# 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 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.

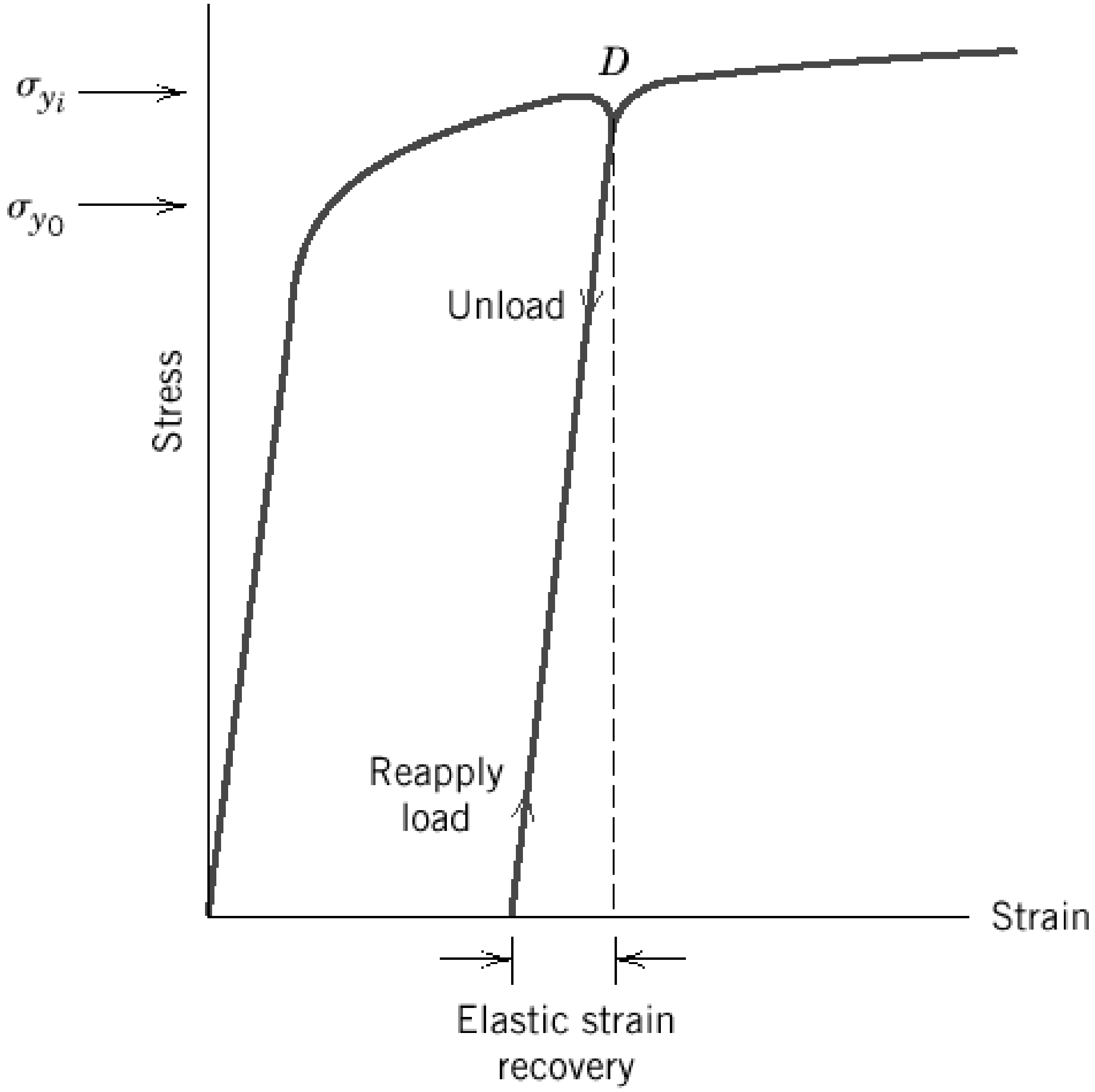
The percent cold work (% CW) is often used to express the degree of plastic deformation:

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

where $A_0$ is the original cross-section area, $A_d$ is the area after deformation.

