Chapter 7 Dislocations and Strengthening Mechanisms

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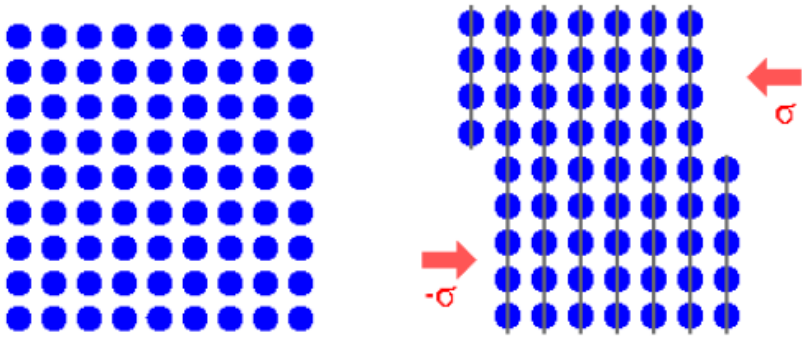
Chapter Outline

- **Dislocations and Strengthening Mechanisms**
- **What is happening in material during plastic deformation?**
- **Dislocations and Plastic Deformation**
- Motion of dislocations in response to stress
- Slip Systems
- Plastic deformation in
  - ✓ single crystals
  - ✓ polycrystalline materials
- **Strengthening mechanisms**
  - ✓ Grain Size Reduction
  - ✓ Solid Solution Strengthening
  - ✓ Strain Hardening
- **Recovery, Recrystallization, and Grain Growth**

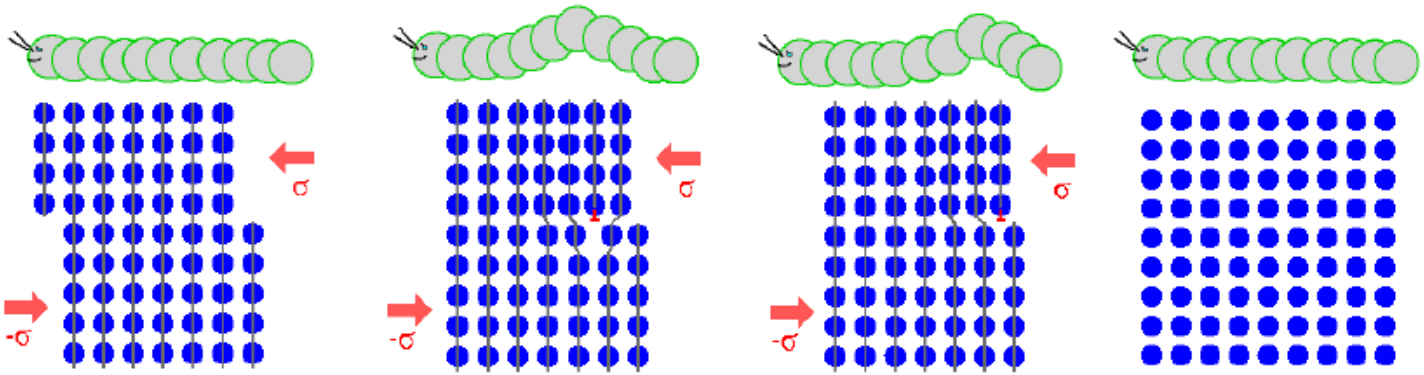
Introduction

- Why metals could be plastically deformed?
- Why the plastic deformation properties could be changed to a very large degree by forging without changing the chemical composition?
- Why plastic deformation occurs at stresses that are much smaller than the theoretical strength of perfect crystals?



- Plastic deformation – the force to break all bonds in the slip plane is much higher than the force needed to cause the deformation. Why?
- These questions can be answered based on the idea proposed in 1934 by Taylor, Orowan and Polyani: **Plastic deformation is due to the motion of a large number of dislocations.**

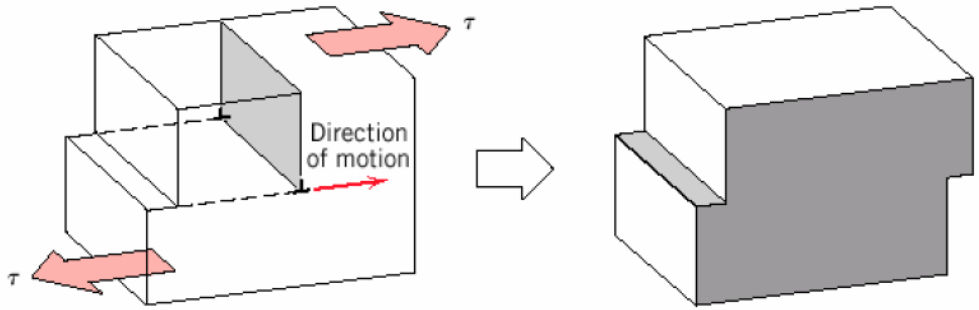
Dislocations allow deformation at much lower stress than in a perfect crystal



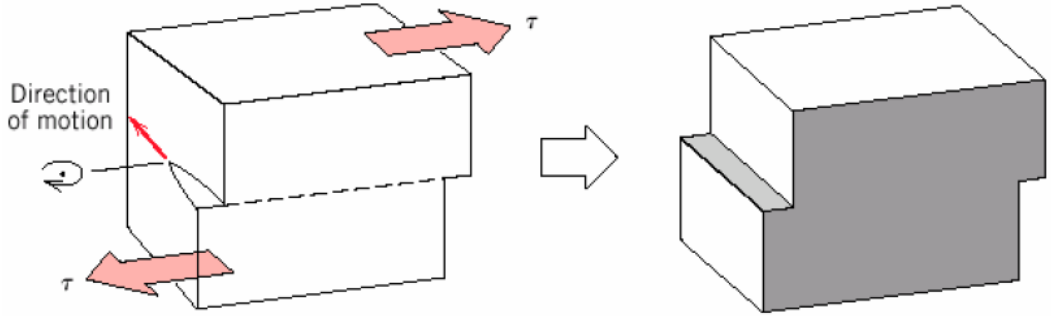
- If the top half of the crystal is slipping one plane at a time then only a small fraction of the bonds are broken at any given time and this would require a much smaller force.
- The propagation of one dislocation across the plane causes the top half of the crystal to move (**to slip) with respect to** the bottom half but we do not have to break all the bonds across the middle plane simultaneously (which would require a very large force).

Direction of the dislocation motion

- **The slip plane – the crystallographic plane of dislocation** motion.



Edge dislocation line moves parallel to applied stress

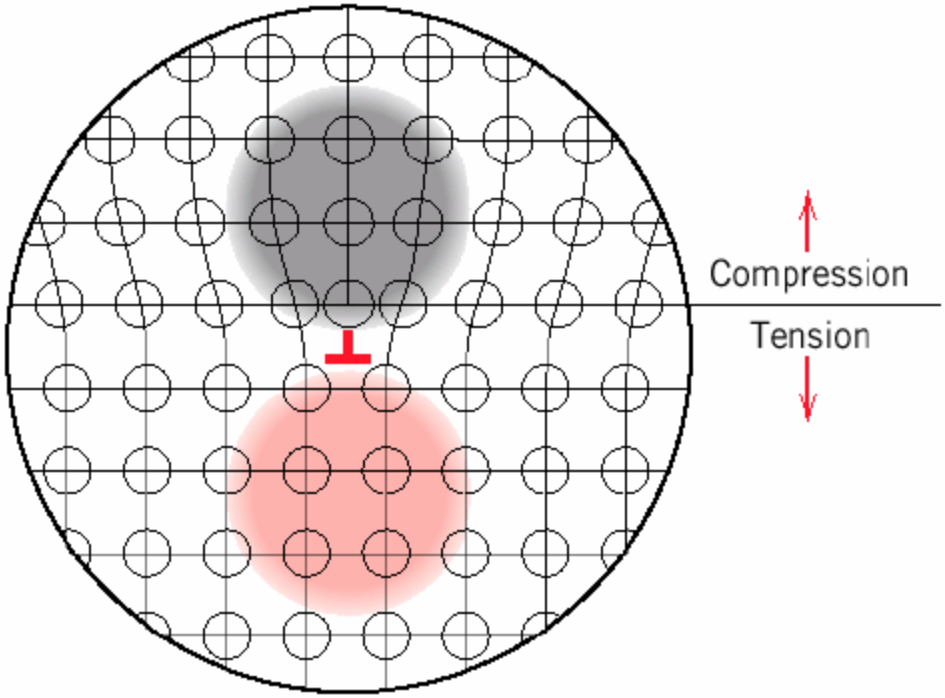


Screw dislocation line moves perpendicular to applied stress

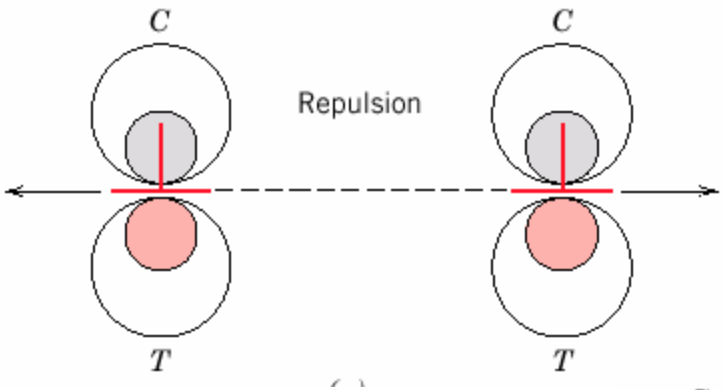
- For mixed dislocations, direction of motion is in between parallel and perpendicular to the applied shear stress.

