Deformation and Strengthening Mechanisms

Deformation and Strengthening Mechanisms

- Plastic deformation caused by dislocation movement.
- Slip systems (slip plane, slip direction).
- Resolved Shear Stress
- Strengthening Mechanisms
- Recovery, Recrystallization, Grain Growth

Deformation Mechanisms (Metals)

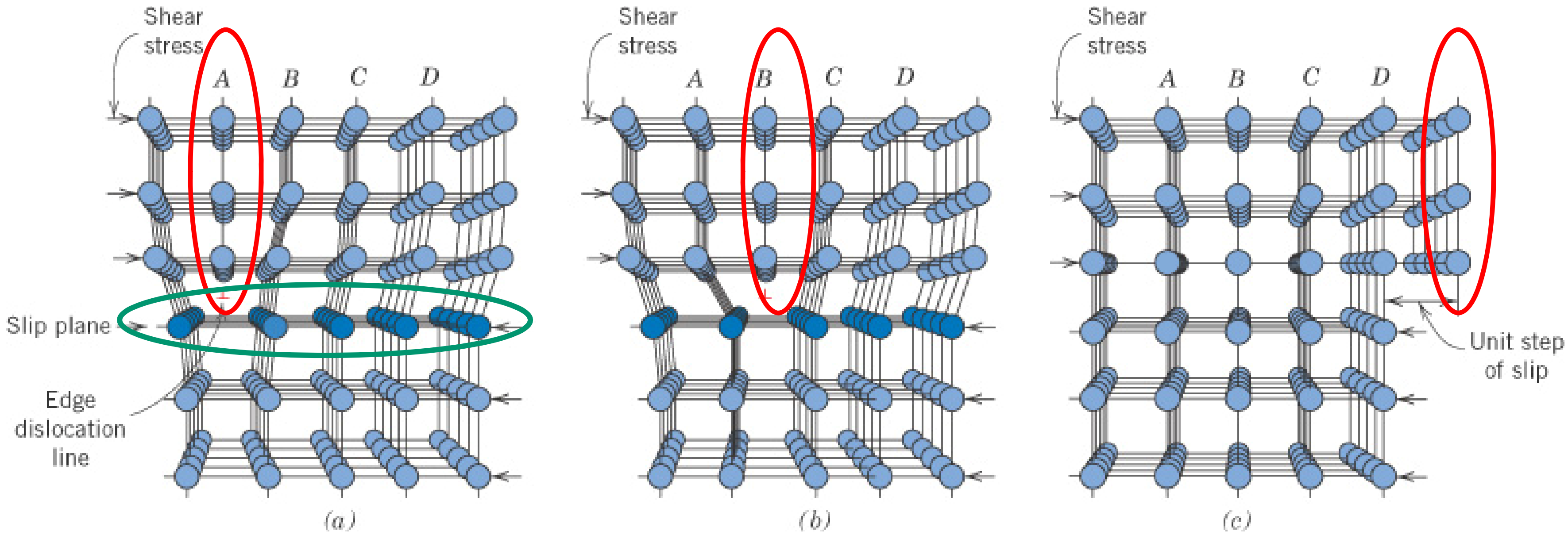
- Theoretical strengths of perfect crystal were much higher than those actually measured.
- It was believed that this discrepancy in mechanical strength could be explained by dislocations.
- On a macroscopic scale, plastic deformation corresponds to the net movement of large numbers of atoms in response to an applied stress.
- Interatomic bonds rupturing and reforming.

Edge and Screw Dislocations

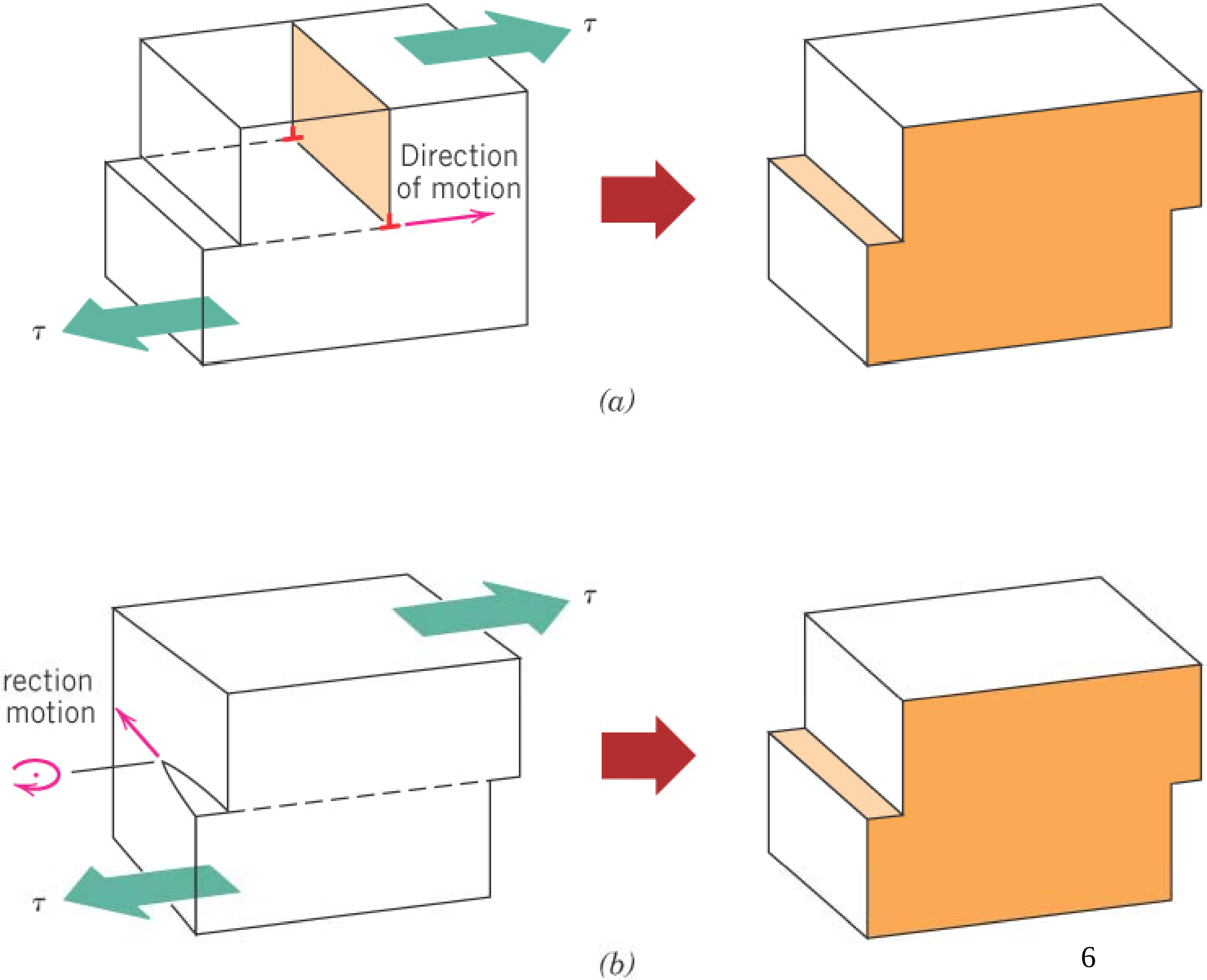
- In an edge dislocation, localized lattice distortion exists along the end of an extra half-plane of atoms.
- A screw dislocation results from shear distortion.
- Many dislocations in crystalline materials have both edge and screws components; these are mixed dislocations.

Dislocation Motion

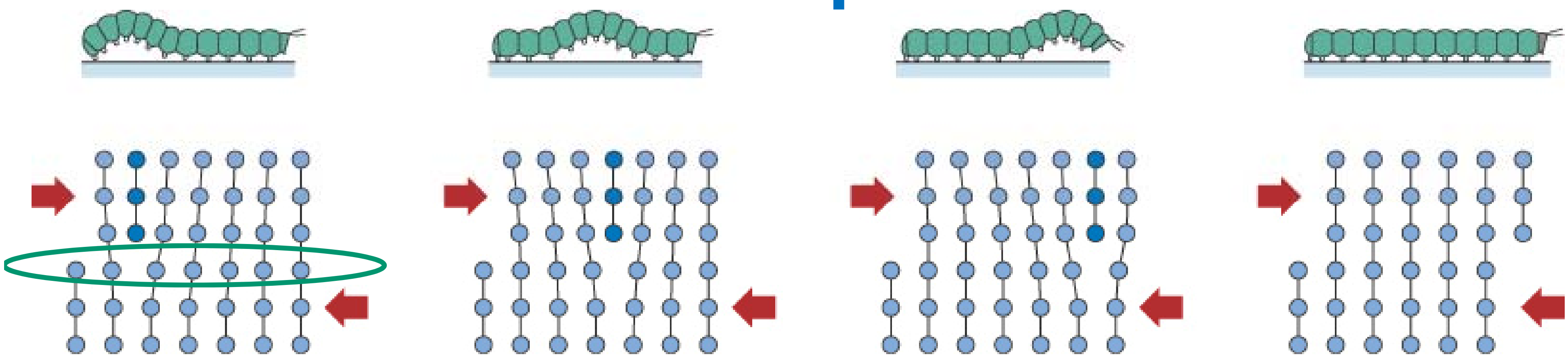
- Dislocation motion leads to plastic deformation.
- An edge dislocation moves in response to a shear stress applied in a direction perpendicular to its line.
- Extra half-plane at A is forced to the right; this pushes the top halves of planes B, C, D in the same direction.
- By discrete steps, the extra 1/2-plane moves from L to R by successive breaking of bonds and shifting of upper 1/2-planes.
- A step forms on the surface of the crystal as the extra 1/2-plane exits.



Formation of a step on the surface of a crystal by the motion of (a) edge dislocation and (b) screw dislocation.

