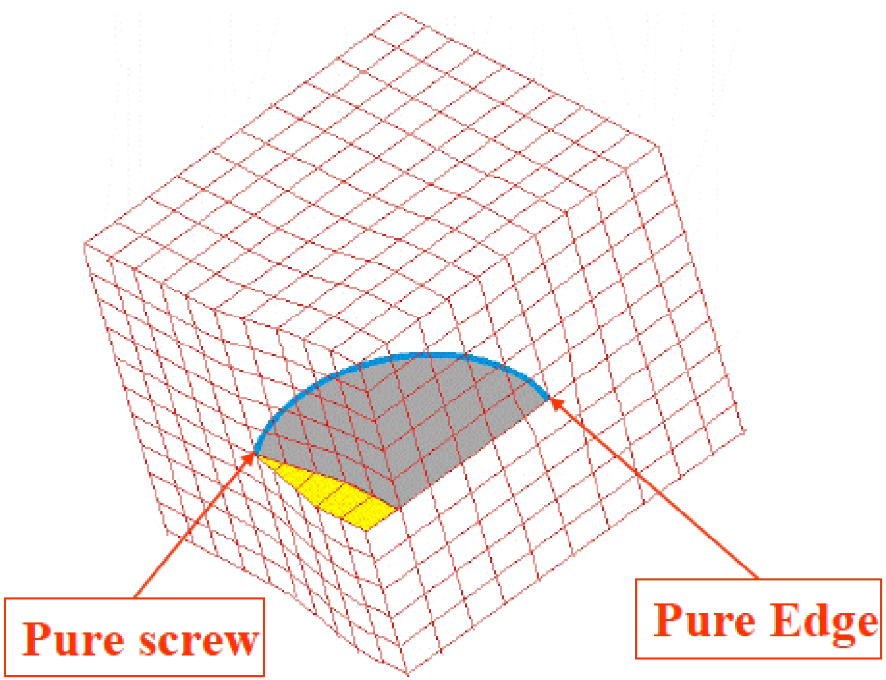
Screw

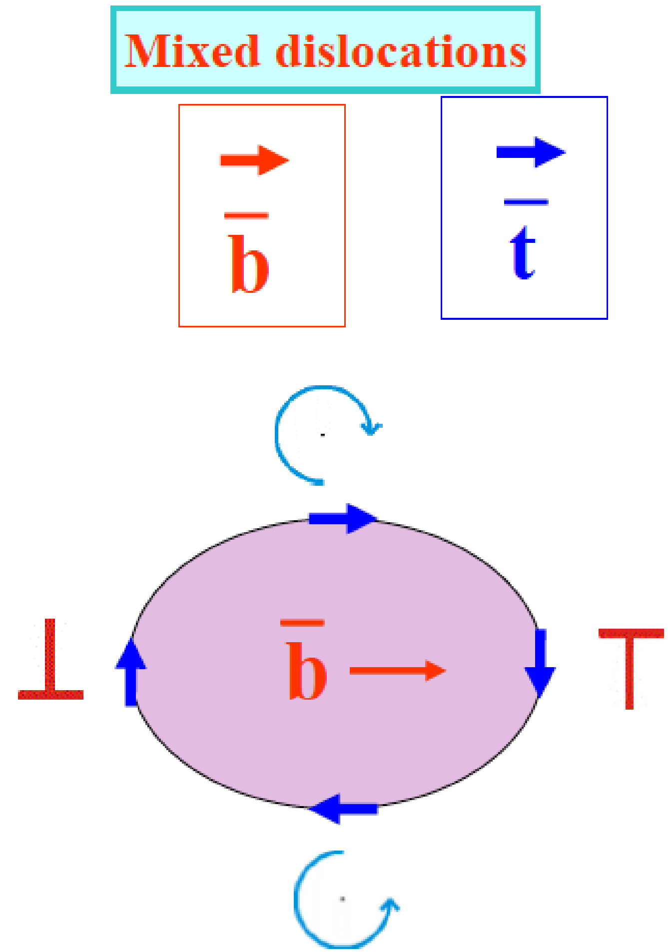


Dislocation Property	Type of dislocation	
	Edge	Screw
Relation between dislocation line (**t**) and **b**	⊥	‖
Slip direction	‖ to **b**	‖ to **b**

3. Mixed dislocations:







Dislocation density:

All metals and alloys contain some dislocations that were introduced during solidification, during plastic deformation, and as a consequence of thermal stresses that result from rapid cooling.

Dislocation density is expressed as:
The total dislocation length per unit volume
(or the number of dislocations that intersect a unit area of a random section)

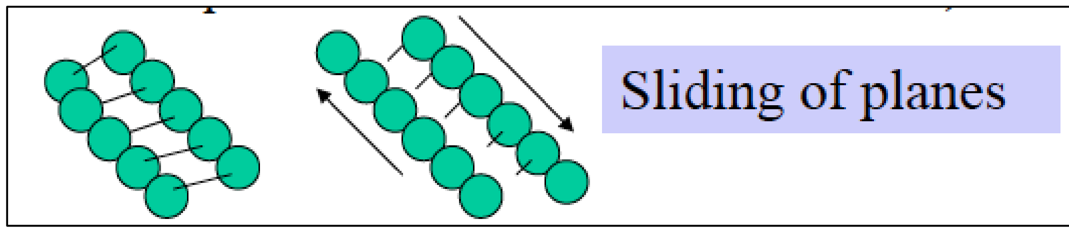
For carefully solidified metals -> $\rho_D = 10^3$ /mm^2
For heavily deformed metals -> $\rho_D = 10^{10}$ /mm^2

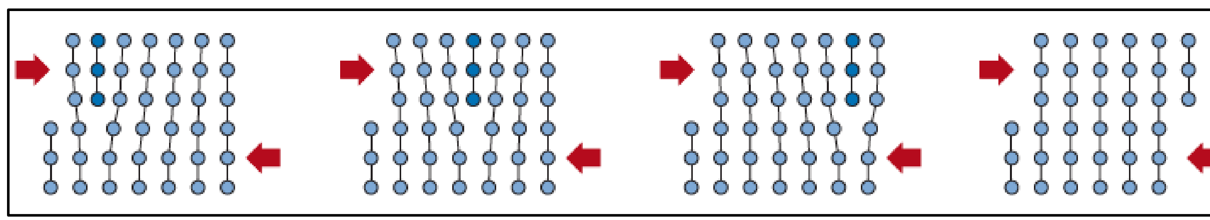
Summary (1)

✓ *Dislocations (Edge, Screw, Mixed)*

Dislocation Property	Type of dislocation	
	Edge	**Screw**
Relation between dislocation line (**t**) and **b**	⊥	‖
Slip direction	‖ to **b**	‖ to **b**

✓ *Basis of presence of dislocations: Slip (main mechanism of plastic deformation in metals)*



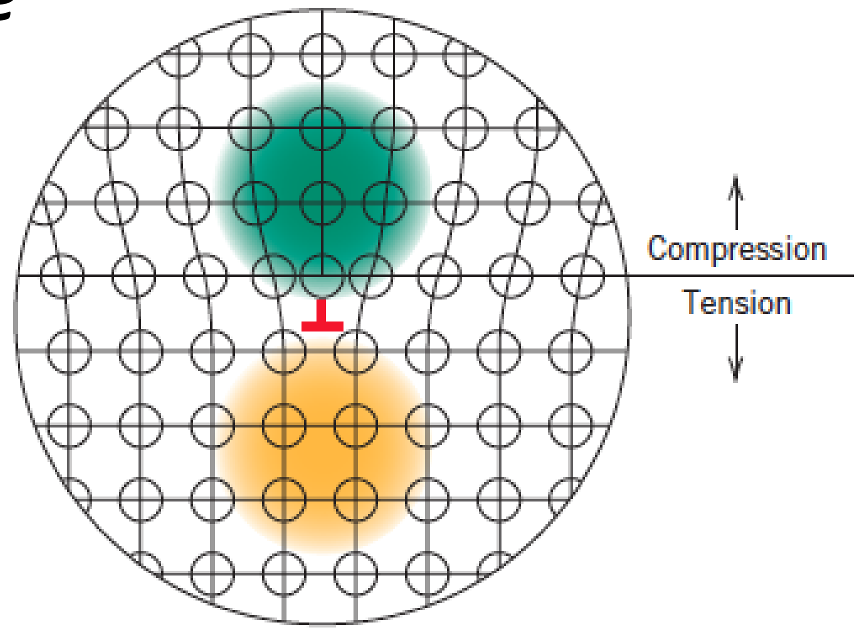


✓ *Dislocation density*

For carefully solidified metals -> $\rho_D = 10^3\ /mm^2$
For heavily deformed metals -> $\rho_D = 10^{10}\ /mm^2$

7.3 CHARACTERISTICS OF DISLOCATIONS

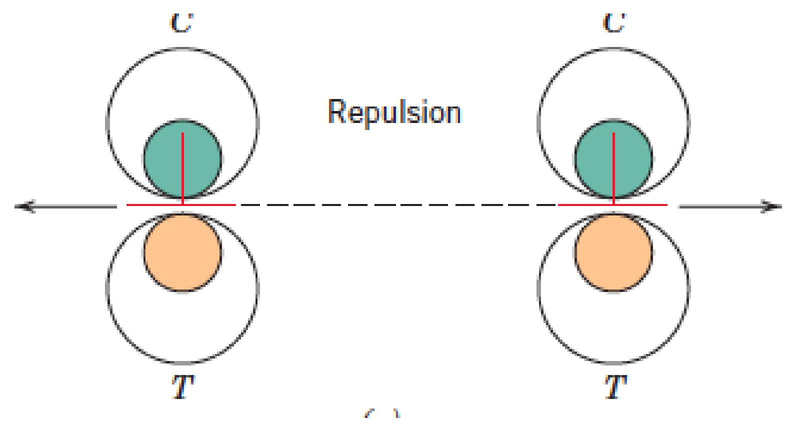
Atomic lattice distortion exists around the dislocation line → **Strain fields around dislocations**



When metals are plastically deformed, some fraction of the deformation energy (~ 5%) is retained internally; mainly as strain energy associated with dislocations *(the remainder is dissipated as heat)*

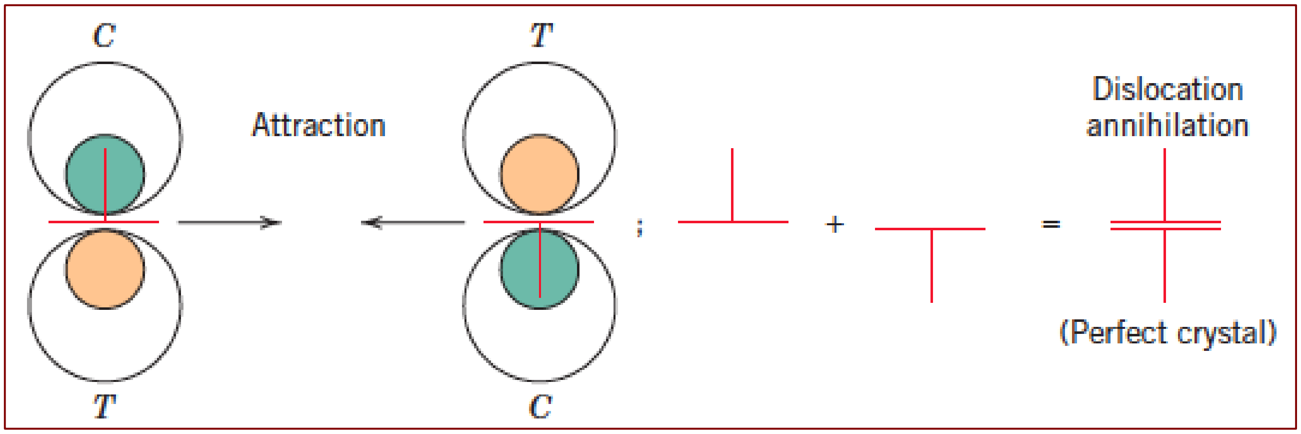
7.3 CHARACTERISTICS OF DISLOCATIONS

- Strain fields around dislocations play an important role in determining the mobility of the dislocations, as well as their ability to multiply.



Dislocation interactions

Strain fields and associated forces are important in the strengthening mechanisms for metals.



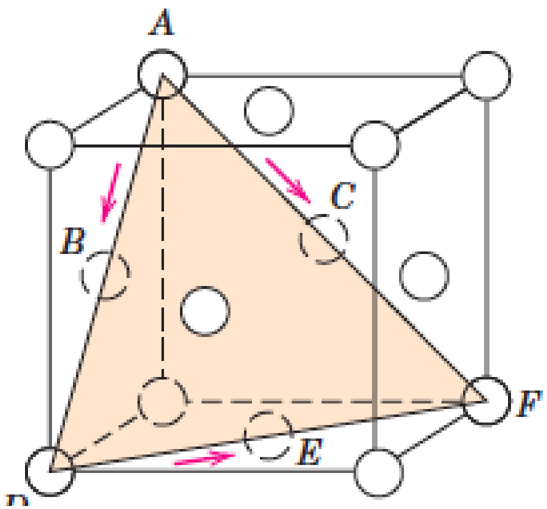
7.4 Slip systems:

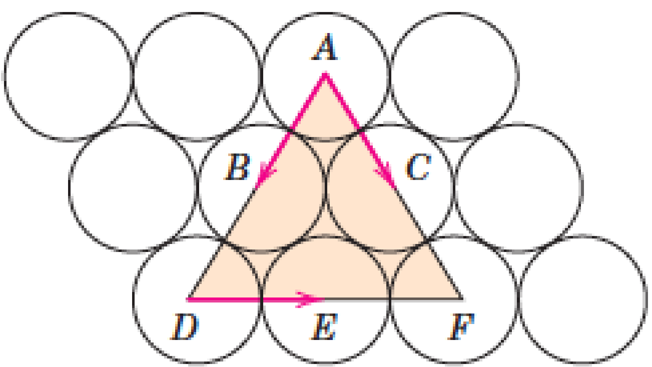
There is a preferred plane (slip plane), and in that plane there are specific directions (slip direction) along which dislocation motion occurs.

Slip system:
- Slip plane: plane swept by the dislocation during slip
- Slip direction: direction on slip plane along which dislocation moves.