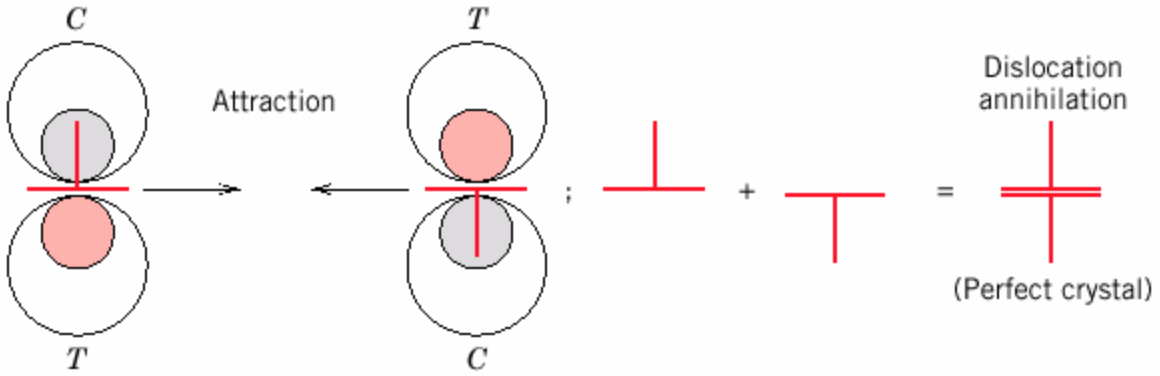
Strain field around dislocations

- **Dislocations have strain fields arising from distortions at their cores - strain drops radially with distance from the dislocation core**
- Edge dislocations introduce compressive, tensile, and shear lattice strains, screw dislocations introduce shear strain
- only.



Interactions between dislocations

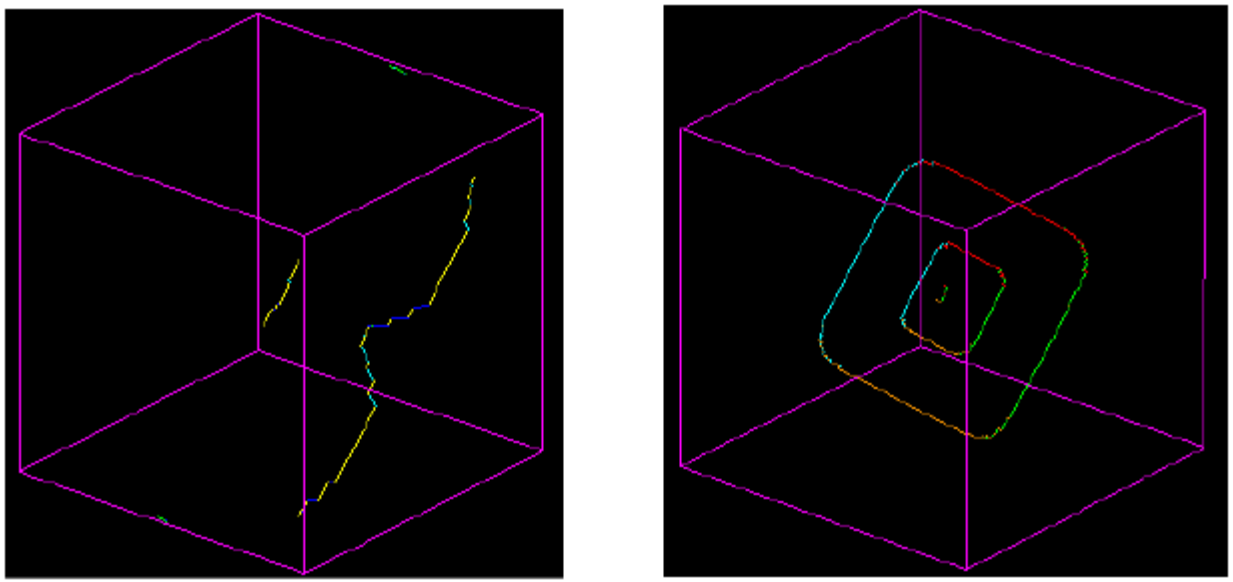




- The strain fields around dislocations cause them to **interact (exert force on each other). When they are in** the same plane, they repel if they have the same sign (direction of the Burgers vector) and attract/annihilate if they have opposite signs.

Where do dislocations come from ?

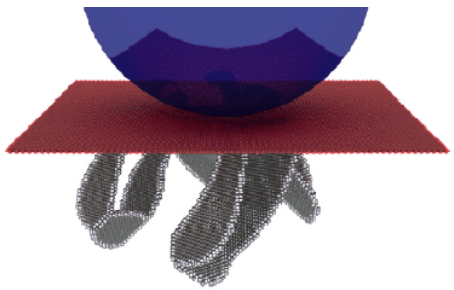
- The number of dislocations in a material is expressed as the **dislocation density - the total dislocation length per unit** volume or the number of dislocations intersecting a unit area. Dislocation densities can vary from 10^5 cm^{-2} in carefully grown metal crystals to 10^{12} cm^{-2} in heavily deformed metals.
- Most crystalline materials, especially metals, have dislocations in their as-formed state, mainly as a result of stresses (mechanical, thermal...) associated with the forming process.



Computer simulation of Frank-Read source: Emission of dislocation loops from a dislocation segment pinned at its ends

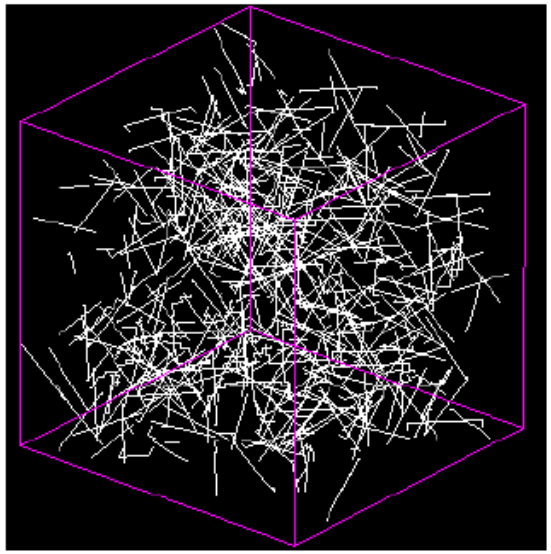
Where do dislocations come from ?

- The number of dislocations increases dramatically during plastic deformation. Dislocations spawn from existing dislocations, grain boundaries and surfaces.