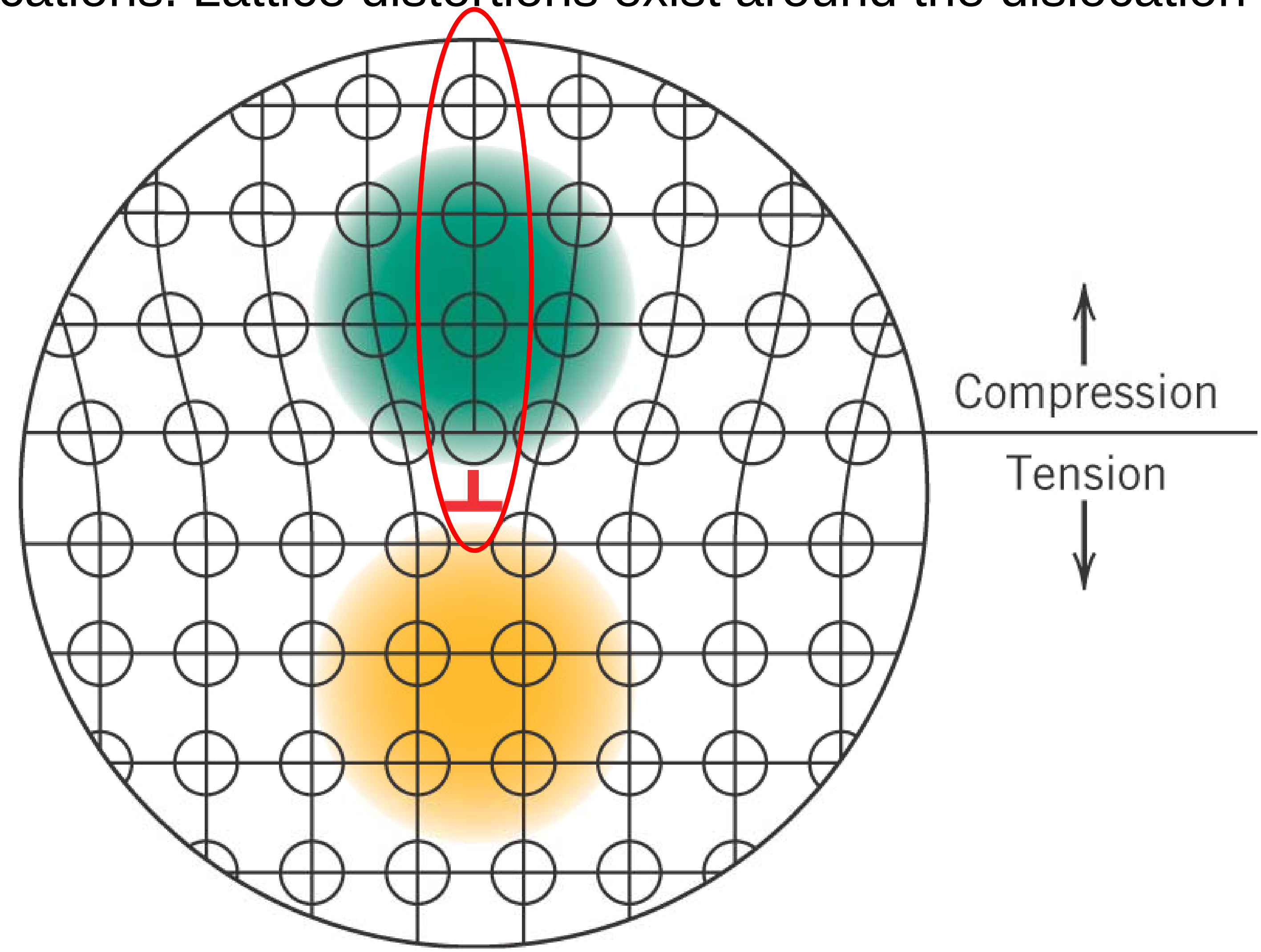


Slip



- The process by which plastic deformation is produced by dislocation motion is called **slip (movement of dislocations)**.
- The extra ½-plane moves along the slip plane.
- Dislocation movement is similar to the way a caterpillar moves. The caterpillar hump is representative of the extra ½-plane of atoms.

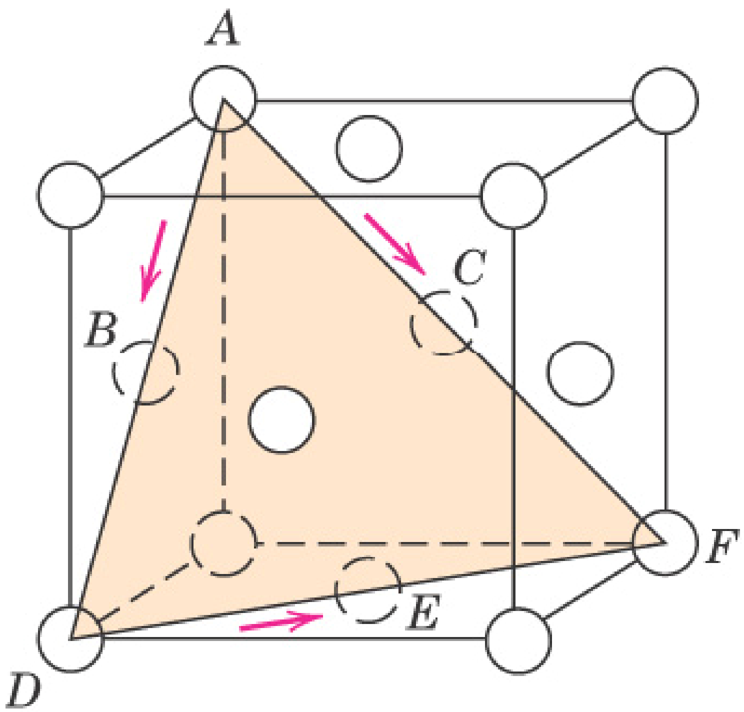
When metals are plastically deformed, some fraction (roughly 5%) of energy is retained internally; the remainder is dissipated as heat. Mainly, this energy is stored as strain energy associated with dislocations. Lattice distortions exist around the dislocation line.



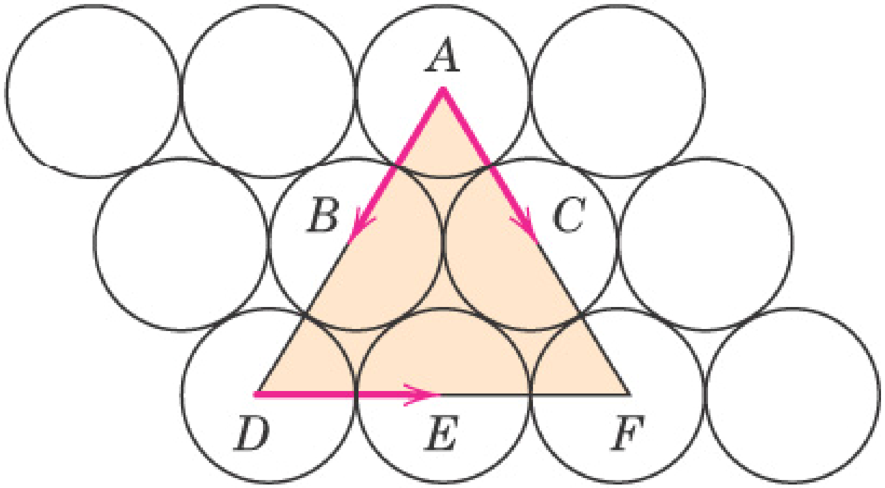
Slip Systems

- Dislocations move more easily on specific planes and in specific directions.
- Ordinarily, there is a preferred plane (slip plane), and specific directions (slip direction) along which dislocations move.
- The combination of slip plane and slip direction is called the slip system.
- The slip system depends on the crystal structure of the metal.
- The slip plane is the plane that has the most dense atomic packing (the greatest planar density).
- The slip direction is most closely packed with atoms (highest linear density).

Slip System – FCC example



(a)



(b)

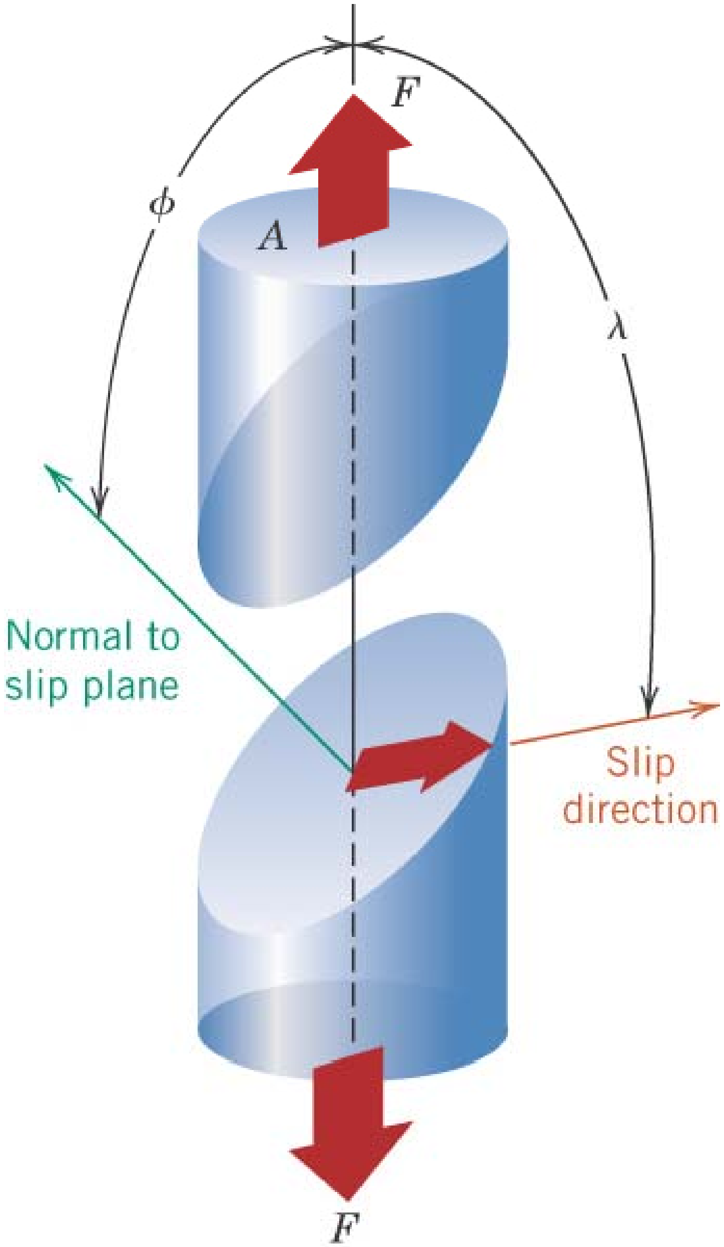
Slip Plane {111}:
most dense atomic packing,

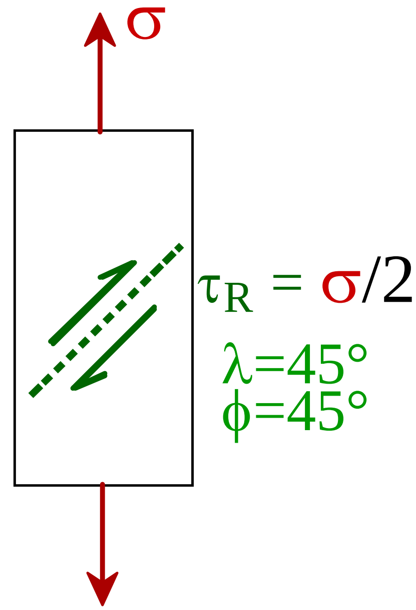
Slip Direction ‹110›:
highest linear density,

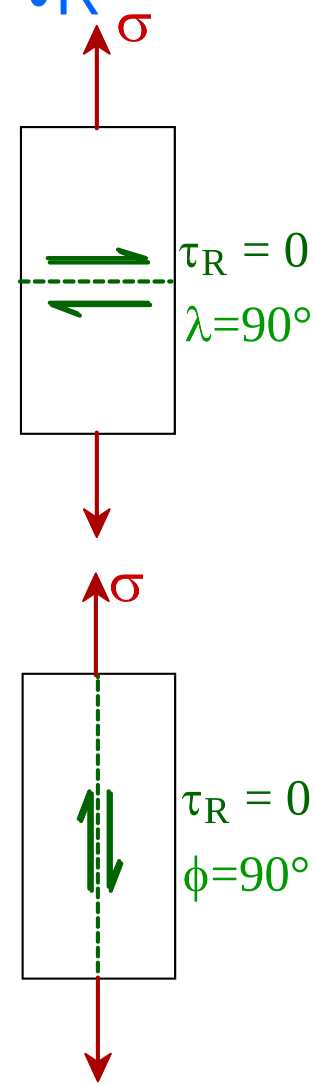
Stress and Dislocation Motion

- Edge and screw dislocations move in response to shear stresses applied along a slip plane in a slip direction.
- Even though an applied stress may be tensile, shear components exist at all but the parallel or perpendicular alignments to the stress direction.
- These are resolved shear stresses (τ_R).
- Crystals slip due to resolved shear stress.