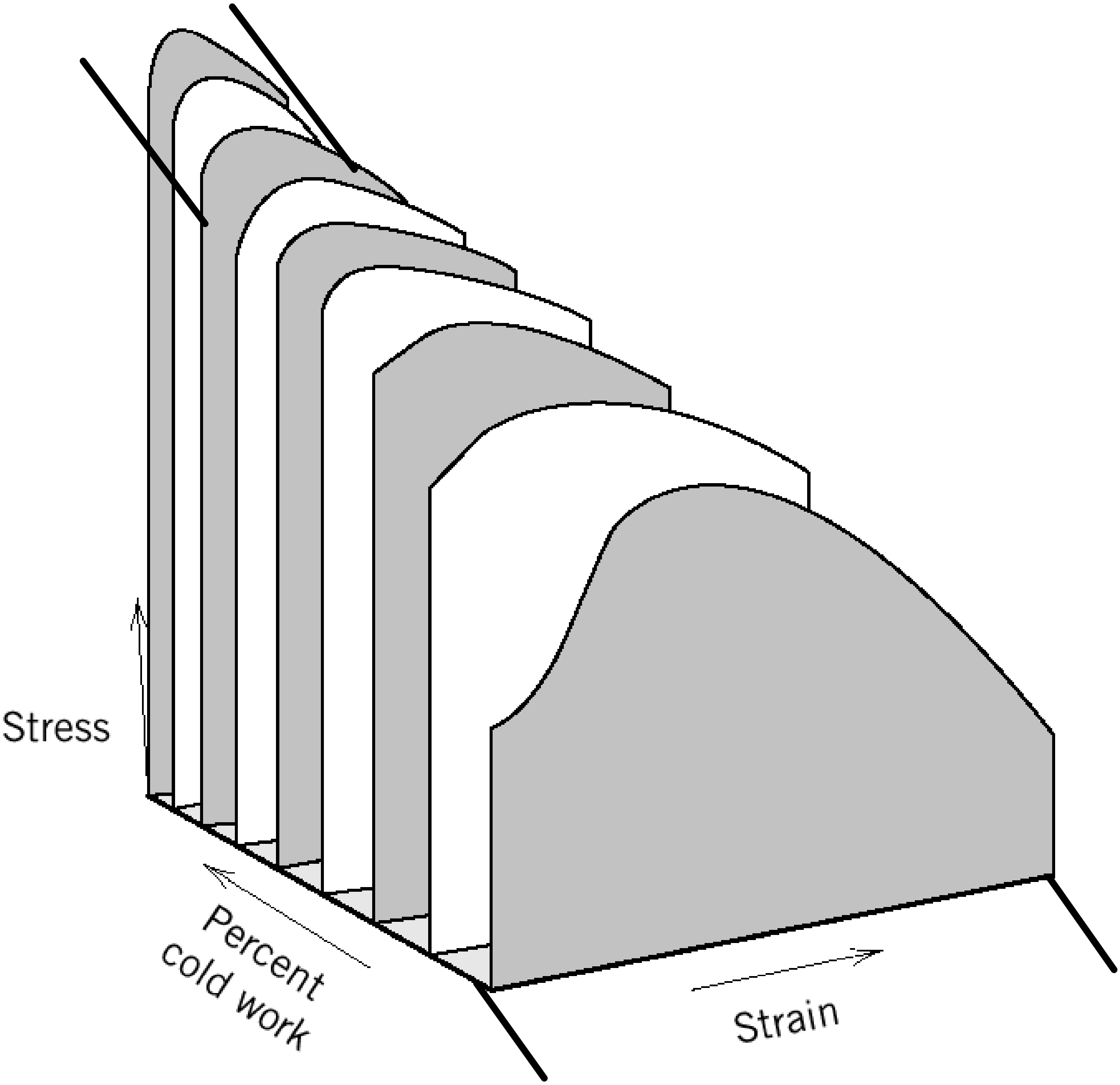
%CW is just another measure of the degree of plastic deformation, in addition to strain.