- Slip plane: it has the greatest planar density
- Slip direction: it has the highest linear density

Slip systems for FCC





α	direction $\mathbf{m}_0^\alpha$	Planes $\mathbf{n}_0^\alpha$
1	1 -1 0	1 1 1
2	1 0 -1	1 1 1
3	0 1 -1	1 1 1
4	1 0 1	-1 1 1
5	1 1 0	-1 1 1
6	0 1 -1	-1 1 1
7	1 0 -1	1 -1 1
8	0 1 1	1 -1 1
9	1 1 0	1 -1 1
10	1 -1 0	1 1 -1
11	1 0 1	1 1 -1
12	0 1 1	1 1 -1

7.4 Slip systems:

Table 7.1 Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

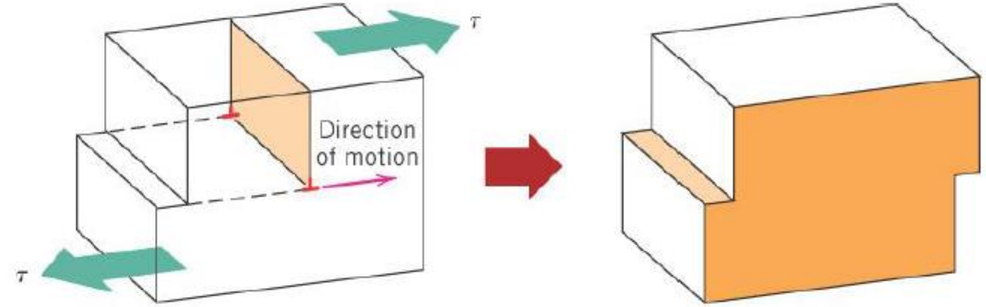
Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	$\{111\}$	$\langle 1\bar{1}0 \rangle$	12
	Body-Centered Cubic		
α-Fe, W, Mo	$\{110\}$	$\langle \bar{1}11 \rangle$	12
α-Fe, W	$\{211\}$	$\langle \bar{1}11 \rangle$	12
α-Fe, K	$\{321\}$	$\langle \bar{1}11 \rangle$	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	$\{0001\}$	$\langle 11\bar{2}0 \rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0 \rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0 \rangle$	6

7.4 Slip systems:

Metals with FCC or BCC crystal structures have a relatively large number of slip systems (at least 12). These metals are quite ductile because extensive plastic deformation is normally possible along the various systems. Conversely, HCP metals, having few active slip systems, are normally quite brittle.

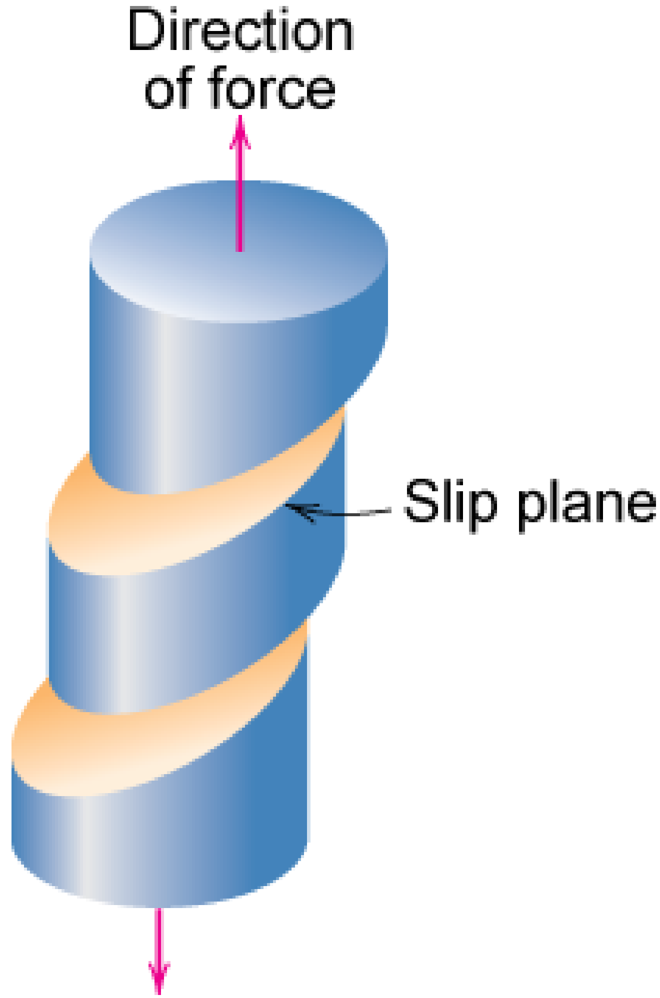
No. of slip systems **>>>** slip activity (dislocation motion) **>>>** Ductility

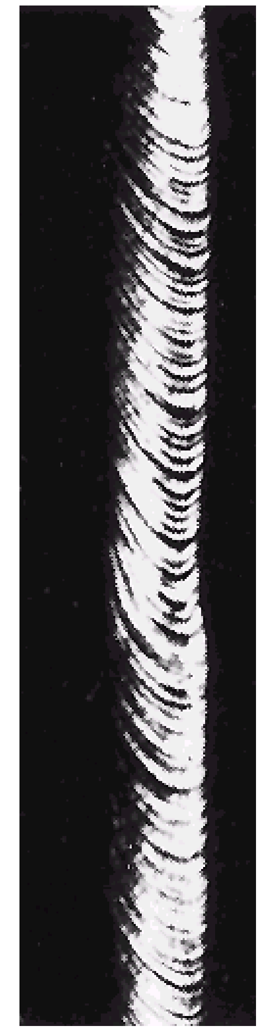
7.5 Slip in Single Crystals



Schmid law:

Slip occurs when the resolved shear stress reaches a critical value, known as the critical resolved shear stress.





$$\tau_{rss} = \tau_{crss}$$

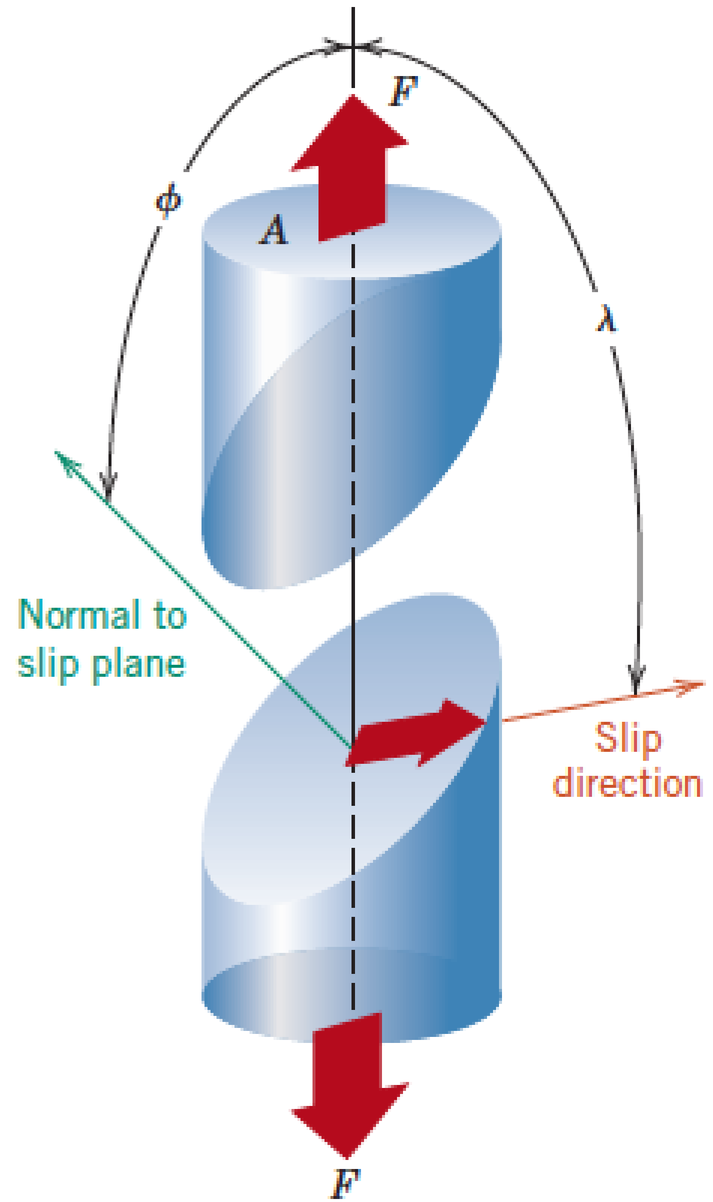
7.5 Slip in Single Crystals

Schmid law:

Slip occurs when $\tau_{rss} \geq \tau_{crss}$

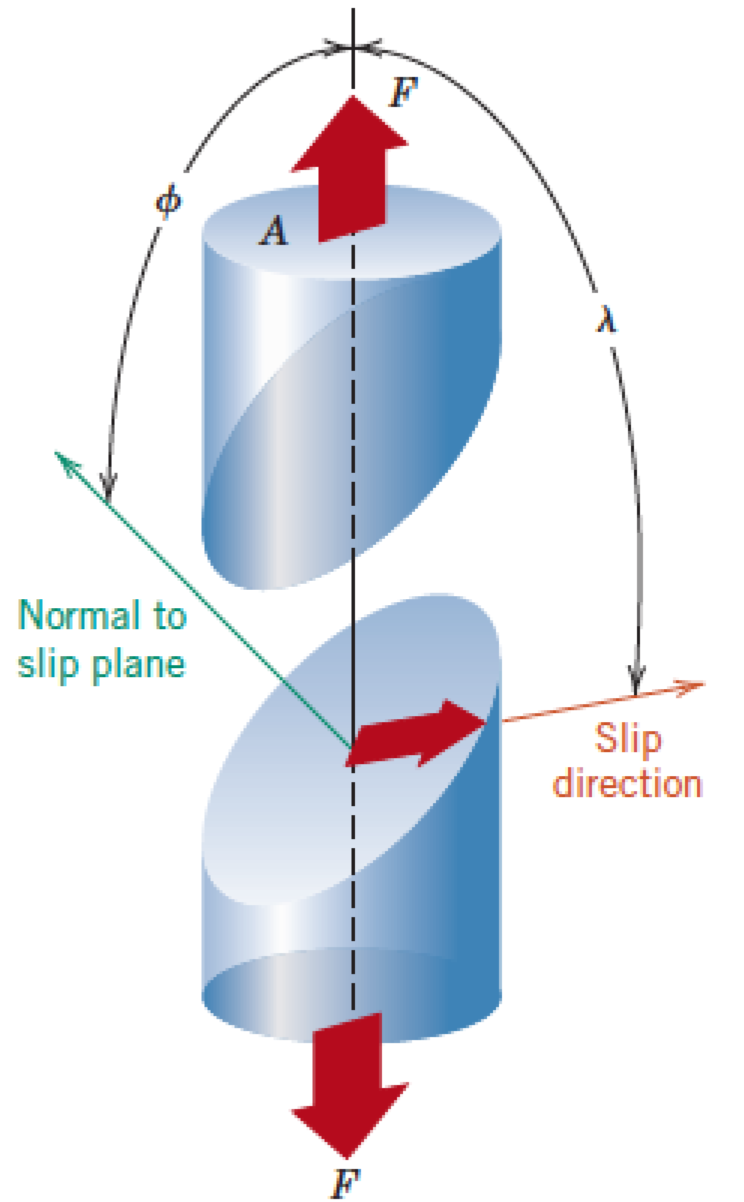
τ_{rss}: The shear component of the stress resolved along a specific plane and direction within that plane.

τ_{crss}: The required shear stress to initiate slip.



7.5 Slip in Single Crystals

λ: Angle b/w load and slip direction
φ: Angle b/w load and slip plan normal



$\tau_{rss} = F_s / A_s$

Component of force in the slip direct

$F_s = F \cos \lambda$

The area of the slip surface:

$A_s = A/\cos \varphi$

$$\tau_{rss} = F_s / A_s = F/A \cos \lambda \ \cos \varphi$$
$$= \sigma \ \cos \lambda \ \cos \varphi$$

Schmid factor=cos λ cos φ

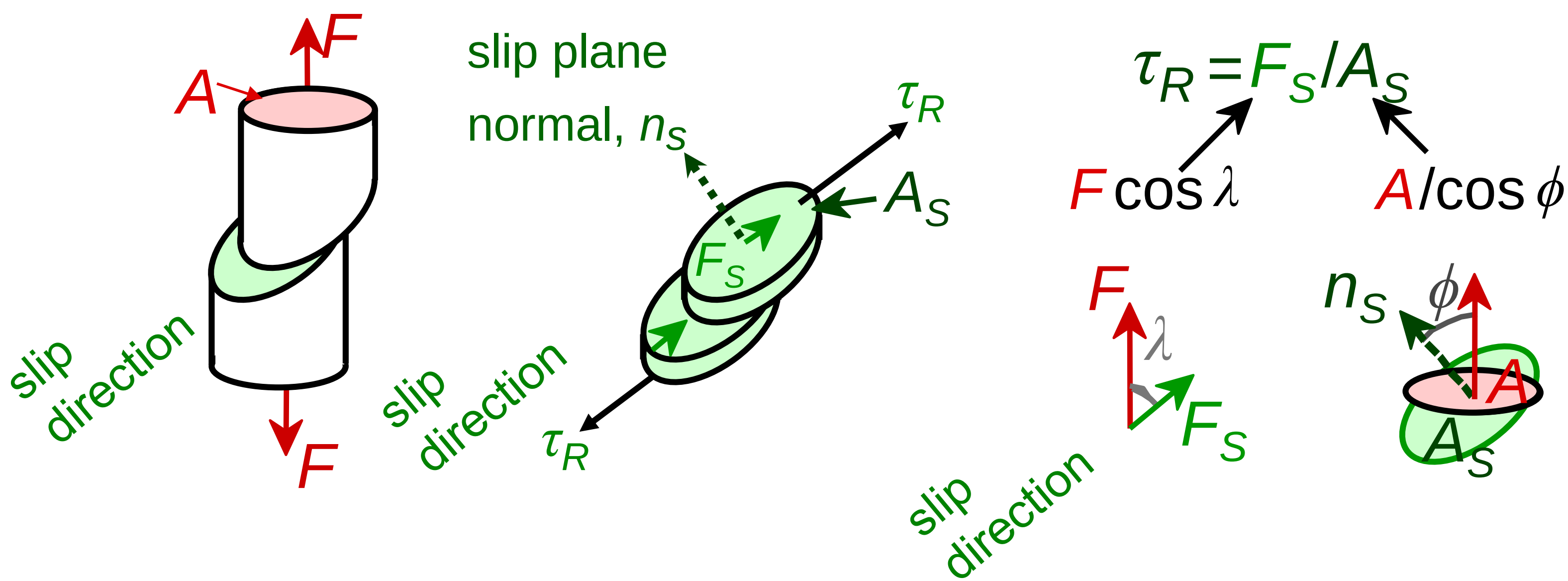
Stress and Dislocation Motion

- Resolved shear stress, τ_R
  - – results from applied tensile stresses

Applied tensile stress: $\sigma = F/A$

Resolved shear stress: $\tau_R = F_S/A_S$

Relation between σ and τ_R



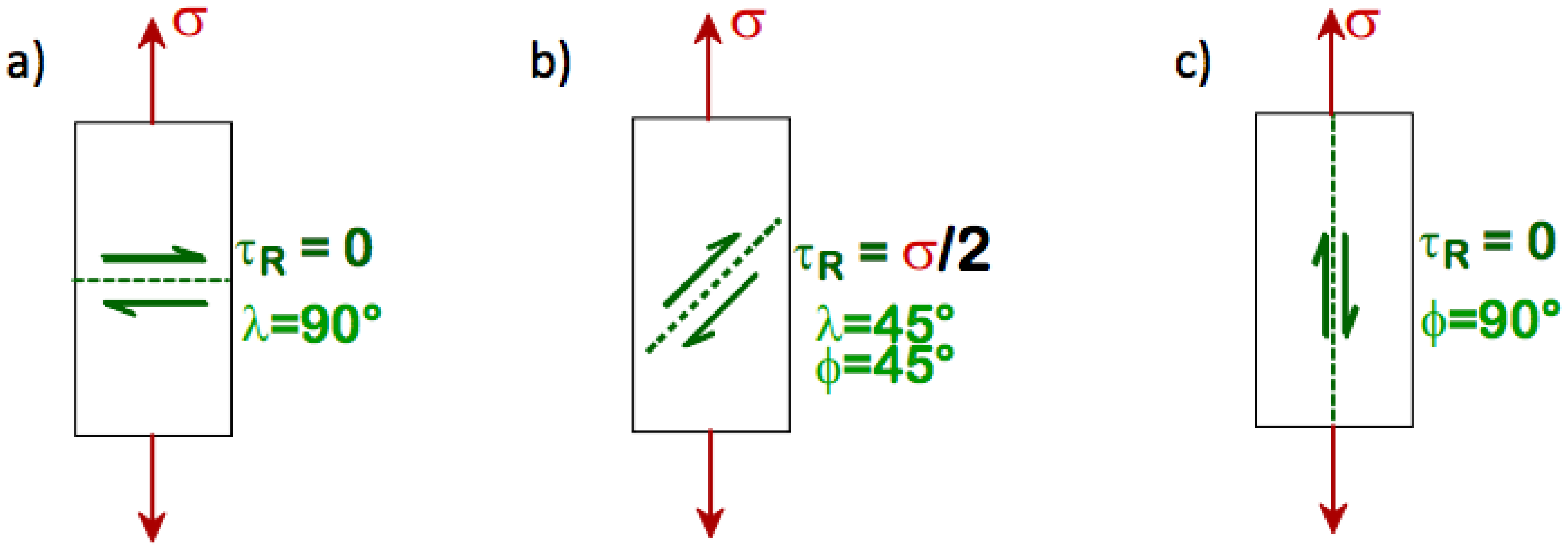
$$\tau_R = \sigma \cos\lambda \cos\phi$$