Resolved Shear Stress, τ_R







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

Critical Resolved Shear Stress

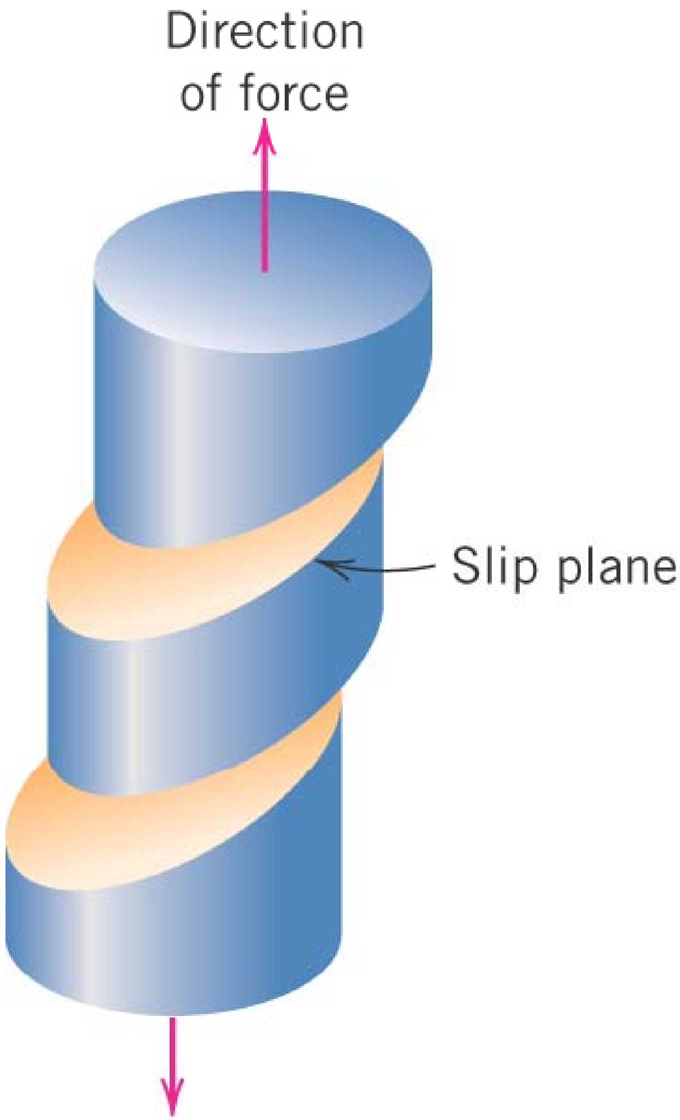
Condition for dislocation motion: $\tau_R > \tau_{crss}$

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

- In response to an applied tensile or compressive stress, slip (dislocation movement) in a single crystal begins when the resolved shear stress reaches some critical value, τ_{crss}.
- It represents the minimum shear stress required to initiate slip and is a property of the material that determines when yielding occurs.

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

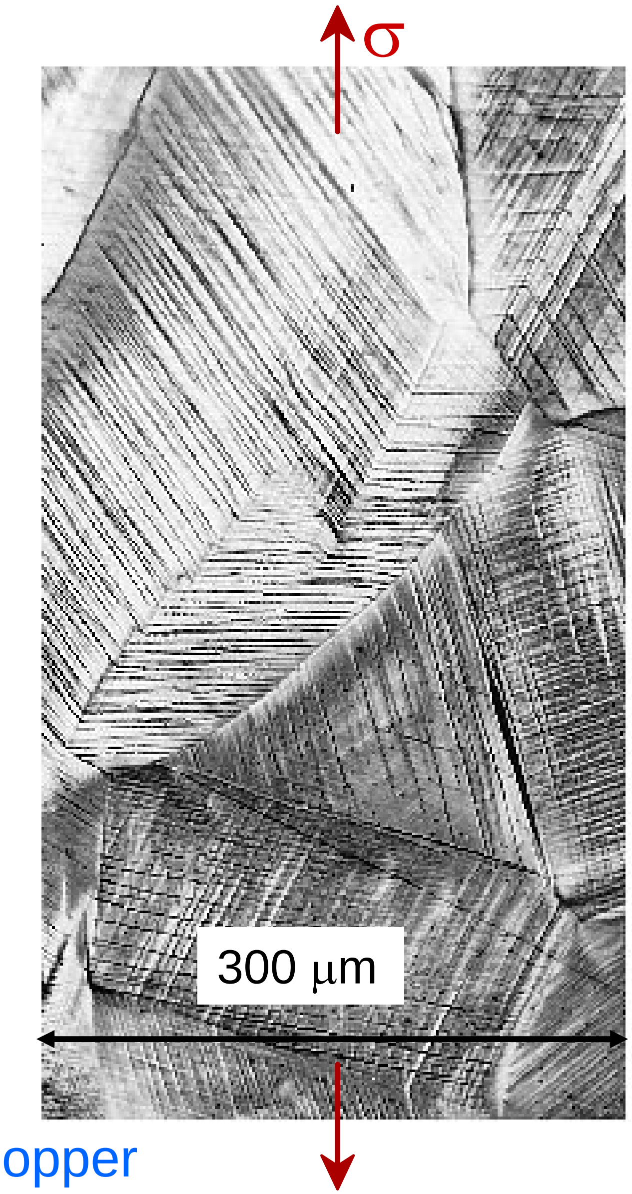
Deformation in a single crystal



- For a single crystal in tension, slip will occur along a number of equivalent and most favorably oriented planes and directions at various positions along the specimen.
- Each step results from the movement of a large number of dislocations along the same slip plane.

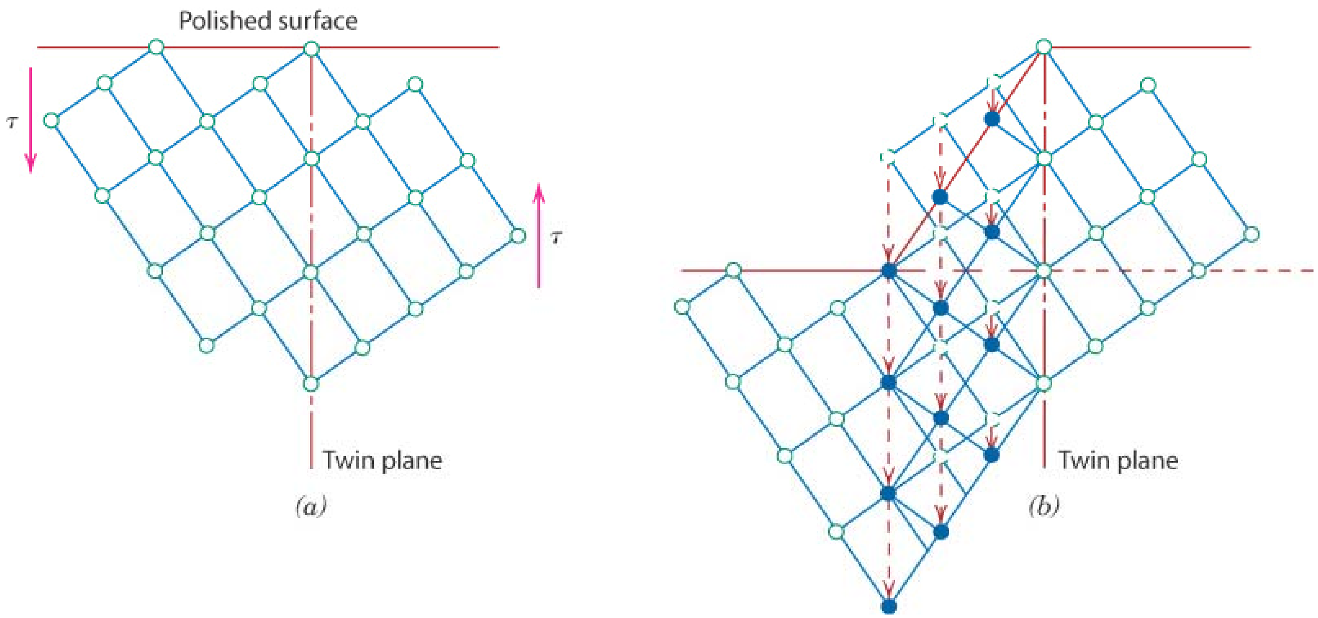
Dislocation Motion in Polycrystals

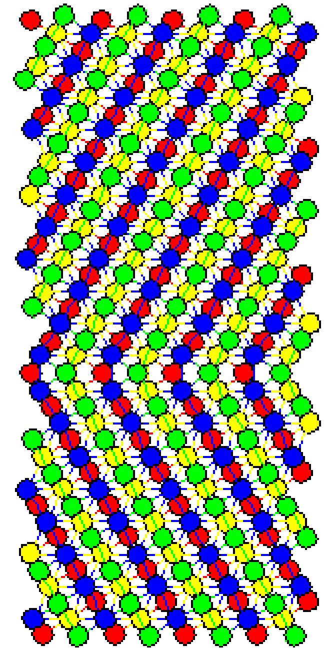
- On the surface of a polished single crystal, these steps appear as lines (slip lines).
- Slip planes & directions (λ, ϕ) change from one crystal to another.
- τ_R will vary from one crystal to another.
- The crystal with the largest τ_R yields first.
- Other (less favorably oriented) crystals yield later.



Polycrystalline Copper

Deformation by Twinning





- In addition to slip (dislocation movement), plastic deformation can occur by twinning.
- A shear force can produce atomic displacements so that on one side of the plane (the twin boundary), atoms are located in mirror image positions to atoms on the other side.
- Twinning may favorably reorient slip systems to promote dislocation movement.

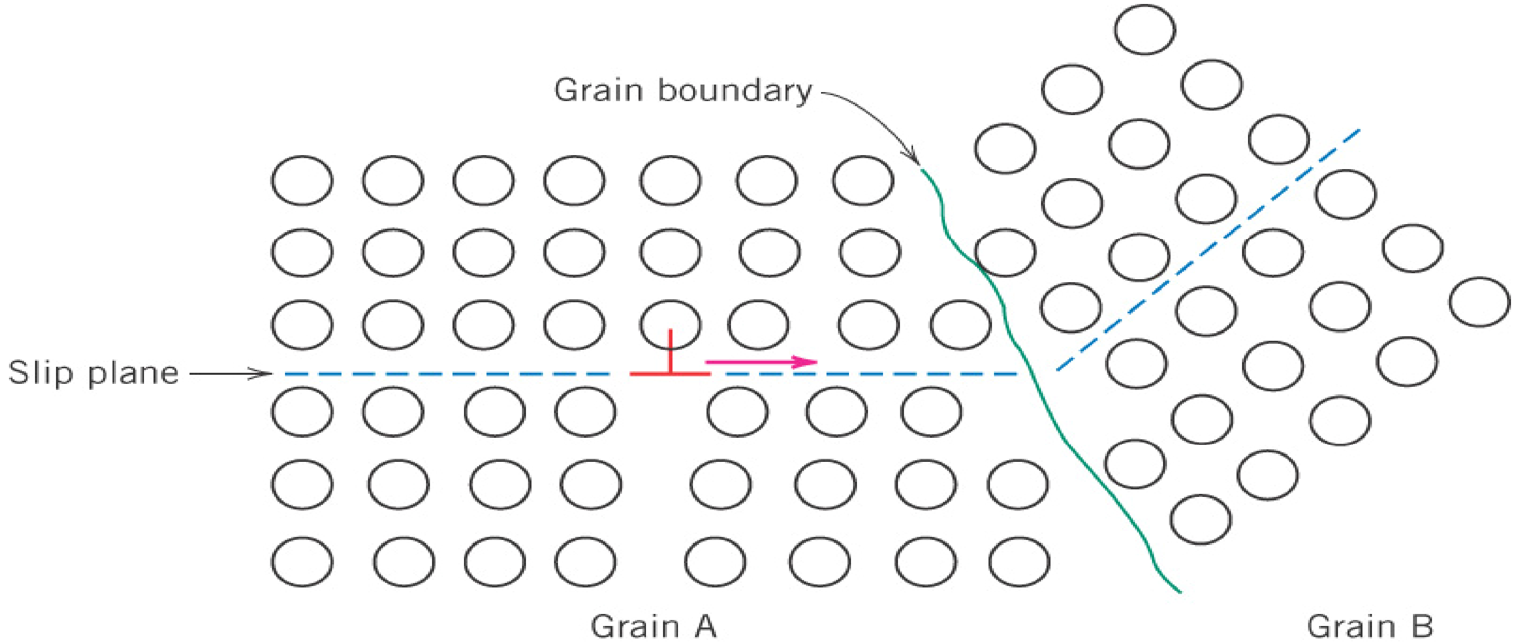
Strengthening

- The ability of a metal to deform plastically depends on the ability of dislocations to move.
- Hardness and strength are related to how easily a metal plastically deforms, so, by reducing dislocation movement, the mechanical strength can be improved.
- Greater mechanical forces will be required to initiate further plastic deformation.
- To the contrary, if dislocation movement is easy (unhindered), the metal will be soft, easy to deform.

