Chapter 7:
Dislocations and Strengthening

ISSUES TO ADDRESS...

1. Why are dislocations observed primarily in metals and their alloys?

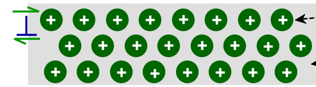
2. How are strength and dislocation motion related?

3. How do we increase strength?

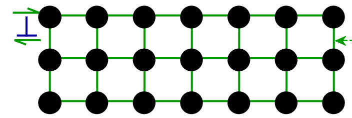
4. How can heating change strength and other properties?

Dislocation motion and material classes

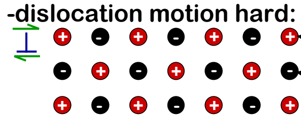
- Metals: Dislocation motion easier:
  - -nondirectional bonding
  - -close-packed directions for slip



- Covalent Ceramics: (Si, diamond)
  - -dislocation motion hard: directional (angular) bonding

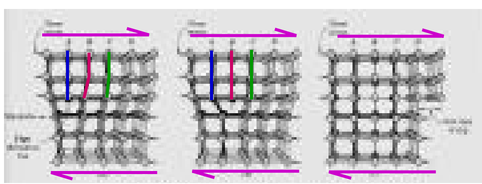


- Ionic Ceramics: (NaCl)
  - -dislocation motion hard: need to avoid ++ and -- neighbors



Dislocation motion...

- Produces plastic deformation
- Depends on incrementally breaking bonds


Callister Fig. 7.1

stretched zinc crystal


Callister Fig. 7.9

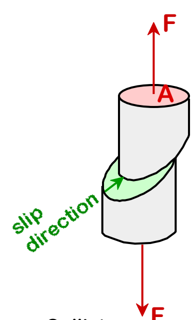
- If dislocations don't move, plastic deformation doesn't happen!


Callister Fig. 7.8

Stress and Dislocation Motion

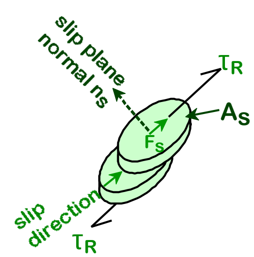
- Crystals slip due to a resolved shear stress
- Applied tension can produce a resolved shear stress

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

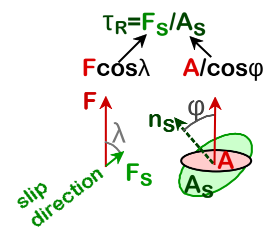


Callister Fig. 7.7

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



Relation between σ and τ_R

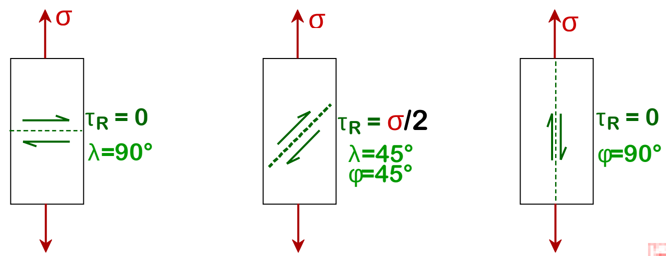


$$\tau_R = \sigma \cos\lambda \cos\varphi$$

Critical Resolved Shear Stress: τ_{CRSS}

- Condition for disl. motion: $\tau_R > \tau_{CRSS}$ ← typically $10^{-4}G$ to $10^{-2}G$
- Crystal orientation can make it easy or hard to move disl.

$$\tau_R = \sigma \cos\lambda \cos\varphi$$



Dislocation motion in polycrystals

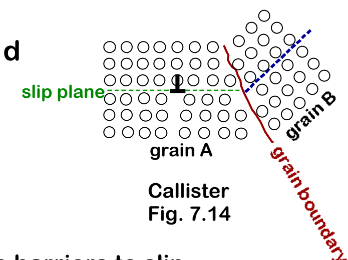
- Slip planes and directions (λ,φ) change from one crystal to another.
- τ_R will vary from one crystal to another.
- Crystal with largest τ_R yields first.
- Other (less favorably oriented) crystals yield later.

