Chapter 7: Dislocations & Strengthening Mechanisms
Dislocation Motion

Dislocations & plastic deformation

• Cubic & hexagonal metals - plastic deformation by plastic shear or slip where one plane of atoms slides over adjacent plane by defect motion (dislocations).

• If dislocations don't move, deformation doesn't occur!
4 Strategies for Strengthening:
1: Reduce Grain Size

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

- Hall-Petch Equation:
\[ \sigma_{yield} = \sigma_o + k_y d^{-1/2} \]
4 Strategies for Strengthening: 2: Solid Solutions

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

- Smaller substitutional impurity
  Impurity generates local stress at A and B that opposes dislocation motion to the right.

- Larger substitutional impurity
  Impurity generates local stress at C and D that opposes dislocation motion to the right.
Stress Concentration at Dislocations

Adapted from Fig. 7.4, Callister 7e.
Strengthening by Alloying

- small impurities tend to concentrate at dislocations
- reduce mobility of dislocation \(\therefore\) increase strength

Adapted from Fig. 7.17, Callister 7e.
Strengthening by alloying

- large impurities concentrate at dislocations on low density side

Adapted from Fig. 7.18, Callister 7e.
Ex: Solid Solution Strengthening in Copper

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

- Empirical relation: $\sigma_y \sim C^{1/2}$

- Alloying increases $\sigma_y$ and $TS$. Adapted from Fig. 7.16 (a) and (b), Callister 7e.
4 Strategies for Strengthening: 3: Precipitation Strengthening

• Hard precipitates are difficult to shear.
  Ex: Ceramics in metals (SiC in Iron or Aluminum).

• Result: \[ \sigma_y \sim \frac{1}{S} \]
Application: Precipitation Strengthening

- Internal wing structure on Boeing 767

- Aluminum is strengthened with precipitates formed by alloying.

Adapted from Fig. 11.26, Callister 7e.

(Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)
4 Strategies for Strengthening:
4: Cold Work (%CW)

- Room temperature deformation.
- Common forming operations change the cross sectional area:

- Forging
  - Force
  - Die
  - Blank
  - Die
  - Adapted from Fig. 11.8, Callister 7e.

- Drawing
  - Force
  - Tensile force
  - Die
  - Adapted from Fig. 11.8, Callister 7e.

- Extrusion
  - Force
  - Ram
  - Billet
  - Container
  - Die holder
  - Extrusion
  - Die

\[
\%CW = \frac{A_o - A_d}{A_o} \times 100
\]
• Ti alloy after cold working:
  • Dislocations entangle with one another during cold work.
  • Dislocation motion becomes more difficult.

Adapted from Fig. 4.6, Callister 7e. (Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)
Result of Cold Work

Dislocation density = \frac{\text{total dislocation length}}{\text{unit volume}}

- Carefully grown single crystal
  \( \rightarrow \text{ca. } 10^3 \text{ mm}^{-2} \)
- Deforming sample increases density
  \( \rightarrow 10^9-10^{10} \text{ mm}^{-2} \)

• Yield stress increases as \( \rho_d \) increases:

\( \sigma_y \)

\( \sigma_{y1} \)

\( \sigma_{y0} \)

large hardening

small hardening
Impact of Cold Work

As cold work is increased

- Yield strength ($\sigma_y$) increases.
- Tensile strength ($TS$) increases.
- Ductility (%$EL$ or %$AR$) decreases.
Effect of Heating After %CW

• 1 hour treatment at $T_{\text{anneal}}$...
  decreases $TS$ and increases $\%EL$.
• Effects of cold work are reversed!

Adapted from Fig. 7.22, Callister 7e. (Fig.
7.22 is adapted from G. Sachs and K.R. van
Horn, Practical Metallurgy, Applied
Metallurgy, and the Industrial Processing of
Ferrous and Nonferrous Metals and Alloys,
American Society for Metals, 1940, p. 139.)
Annihilation reduces dislocation density.

- Scenario 1
  Results from diffusion

1. dislocation blocked; can’t move to the right
2. grey atoms leave by vacancy diffusion allowing disl. to “climb”
3. “Climbed” disl. can now move on new slip plane

- Scenario 2

4. opposite dislocations meet and annihilate
Obstacle dislocation

\[ \tau_R \]
Recrystallization

• New grains are formed that:
  -- have a small dislocation density
  -- are small
  -- consume cold-worked grains.

33% cold worked brass

New crystals nucleate after 3 sec. at 580°C.
Further Recrystallization

- All cold-worked grains are consumed.

Adapted from Fig. 7.21 (c),(d), *Callister 7e.*
(Fig. 7.21 (c),(d) are courtesy of J.E. Burke, General Electric Company.)
Grain Growth

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

\[ d^n - d_o^n = Kt \]

- Empirical Relation:
  - Exponent typ. ~ 2
  - Grain diam. at time \( t \)
  - Coefficient dependent on material and \( T \).
  - Elapsed time

Ostwald Ripening

Adapted from Fig. 7.21 (d),(e), Callister 7e. (Fig. 7.21 (d),(e) are courtesy of J.E. Burke, General Electric Company.)
Adapted from Fig. 7.22, Callister 7e.

$T_R = \text{recrystallization temperature}$
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. This decreases the strength.