Strengthening Mechanisms

1. Grain Size Reduction
2. Solid Solution Alloying
3. Strain Hardening (Cold Working)

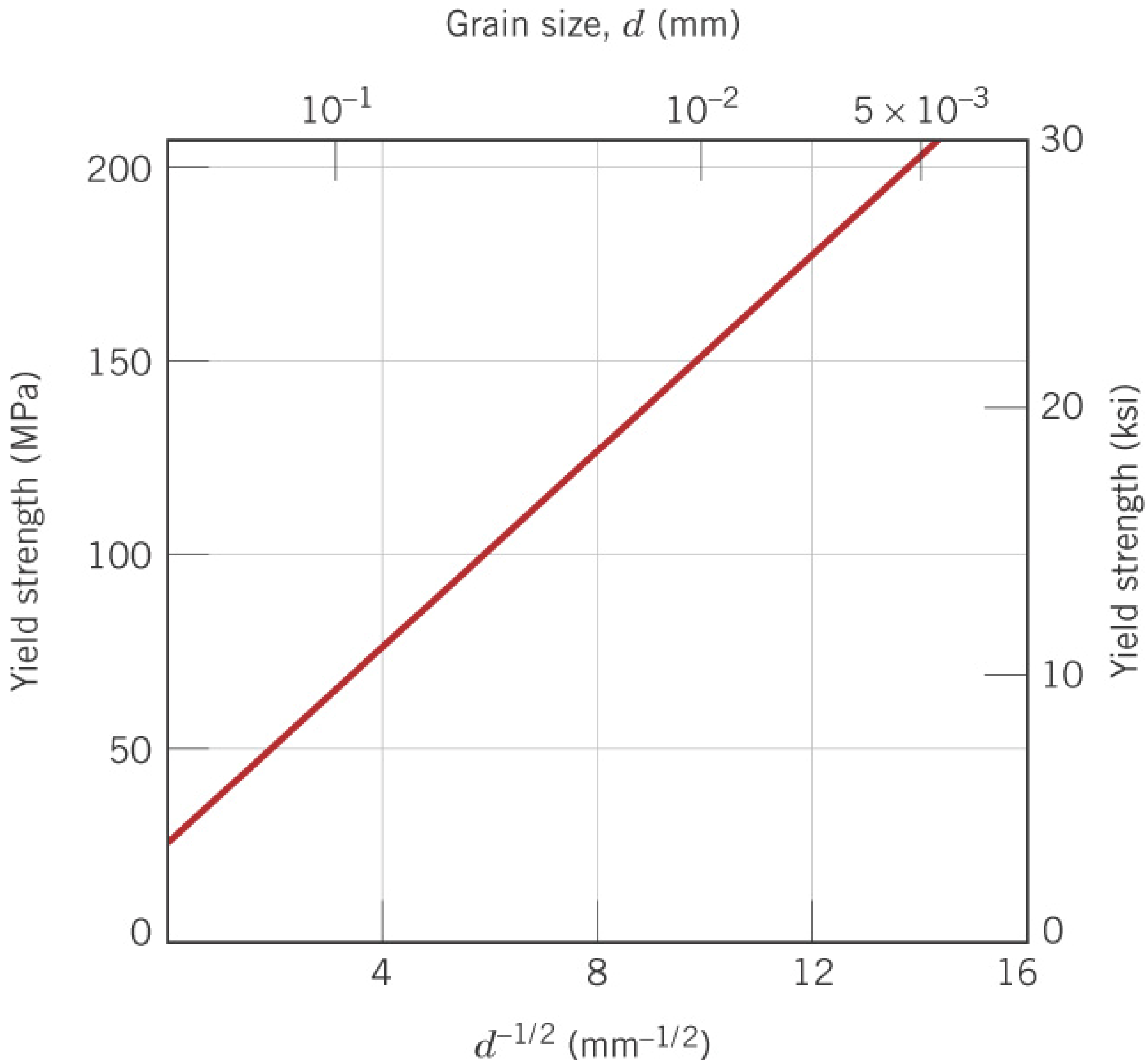
1. REDUCE GRAIN SIZE



- Grain boundaries are barriers to slip.
- Barrier "strength“ increases with misorientation.
- Smaller grain size: more barriers to slip.

Hall-Petch Equation:

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

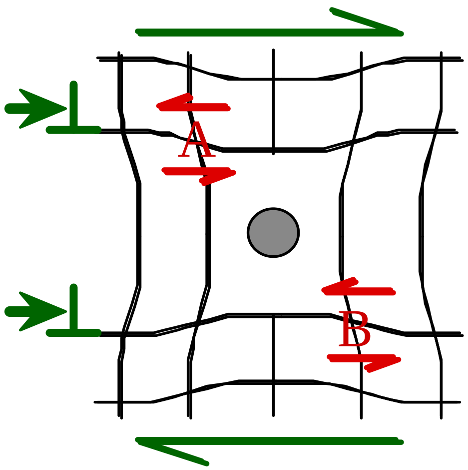


Grain size, d (mm)
10⁻¹
10⁻²
5 × 10⁻³
Yield strength (MPa)
Yield strength (ksi)
200
150
100
50
0
30
20
10
0
4
8
12
16
d^{-1/2} (mm^{-1/2})

2. Solid Solutions

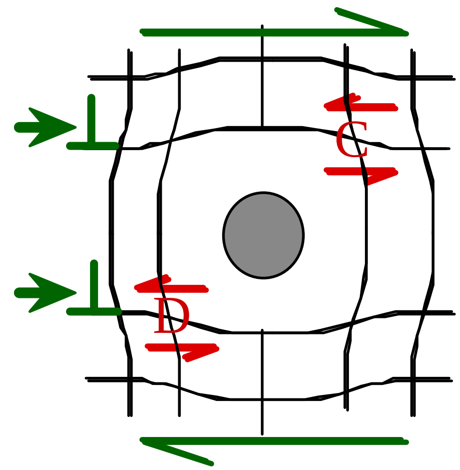
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

Smaller substitutional impurity



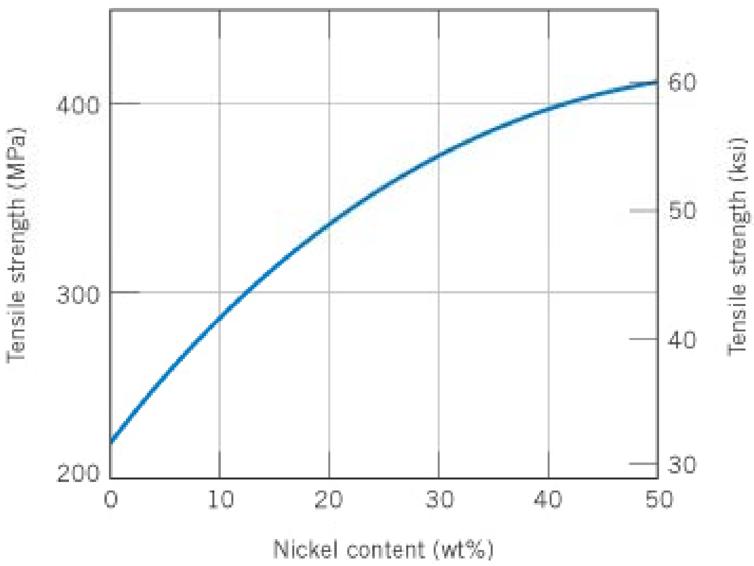
Impurity generates local shear at A and B that opposes dislocation motion to the right.

Larger substitutional impurity

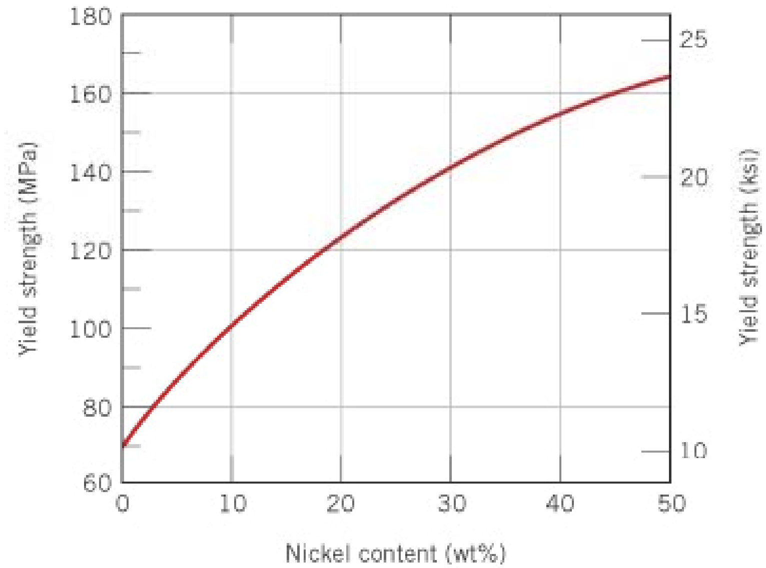


Impurity generates local shear at C and D that opposes dislocation motion to the right.

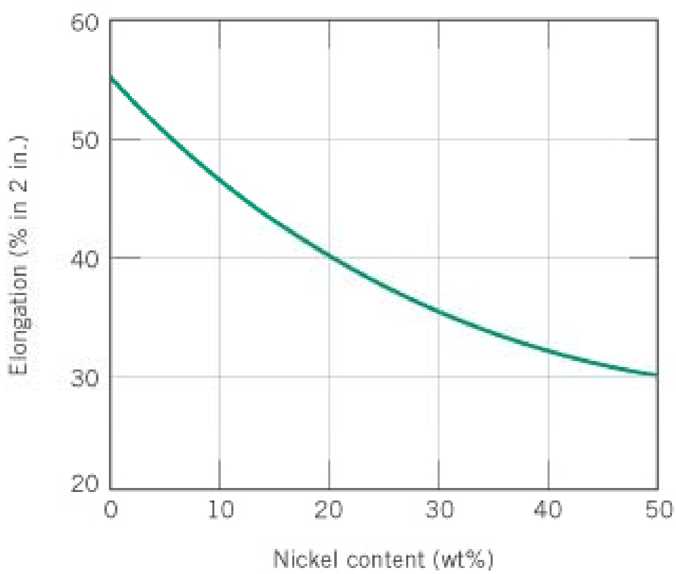
Solid Solution Strengthening in Copper



(a)



(b)



(c)

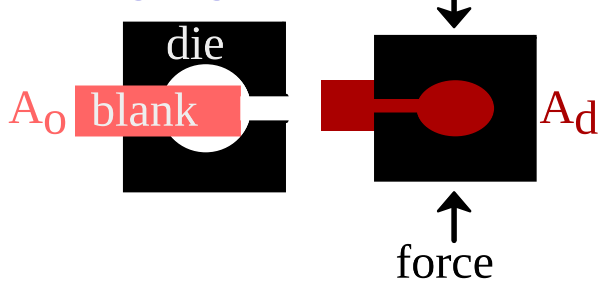
Effects of Nickel (solute) content in Copper (host) - Tensile strength (a), Yield strength (b) and Ductility, % Elongation (c).