Emission of dislocation loops in nanoindentation of copper

http://merapi.physik.uni-kl.de/~gerolf/Nanoindentation/

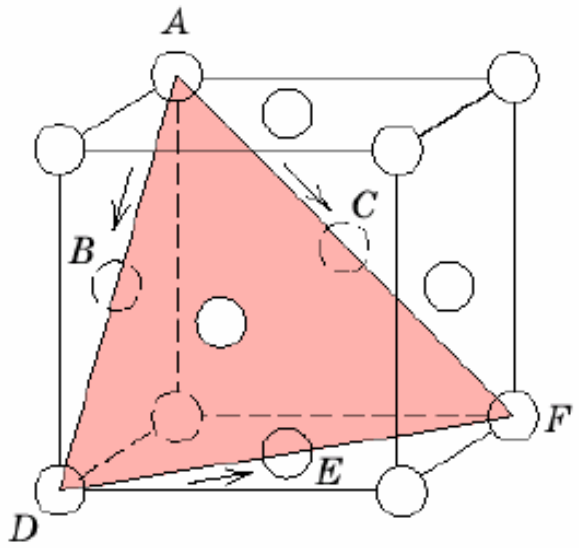


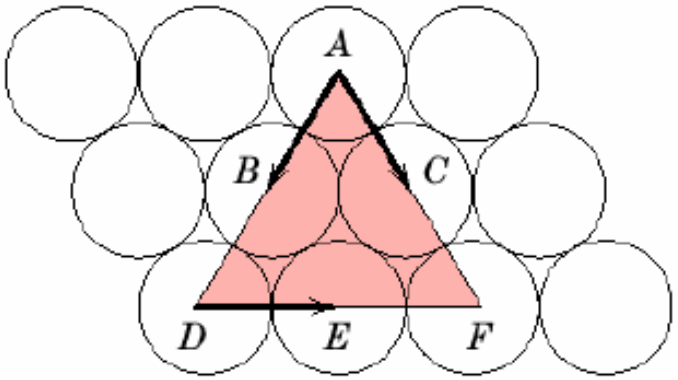
Simulation of plastic deformation in a fcc single crystal (Cu) of linear dimension 15 micrometers.

http://zig.onera.fr/lem/DisGallery/3D.html

Slip Systems

- In single crystals there are preferred planes where dislocations move (**slip planes). Within the slip planes** there are preferred crystallographic directions for dislocation movement (**slip directions). The set of slip** planes and directions constitute **slip systems.**
- **The slip planes and directions are those of highest packing density. Since the distance between atoms is shorter** than the average, the distance perpendicular to the plane has to be longer than average. Being relatively far apart, the planes can slip more easily relatively to each other.
- BCC and FCC crystals have more slip systems as compared to HCP, there are more ways for dislocation to propagate ⇒ FCC and BCC crystals are more ductile than HCP crystals. Remember our discussion of close packed planes in FCC and HCP, Chapter 3.


A
B
C
D
E
F


A
B
C
D
E
F

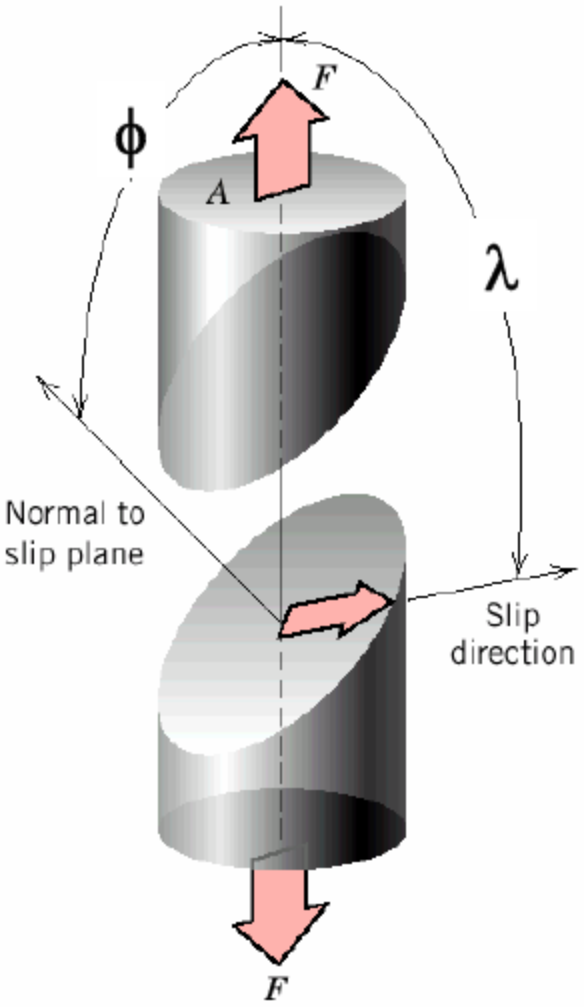
Slip in single crystals - resolving the applied stress onto the slip system

- Dislocations move in particular directions on particular planes (the slip system) in response to shear stresses applied along these planes and directions ⇒ we need to determine how the applied stress is **resolved onto the slip** systems.

Slip in single crystals - resolving the applied stress onto the slip system

- Let us define the **resolved shear stress, τ_R, (which** produces plastic deformation) that result from application of a simple tensile stress, σ.

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



Slip in single crystals - critical resolved shear stress

- When the resolved shear stress becomes sufficiently large, the crystal will start to yield (dislocations start to move along the most favorably oriented slip system). The onset of yielding corresponds to the yield stress, σy (Chapter 6).
- The minimum shear stress required to initiate slip is termed **the critical resolved shear stress:**

$$\tau_{CRSS} = \sigma_y (\cos\phi \cos\lambda)_{MAX}$$

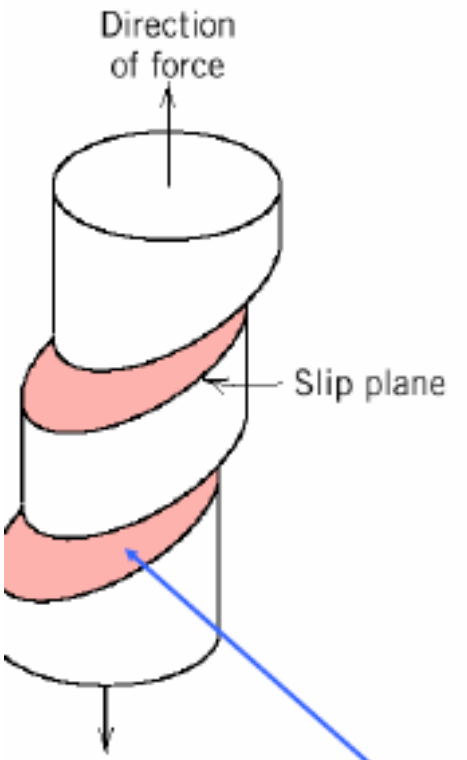
$$\sigma_y = \frac{\tau_{CRSS}}{(\cos\phi \cos\lambda)_{MAX}}$$

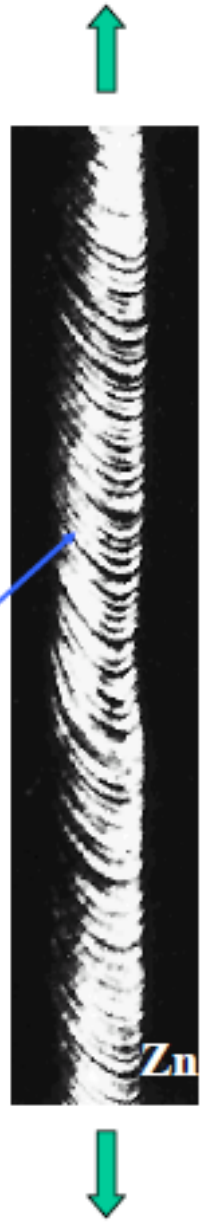
Maximum value of ($\cos\phi \cos\lambda$) corresponds to

$\phi = \lambda = 45^o \Rightarrow \cos\phi \cos\lambda = 0.5 \Rightarrow \sigma_y = 2\tau_{CRSS}$

Slip will occur first in slip systems oriented close to these angles ($\phi = \lambda = 45^o$) with respect to the applied stress

Slip in a single crystal

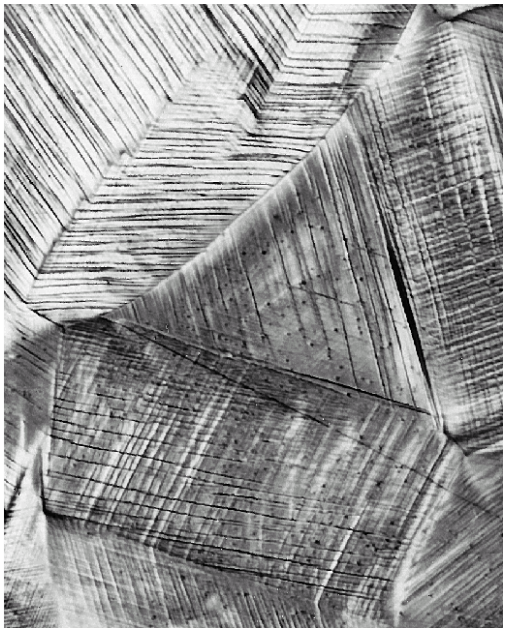




Each step (shear band) result from the generation of a large number of dislocations and their propagation in the slip system with maximum resolved shear stress.