# Strain Hardening (I)



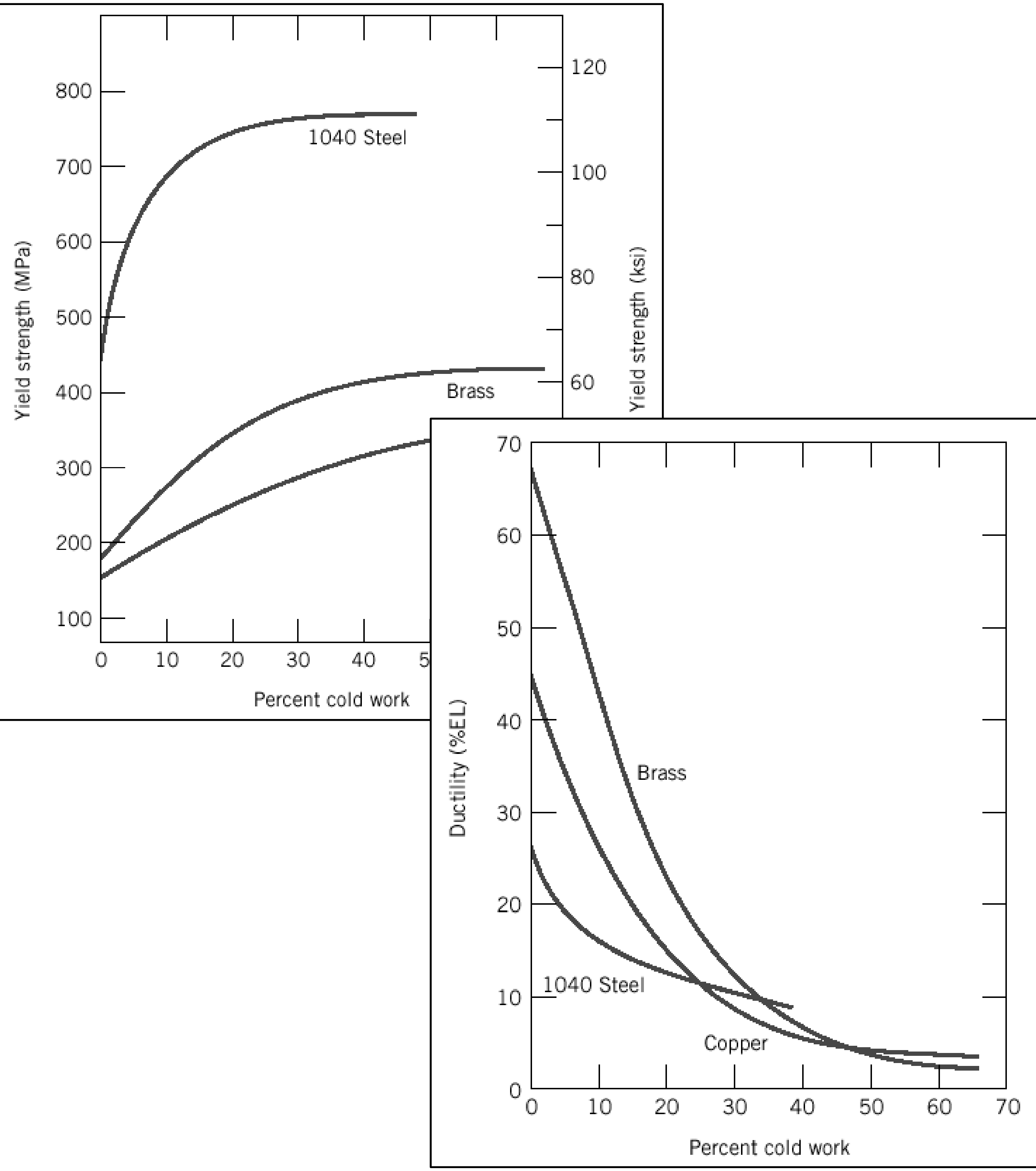
The new yield strength, $\sigma_{yi}$, is higher than the initial yield strength $\sigma_{yo}$. The reason for this effect - strain hardening.