3. Strain Hardening

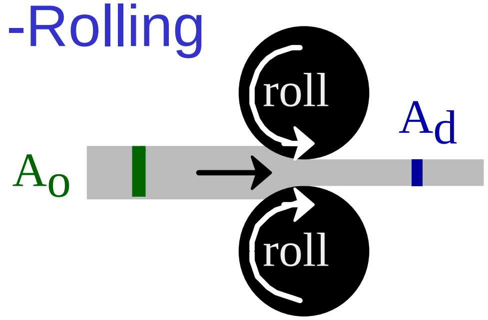
- Room temperature deformation.
- Common forming techniques used to change the cross sectional area:

$$\%CW = \frac{A_o - A_d}{A_o} x100$$

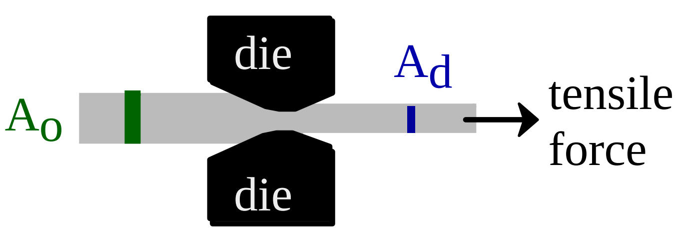
-Forging



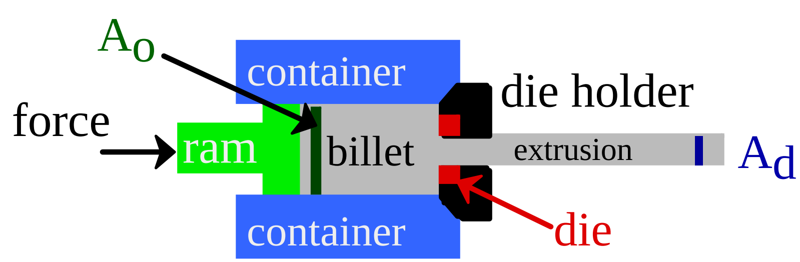
-Rolling



-Drawing



-Extrusion



Dislocations DURING COLD WORK

- Ti alloy after cold working.
- Dislocations entangle one another during cold work.
- Dislocation motion becomes more difficult.

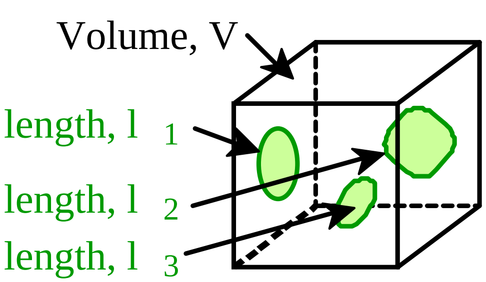
Result of Cold Work

- Dislocation density (ρ_d) increases:

  Carefully prepared sample: $\rho_d \sim 10^3$ mm/mm^3

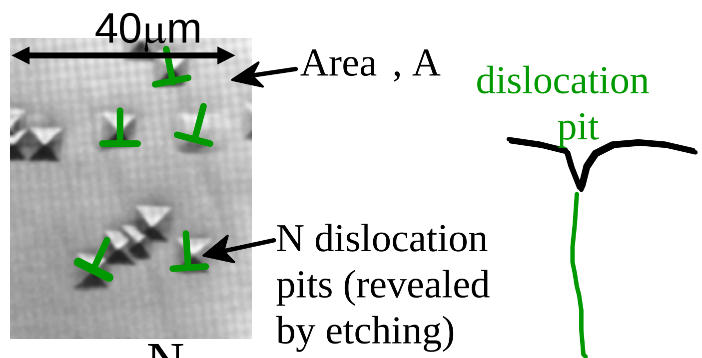
  Heavily deformed sample: $\rho_d \sim 10^{10}$ mm/mm^3

- Ways to measure dislocation density:



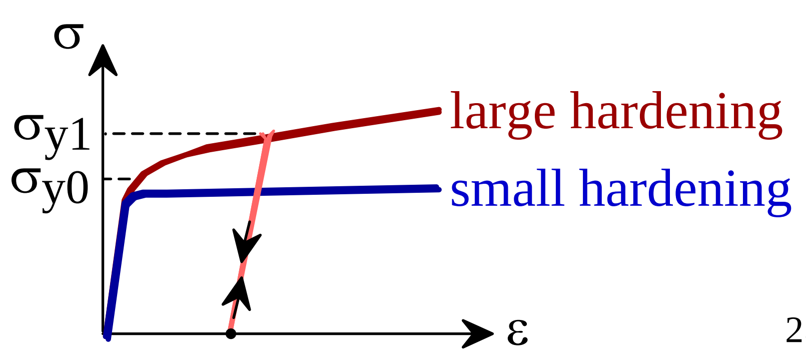
$$\rho_d = \frac{l_1 + l_2 + l_3}{V}$$

OR

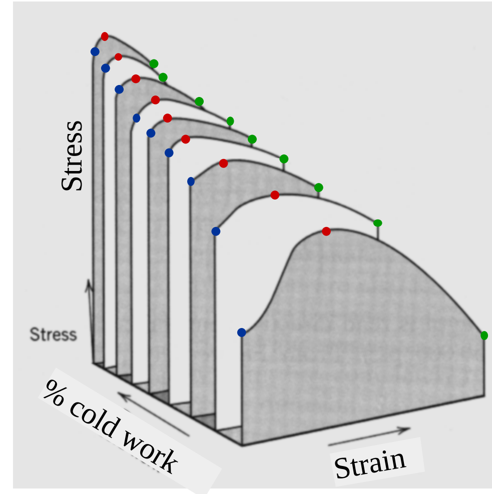


$$\rho_d = \frac{N}{A}$$

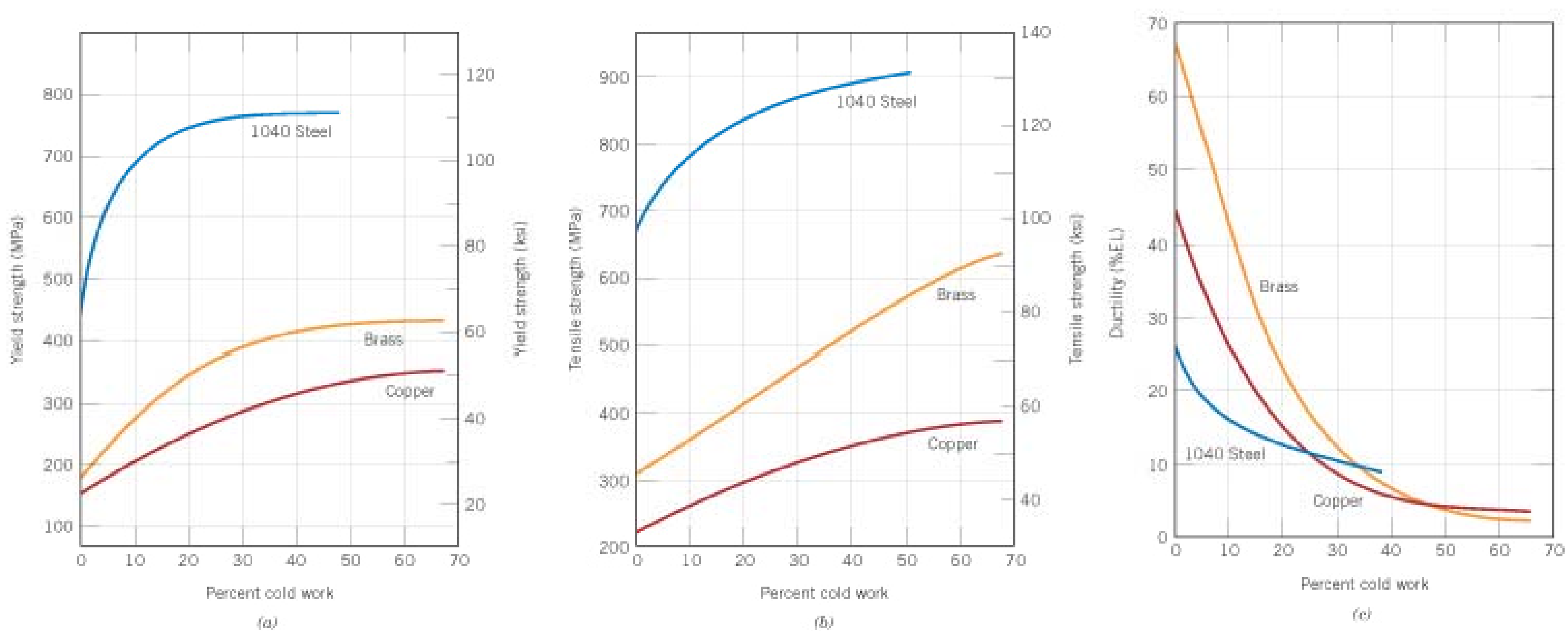
- Yield stress increases as ρ_d increases:



Impact of Cold Work



- Yield strength (σ_y) increases.
- Tensile strength (TS) increases.
- Ductility (%EL or %AR) decreases.

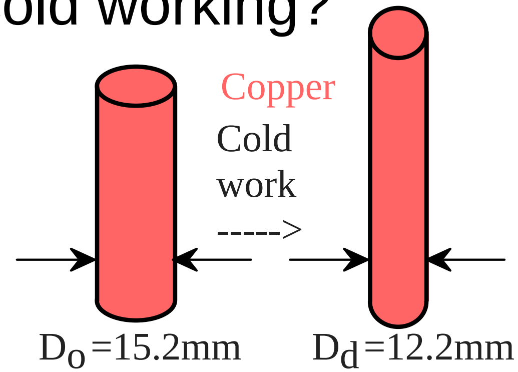


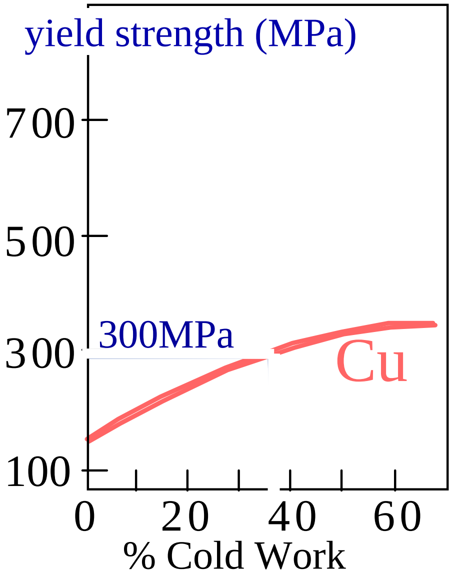
Cold Work Analysis

- What is the tensile strength & ductility after cold working?