7.5 Special cases: Slip in Single Crystals

$$\tau_{rss} = \sigma \; \cos\lambda \; \cos\varphi$$

λ: Angle b/w load and slip direction

φ: Angle b/w load and slip plan normal



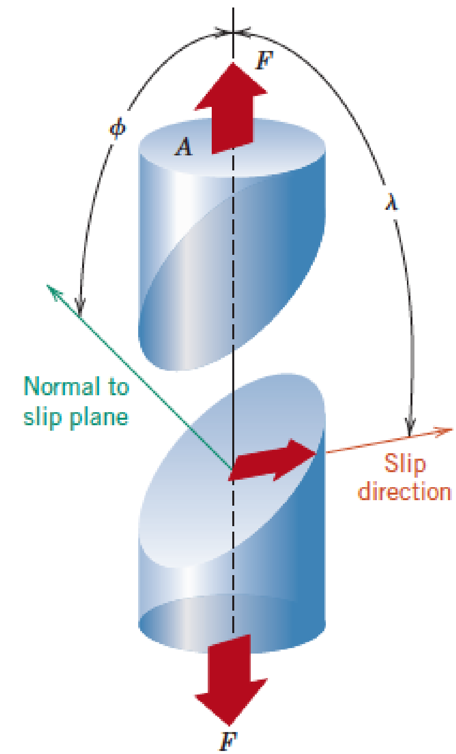
7.5 Slip in Single Crystals

λ: Angle b/w load and slip direction

φ: Angle b/w load and slip plan normal

$$\tau_{rss} = \sigma \cos\lambda \cos\varphi$$

$$\tau_{crss} = \sigma_y (\cos\phi \cos\lambda)$$



7.12 Consider a metal single crystal oriented such that the normal to the slip plane and the slip direction are at angles of 60° and 35°, respectively, with the tensile axis. If the critical resolved shear stress is 6.2 MPa (900 psi), will an applied stress of 12 MPa (1750 psi) cause the single crystal to yield? If not, what stress will be necessary?

7.12 Consider a metal single crystal oriented such that the normal to the slip plane and the slip direction are at angles of 60° and 35°, respectively, with the tensile axis. If the critical resolved shear stress is 6.2 MPa (900 psi), will an applied stress of 12 MPa (1750 psi) cause the single crystal to yield? If not, what stress will be necessary?

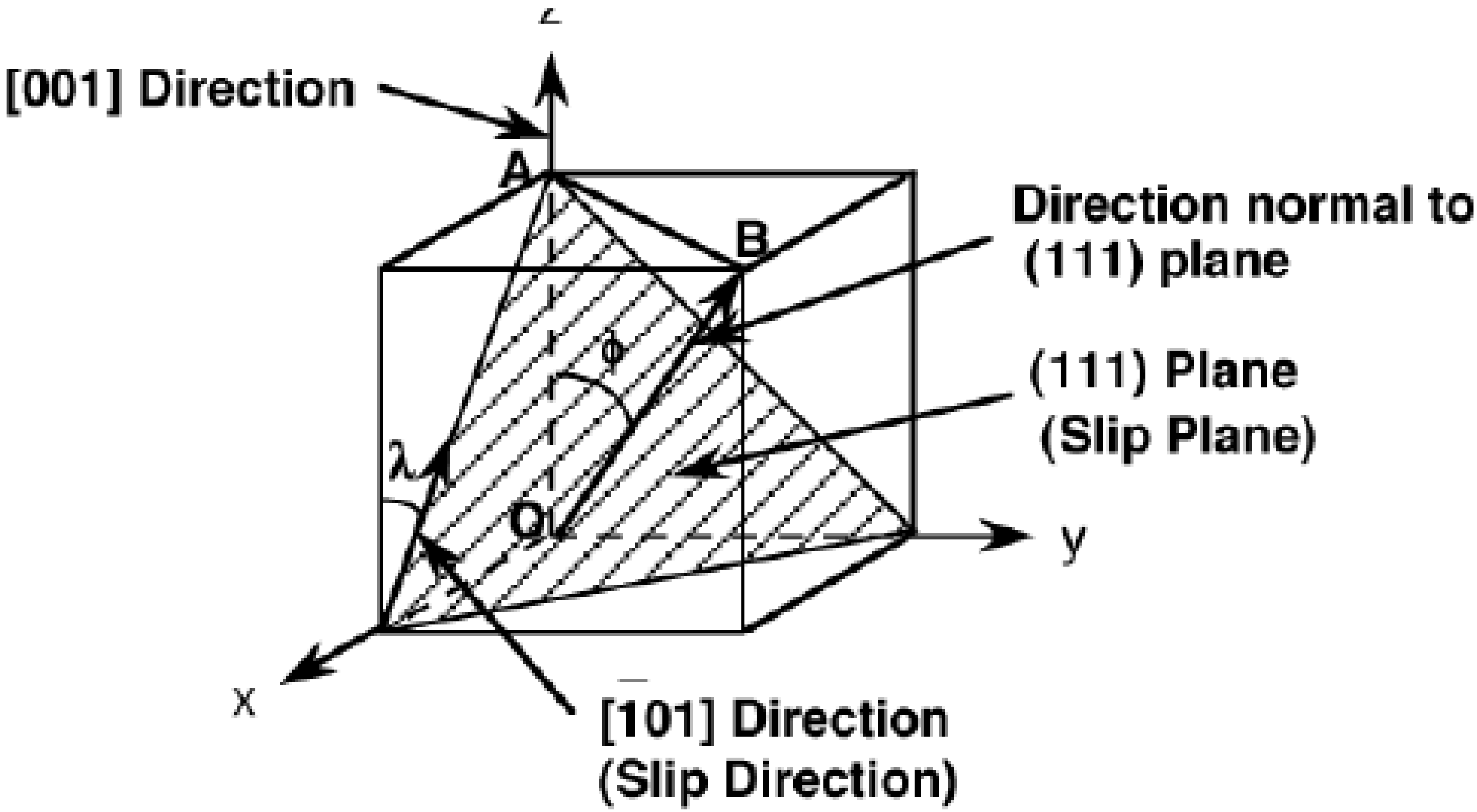
$$\tau_R = \sigma \cos\phi \cos\lambda = (12\text{ MPa})(\cos 60^\circ)(\cos 35^\circ) = 4.91\text{ MPa}$$

→ No yielding since $\tau_{rss} < \tau_{crss}$

$$\sigma_y = \frac{\tau_{crss}}{\cos\phi \cos\lambda} = \frac{6.2\text{ MPa}}{(\cos 60^\circ)(\cos 35^\circ)} = 15.1\text{ MPa}$$

7.14 Consider a single crystal of nickel oriented such that a tensile stress is applied along a [001] direction. If slip occurs on a (111) plane and in a $[\bar{1}01]$ direction, and is initiated at an applied tensile stress of 13.9 MPa (2020 psi), compute the critical resolved shear stress.

Prob. 7.14



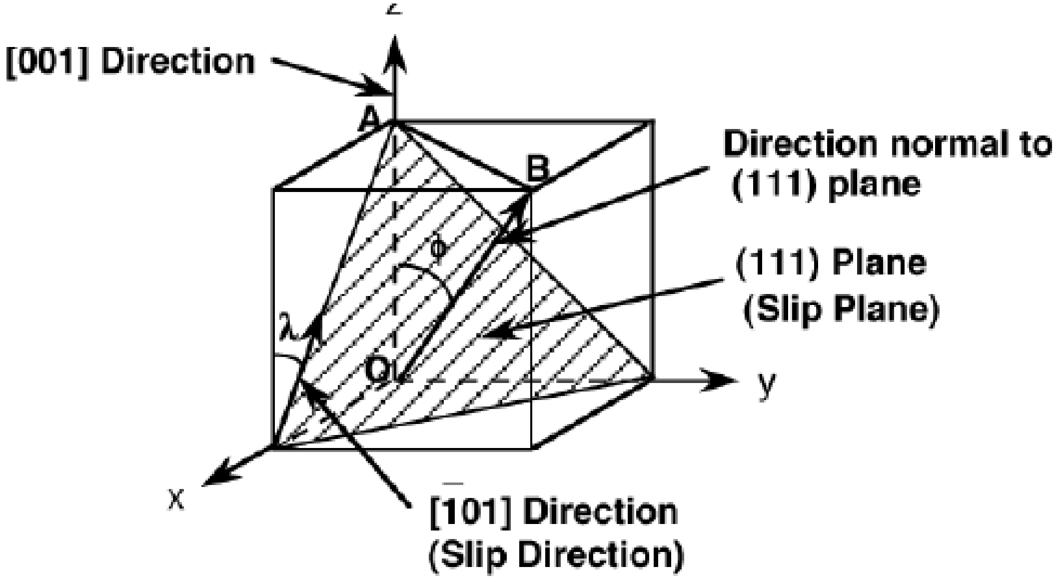
z
[001] Direction
A
B
Direction normal to (111) plane
ϕ
(111) Plane (Slip Plane)
λ
O
y
x
[$\bar{1}$01] Direction (Slip Direction)

Prob. 7.14

$$\lambda = \tan^{-1}\left(\frac{a}{a}\right) = 45^\circ$$

$$\phi = \tan^{-1}\left(\frac{a\sqrt{2}}{a}\right) = 54.7^\circ$$

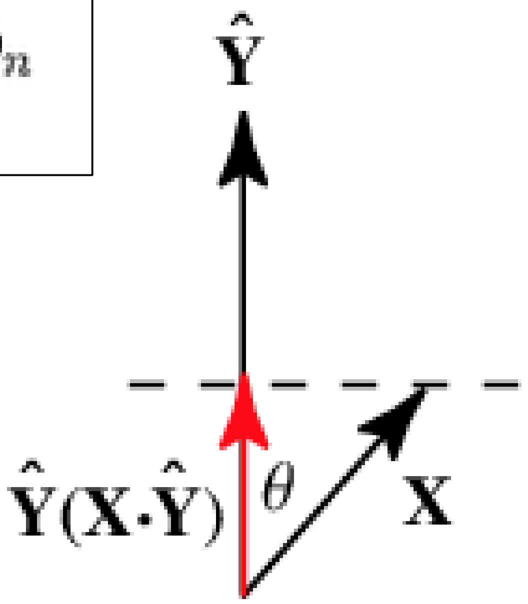
$$\tau_{crss} = \sigma_y (\cos\phi \cos\lambda)$$



= 13.9 *cos(45) * cos (54.7) = 5.68 MPa

Review of dot product:

$$\mathbf{a} \cdot \mathbf{b} = \sum_{i=1}^{n} a_i b_i = a_1 b_1 + a_2 b_2 + \cdots + a_n b_n$$



$$\begin{aligned}[1, 3, -5] \cdot [4, -2, -1] &= (1)(4) + (3)(-2) + (-5)(-1) \\ &= 4 - 6 + 5 \\ &= 3.\end{aligned}$$

$$\mathbf{A} \cdot \mathbf{B} = \|\mathbf{A}\| \, \|\mathbf{B}\| \cos\theta$$

$$\|\mathbf{x}\| := \sqrt{x_1^2 + x_2^2 + \cdots + x_n^2}.$$

[4, 5, 6] is $\sqrt{(4^2 + 5^2 + 6^2)} = \sqrt{77}$

Using dot product to find λ and φ:

$$\textit{Loading direction:} \quad \vec{LD} = [001]$$
$$\textit{Slip direction:} \quad \vec{SD} = [-1\ 0\ 1]$$
$$\textit{Plane normal direction:} \quad \vec{PD} = [111]$$

Since λ is the angle between loading direction and slip direction, it can be computed from the relation:

$$\vec{LD} \cdot \vec{SD} = |\vec{LD}|\,|\vec{SD}|\,cos\lambda$$

where

$$\vec{LD} \cdot \vec{SD} = [001] \cdot [-1\ 0\ 1] = 0 * -1 + 0 * 0 + 1 * 1 = 1$$

$$|\vec{LD}| = \sqrt{0^2 + 0^2 + 1^2} = 1$$

$$|\vec{SD}| = \sqrt{(-1)^2 + 0^2 + 1^2} = \sqrt{2}$$

Thus,

$$\vec{LD} \cdot \vec{SD} = |\vec{LD}|\,|\vec{SD}|\,cos\lambda \quad \longrightarrow \quad 1 = \sqrt{2}\,cos\lambda \quad \longrightarrow \quad cos\lambda = \frac{1}{\sqrt{2}}$$

Using dot product to find λ and φ:

Loading direction: $\overrightarrow{LD} = [001]$

Slip direction: $\overrightarrow{SD} = [-1\ 0\ 1]$

Plane normal direction: $\overrightarrow{PD} = [111]$

The angle Φ , the angle between loading direction and slip plane normal, can be computed from the relation:

$$\overrightarrow{LD} \cdot \overrightarrow{PD} = |\overrightarrow{LD}|\ |\overrightarrow{PD}| \cos\Phi$$

where

$$\overrightarrow{LD} \cdot \overrightarrow{SD} = [001] \cdot [11\ 1] = 1$$

$$|\overrightarrow{PD}| = \sqrt{(1)^2 + 1^2 + 1^2} = \sqrt{3}$$

Thus,

$$\overrightarrow{LD} \cdot \overrightarrow{PD} = |\overrightarrow{LD}|\ |\overrightarrow{PD}| \cos\Phi \quad \longrightarrow \quad 1 = \sqrt{3}\ cos\Phi \quad \longrightarrow \quad cos\Phi = \frac{1}{\sqrt{3}}$$

$$\tau_{rss} = \sigma\ cos\lambda\ \ cos\Phi = 13.9 * \frac{1}{\sqrt{2}} * \frac{1}{\sqrt{3}} = 5.67\ \text{MPa}$$

Summary (2)

