Recovery

• **Scenario 1**
  Results from diffusion
  
  extra half-plane of atoms
  atoms diffuse to regions of tension
  extra half-plane of atoms
  
  Dislocations annihilate and form a perfect atomic plane.

• **Scenario 2**
  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
  4. opposite dislocations meet and annihilate

Obstacle dislocation

\[ \tau_R \]
Recrystallization

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

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.

Adapted from Fig. 7.21 (d),(e), Callister 7e. (Fig. 7.21 (d),(e) are courtesy of J.E. Burke, General Electric Company.)
Influence of temperature on strength and ductility

Adapted from Fig. 7.22, Callister 7e.
Influence of temperature on strength and ductility

- $T_R = \text{recrystallization temperature} = \text{point of highest rate of property change}$
Mechanical failure

- How do flaws in a material initiate failure?
- How is fracture resistance quantified; how do different material classes compare?
- How do we estimate the stress to fracture?
- How do loading rate, loading history, and temperature affect the failure stress?

Ship-cyclic loading from waves.
Adapted from chapter-opening photograph, Chapter 8, Callister 7e. (by Neil Boenzi, The New York Times.)

Computer chip-cyclic thermal loading.
Adapted from Fig. 22.30(b), Callister 7e. (Fig. 22.30(b) is courtesy of National Semiconductor Corporation.)

Hip implant-cyclic loading from walking.
Adapted from Fig. 22.26(b), Callister 7e.
Ductile vs. brittle failure

- Classification:

Fracture behavior:

Very Ductile

Moderately Ductile

Brittle

%AR or %EL

Large

Moderate

Small

• Ductile fracture is usually desirable!

Ductile: warning before fracture

Brittle: No warning

Adapted from Fig. 8.1, Callister 7e.
Example: failure of a pipe

• **Ductile failure:**

![Ductile failure image](image)

• **Brittle failure:**

![Brittle failure image](image)

Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66. John Wiley and Sons, Inc., 1987. Used with permission.
Moderately ductile failure

- Evolution to failure:

- Resulting fracture surfaces (steel)

Particles serve as void nucleation sites.


Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.
Ductile vs. brittle failure

Adapted from Fig. 8.3, *Callister 7e.*
Brittle failure

Arrows indicate point at which failure originated

Adapted from Fig. 8.5(a), *Callister 7e.*
Brittle fracture surfaces

304 S. Steel (metal)

316 S. Steel (metal)
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 650, p. 357. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by D.R. Diercks, Argonne National Lab.)
Ideal vs. real materials

• Stress-strain behavior (Room $T$):
Ideal vs. real materials

Adapted from Fig. 8.8(a), *Callister 7e.*
Crack propagation

Crack propagates if above critical stress

where

\[ E = \text{modulus of elasticity} \]
\[ \gamma_s = \text{specific surface energy} \]
\[ a = \text{one half length of internal crack} \]
\[ K_c = \frac{\sigma_c}{\sigma_0} \]

For ductile \( \Rightarrow \) replace \( \gamma_s \) by \( \gamma_s + \gamma_p \)

where \( \gamma_p \) is plastic deformation energy
Impact testing

- Impact loading:
  -- severe testing case
  -- makes material more brittle
  -- decreases toughness

Adapted from Fig. 8.12(b), Callister 7e. (Fig. 8.12(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, The Structure and Properties of Materials, Vol. III, Mechanical Behavior, John Wiley and Sons, Inc. (1965) p. 13.)
Temperature effects

- **Increasing temperature...**
  --increases \( \% EL \) and \( K_c \)

- **Ductile-to-Brittle Transition Temperature (DBTT)...**

  ![Graph showing impact energy vs temperature for different materials]

<table>
<thead>
<tr>
<th>Impact Energy</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FCC metals (e.g., Cu, Ni)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>BCC metals (e.g., iron at ( T &lt; 914°C ))</strong></td>
<td></td>
</tr>
<tr>
<td><strong>polymers</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Brittle</strong></td>
<td><strong>More Ductile</strong></td>
</tr>
<tr>
<td><strong>High strength materials (( \sigma_y &gt; E/150 ))</strong></td>
<td></td>
</tr>
</tbody>
</table>

Adapted from Fig. 8.15, *Callister 7e.*
Stay above DBTT

• Pre-WWII: The Titanic


• WWII: Liberty ships


• Problem: Used a type of steel with a DBTT ~ Room temp.
Fatigue

• Fatigue limit, $\sigma_{fat}$:
  --no fatigue if $\sigma < \sigma_{fat}$

• Sometimes, the fatigue limit is zero!

[Image showing crack origin]
Creep

Adapted from Fig. 8.28, Callister 7e.
Secondary creep

- Strain rate is constant at a given $T, \sigma$
  -- strain hardening is balanced by recovery

- Strain rate increases for higher $T, \sigma$

Adapted from Fig. 8.31, Callister 7e.
(Fig. 8.31 is from Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)