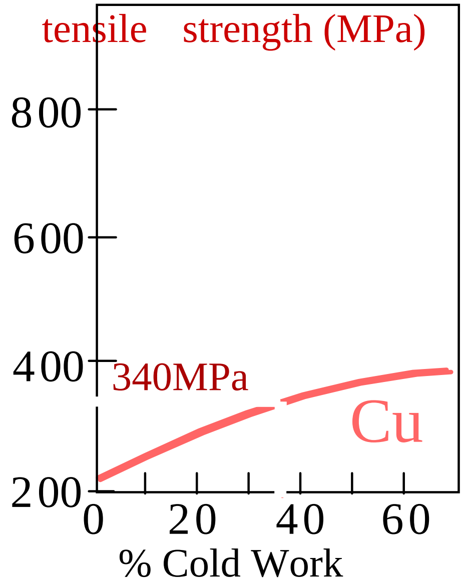
$$\%CW = \frac{A_o - A_d}{A_o} x100$$

$$\%CW = \frac{\pi r_o^2 - \pi r_d^2}{\pi r_o^2} x100 = 35.6\%$$

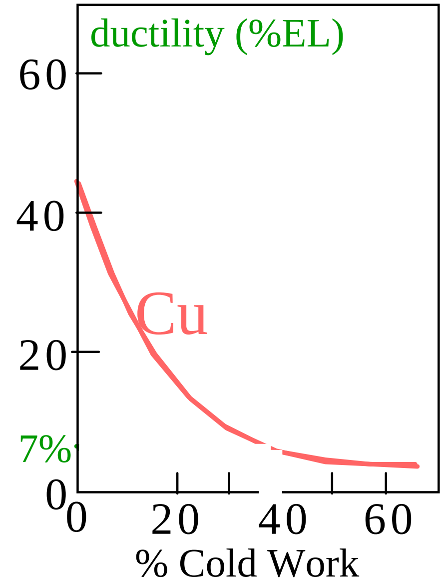




σ_y=300MPa



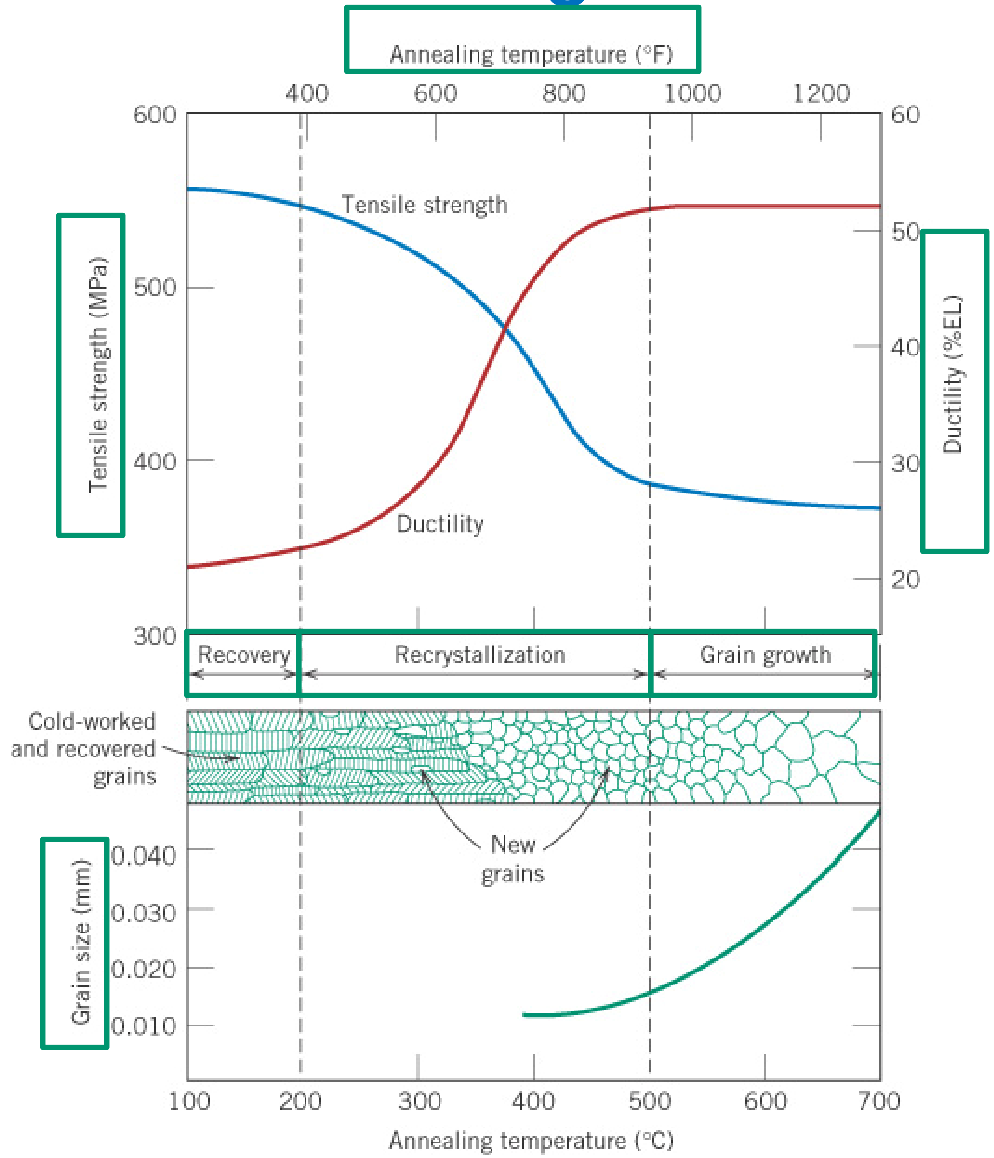
TS=340MPa



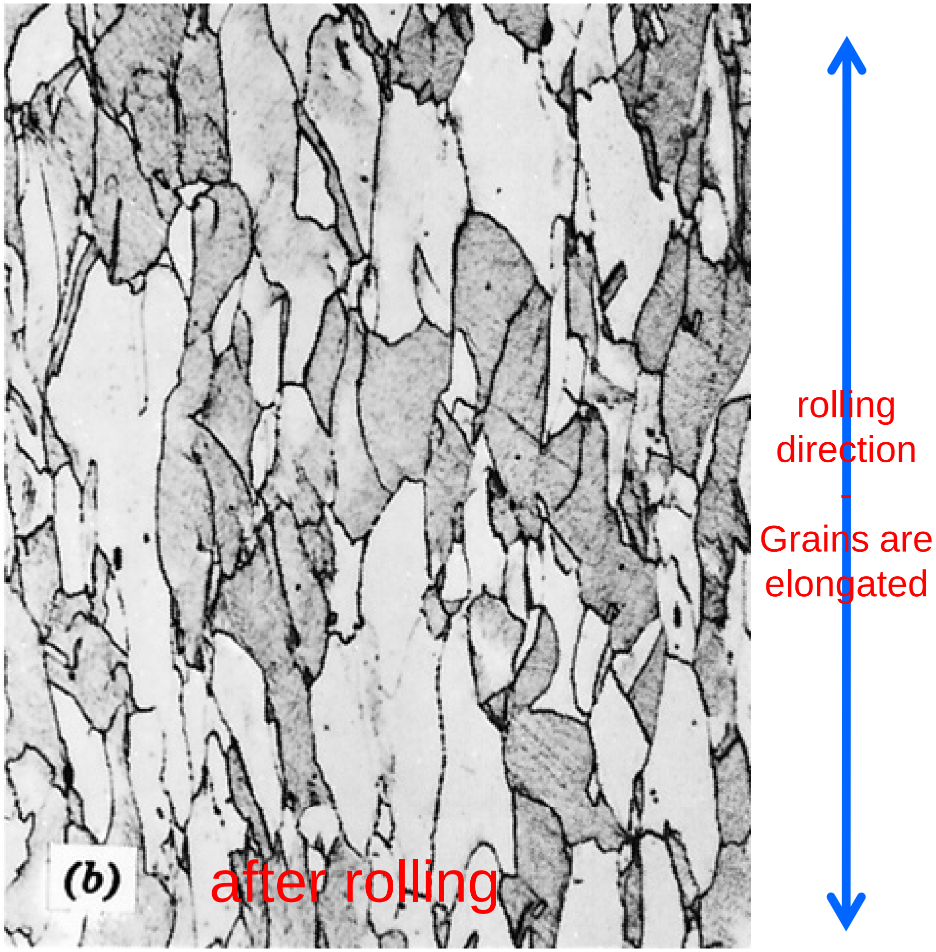
%EL=7%

Effect of Heating After %CW

The influence of annealing temperature (1 hour) on the tensile strength and ductility of a brass alloy. Grain size is shown as a function of annealing temperature.