November 24, 2014

- ✓ *Dislocations (Edge, Screw, Mixed)*
- ✓ *Basis of presence of dislocations*
- ✓ *Slip (plastic deformation)*
- ✓ *Dislocation density*

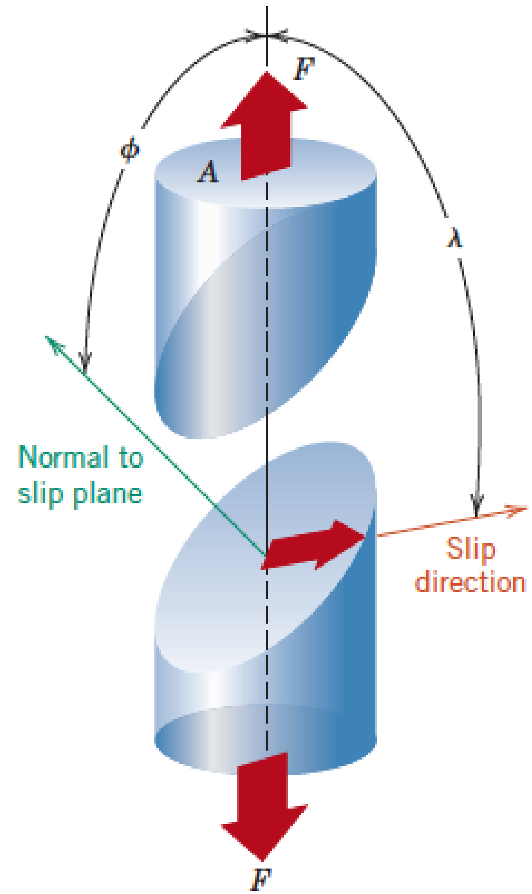
- ✓ **Strain fields around dislocations** *(Dislocation interactions, annihilation)*

- ✓ **Slip systems** *(no. of slip systems, relation to ductility)*

- ✓ **Slip in single crystals (Schmid law):**

Slip occurs if $\tau_{rss} >= \tau_{crss}$

$$\tau_{rss} = \sigma \cos\lambda \cos\varphi$$

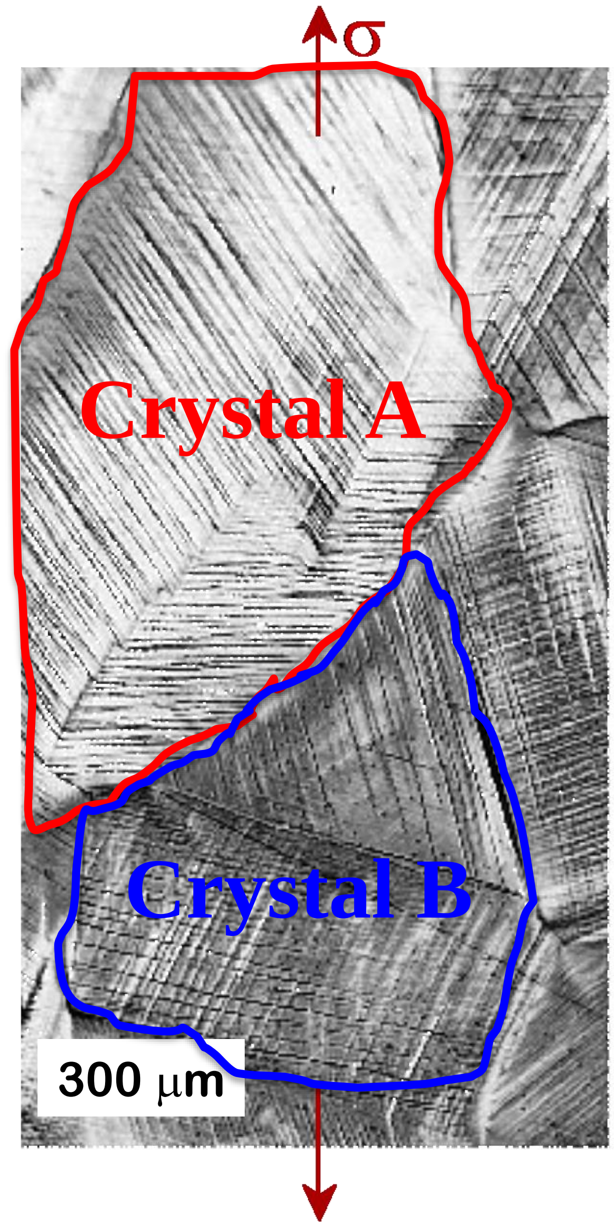


Schmid factor=cos λ cos φ

7.6 Cont'd: Plastic deformation of polycrystalline materials

Polycrystalline metals are stronger than their single-crystal ➔ greater stresses are required for yielding.

This is, to a large degree, a result of geometrical constraints that are imposed on the grains during deformation.



Strengthening mechanisms:

- Understand the relation between dislocation motion and mechanical behavior of metals.

  - The ability of a metal to plastically deform depends on the ability of dislocations to move .

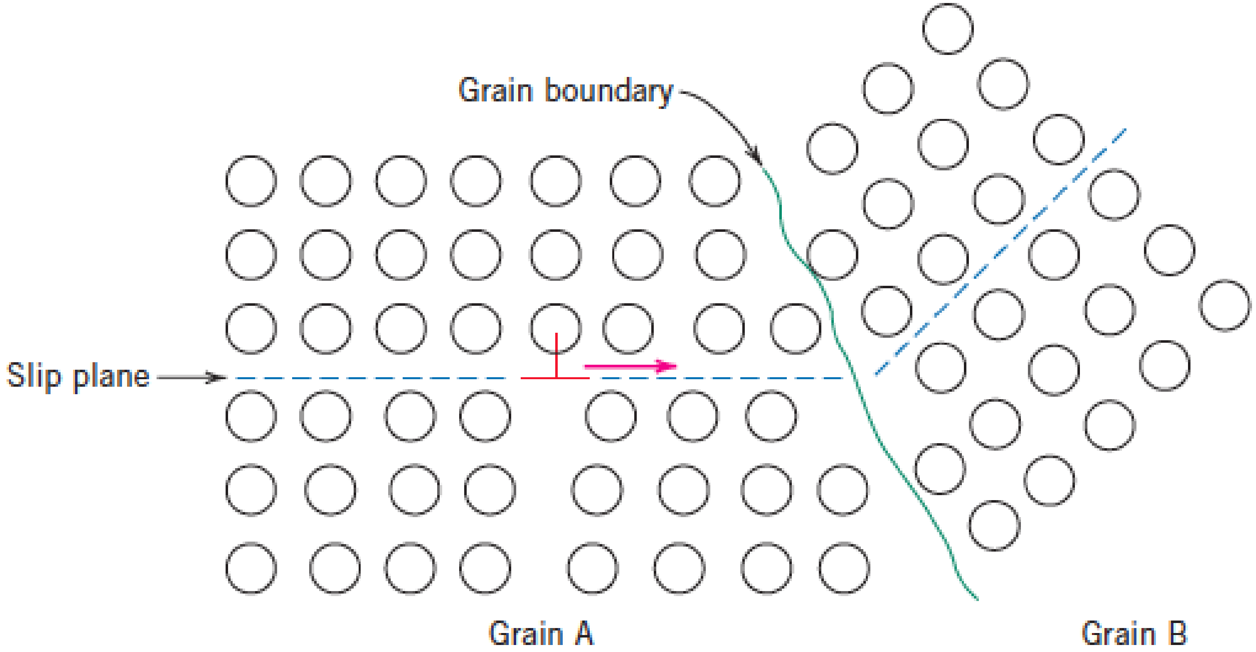
  - By reducing the mobility of dislocations, the mechanical strength may be enhanced; that is, greater mechanical forces will be required to initiate plastic deformation.

Strengthening by grain size reduction, solid-solution strengthening, and strain hardening.

A. Strengthening by grain size reduction:

Roles of grain boundaries:

- The grain boundary acts as a barrier to dislocation motion
- Dislocation pile-up ➔ Stress concentrations ➔ dislocation sources



A. Cont'd: Strengthening by grain size reduction:

Reason for increase in strength by reducing grain size:

Small grain size (fine-grained material) → large grain boundary area (compared to coarse-grained material) → dislocations motion becomes more difficult → higher strength

Hall-Petch equation

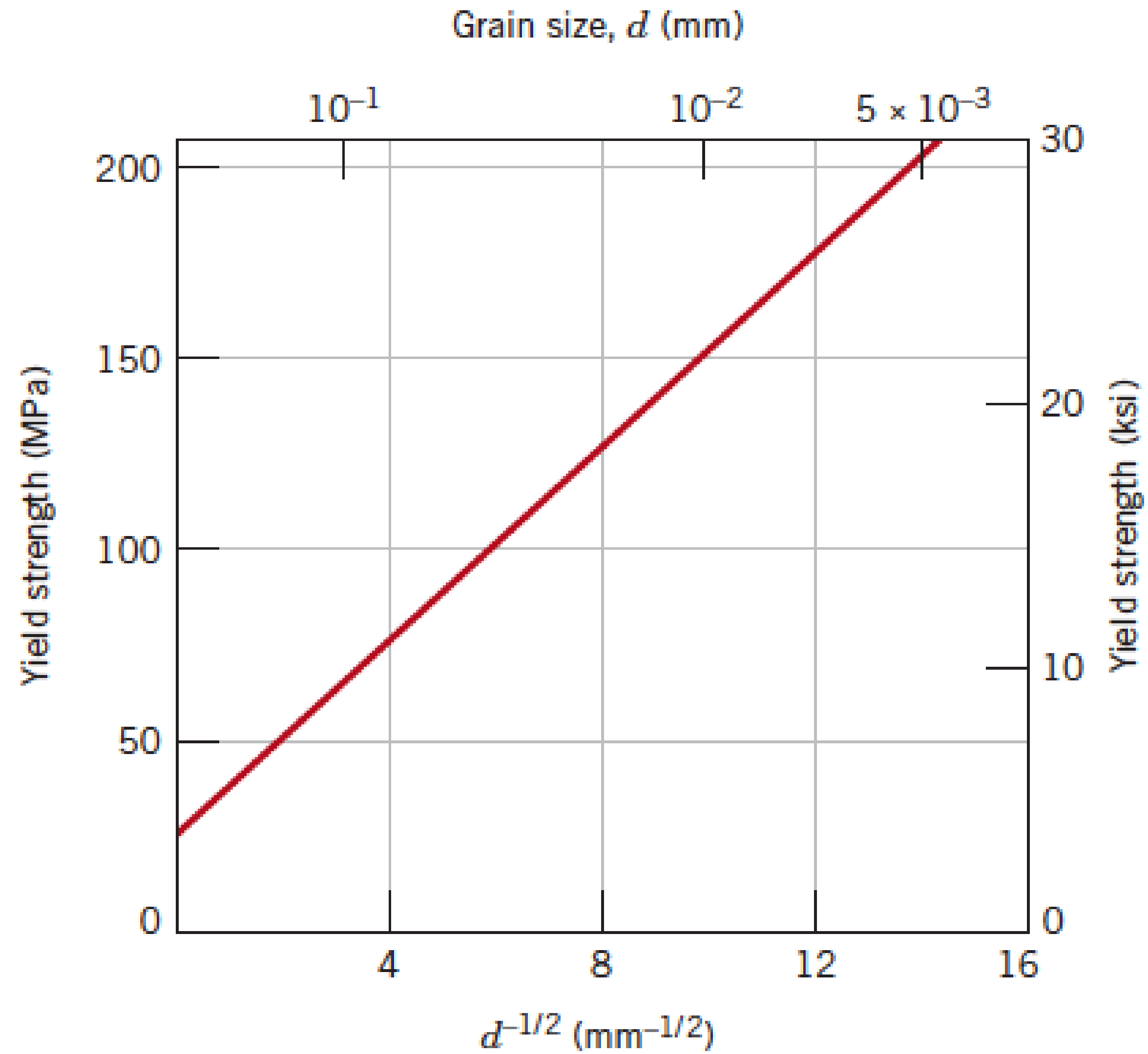
$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

dependence of yield strength on grain size

A. Cont'd: Strengthening by grain size reduction:

Hall-Petch equation

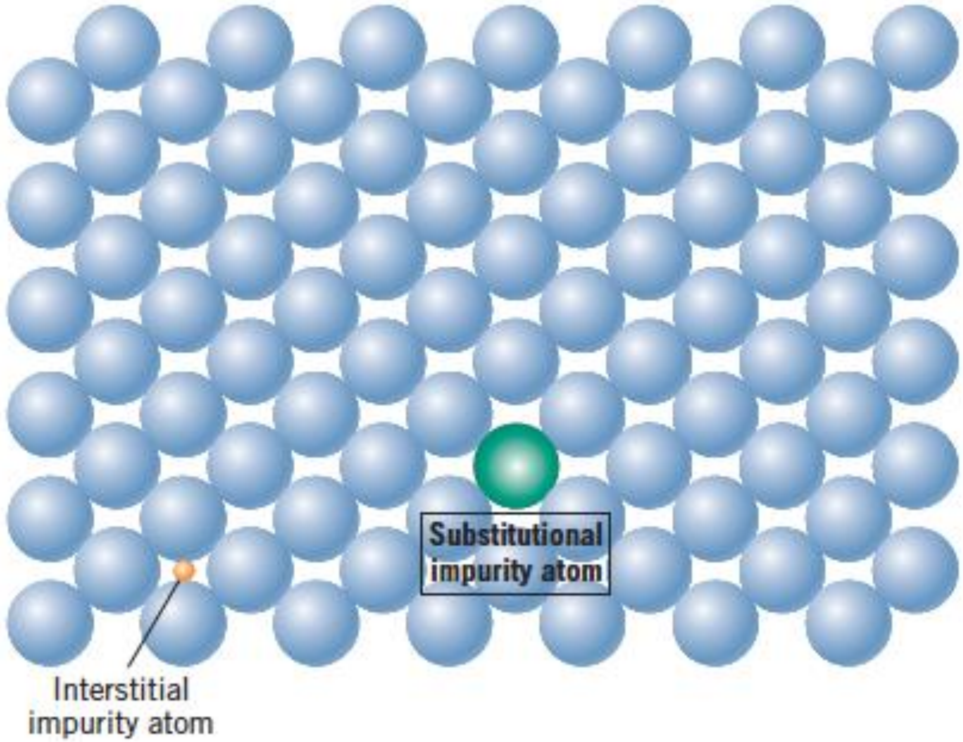
$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$



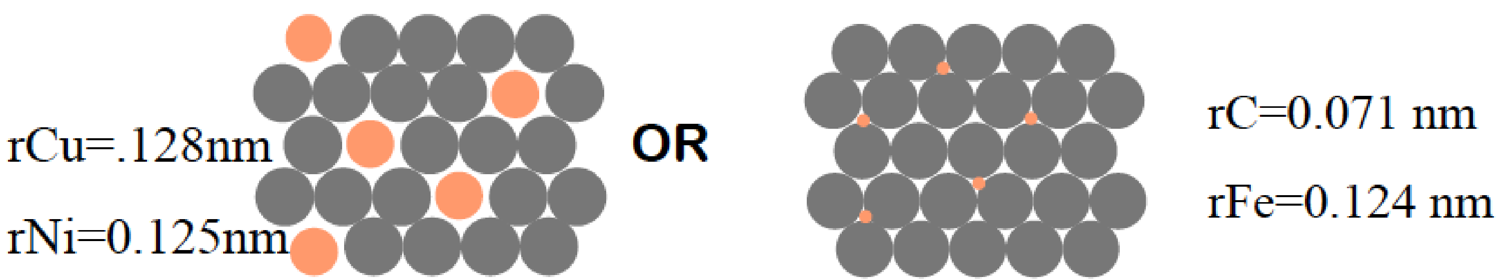
B. Solid-Solution Strengthening

From Chapter 4:

A. **Substitutional** solid solutions: The solute atoms substitute the hos atoms.



A. **Interstitial** solid solutions: solute atoms occupy interstitial positions



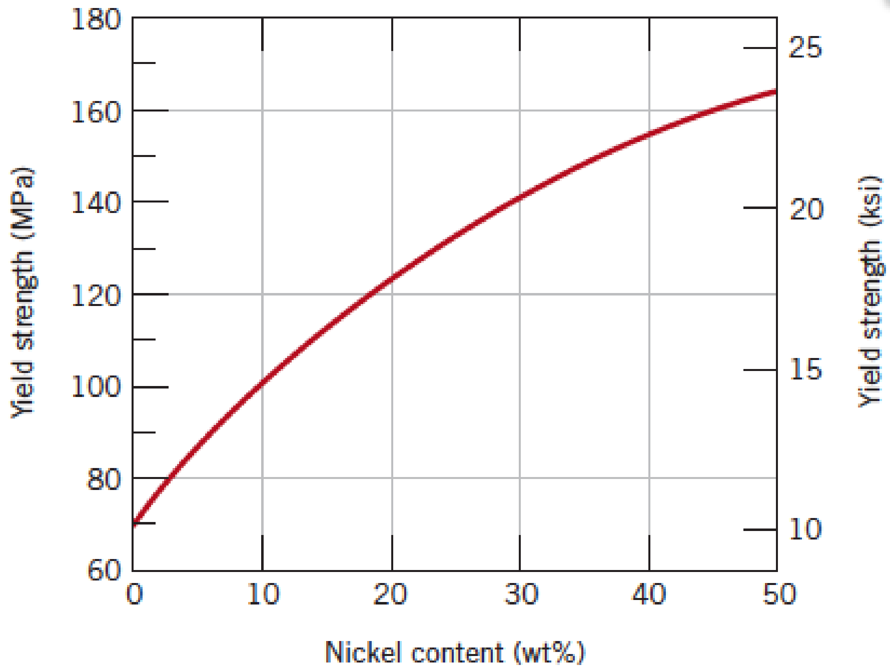
Substitutional alloy (e.g., Cu in Ni)

Interstitial alloy (e.g., C in Fe)

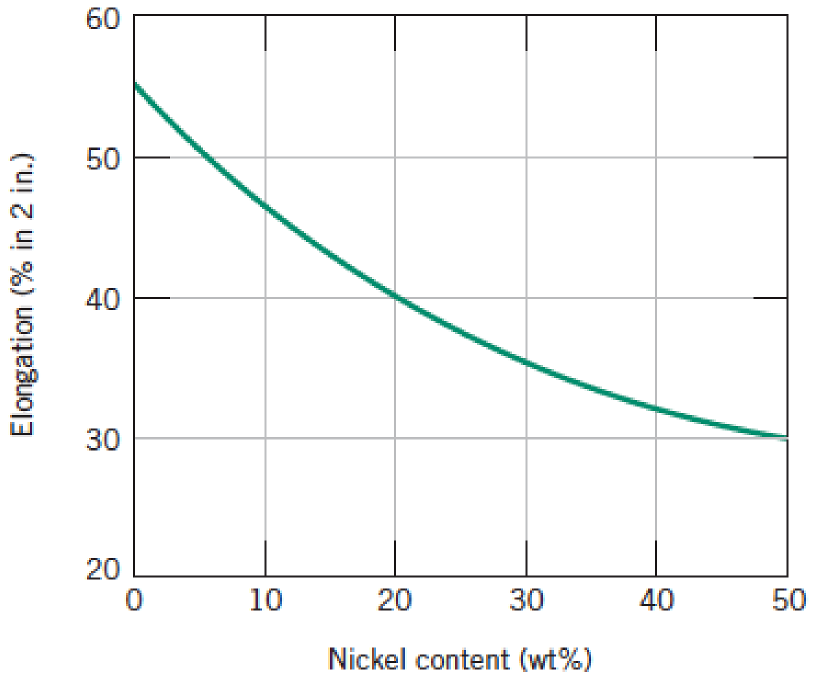
B. Cont'd: Solid-Solution Strengthening

- Alloys are stronger than pure metals
- Increasing the concentration of the impurity results in an attendant increase in tensile and yield strengths

Copper–Nickel alloys



Increase in yield strengths

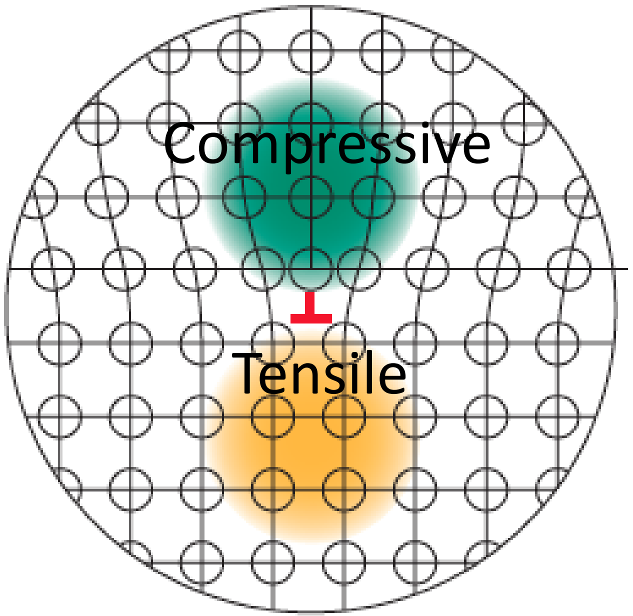


Decrease in ductility

B. Cont'd: Solid-Solution Strengthening

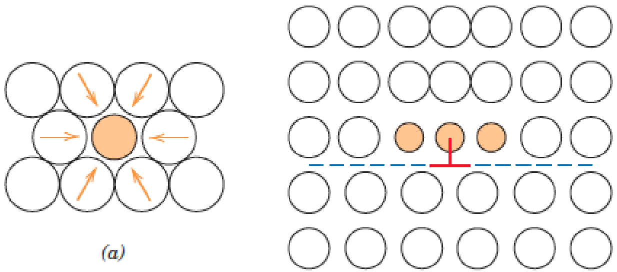
Reason for the increase in strength:

Impurity atoms
➔impose lattice strains on the surrounding host atoms
➔interaction with strain fields around dislocations
➔oppose dislocation movement

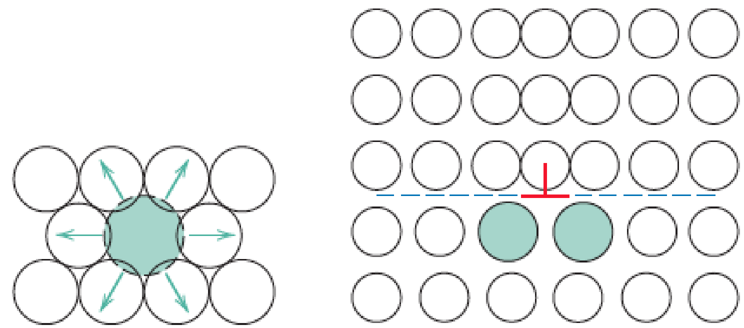


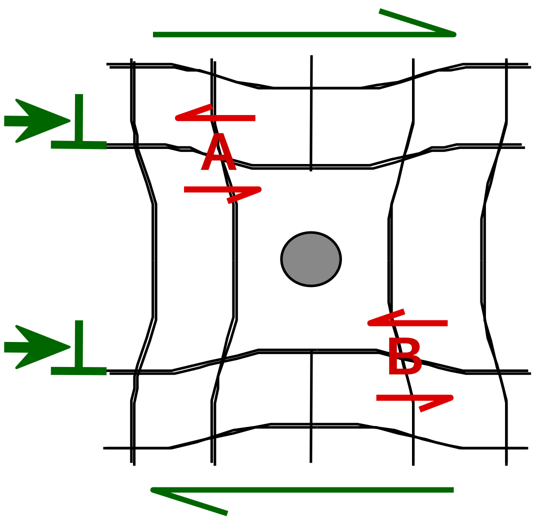
B. Cont'd: Solid-Solution Strengthening

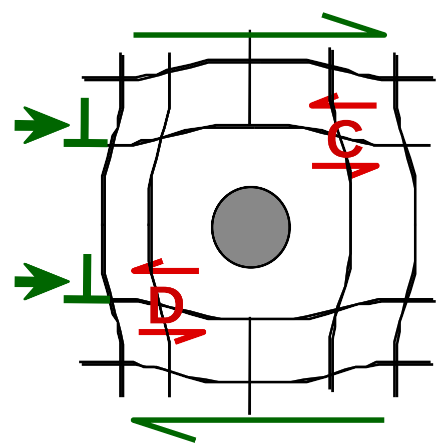
Impurity atoms distort the lattice & generate lattice strains ➔ These strains can act as barriers to dislocation motion.



(a)







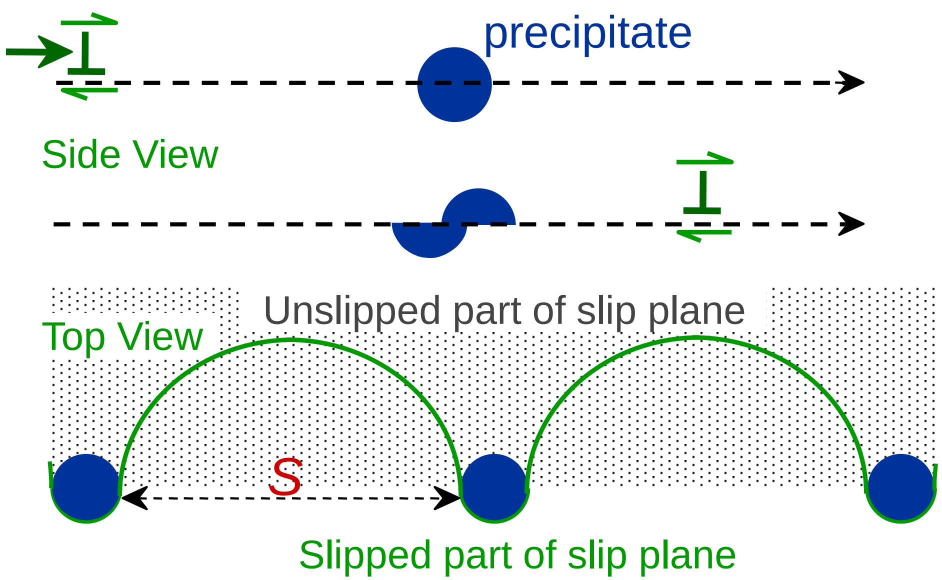
If impurity is smaller than a host atom ➔impose tensile

If impurity is larger ➔ impose compressive strains

NOTE: Precipitation Strengthening

- Hard precipitates are difficult to shear.

  e.g. Ceramics in metals (SiC in Iron or Aluminum).



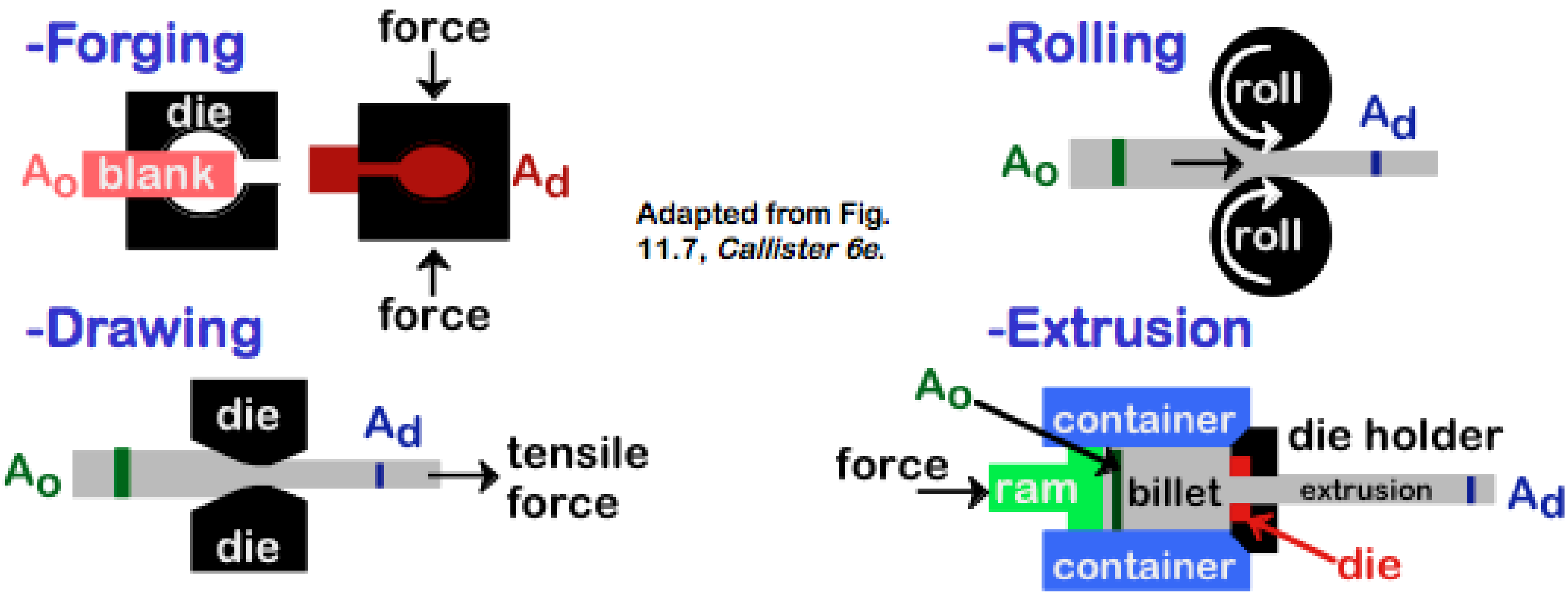
spacing

Large shear stress needed to move dislocation toward precipitate and shear it.