# Strain Hardening (II)



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

# Strain Hardening (III)



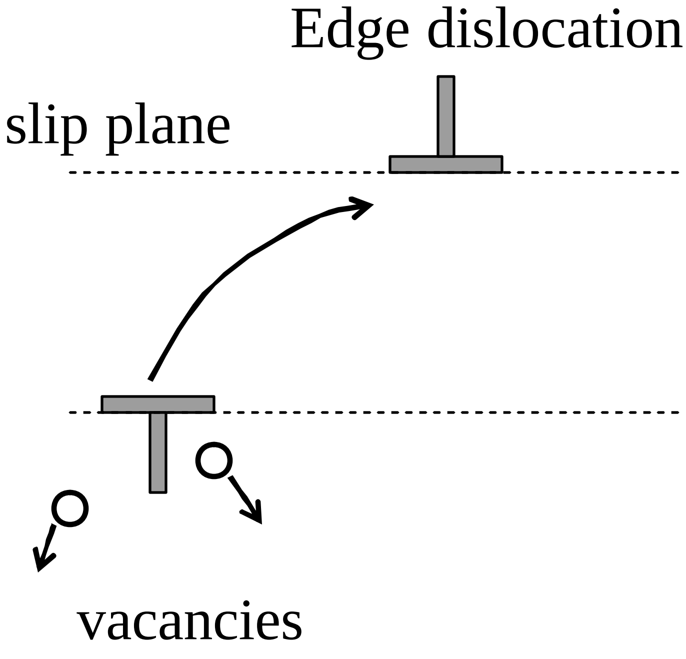
# Recovery, Recrystallization, and Grain Growth

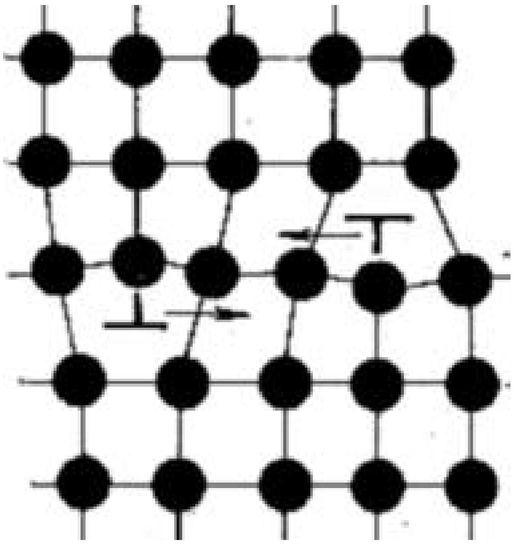
- **Plastic deformation increases the dislocation density (single and polycrystalline materials) and changes grain size distributions (polycrystalline materials).**
- This corresponds to stored strain energy in the system (dislocation strain fields and grain distortions).
- When the applied external 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 primarily 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.