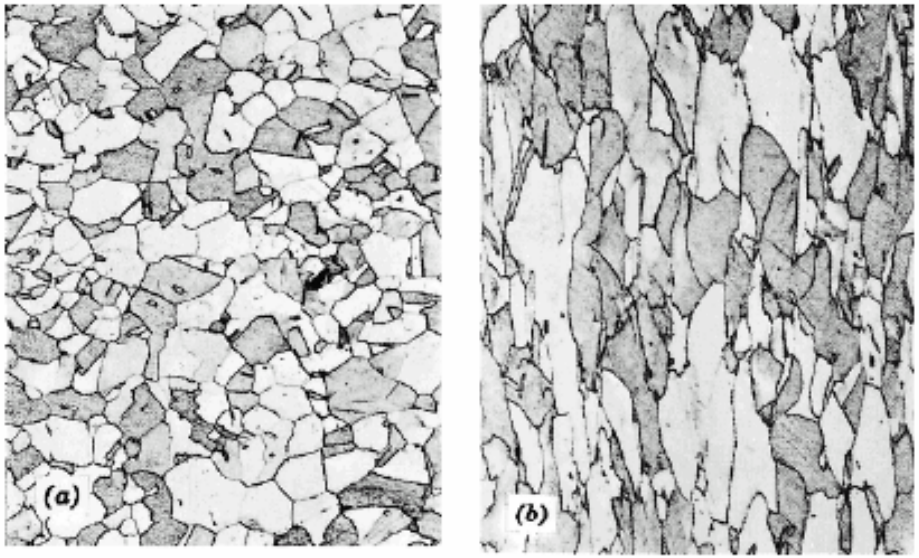
Plastic Deformation of polycrystalline materials

- Grain orientations with respect to applied stress are random.
- The dislocation motion occurs along the slip systems with favorable orientation (i.e. that with highest resolved shear stress).



Plastic deformation of polycrystalline materials

- Larger plastic deformation corresponds to elongation of grains along direction of applied stress.



Before *After*

Plastic deformation of polycrystalline materials

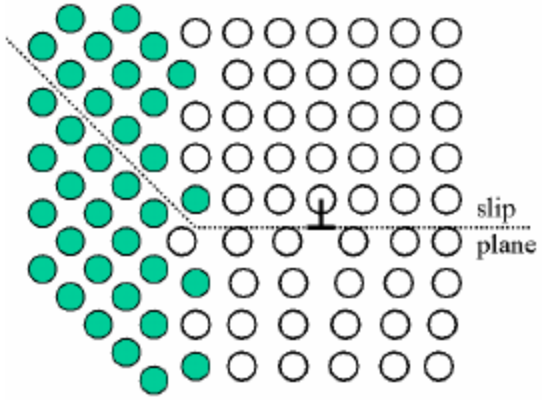
- Slip directions vary from crystal to crystal ⇒ Some grains are unfavorably oriented with respect to the applied stress (i.e. cosϕ cosλ low)
- Even those grains for which cosϕ cosλ is high may be limited in deformation by adjacent grains which cannot deform so easily
- Dislocations cannot easily cross grain boundaries because of changes in direction of slip plane and atomic disorder at grain boundaries
- **As a result, polycrystalline metals are stronger than single crystals (the exception is the perfect single** crystal without any defects, as in whiskers)

Strengthening

- **The ability of a metal to deform depends on the ability of dislocations to move.**
- **Restricting dislocation motion makes the material stronger.**
- Mechanisms of strengthening in single-phase metals:
  - ✓ grain-size reduction
  - ✓ solid-solution alloying
  - ✓ strain hardening
- **Ordinarily, strengthening reduces ductility**

Strengthening by grain-size reduction (I)

- Grain boundary barrier to dislocation motion: slip plane discontinues or change orientation.



•Small angle grain boundaries are not very effective in blocking dislocations.

•High-angle grain boundaries block slip and increase strength of the material. A stress concentration at end of a slip plane may trigger new dislocations in an adjacent grain.

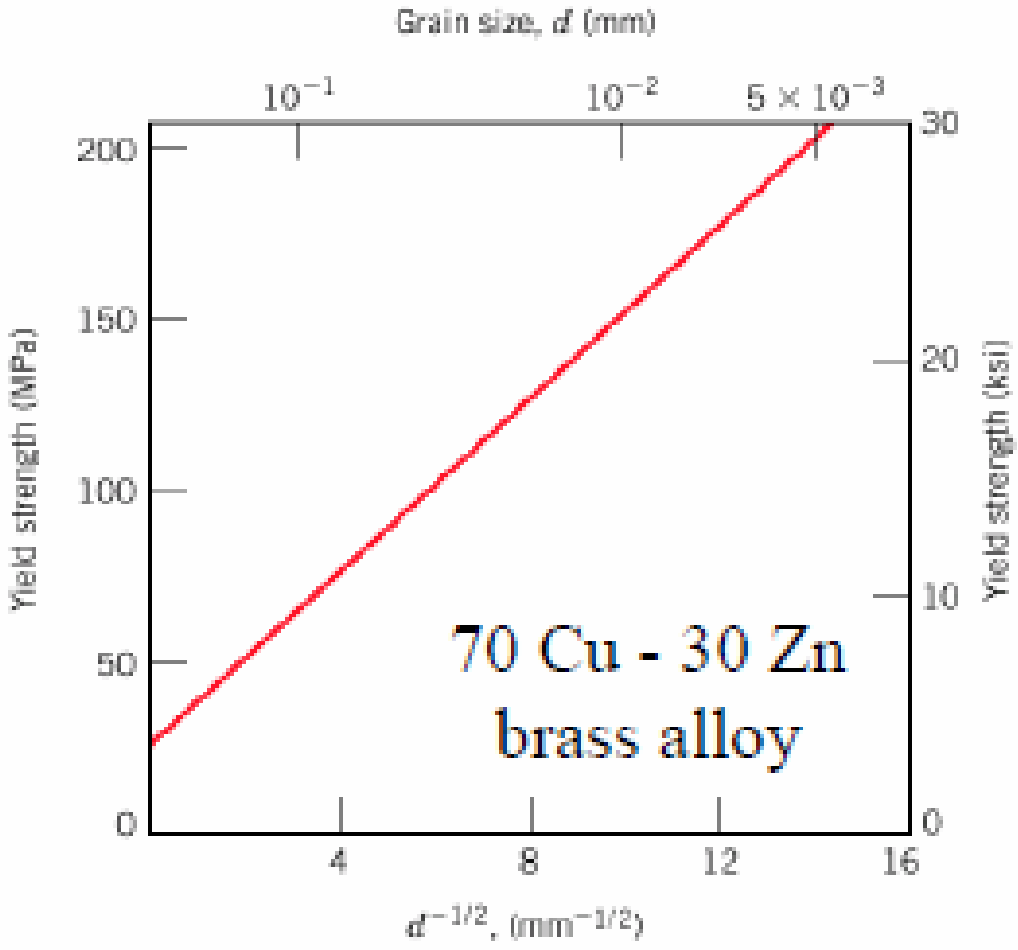
Strengthening by grain-size reduction (II)

- The finer the grains, the larger the area of grain boundaries that impedes dislocation motion. Grain-size reduction usually improves toughness as well. Usually, the yield strength varies with grain size d according to Hall-Petch equation:

$$\sigma_y = \sigma_0 + k_y / \sqrt{d}$$

where σ_o **and** k_y **are constants for a particular material, d is** the average grain diameter.