Dislocation "advances" but precipitates act as "pinning" sites

C. Strengthening by plastic deformation

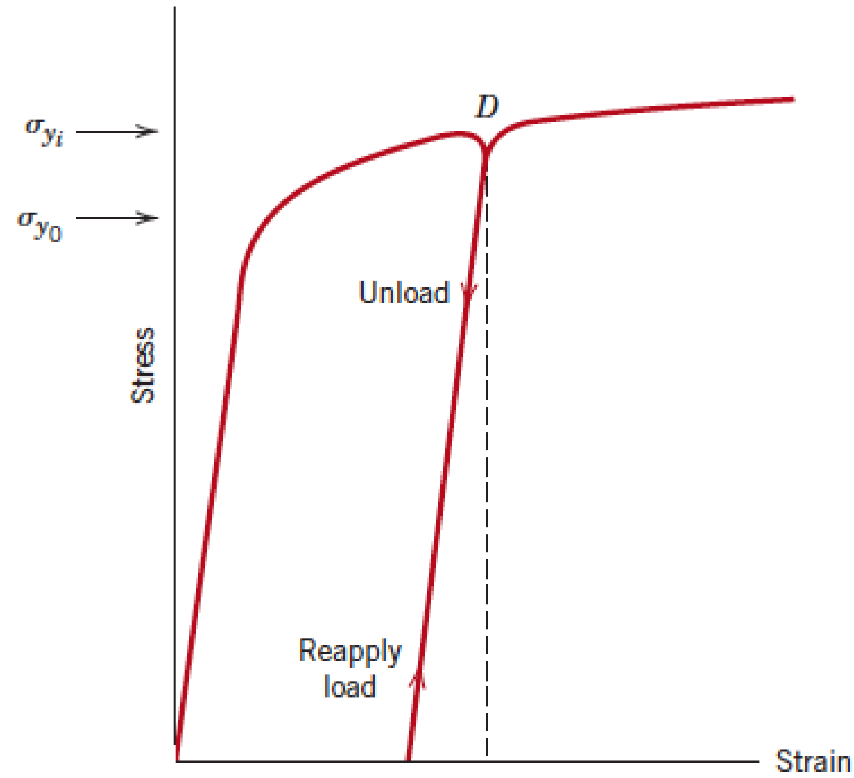
Strain hardening (*work hardening or cold working)*:
The increase in strength of a ductile metal as it is plastically deformed.



Adapted from Fig. 11.7, *Callister 6e.*

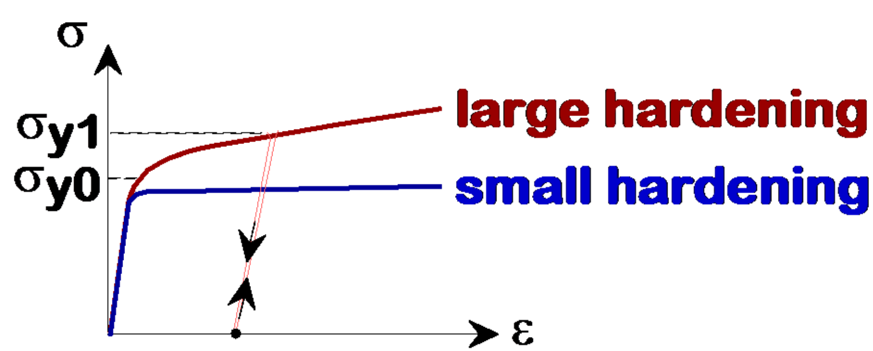
C. Strengthening by plastic deformation

Strain hardening (*work hardening or cold working*): The increase in strength of a ductile metal as it is plastically deformed.



$$\sigma_T = K\epsilon_T^n$$

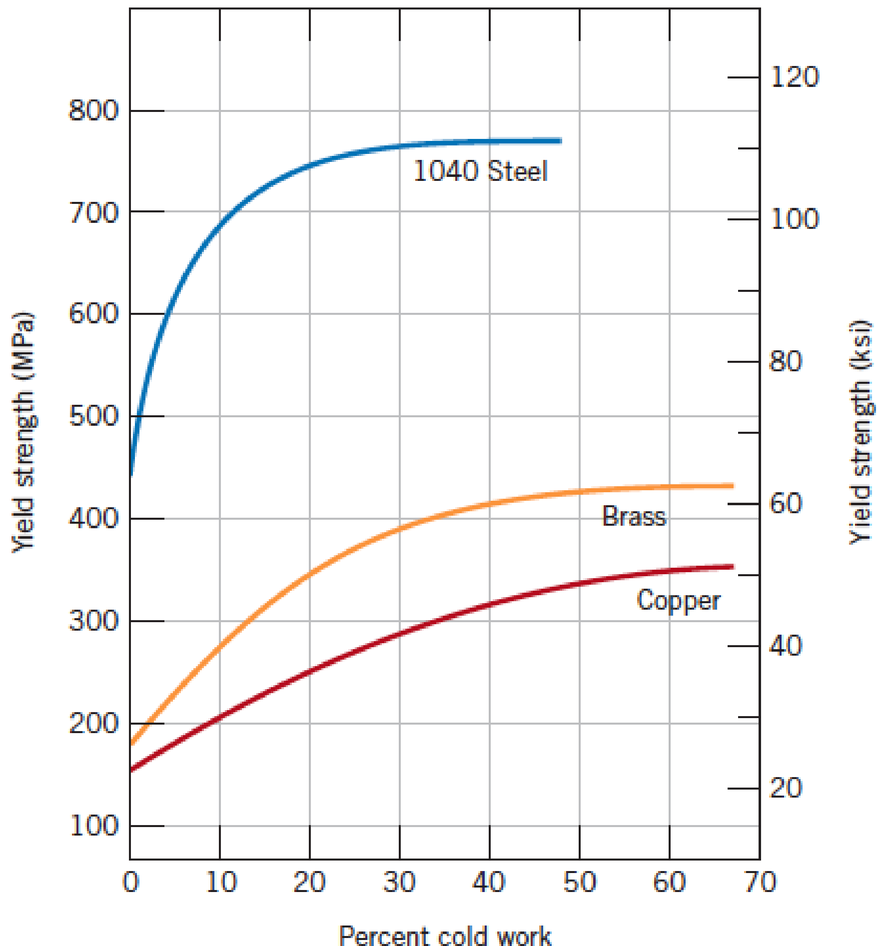
n: strain hardening exponent

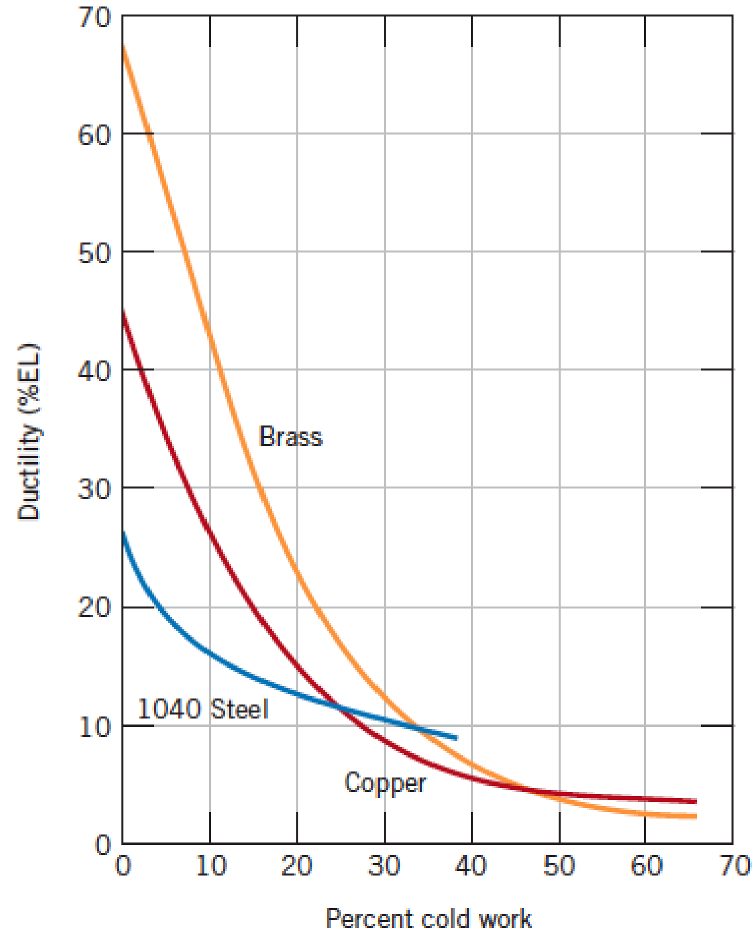


C. Cont'd: Strengthening by plastic deformation

Percent cold work (%CW) can be used to express the degree of plastic deformation

$$\%\,CW = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$





C. Cont'd: Strengthening by plastic deformation

Reason for increase in strength: Interactions between dislocations:

How?

Plastic deformation → dislocation density increases due to dislocation multiplication → the average distance of separation between dislocations decreases → resistance to dislocation motion by other dislocations increases → imposed stresses necessary to deform a metal increase

Summary (3)

Covered so far:

- ✓ *Dislocations (Edge, Screw, Mixed)*
- ✓ *Basis of presence of dislocations*
- ✓ *Slip (plastic deformation)*
- ✓ *Dislocation density*

- ✓ *Strain fields around dislocations*
- ✓ *Slip systems (effect on ductility)*
- ✓ *Slip in single crystals (Schmid law)*

- ✓ **Plastic deformation of polycrystalline materials**
- ✓ **Strengthening mechanisms** *(depends on the ability of dislocations to move. In short, restricting dislocation motion increases strength)*:
  - **Grain size reduction**
  - **Solid-solution strengthening**
  - **Strain hardening.**

Recovery, recrystallization, and grain growth

- Cold worked metal: it is plastically deformed at temperature lower than 0.5 T_m (absolute scale)

- Most of the energy expended in cold work appears in the form of heat.

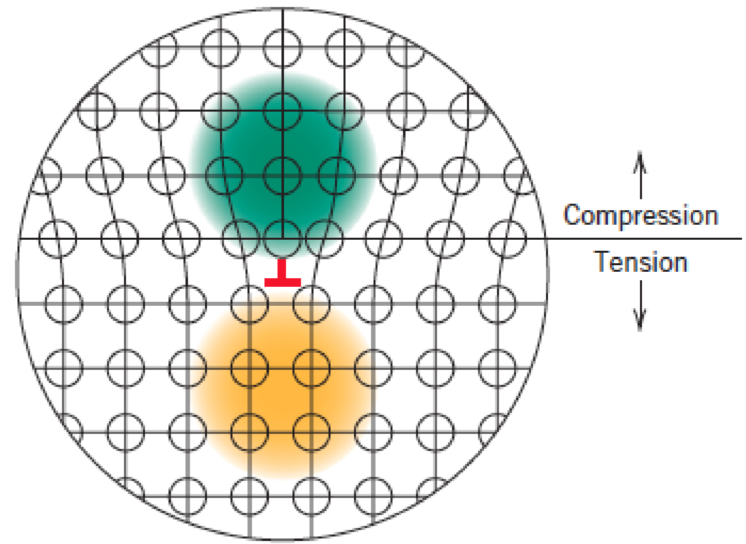
- Small fraction (from a low percentage to 10%) is stored in the metal as strain energy associated with various lattice defects created by the deformation.

- Cold working increases greatly the number of dislocations in a metal by a factor as large as 10,000 to 1,000,000. → increase dislocation density → increase the strain energy of the metal

Reed-Hill, R. E. (1991).Physical Metallurgy Principles. 3rd edition. Ch. 8.

Recovery, recrystallization, and grain growth

When metals are plastically deformed, some fraction of the deformation energy (~ 5%) is retained internally; mainly as strain energy associated with dislocations



Can you go back to the original (undeform) state?

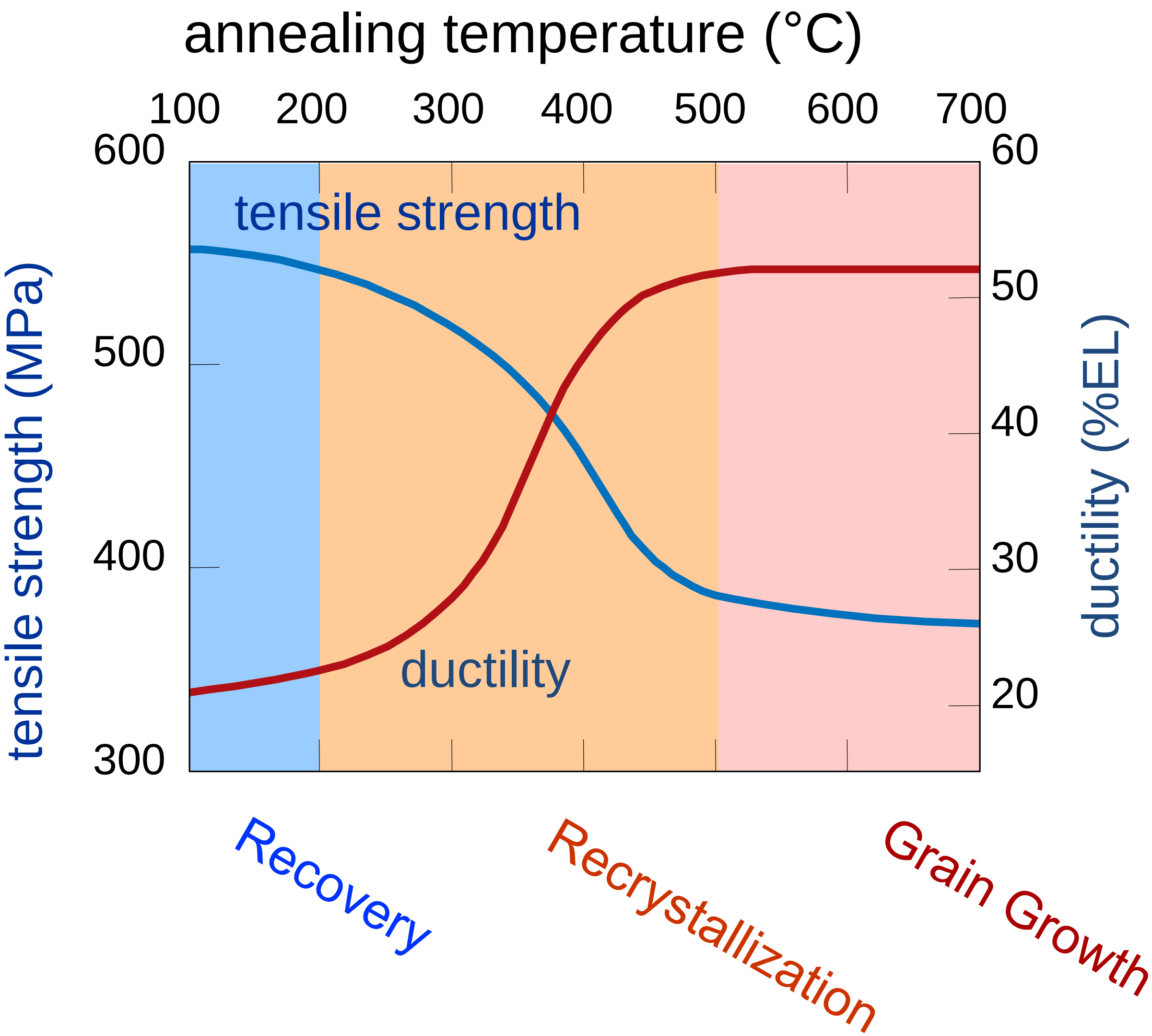
Heat treatment (annealing treatment)!