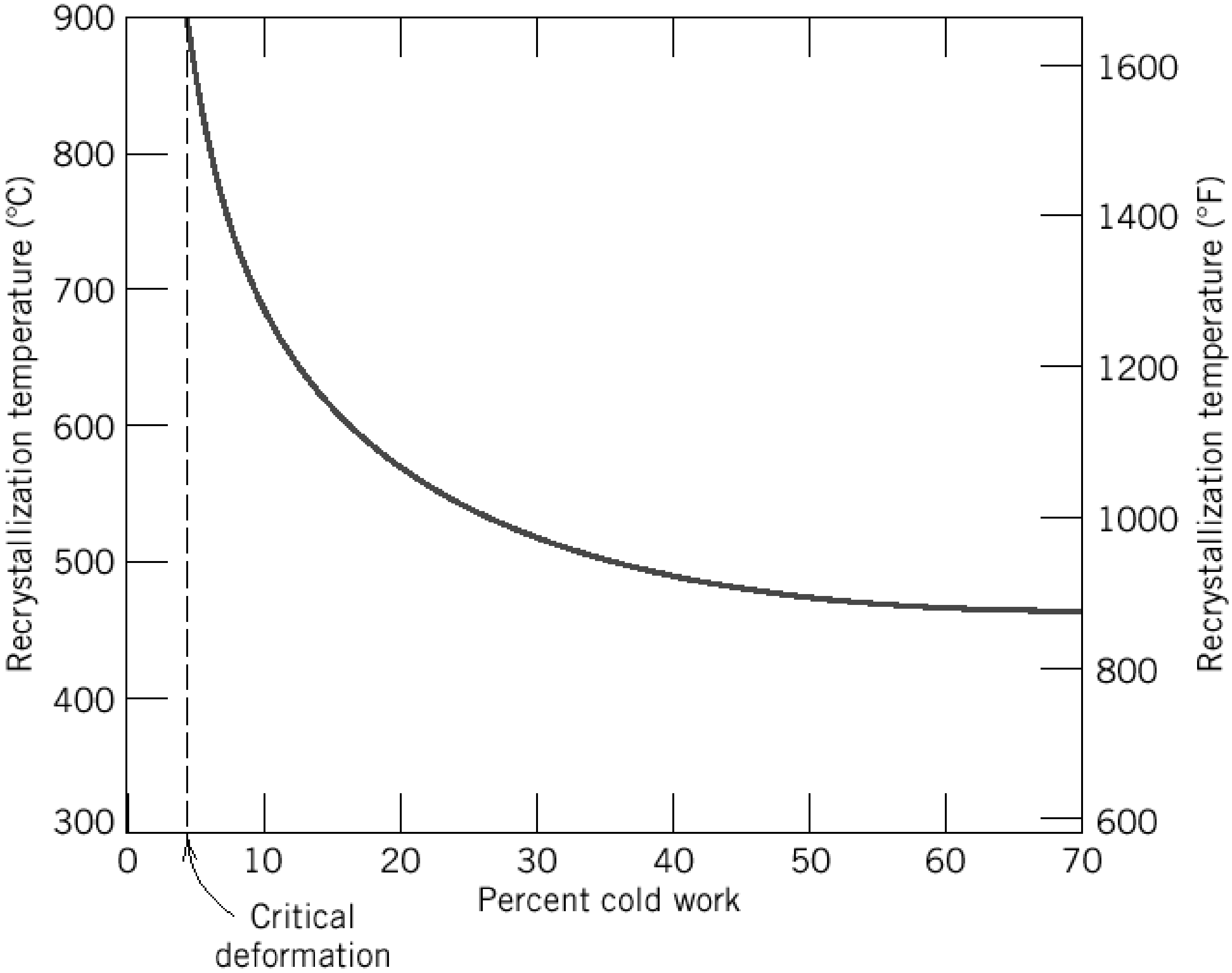
- Grain growth involves short-range diffusion → the extent of recrystallization depends on both temperature and time.

