Chapter 7: Dislocations and strengthening mechanisms

Mechanisms of strengthening in metals

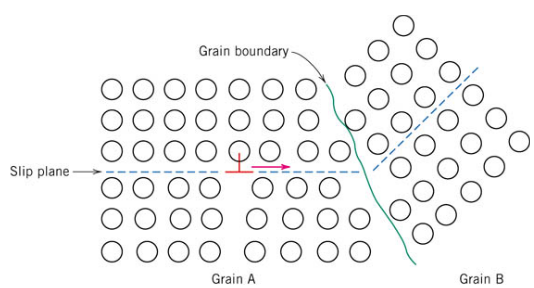
- Strengthening by grain size reduction
- Solid-solution strengthening
- Strain hardening

Recovery, recrystallization, and grain growth

- Recovery
- Recrystallization
- Grain growth

Strengthening by grain size reduction

- Grain boundary acts as a barrier to dislocation motion
  - Different crystallographic grains impede dislocation movement
  - The atomic disorder within a grain boundary region will result in a discontinuity of slip plans
- Smaller size grains have more grain boundary than larger ones



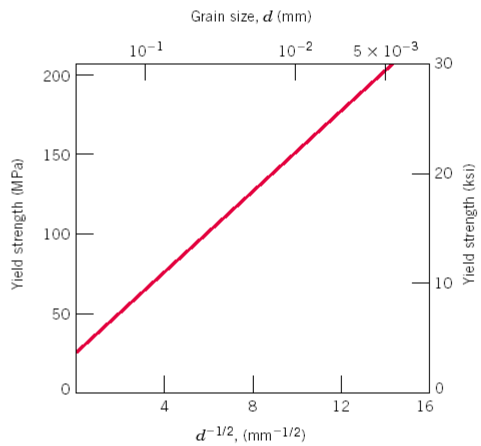
Strengthening by grain size reduction (*continue*)

- A fine-grained material is harder and stronger than coarse-grained one

Hall-Petch equation

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

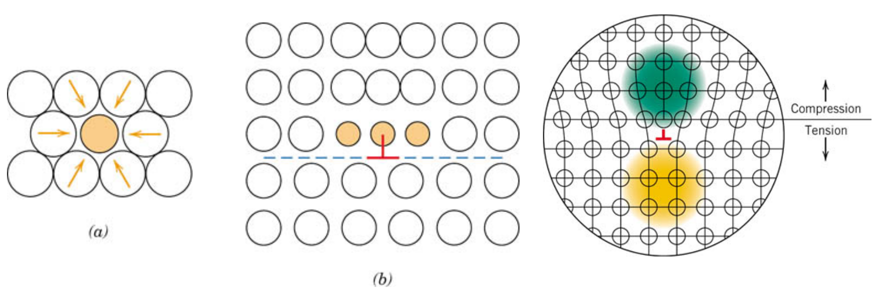
- Other grain boundary factors:
  - high/small angle grain boundary
  - twin boundary
  - boundaries with different phases



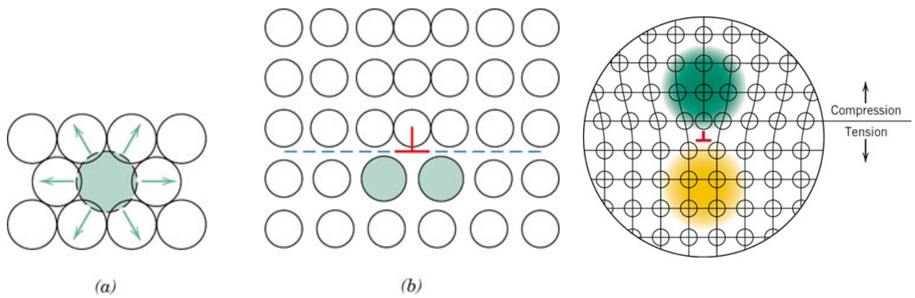
Yield strength versus d for Cu-Zn alloy

Solid-solution strengthening

- Impurity atoms generate stresses by distorting the lattice
- This stress can produce a barrier to dislocation motion