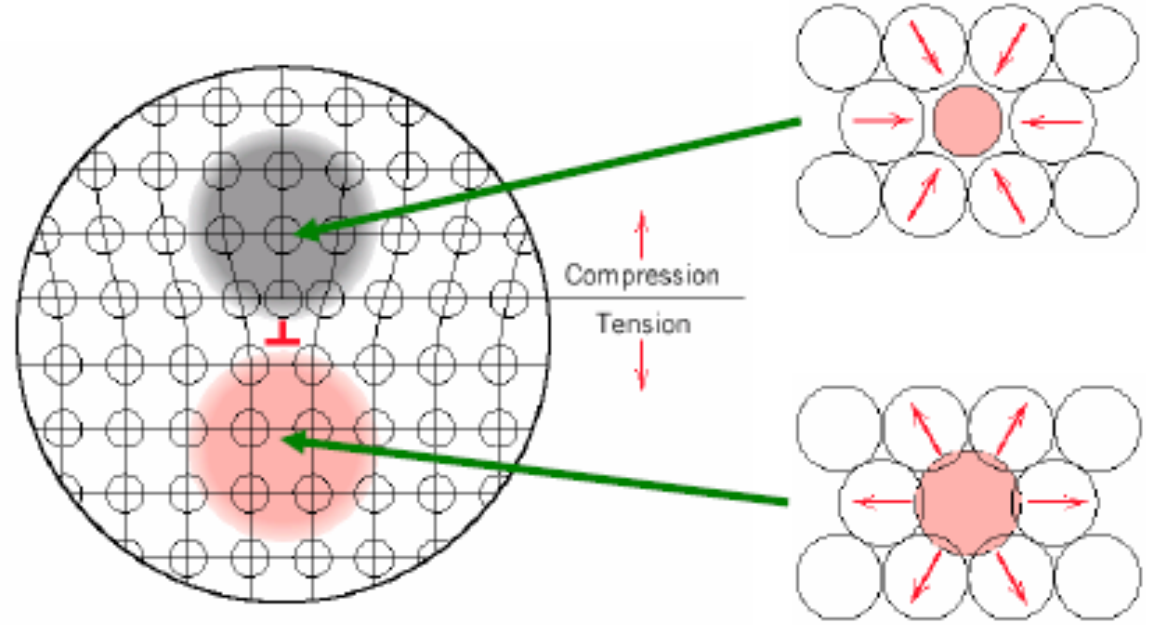
Grain size **d can be controlled by the rate of solidification,** by plastic deformation and by appropriate heat treatment.


Grain size, d (mm)
10^-1
10^-2
5 × 10^-3
200
150
100
50
0
30
20
10
0
Yield strength (MPa)
Yield strength (ksi)
70 Cu - 30 Zn
brass alloy
4
8
12
16
d^-1/2, (mm^-1/2)

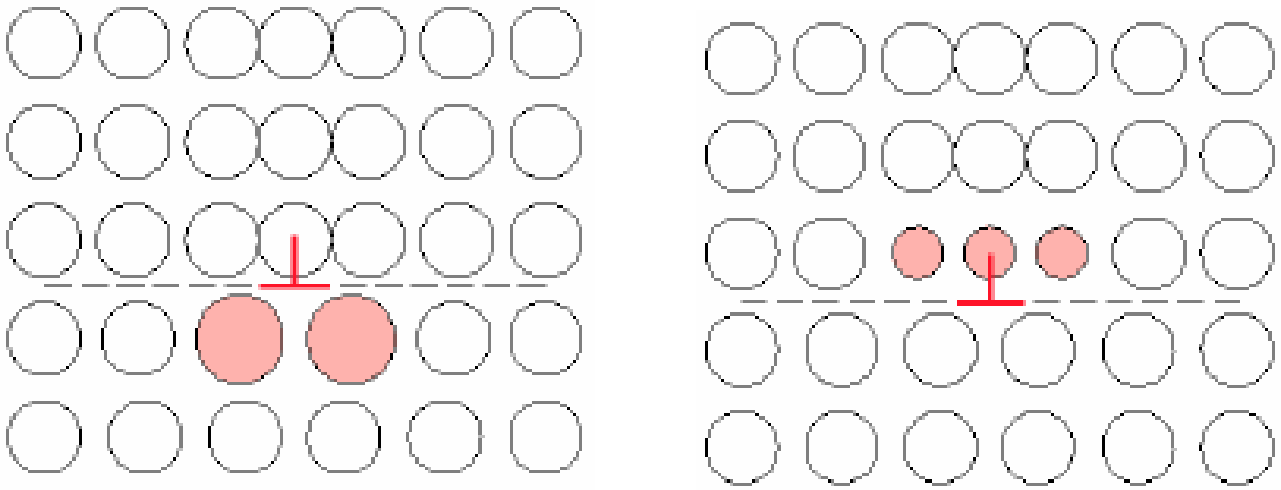
Solid-Solution Strengthening (I)

- **Alloys are usually stronger than pure metals**
- Interstitial or substitutional impurities cause lattice strain. As a result, these impurities interact with dislocation strain fields and **hinder dislocation motion.**
- Impurities tend to diffuse and **segregate around dislocation cores to find atomic sites that suit their** radii. This reduces the overall strain energy and "anchors" the dislocations.
- Motion of a dislocation core away from the impurities moves it to a region of lattice where the atomic strains are greater (i.e. the dislocation strains are no longer compensated by the impurity atoms).

Solid-Solution Strengthening (II)

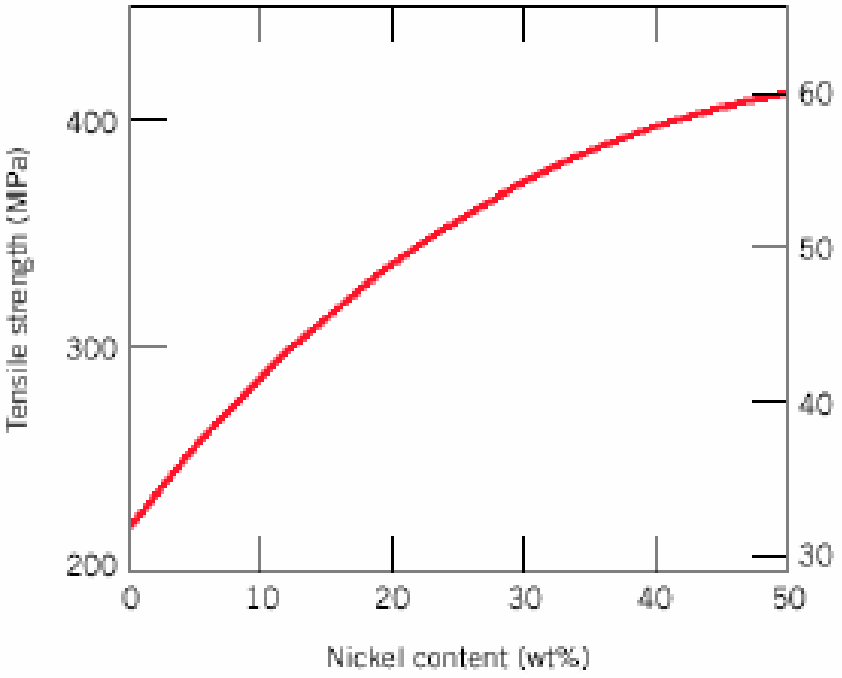


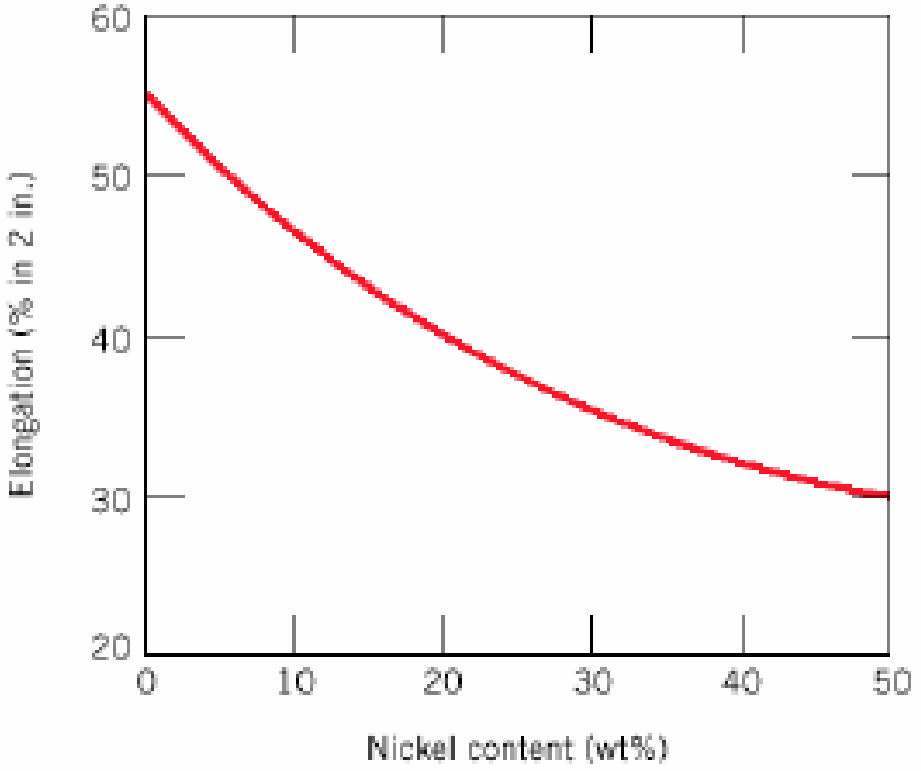
Solid-Solution Strengthening (II)



Smaller and larger substitutional impurities tend to diffuse into strained regions around dislocations, leading to partial cancellation of impurity-dislocation lattice strains.