- Recristallization is slower in alloys as compared to pure metals

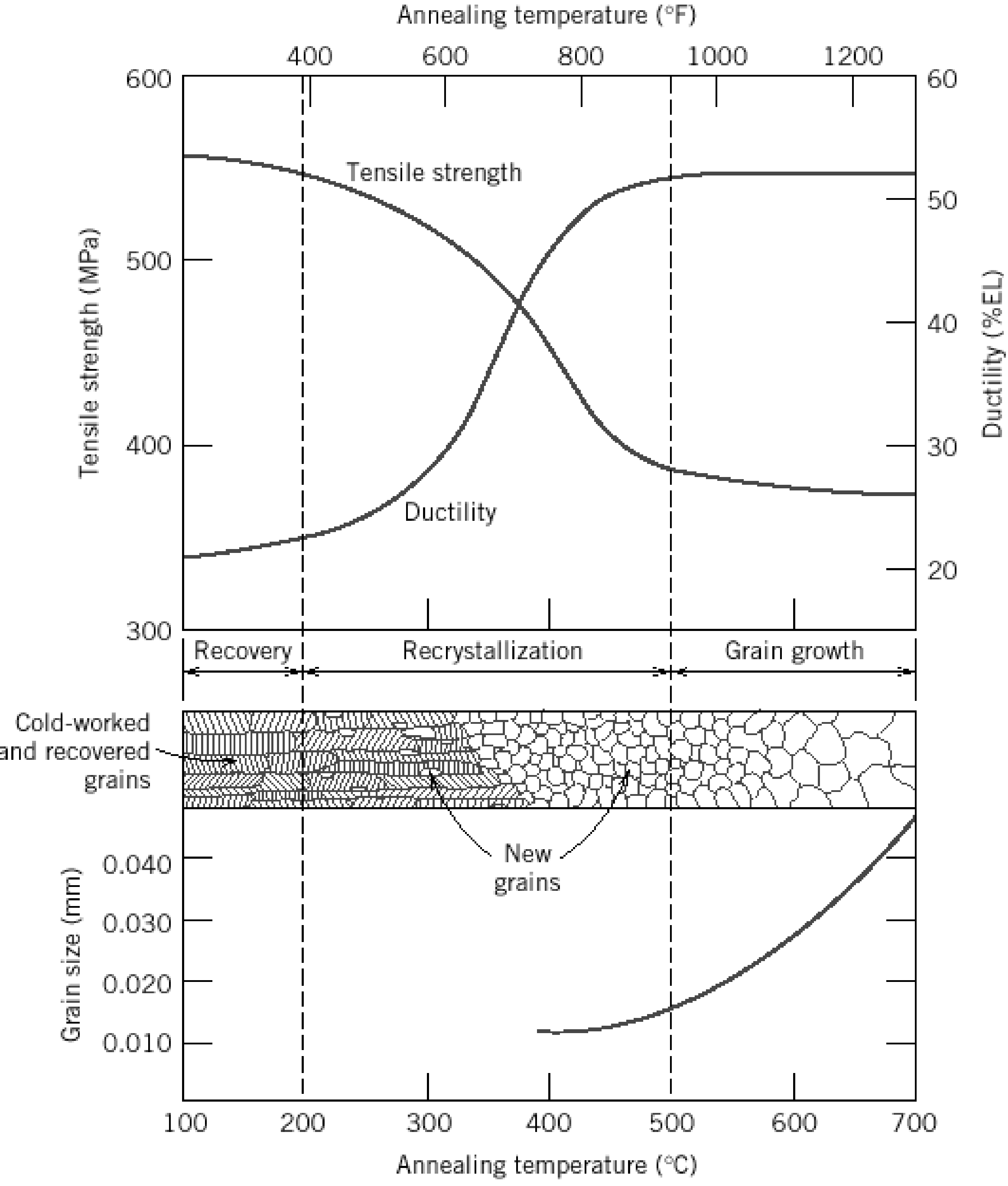
# Recrystallization (II)

**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 $T_m$ in some alloys).

**The recrystallization temperature decreases as the %CW is increased. Below a "critical deformation", recrystallization does not occur.**



# Recrystallization (III)



# Grain Growth

- If deformed polycrystalline material is maintained at annealing temperature following complete recrystallization, then **further grain growth** occurs.
- ***The Driving force*** is reduction of grain boundary area and hence energy 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.