Callister Fig. 7.10

Strategy for Strengthening: Make dislocations hard to move

4 ways to do this:

1. Reduce the grain size, d
   - Grain boundaries are barriers to slip.
   - Barrier "Strength" increases with misorientation



Callister Fig. 7.14

- Smaller grain size: more barriers to slip
- Hall-Petch Equation: $\sigma_{yield} = \sigma_o + k_y d^{-1/2}$

Example of grain size strengthening

- 70wt%Cu-30wt% Zn brass alloy

Fig. 4.11(b) Callister

40μm

- $\sigma_{yield} = \sigma_o + k_y(\text{grain size})^{-1/2}$

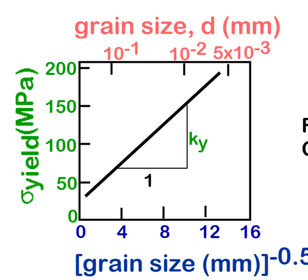
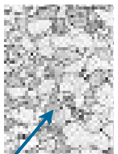


Fig. 7.15 Callister

Anisotropy in σ_{yield}

- Can be induced by rolling a polycrystalline metal

Before rolling



After rolling

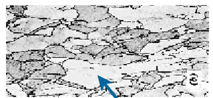


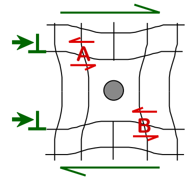
Fig. 7.11 Callister

isotropic (since grains are approx. spherical and randomly oriented).

anisotropic (since rolling affects grain orientation and shape).

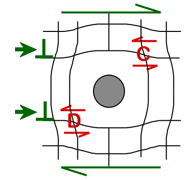
2. Solid Solution Strengthening

- Impurity atoms generate stress by distorting the lattice.
- This stress can produce a barrier to dislocation motion.
- Example: smaller substitutional impurity



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

- Example: larger substitutional impurity



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

Ex: Solution Strengthening in Copper

- Tensile strength and yield strength increase with wt%Ni

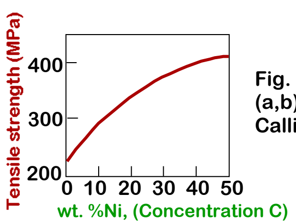
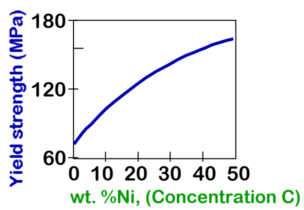


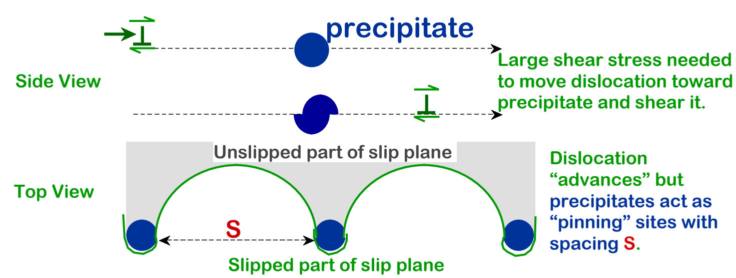
Fig. 7.16 (a,b) Callister



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

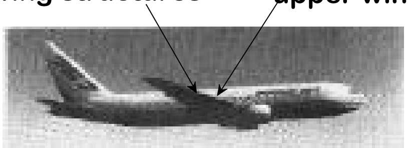
3. Precipitation Strengthening

- Hard precipitates are difficult to shear
  Ex.: ceramics in metals
  (SiC precipitates in iron or in aluminum)



- Contribution to σ_{yield} scales as: $1/S$

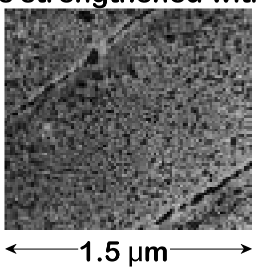
Example: Precipitation-strengthened alloy



Boeing 767

Callister, Fig. 11.0

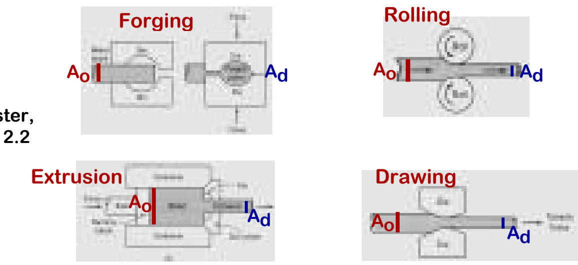
- Aluminum is strengthened with precipitates formed by alloying.