Solid-Solution Strengthening (III)





Strengthening by increase of dislocation density
(Strain Hardening = Work Hardening = Cold Working)

- Ductile metals become stronger when they are deformed plastically at temperatures well below the melting point.
- **The reason for strain hardening is the increase of dislocation density with plastic deformation. The** average distance between dislocations decreases and dislocations start blocking the motion of each other.

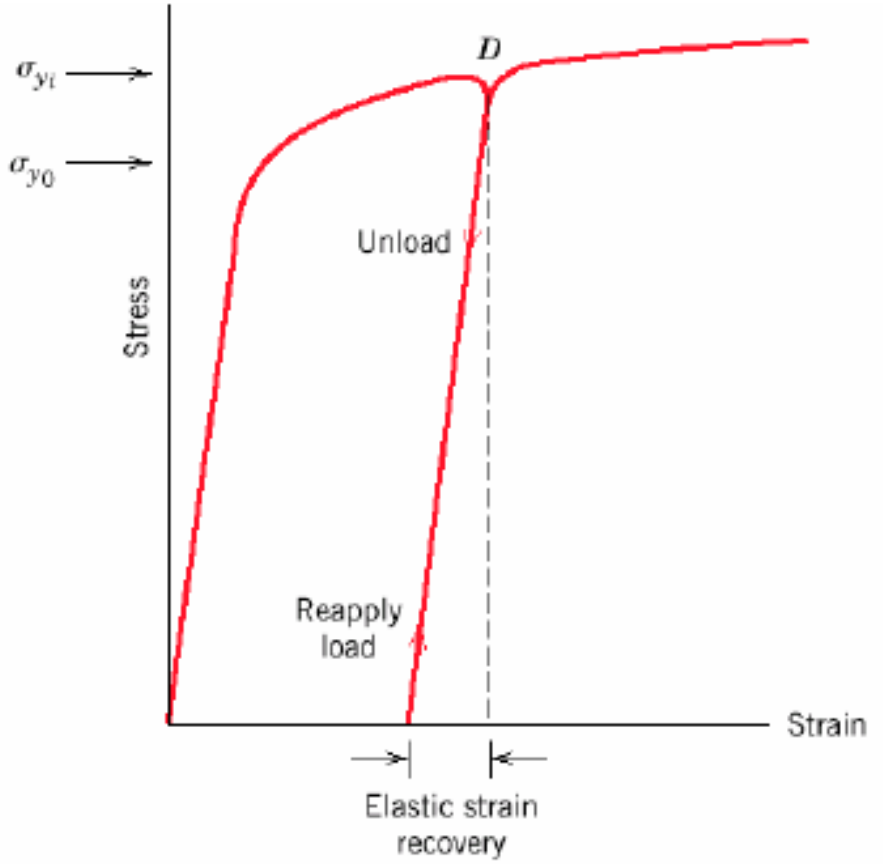
Strengthening by increase of dislocation density
(Strain Hardening = Work Hardening = Cold Working)

- The percent cold work (%CW) is often used to express the degree of plastic deformation:

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

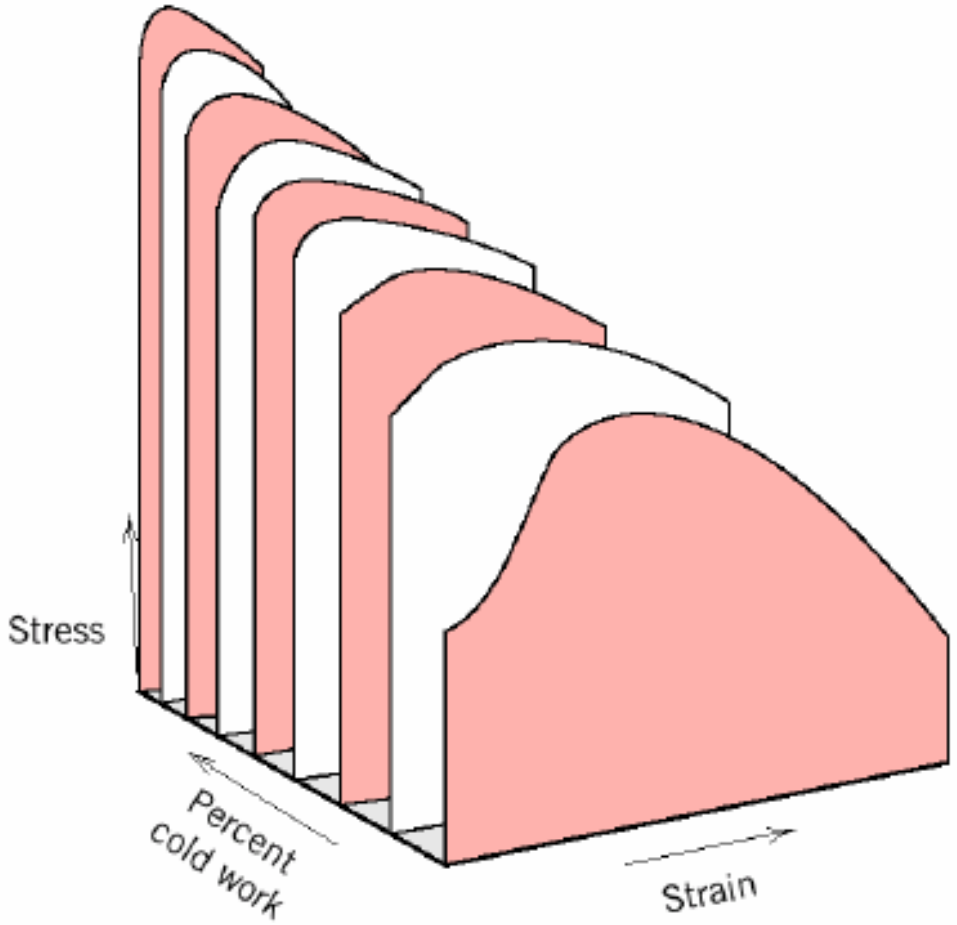
- where A_0 is the original cross-section area, A_d is the area after deformation.
- %CW is just another measure of the degree of plastic deformation, in addition to strain.

Strain hardening (II)