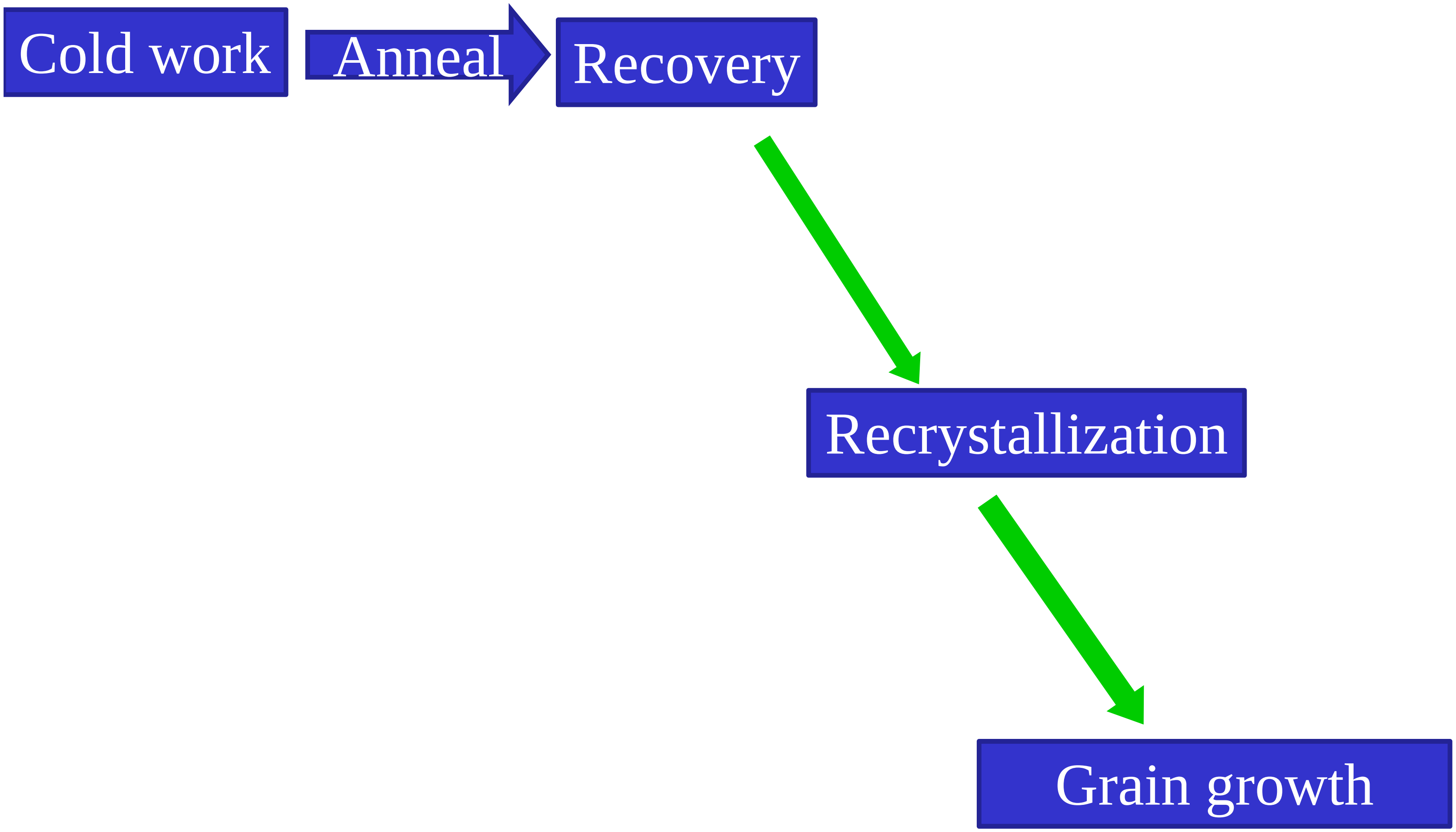
Anisotropy - Polycrystals



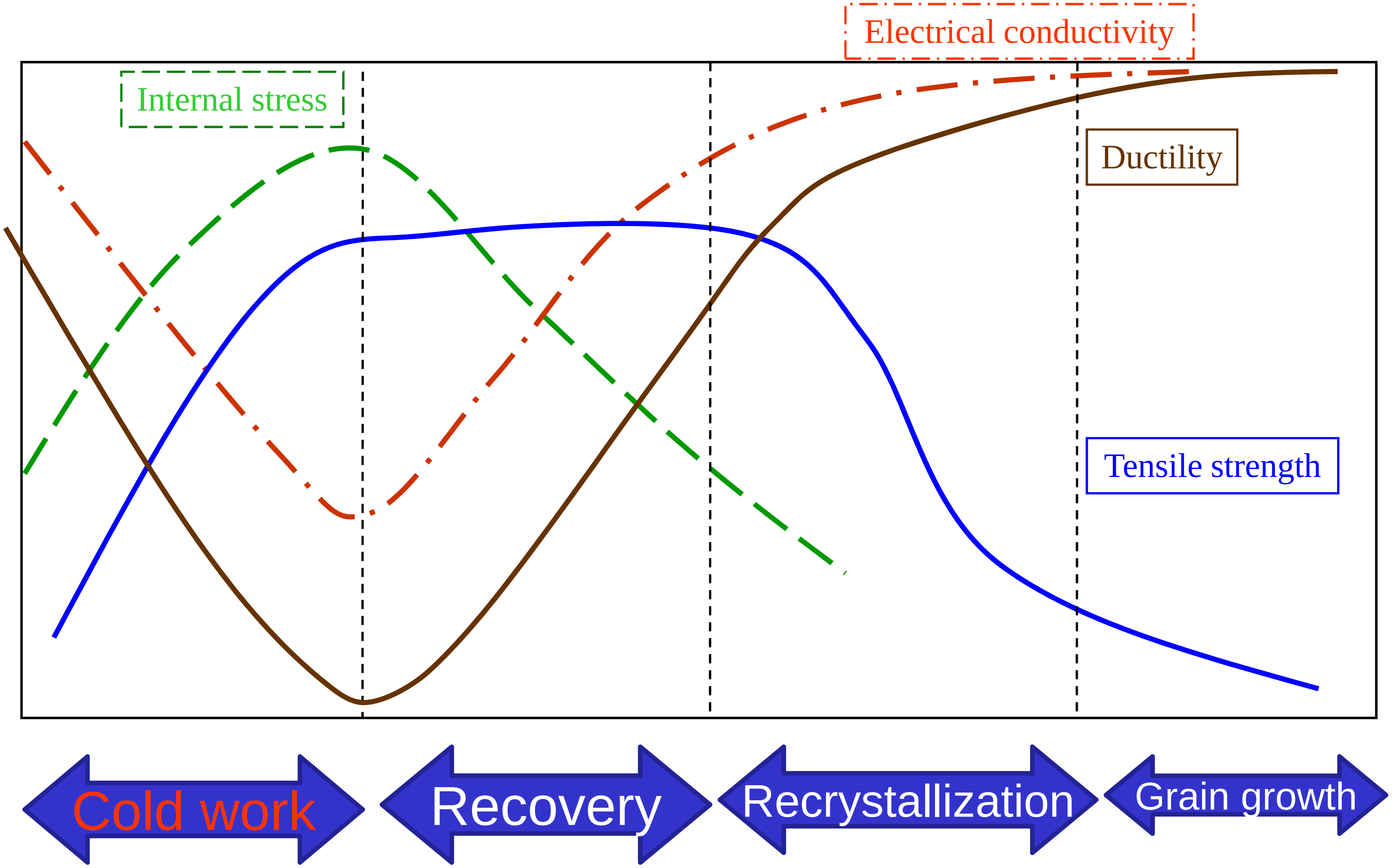
<u>Isotropic</u>
grains are approx. spherical, equiaxed & randomly oriented.

<u>Anisotropic (directional)</u>
since rolling affects grain orientation and shape.

Recovery-Recrystallization-Grain-Growth



Recovery-Recrystallization-Grain-Growth



Recovery-Recrystallization-Grain-Growth

- Plastically deforming a polycrystalline metal specimen at temperatures that are low relative (performing metal-forming operations such as rolling, forging, extrusion etc cold) to its absolute melting temperature produces microstructural and property changes that include:

- Change in grain shape (grains are stretch and deformed).

- Strain hardening.

- Increase in dislocation density.

Recovery-Recrystallization-Grain-Growth

- Many times the reduced ductility of the cold worked metal is undesirable and softer metal is desired.

- The properties and structures may revert back to pre-cold work states by appropriate heat treatment (sometimes termed an annealing treatment).

- The cold-worked state is a condition of higher internal energy than the undeformed metal. Although the cold-worked dislocation cell structure is mechanically stable, it is not thermodynamically stable.

Recovery-Recrystallization-Grain-Growth

With increasing temperature, the cold-worked metal becomes more and more unstable. Eventually the metal softens and returns to a strain-free condition.

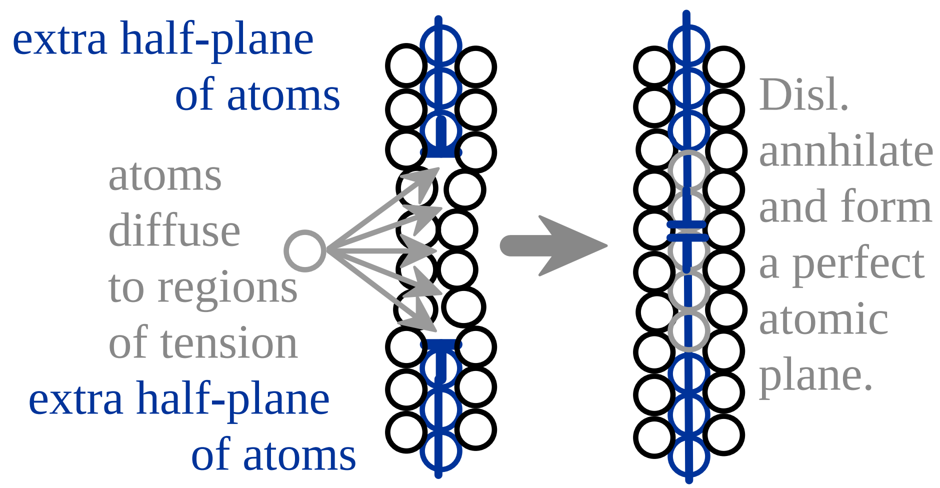
- The overall process by which this occurs is known as annealing. Annealing is a very important process, because it restores the ductility of a metal that has been severely strain-hardened. The reheating treatment that softens a cold-worked metal is known as annealing.

- To achieve this the cold worked metal is heated in a furnace. If the metal is reheated to a sufficiently high temperature for a long enough time, the cold worked metal structure will undergo a series of changes.

Recovery

- During recovery, some of the stored internal strain energy is relieved through dislocation motion due to enhanced atomic diffusion at the elevated temperatures.
- There is some reduction in the number of dislocations.
- Physical properties (electrical and thermal conductivity) are recovered to their pre-cold worked states.

Annihilation reduces dislocation density.



Recovery

During recovery, metal is heated to a temperature of 0.1 T_m. The following objectives are achieved.

- Some of the stored internal energy is relieved (by virtue of dislocation motion as a result of enhanced atomic diffusion at an elevated temperature).During recovery sufficient thermal energy is supplied to allow the dislocations to rearrange themselves into low energy configurations.

- The internal energy of a cold worked metal is lower than the cold-worked state since many dislocations are annihilated or moved into lower energy configurations by the recovery process.

Recovery

- Distortion in lattice is reduced.
- Ductility is significantly improved.
- Physical properties like electrical and thermal conductivities are recovered to pre-cold worked state.
- No observable change in microstructure.

Recrystallization

- During recrystallization metal is heated to a temperature of 0.3 T_m.
- Even after the recovery operation is complete, the grains are still in a relatively high strain energy state.
- In Recrystallization the deformed grains are replaced by a new set of strain-free and equiaxed grains (having approximately equal dimensions in all directions) that have low dislocation densities and are characteristic of the pre-cold worked condition.
- The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material.
- The new grains form as very small nuclei and grow until they completely consume the parent material, processes that involve short range diffusion.

Recrystallization

During recrystallization, the following changes take place in metals:

- Mechanical properties that were changed as a result of cold-working are restored to their precold work values i.e. the metal becomes softer and more ductile.
- Distorted grain disappear and new equiaxed grains form.
- Internal strain energy is further reduced.
- Grain refinement occurs.
- Dislocation density is reduced from $10^{10} – 10^{12}/cm^2$ to $10^6/cm^{2.}$

Recrystallization

- Recrystallization is a process which depends on both time and temperature. The degree of recrystallization increases with time.

- The recrystallization behavior of a particular metal alloy is sometimes specified in terms of recrystallization temperature, the temperature at which recrystallization reaches completion in 1 hour. Typically recrystallization temperature is about 0.3 to 0.5 T_m.

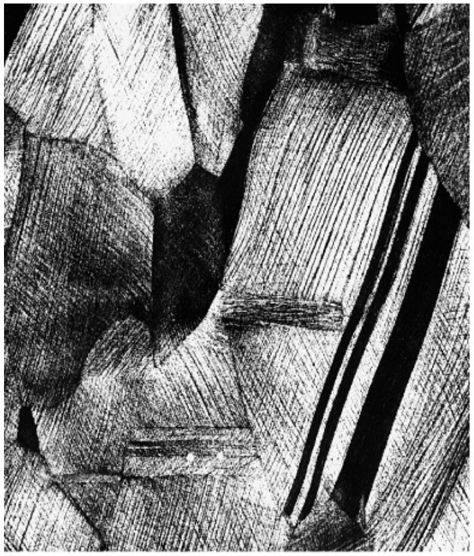
- Hot working: Plastic deformation processes that are conducted above the recrystallization temperature are termed as hot working. Here, the material remains relatively soft and ductile during deformation because it does not strain harden and thus large deformations are possible.

Recrystallization

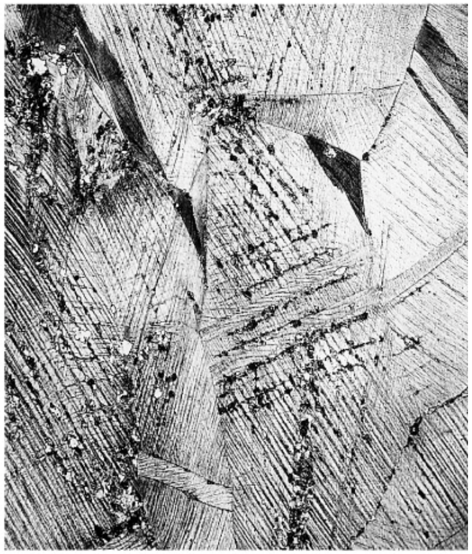
- Even after recovery is complete, the grains are still in a relatively high strain energy state.
- Recrystallization is the formation of a new set of strain-free and equiaxed grains that have low dislocation densities (pre-cold work state).
- The driving force to produce the new grain structure is the internal energy difference between strained and unstrained material.
- The new grains form as very small nuclei and grow until they consume the parent material.
- Recrystallization temperature is $1/3 < T_m < 1/2$.

Further Recrystallization

- Brass: shows several stages of recrystallization and grain growth.