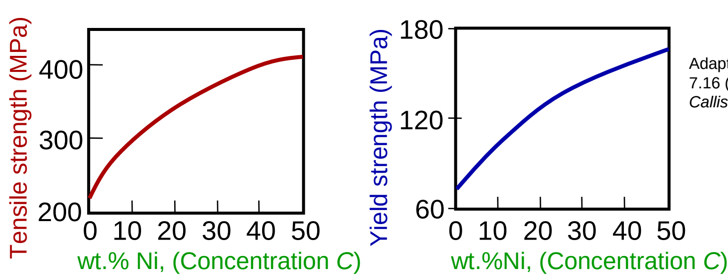


Solid-solution strengthening (*cont.*)



Ex: Solid Solution: Strengthening in Copper

- Tensile strength & yield strength increase with wt% Ni.

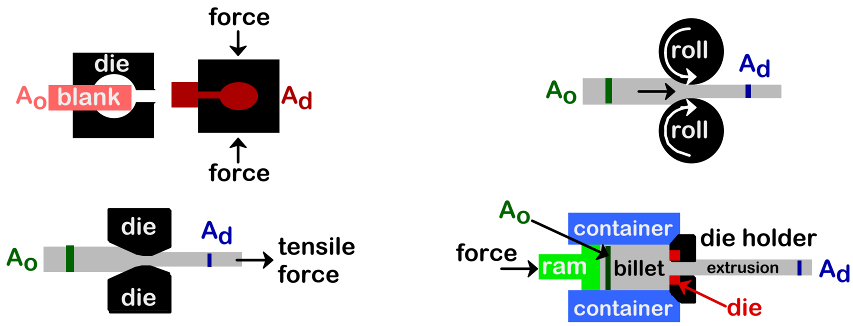


Adapted from Fig. 7.16 (a) and (b), *Callister 7e.*

- Empirical relation: $\sigma_y \sim C^{1/2}$
- Alloying increases σ_y and *TS*

Strain hardening

- Strain hardening (cold working) : a ductile metal becomes harder and stronger as it is plastically deformed



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

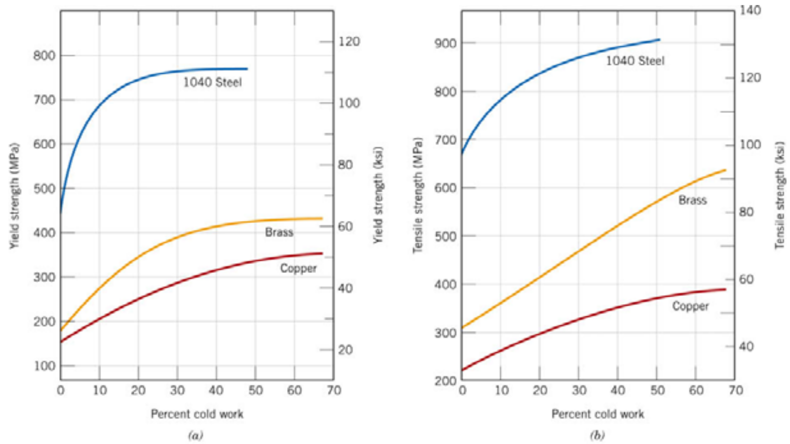
Strain hardening

- Mechanisms: dislocation-dislocation interactions
  - **Dislocations entangle with one another during cold work.**
  - **Dislocation motion becomes more difficult.**

Ti alloy after cold working:

Strain hardening

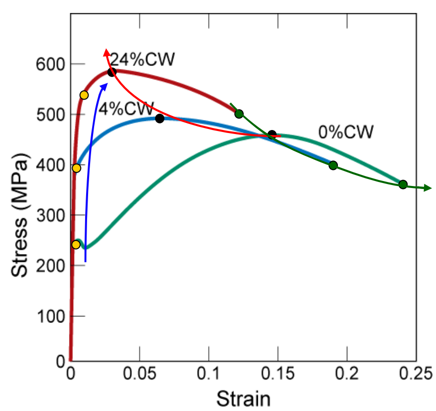
- Yield and tensile strength increase with cold work