Callister, Fig. 11.0

4. Cold Work (%CW)

- Room Temperature Deformation
- Common forming operations change the cross sectional area.

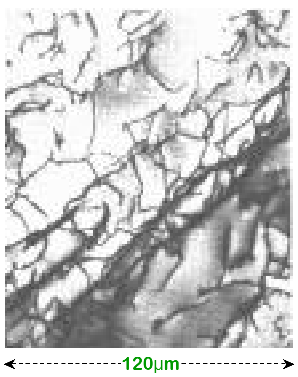


Callister, Fig. 12.2

$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

Dislocations during cold work

- Titanium alloy after cold working



Callister, Fig. 4.6

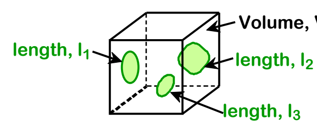
- Dislocations entangle with one another during cold work.
- Dislocation motion becomes more difficult.

Result of Cold Work

- Dislocation density (ρ_d)

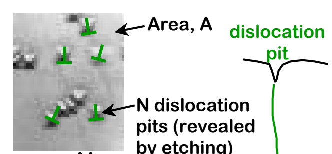
Material condition	ρ_d [mm/mm^3] (typical values)
Carefully prepared	10^3
Heavily deformed	10^{10}

- Ways of measuring ρ_d:



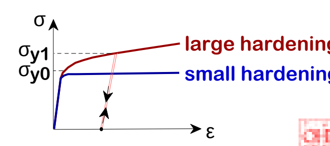
$$\rho_d = \frac{l_1 + l_2 + l_3}{V}$$

OR



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

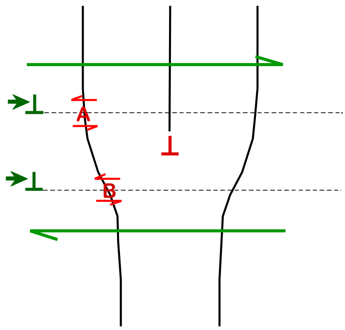
- Yield stress as ρ_d (i.e., the material hardens)



Dislocation-dislocation trapping

- Dislocations generate stress
- This stress traps other dislocations

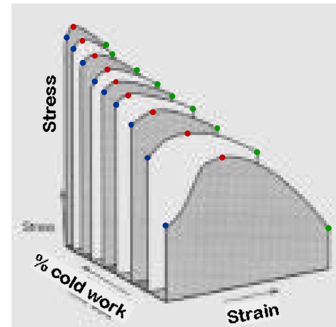
Red dislocation generates shear at pts A and B that opposes motion of green disl. from left to right.



Impact of Cold Work

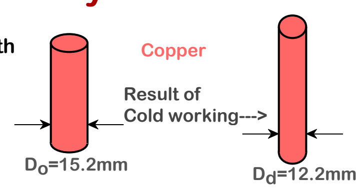
- Yield strength (σ_y) increases
- Tensile strength (TS) increases
- Ductility (%EL or %AR) decreases

Callister, Fig. 7.20



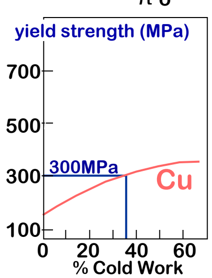
Cold Work Analysis

Question: what is the tensile strength and ductility after cold working?

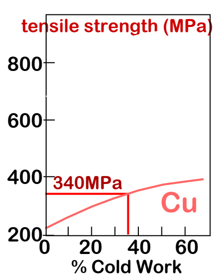


7.6mm 6.1mm

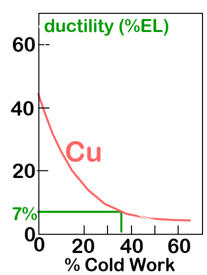
$$\%CW = \frac{\pi r_o^2 - \pi r_d^2}{\pi r_o^2} \times 100 = 35.6\%$$



σ_y=300MPa



TS=340MPa



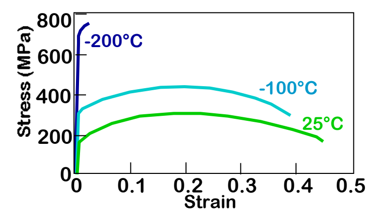
%EL=7%

Callister, Figs. 7.20(a,b,c)