Different processes occur at elevated temperatures:

Recovery → Recrystallization → Grain growth

Three Annealing stages:

1. Recovery
2. Recrystallization
3. Grain Growth



Driving force for recovery and recrystallization:

$\Delta G = \Delta H - T\,\Delta S$

ΔG: The free energy
ΔH: The enthalpy (or strain energy, internal energy)
S: The entropy

Plastic deformation increases S but the effect is small ➔ $\Delta G \approx \Delta H$

Since plastic deformation increases ΔH (strain energy)➔ Free energy of cold-worked metals is greater than the free energy of annealed metals ➔ the cold-worked metal may soften spontaneously

- ➔Number of different reactions occur (many of these involve atom movement) to recover the condition of the metal before cold working
- ➔Since many of the reaction involve atom movement ➔ these reactions are extremely temperature sensitive

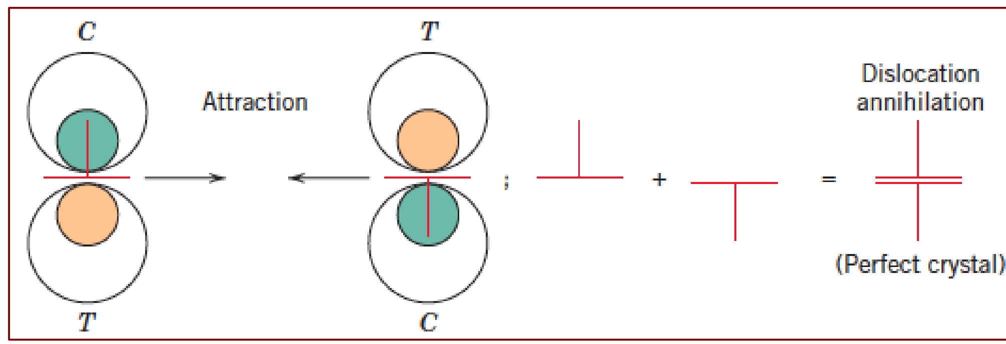
Reed-Hill, R. E. (1991).Physical Metallurgy Principles. 3rd edition. Ch. 8.

1) Recovery

In the recovery stage of annealing, some of the stored internal strain energy is released ➔ physical and mechanical properties tend to *recover* their original values.

High temperature➔ enhances atomic diffusion ➔ dislocation motion ➔ :

1) Annihilation of dislocations *(reduce dislocation density)*



2) Formation of new dislocation configurations with low strain energy

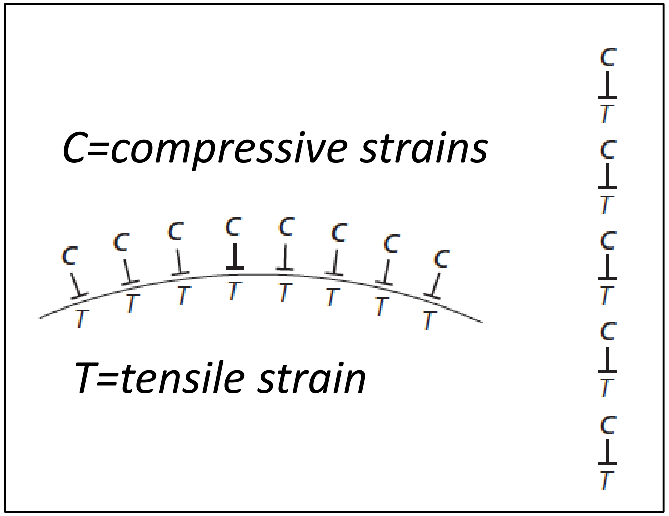
Recovery

2) **Formation of new dislocation configurations with low strain energy**

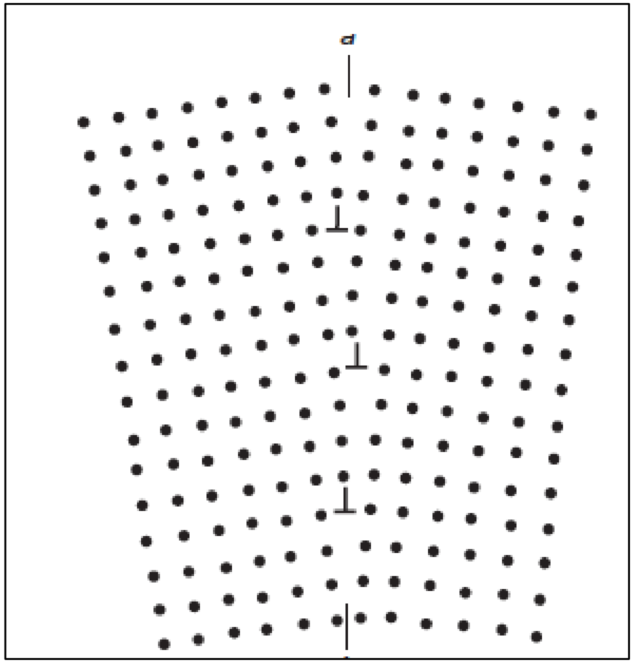
Also called:

Polygonization (regrouping of dislocations to form Low-Energy Dislocation Structures, LEDS)

Note that the rate of polygonization depends on temperature because polygonization involves both slip and climb. Climb requires movement of vacancies which is extremely temperature sensitive, and slip depends on CRSS which decrease with temperature)

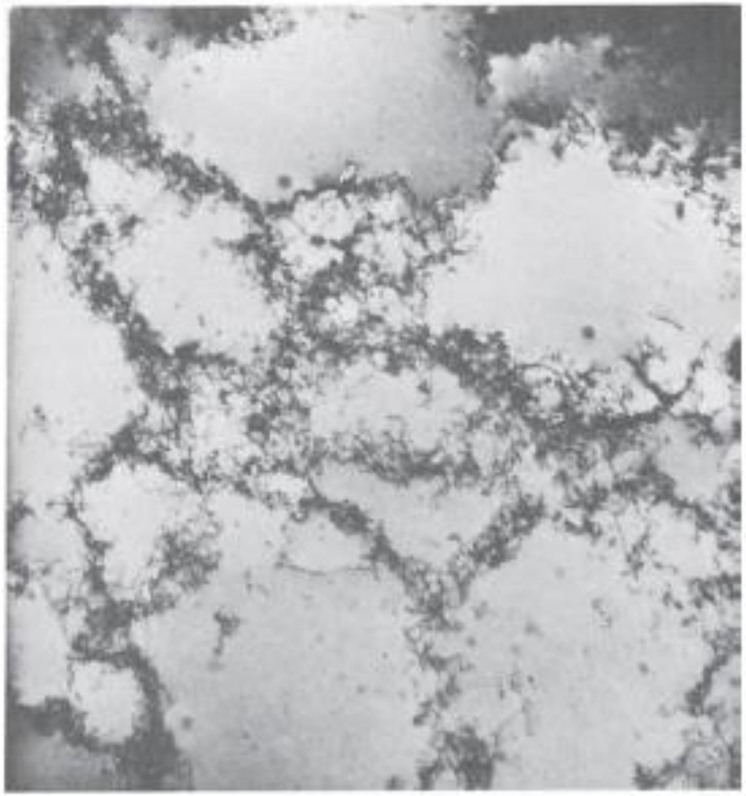


Tilt boundary



Dynamic Recovery

Dislocations tend to form cell structure during deformation



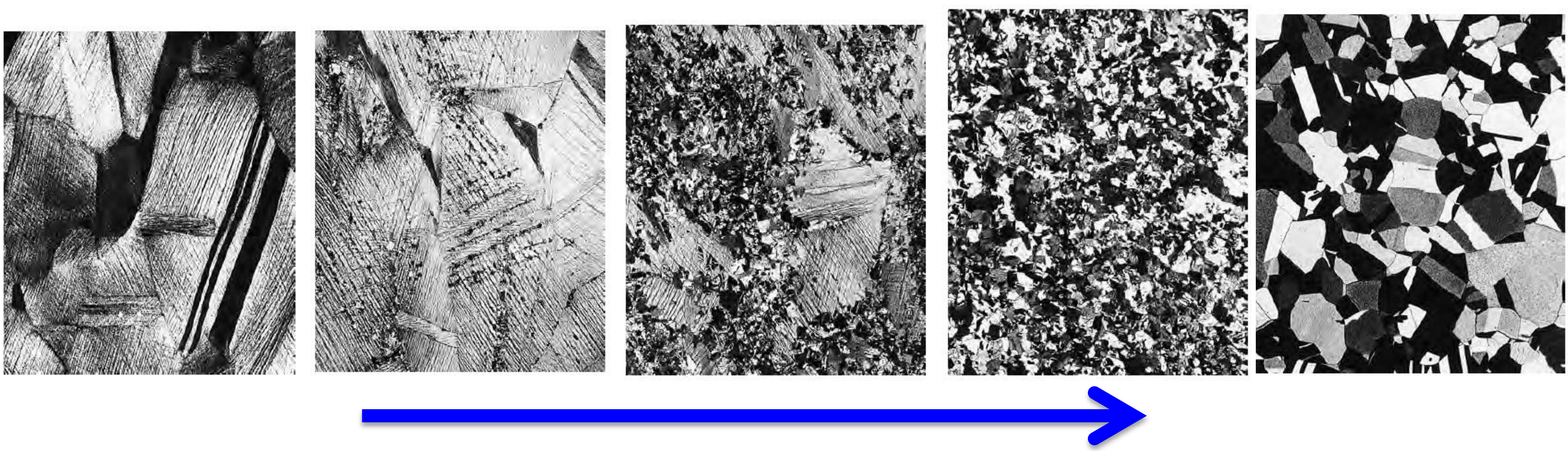
2) Recrystallization:

Recrystallization is the formation of a new set of strain-free grains that have low dislocation densities.

Steps:

1) Nuclei are formed (at points of high-lattice strain energy such as grain boundaries)

1) Small nuclei grow until they consume the parent grains

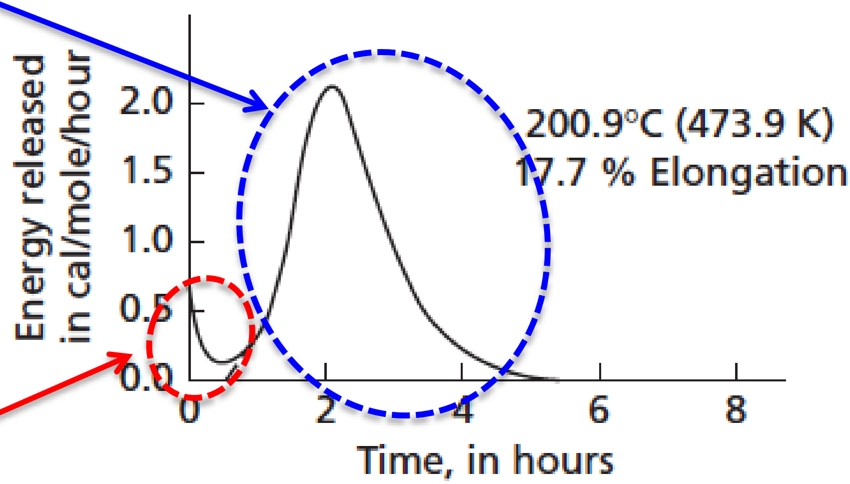


Recovery, recrystallization, and grain growth

Energy release associated with

recrystallization:

- ✓ Max. energy release
- ✓ New set of essentially strain-free grains, which grow at the expense of the originally deformed grains (recrystallization=realignment of the atoms into crystals with a lower free energy)



Energy release associated with

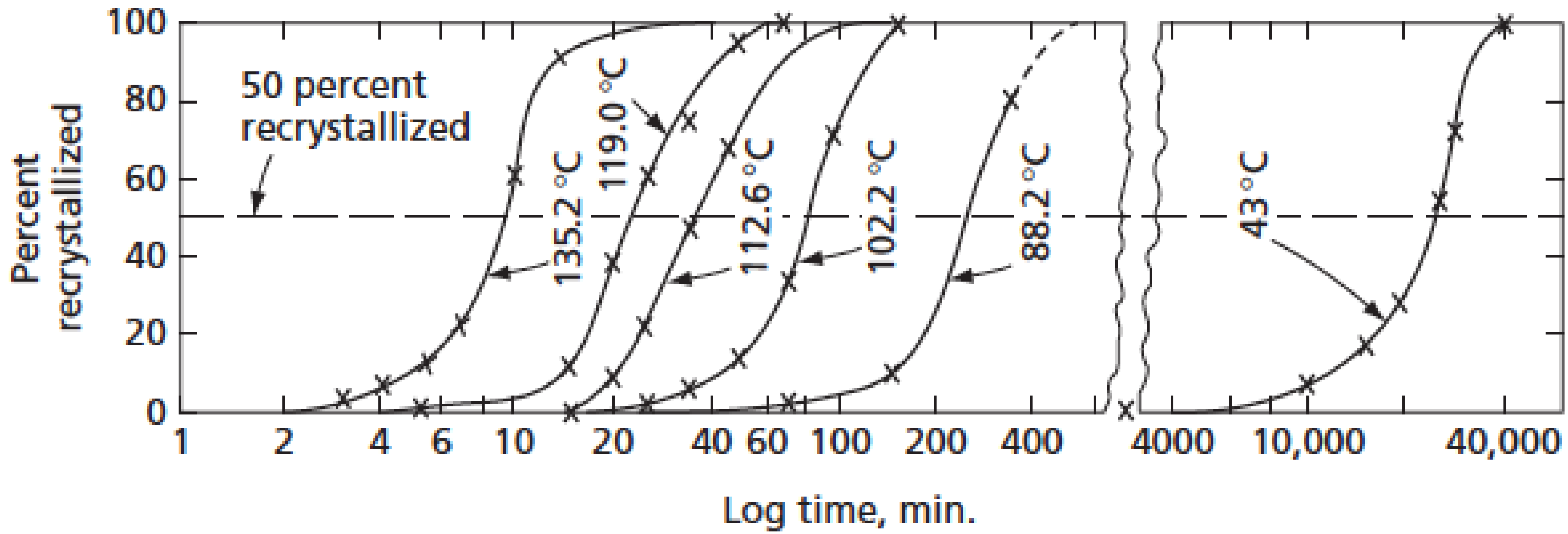
recovery

NOTE: The free energy is measured while the specimen is maintained at a constant temperature (isothermal annealing) using micro-calorimeter which has a sensitivity of measuring a heat flow as low as 13 mJ/hr