Impact of Cold Work

As cold work is increased

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



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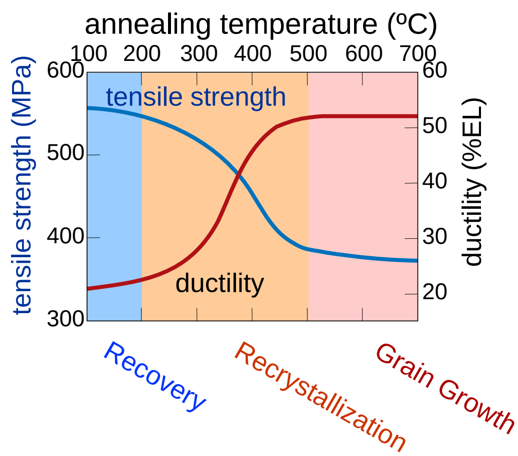
Effect of heating after %CW

- The influence of annealing temperature on the tensile strength and ductility of a brass alloy
- Recrystallization temperature (RT): the temp at which recrystallization just reaches completion in 1 h

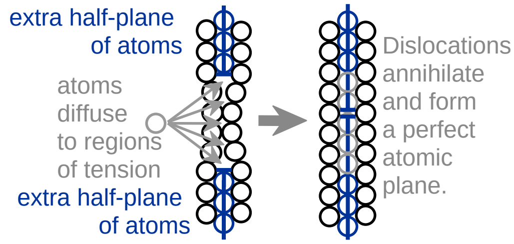


Recovery, recrystallization, and grain growth

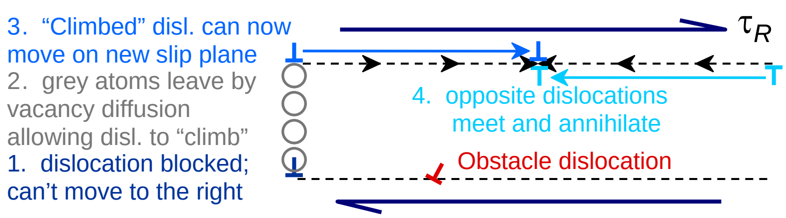
- Recovery: dislocation motion reduces some of the stored internal energy when metals are heated up
- Recrystallization: formation of a new set of strain-free grains and equiaxed grains that have low dislocation densities
- Grain growth: the strain-free grains will continue to grow after recrystallization is complete

Recovery

- Annihilation reduces dislocation density.
  - Scenario 1
    Results from diffusion

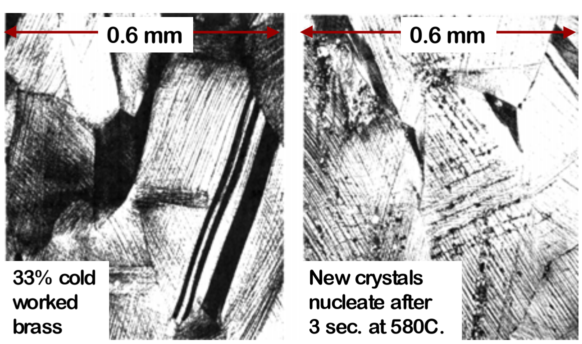


  - Scenario 2



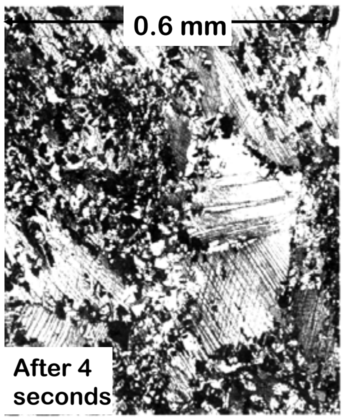
Recrystallization

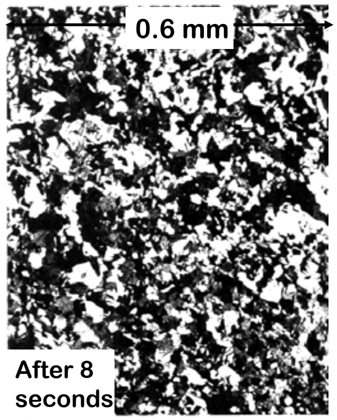
- Driving force: internal energy of unstrained and strained grains
- New crystals are formed that
  - have a small disl. Density
  - are small
  - consume cold-work crystals