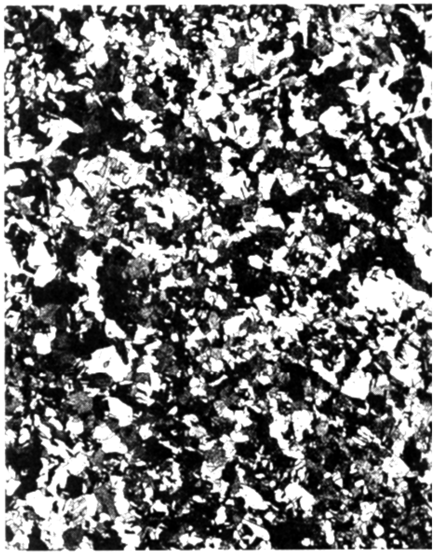


33% CW grains



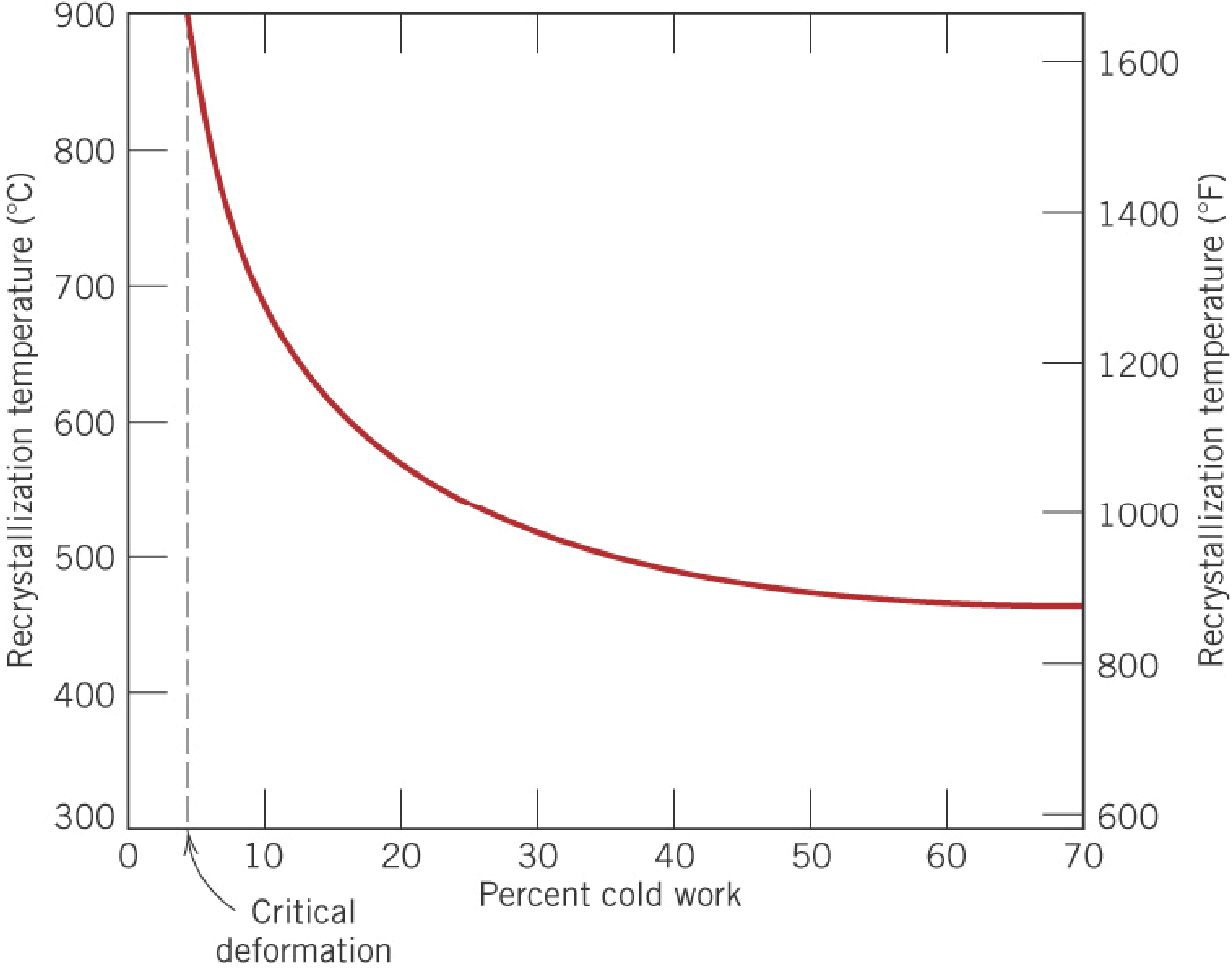
Initial recrystallization; After 3 seconds, 580˚C

Partial replacement of CW grains; After 4 seconds

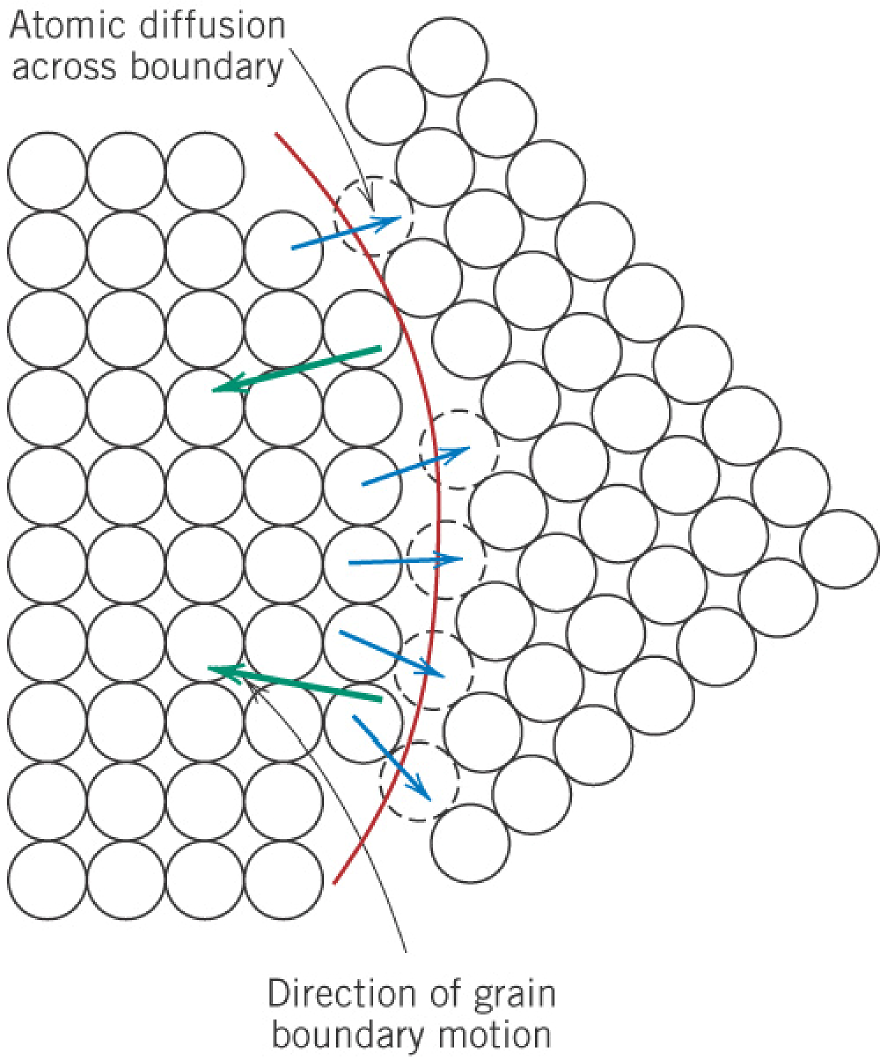


Complete recryst. after 8 seconds

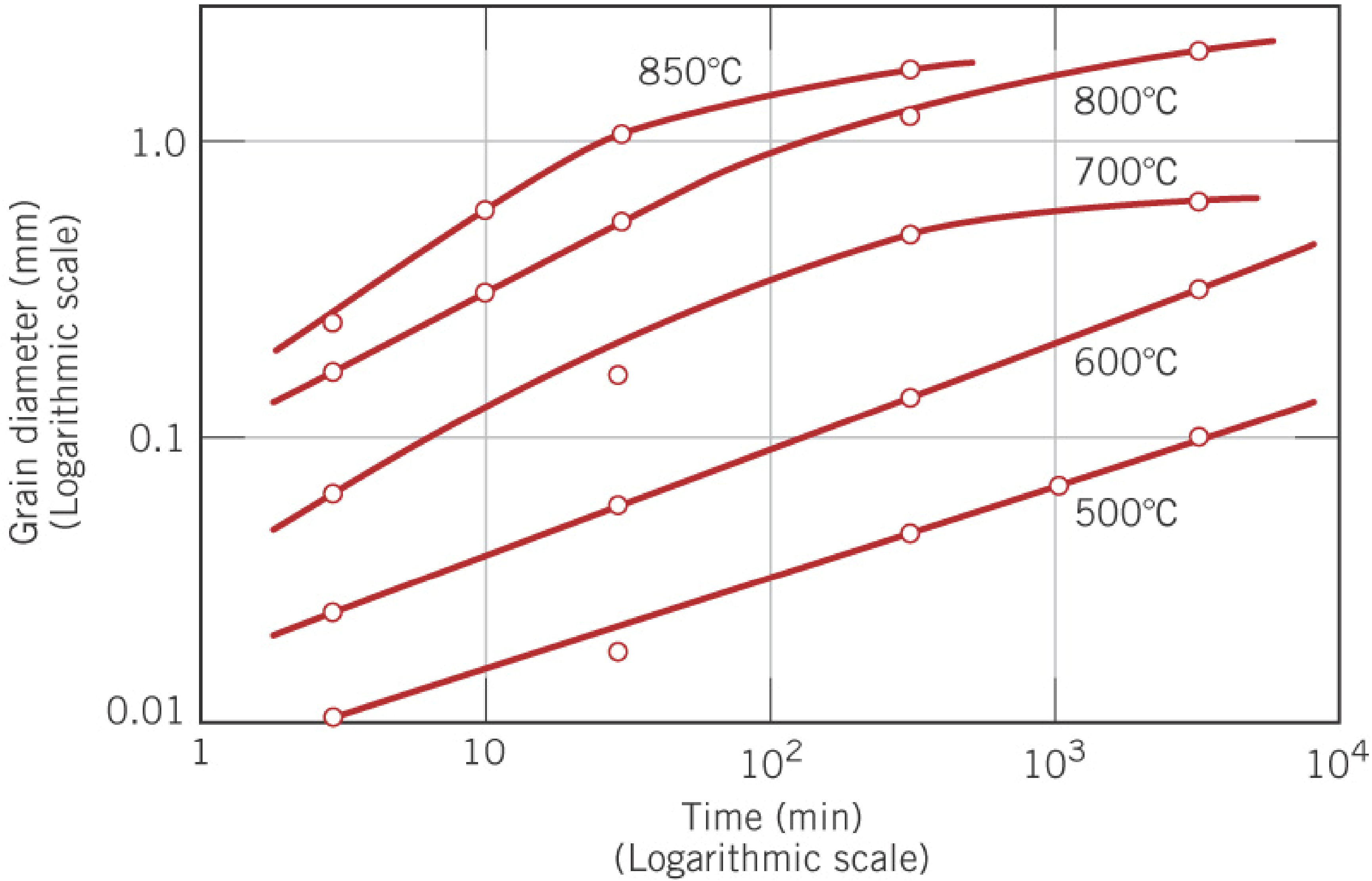
Recrystallization with temperature vs %CW for iron. For deformations less than 5% CW, recrystallization will not occur.



GRAIN GROWTH



- After recrystallization is complete, the strain-free grains will continue to grow if the metal specimen is left at elevated temperatures.
- As grains increase in size, the total boundary area decreases, as does the total energy.
- Large grains grow at the expense of smaller grains.



- Grain diameter versus time for grain growth at specific temperatures (log scale). Brass Alloy example

What Is The Driving Force For Grain Growth?

- An energy is associated with grain boundaries. As grains increase in size, the total boundary area decreases, yielding an attendant reduction in the total energy; this is the driving force for grain growth.

- Grain-growth occurs by the migration of grain boundaries. Obviously, not all grains can enlarge, but large grains grow at the expense of small grains that shrink.

- Grain boundary motion is short range diffusion of atoms from one side of the boundary to another. The direction of the boundary and atomic motion are opposite to one another.

- The mechanical properties at room temperature of a fine-grained material are generally superior (i.e., higher strength and toughness) to those of a coarse-grained material.