Reed-Hill, R. E. (1991).Physical Metallurgy Principles. 3rd edition. Ch. 8

2) Cont'd: Recrystallization

Recrystallization depends on both time and temperature



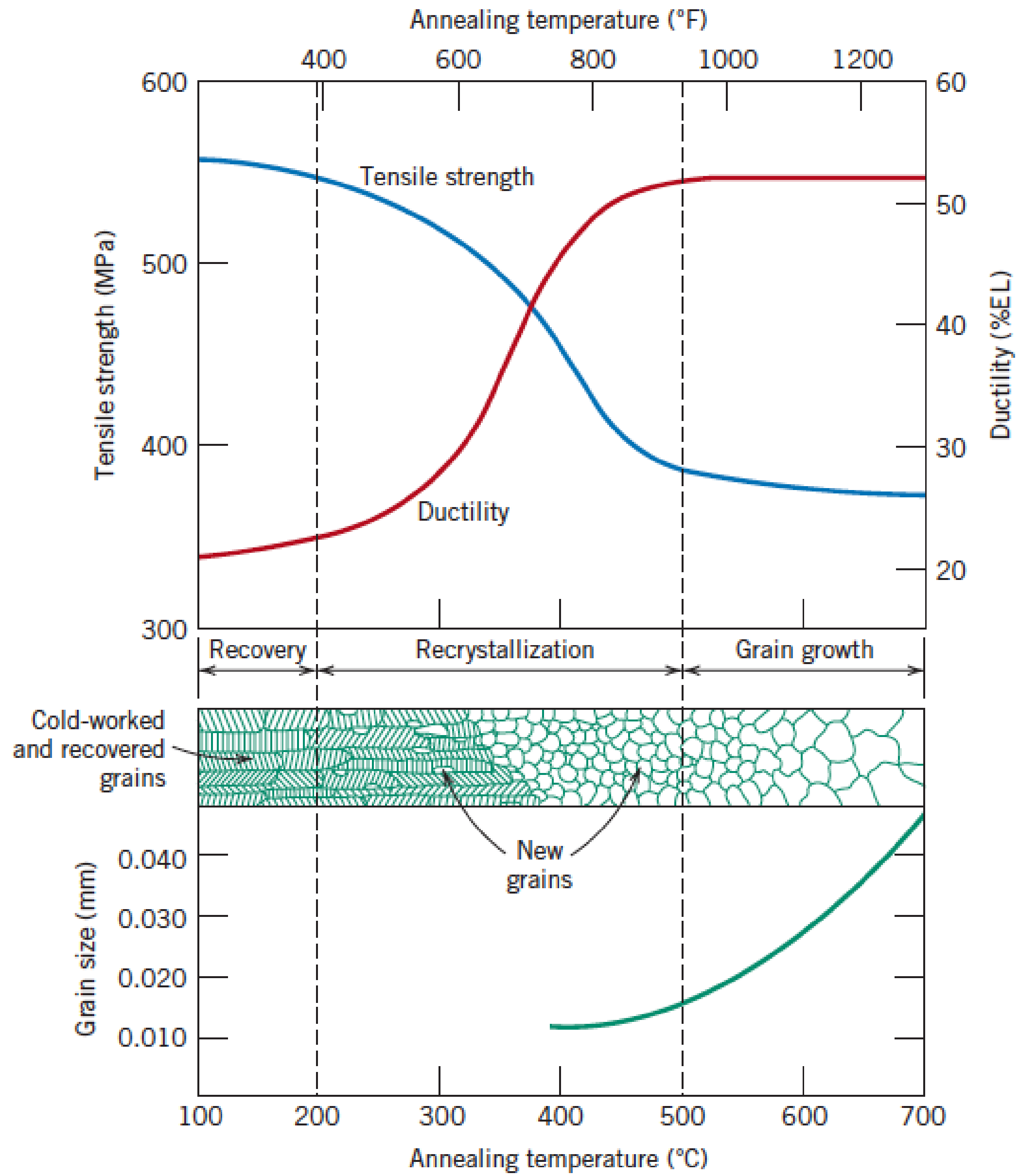
The higher the temperature, the shorter the time needed to finish the recrystallization

2) Cont'd: Recrystallization

Recrystallization temperature: the temperature at which recrystallization just reaches completion in 1h.

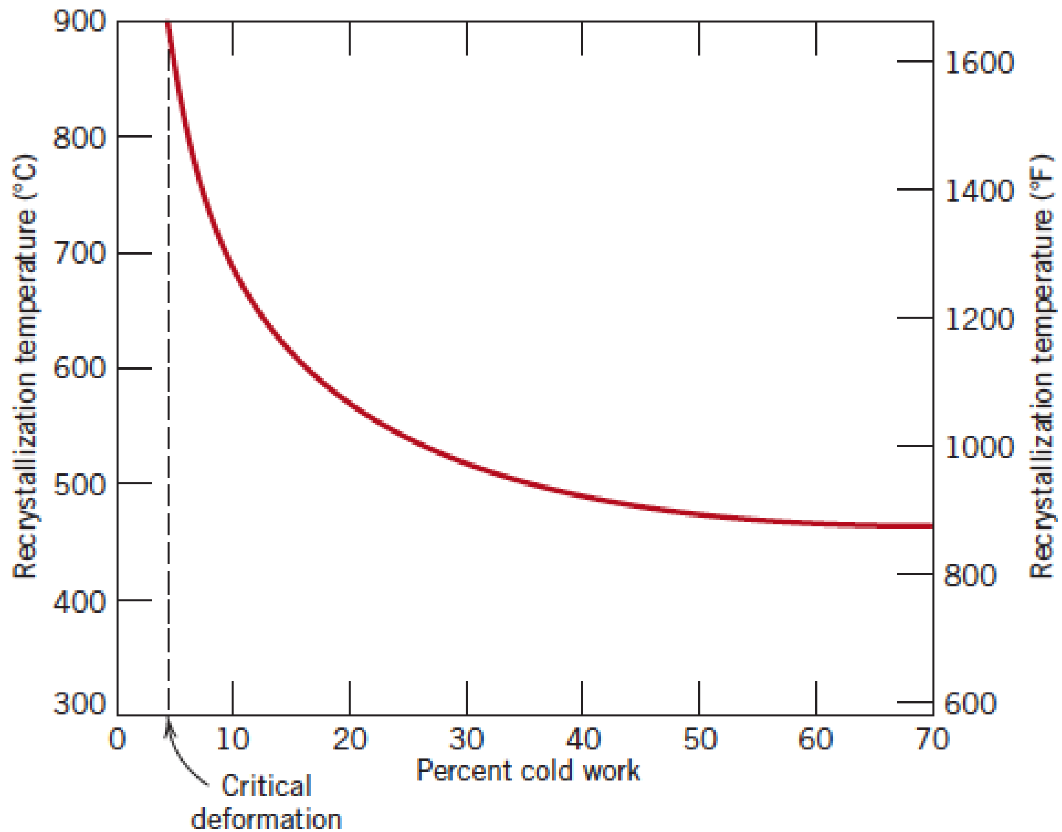
- ✓ Pure metals: ~ 0.3 T_m
- ✓ Some commercial alloys: ~ 0.7 T_m

Hot working: Plastic deformation at T > Recryst. Temp.



2) Cont'd: Recrystallization

- Increasing the percentage of cold work enhances the rate of recrystallization.
- Critical degree of cold work below which recrystallization cannot occur

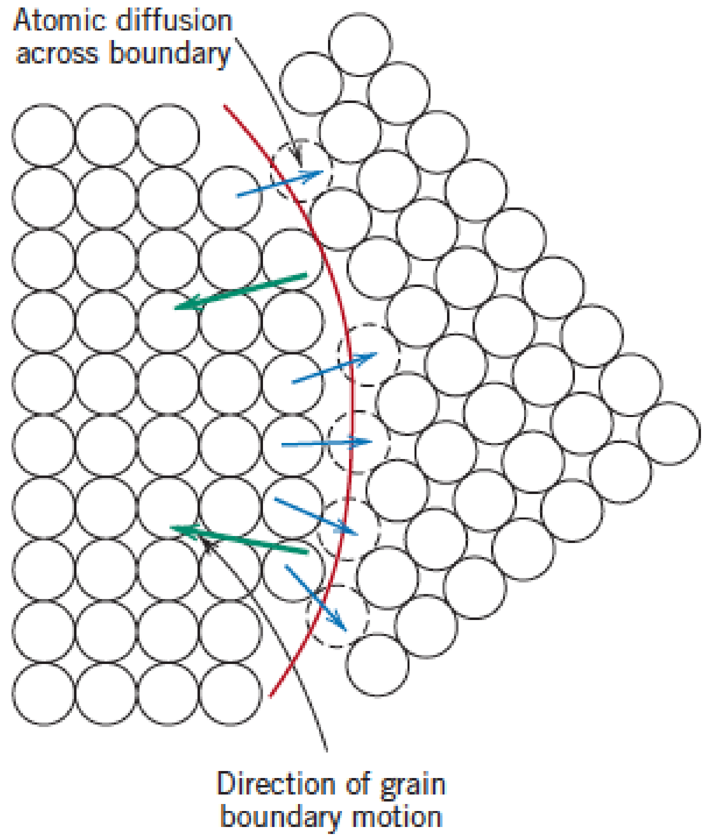


3) GRAIN GROWTH

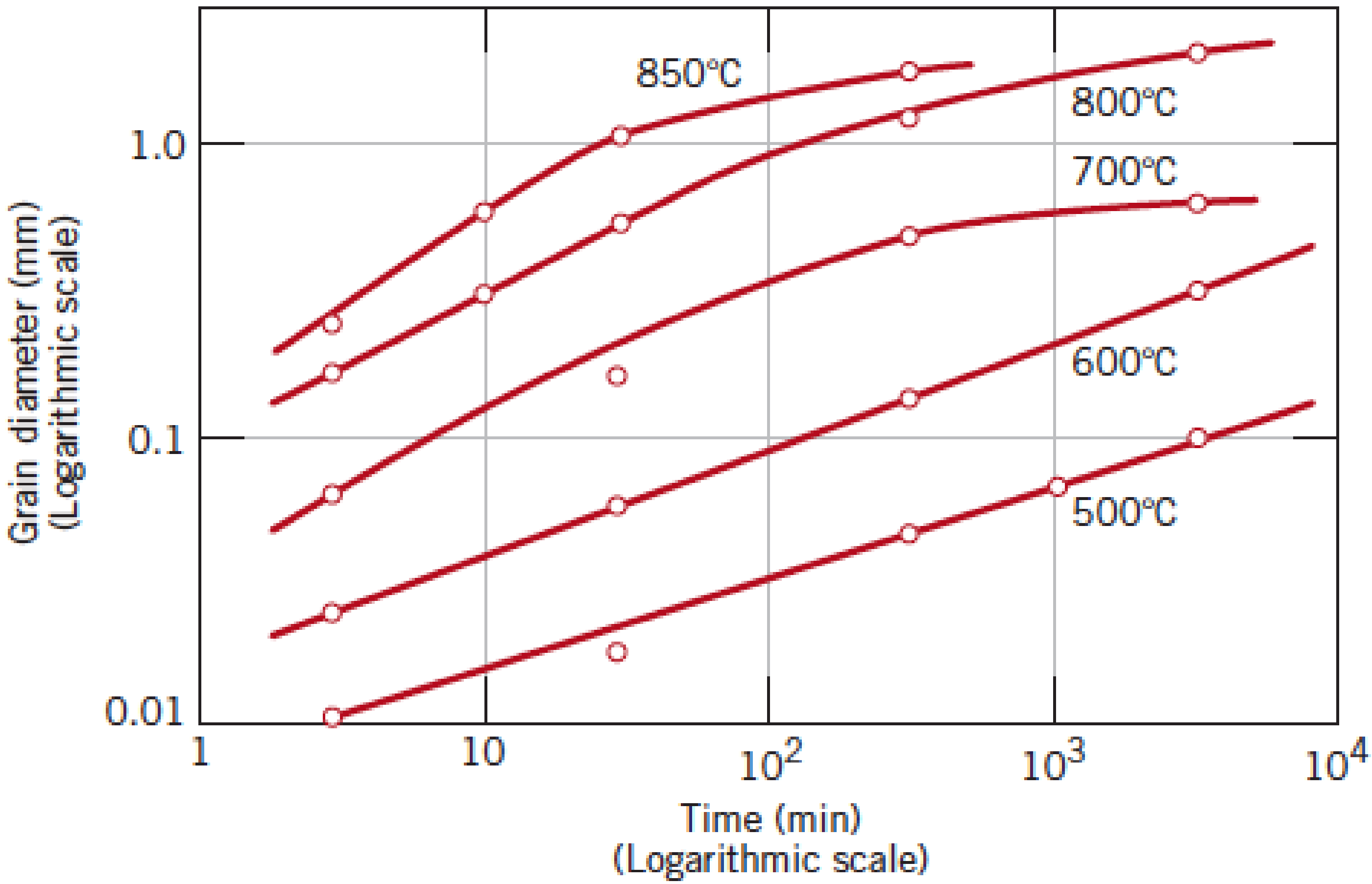
Driving force for grain growth:

Grain size increases ➔ total grain boundary area decreases ➔ surface (GB) energy decreases

"Boundary motion is just the short-range diffusion of atoms from one side of the boundary to the other. The directions of boundary movement and atomic motion are opposite to each other"



3) Cont'd: GRAIN GROWTH



The grain growth proceeds more rapidly as temperature increases which can be explained by the enhancement of diffusion rate with rising temperature.

Problems

7.13 A single crystal of zinc is oriented for a tensile test such that its slip plane normal makes an angle of 65° with the tensile axis. Three possible slip directions make angles of 30°, 48°, and 78° with the same tensile axis.

(a) Which of these three slip directions is most favored?

(b) If plastic deformation begins at a tensile stress of 2.5 MPa (355 psi), determine the critical resolved shear stress for zinc.

7.13 A single crystal of zinc is oriented for a tensile test such that its slip plane normal makes an angle of 65° with the tensile axis. Three possible slip directions make angles of 30°, 48°, and 78° with the same tensile axis.

(a) Which of these three slip directions is most favored?

(b) If plastic deformation begins at a tensile stress of 2.5 MPa (355 psi), determine the critical resolved shear stress for zinc.

$$\cos(30^\circ) = 0.87$$

$$\cos(48^\circ) = 0.67$$

$$\cos(78^\circ) = 0.21$$

$$\tau_{crss} = \sigma_y (\cos\phi \cos\lambda)_{max}$$

$$= (2.5\ \text{MPa})[\cos(65^\circ)\cos(30^\circ)] = 0.90\ \text{MPa}$$

7.15 A single crystal of a metal that has the FCC crystal structure is oriented such that a tensile stress is applied parallel to the [100] direction. If the critical resolved shear stress for this material is 0.5 MPa, calculate the magnitude(s) of applied stress(es) necessary to cause slip to occur on the (111) plane in each of the $[1\bar{1}0]$, $[10\bar{1}]$, and $[0\bar{1}1]$ directions.

7.15 A single crystal of a metal that has the FCC crystal structure is oriented such that a tensile stress is applied parallel to the [100] direction. If the critical resolved shear stress for this material is 0.5 MPa, calculate the magnitude(s) of applied stress(es) necessary to cause slip to occur on the (111) plane in each of the $[1\bar{1}0]$, $[10\bar{1}]$, and $[0\bar{1}1]$ directions.

$$\sigma_y = \frac{\tau_{crss}}{(\cos\phi \cos\lambda)}$$

$(111)-[1\bar{1}0]$

$$\sigma_y = \frac{0.5\text{ MPa}}{\cos(54.7^\circ)\cos(45^\circ)} = \frac{0.5\text{ MPa}}{(0.578)(0.707)} = 1.22\text{ MPa}$$

$(111)-[10\bar{1}]$

$$\sigma_y = 1.22\text{ MPa.}$$

$(111)-[0\bar{1}1]$

$$\sigma_y = \frac{0.5\text{ MPa}}{\cos(54.7^\circ)\cos(90^\circ)} = \frac{0.5\text{ MPa}}{(0.578)(0)} = \infty$$

Homework

7.16 **(a)** A single crystal of a metal that has the BCC crystal structure is oriented such that a tensile stress is applied in the [100] direction. If the magnitude of this stress is 4.0 MPa, compute the resolved shear stress in the $[\bar{1}11]$ direction on each of the (110), (011), and $(10\bar{1})$ planes.

(b) On the basis of these resolved shear stress values, which slip system(s) is (are) most favorably oriented?

7.22 Describe in your own words the three strengthening mechanisms discussed in this chapter (i.e., grain size reduction, solid-solution strengthening, and strain hardening). Be sure to explain how dislocations are involved in each of the strengthening techniques.