Recrystallization (*continue*)

- All cold-worked crystals are consumed





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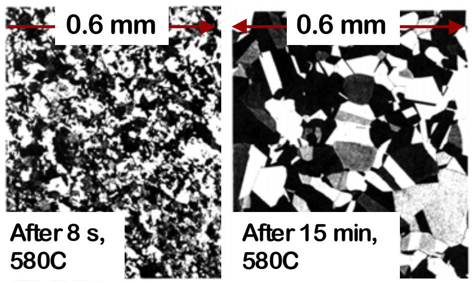
Recrystallization (*continue*)

- Recrystallization-melting temp

Metal	Recrystallization Temperature °C	Recrystallization Temperature °F	Melting Temperature °C	Melting Temperature °F
Lead	−4	25	327	620
Tin	−4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu–40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

Grain growth

- At longer times, larger grains consume smaller ones.
- Why? Grain boundary area (and therefore energy) is reduced.



- Empirical Relation:

exponent typ. ~ 2

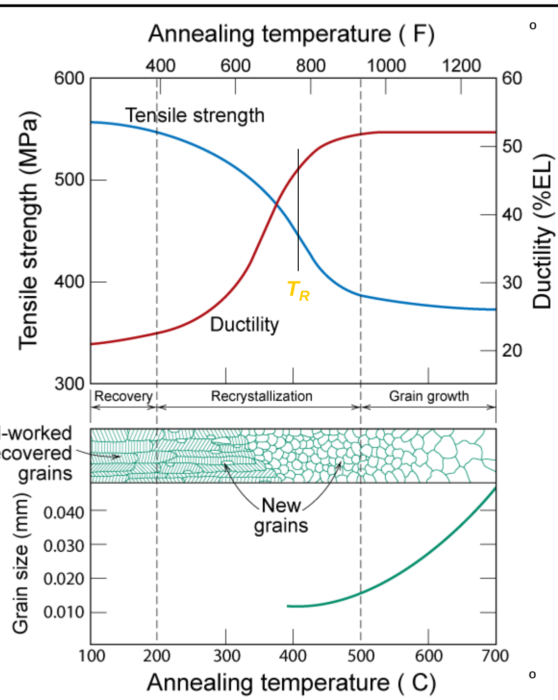
grain diam. at time t.

$$d^n - d_o^n = Kt$$

coefficient dependent on material and *T*.

elapsed time

Ostwald Ripening



T_R = recrystallization temperature

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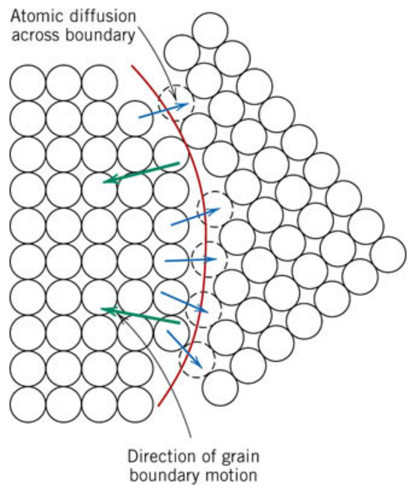
Grain growth

- Driving force for grain growth: reduction in total energy
- Grain growth via atomic diffusion



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Summary

- Strength is increased by making dislocation motion difficult.
- Particular ways to increase strength are to:

  --decrease grain size
  --solid solution strengthening
  --precipitate strengthening
  --cold work

- Heating (annealing) can reduce dislocation density and increase grain size.