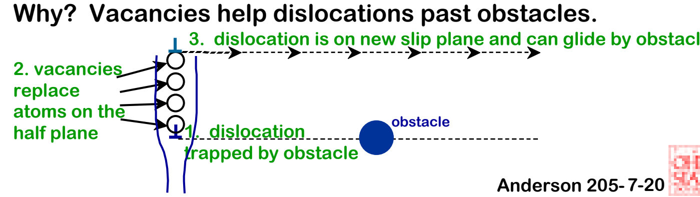
σ–ε Behavior at different temperatures

- Results for polycrystalline iron:

Callister, Fig. 6.13

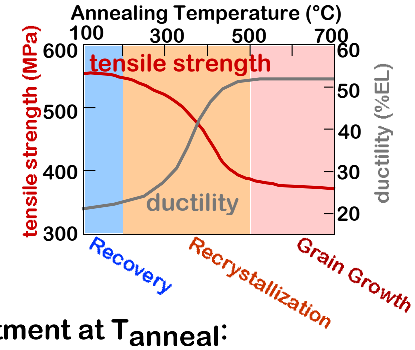


- σ_y and TS decrease with increasing test temperature.
- %EL increases with increasing test temperature.
- Why? Vacancies help dislocations past obstacles.



Effect of heating after cold work

Callister, Fig. 7.22

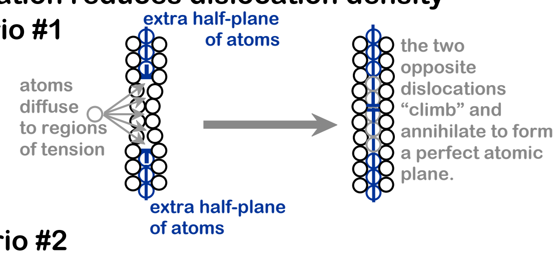


- 1 hr treatment at T_{anneal}:
  - -decreases TS
  - -increases %EL
- Effects of cold work are reversed!
- 3 Annealing stages to discuss...

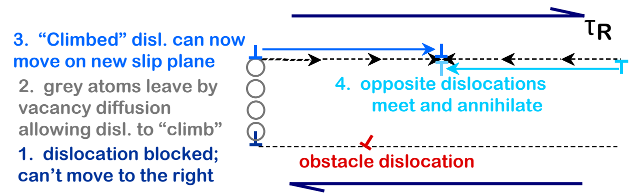
Recovery:

Annihilation reduces dislocation density

- Scenario #1

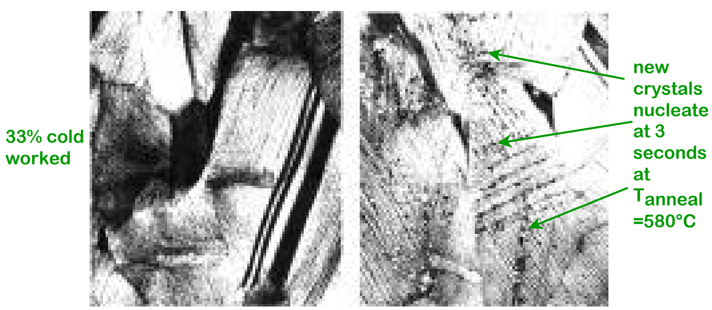


- Scenario #2



Recrystallization

- formation of new crystals that
  - -have small ρ_d
  - -are small
  - -consume cold-worked crystals
- brass

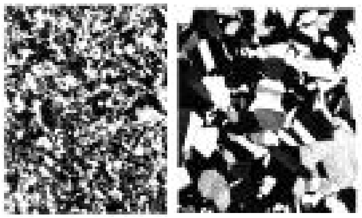


Callister, Fig. 7.21(a,b)

Further Recrystallization

Grain Growth

- Larger grains consume smaller grains
- Why? Grain boundary area is reduced.



after 8 seconds (580°C) | after 15 minutes (580°C)

- empirical relation

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

- d: grain diameter at time=t
- d_o: grain diameter at t=0
- n: exponent: material-dependent (typ. ~2)
- t: elapsed time
- K: coefficient: material and temperature-dependent