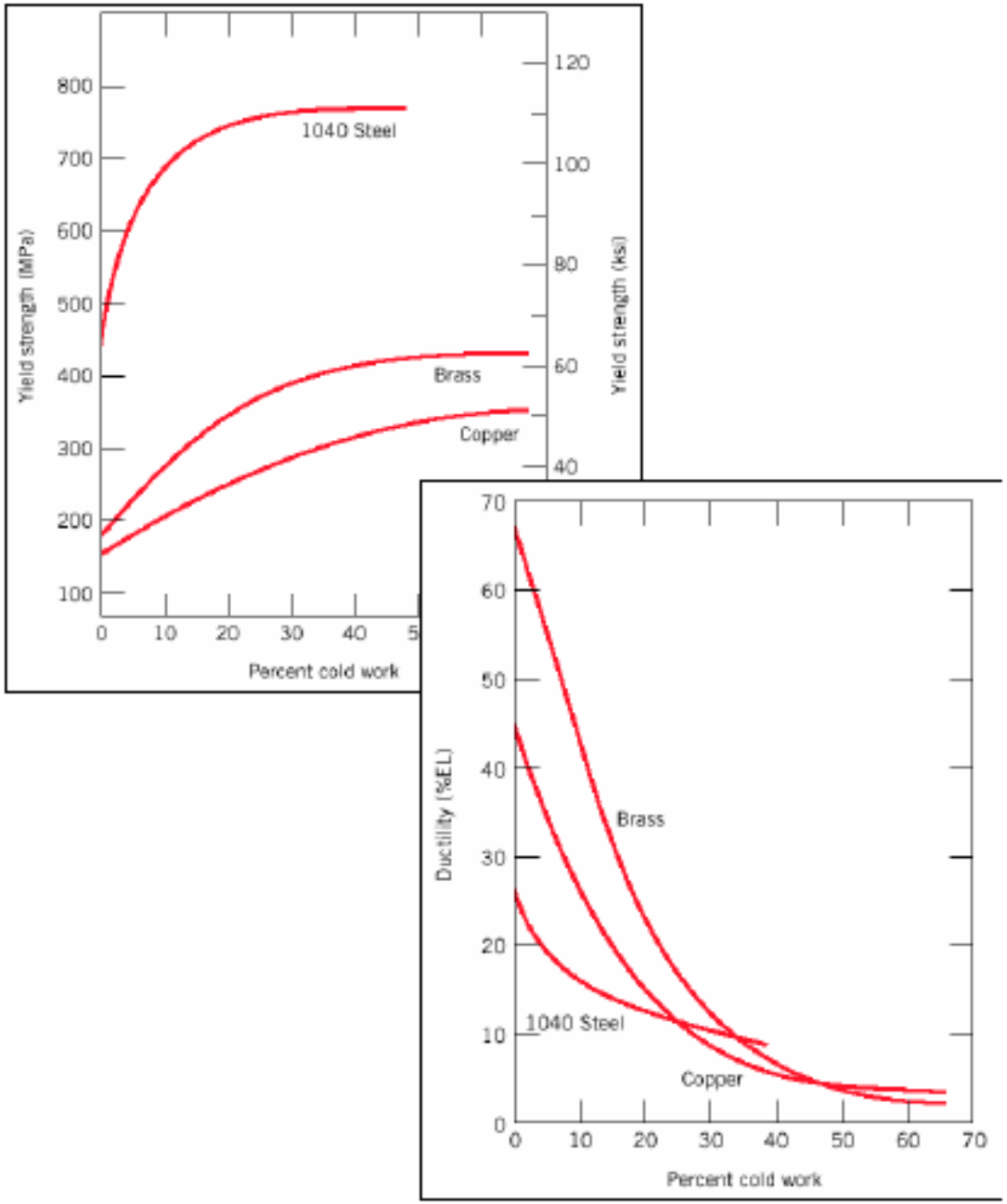
New yield strength σ_{y_i} is higher than the initial yield strength, σ_{y_0}. The reason for this effect - strain hardening.

Strain hardening (III)



Yield strength and hardness are increasing as a result of strain hardening but **ductility is decreasing (material** becomes more brittle).

Strain hardening (IV)

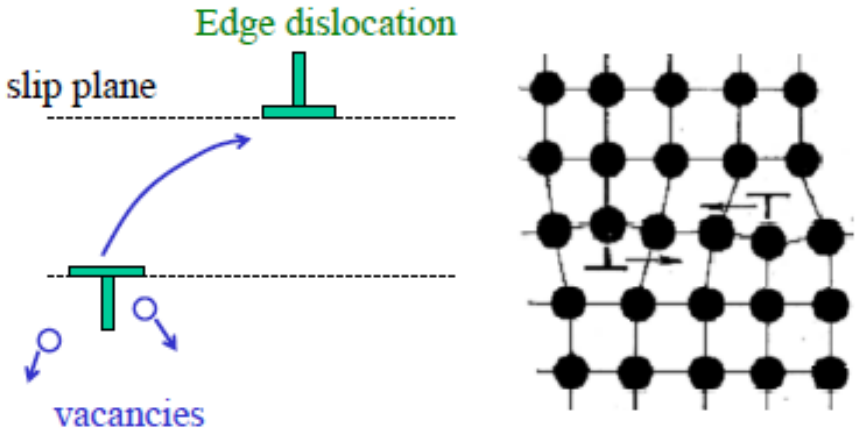


Recovery, recrystallization, and grain growth

- **Plastic deformation increases dislocation density (single and polycrystalline materials) and changes grain size distributions (polycrystalline materials).**
- This corresponds to stored strain energy in the system (dislocation strain fields and grain distortions).
- When applied external stress is removed - most of the dislocations, grain distortions and associated strain energy are retained.
- Restoration to the state before cold-work can be done by heat-treatment and involves two processes: **recovery** and **recrystallization. These may be followed by grain growth.**

Recovery

- **Heating → increased diffusion → enhanced dislocation motion → decrease in dislocation density by annihilation, formation of low-energy dislocation configurations → relieve of the internal strain energy**
- Some of the mechanisms of dislocation annihilation:

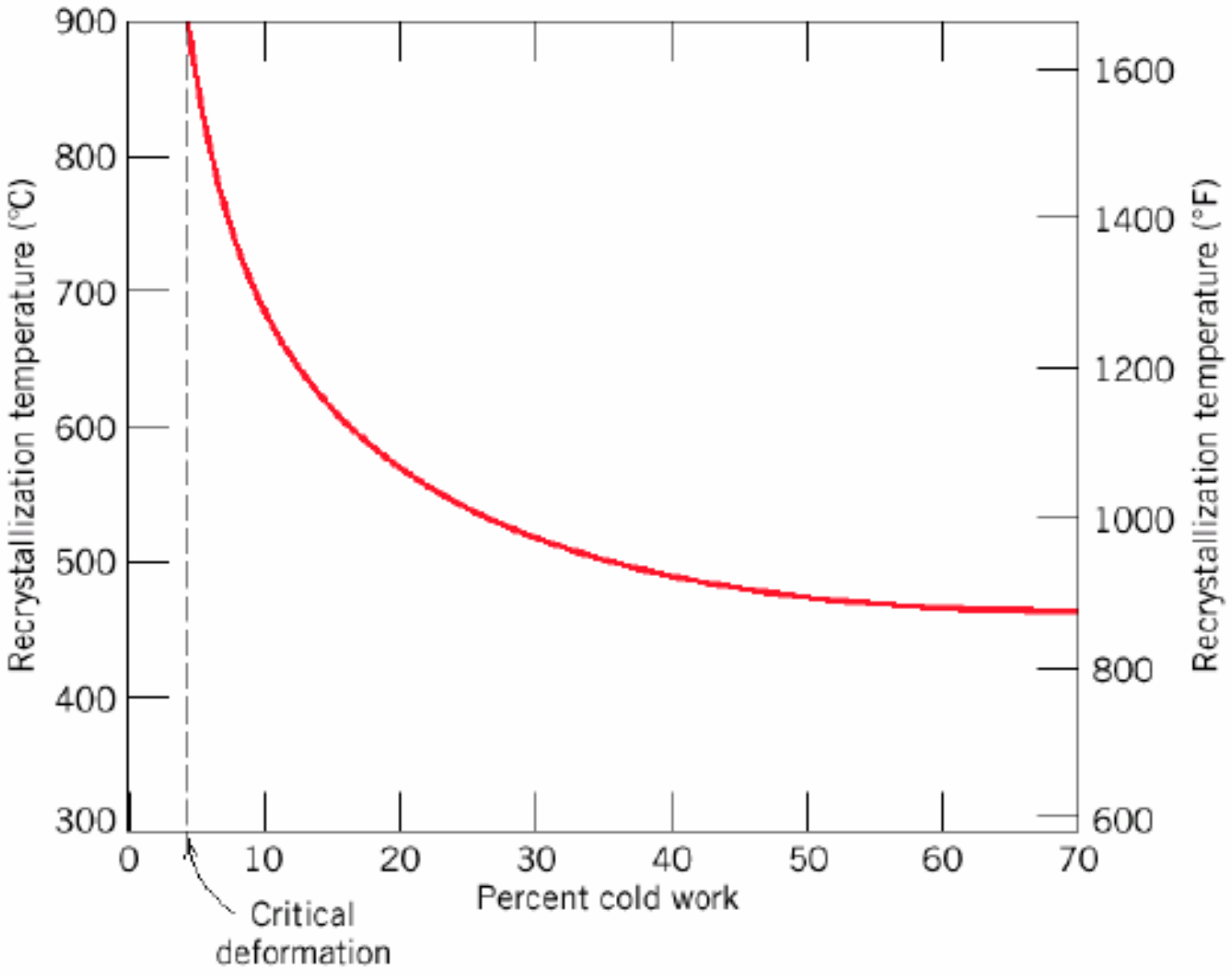


Recrystallization (I)

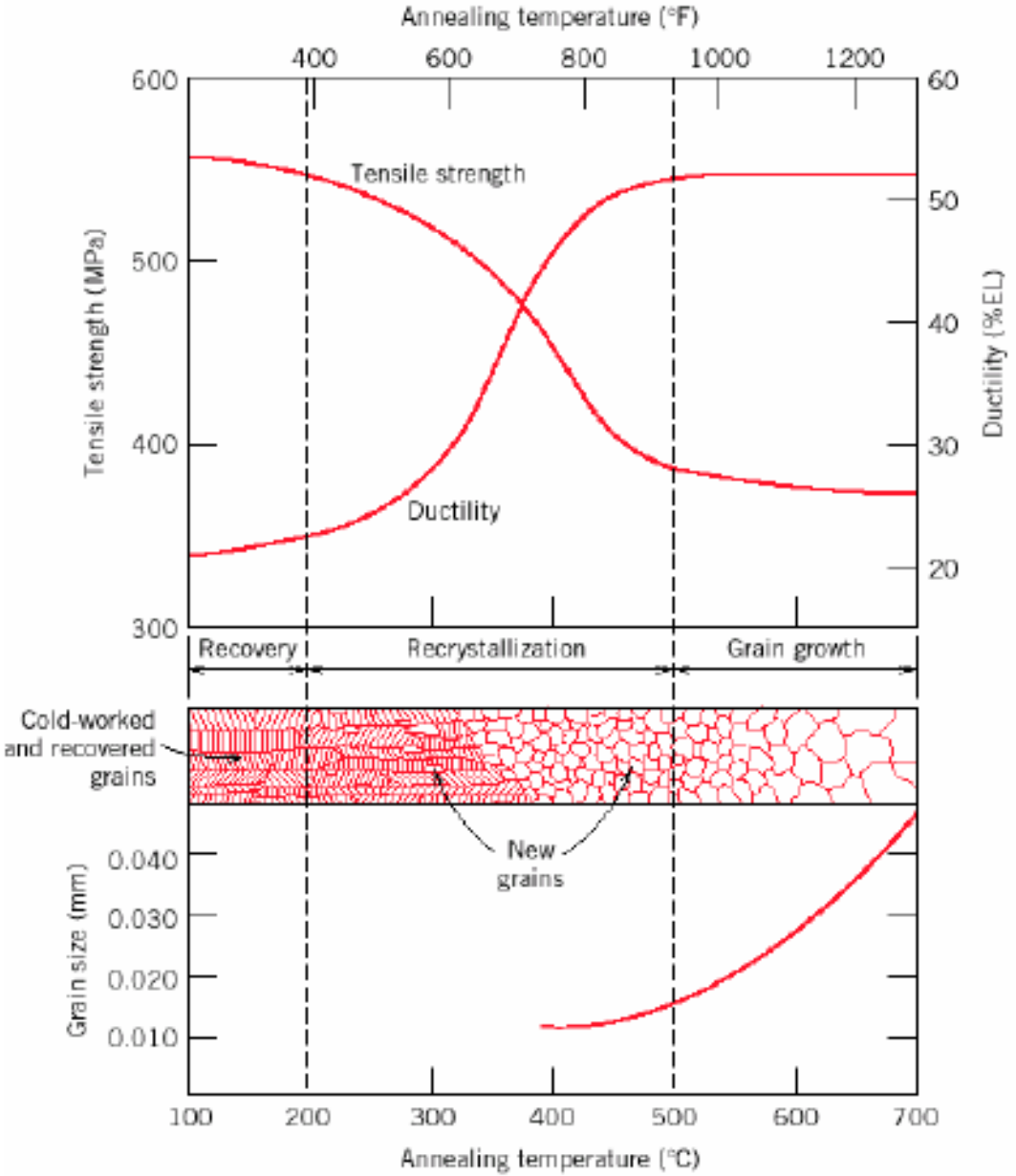
- Even after recovery the grains can be strained. These strained grains of cold-worked metal can be replaced, upon heating, by strain-free grains with low density of dislocations.
- This occurs through **recrystallization – nucleation and growth of new grains.**
- The *driving force for recrystallization is the difference* in internal energy between strained and unstrained material.
- Grain growth involves short-range diffusion → the extend of recrystallization depends on both temperature and time.
- Recristallization is slower in alloys as compared to pure metals

Recrystallization (II)

- **Recrystallization temperature: The temperature at which** the process is complete in one hour. It is typically 1/3 to 1/2 of the melting temperature (can be as high as 0.7 Tm in some alloys).
- **Recrystallization temperature increases as the %CW is decreased. Below a "critical deformation",** recrystallization does not occur.

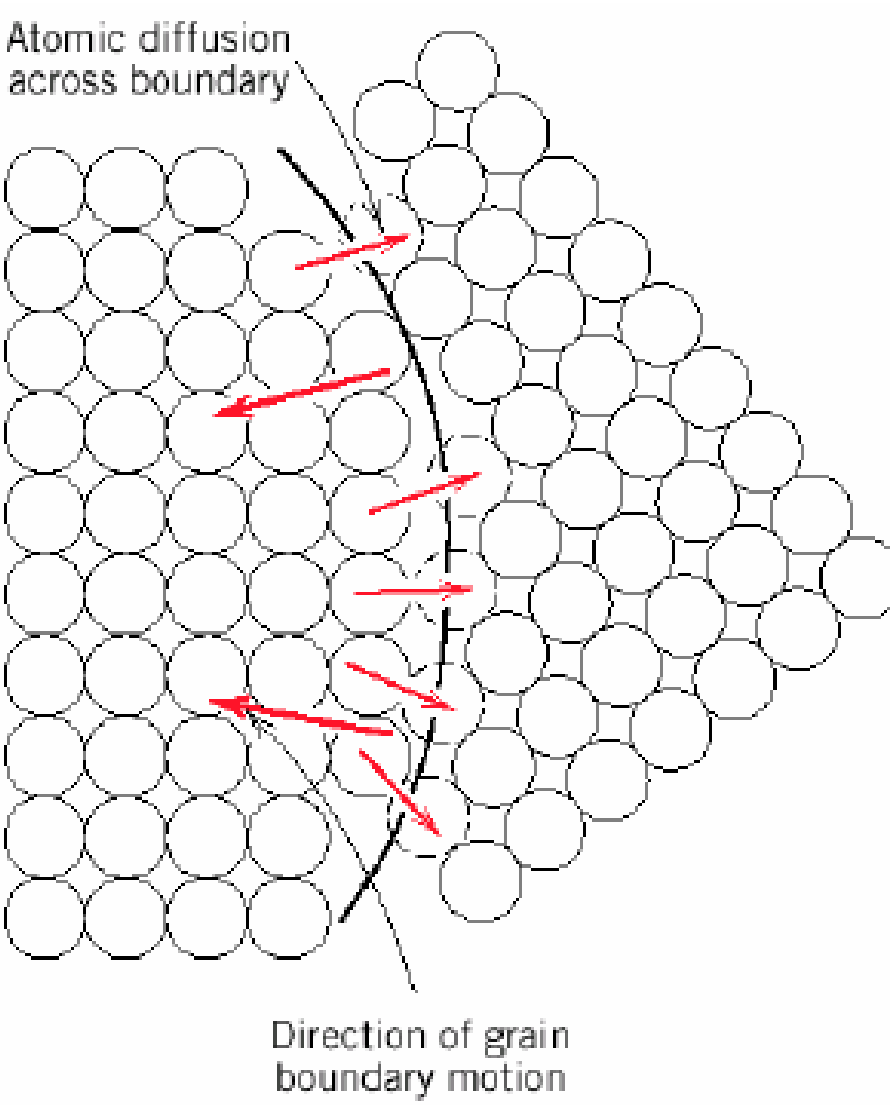

900
800
700
600
500
400
300
Recrystallization temperature (°C)
1600
1400
1200
1000
800
600
Recrystallization temperature (°F)
0
10
20
30
40
50
60
70
Percent cold work
Critical
deformation

Recrystallization (III)



Grain growth

- If deformed polycrystalline material is maintained at annealing temperature following complete recrystallization, then further **grain growth occurs.**
- *Driving force is reduction of the total grain boundary* area and, hence, the energy of the system. Big grains grow at the expense of the small ones.
- Grain growth during annealing occurs in all polycrystalline materials (i.e. they do not have to be deformed or undergo recrystallization first).
- Boundary motion occurs by short range diffusion of atoms across the grain boundary → strong temperature dependence of the grain growth.


Atomic diffusion
across boundary
Direction of grain
boundary motion

Summary

* Make sure you understand language and concepts:

- Cold working
- Critical resolved shear stress
- Dislocation density
- Grain growth
- Lattice strain
- Recovery
- Recrystallization
- Recrystallization temperature
- Resolved shear stress
- Slip
- Slip system
- Strain hardening
- Solid-solution strengthening