Recovery: Rearrangement of dislocations, annihilation reduces dislocation density.

- **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
Recrystallization

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

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

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

exponent typ. ~ 2

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.)

Empirical Relation:

After 8 s, 580°C

After 15 min, 580°C
Influence of temperature on strength and ductility

Adapted from Fig. 7.22, Callister 7e.

\[ T_R = \text{recrystallization temperature} \]
Influence of temperature on strength and ductility

- \( T_R = \) recrystallization temperature = point of highest rate of property change
  - \( T_m \Rightarrow T_R \approx 0.3-0.6 \ T_m \ (K) \)
  - Due to diffusion \( \rightarrow \) annealing time \( \rightarrow \) \( T_R = f(t) \) shorter annealing time \( \Rightarrow \) higher \( T_R \)
  - Higher %CW \( \Rightarrow \) lower \( T_R \) – strain hardening
  - Easier to move in pure metals \( \Rightarrow \) lower \( T_R \)
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?


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:**
  -- one piece
  -- large deformation

• **Brittle failure:**
  -- many pieces
  -- small deformation

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*. 

- cup-and-cone fracture
- brittle fracture
Brittle failure

Arrows indicate point at which failure originated

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

• Intergranular (between grains)

304 S. Steel
(metal)

4 mm

• Intragranular (within grains)

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.)

160 mm
Ideal vs. real materials

- Stress-strain behavior (Room $T$):

\[ \sigma = \frac{E}{10} \quad \text{perfect mat'l-no flaws} \]

\[ E/100 \quad \text{carefully produced glass fiber} \]

\[ E/1000 \quad \text{perfect mat'l-no flaws} \]

\[ E/10000 \quad \text{typical ceramic} \]

\[ E/100000 \quad \text{typical strengthened metal} \]

\[ E/1000000 \quad \text{typical polymer} \]

Flaws are Stress Concentrators!
Ideal vs. real materials

Griffith Crack

\[ \sigma_m = 2\sigma_0 \left( \frac{a}{\rho_t} \right)^{1/2} = K_t \sigma_0 \]

where

- \( \rho_t = \) radius of curvature
- \( \sigma_0 = \) applied stress
- \( \sigma_m = \) stress at crack tip

\( K_t = \) Stress concentration factor

\[ \frac{\sigma_m}{\sigma_0} = 2 \left( \frac{a}{\rho_t} \right)^{1/2} \]

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

Crack propagates if above critical stress

\[ \sigma_m > \sigma_c \]

or \[ K_t > K_c \]

where

- \( E \) = modulus of elasticity
- \( \gamma_s \) = specific surface energy
- \( a \) = one half length of internal crack
- \( K_c = \sigma_c/\sigma_0 \) = fracture toughness

For ductile => replace \( \gamma_s \) by \( \gamma_s + \gamma_p \)

where \( \gamma_p \) is plastic deformation energy

\[ \sigma_c = \left( \frac{2E\gamma_s}{\pi a} \right)^{1/2} \]

\[ K_c = Y\sigma_c \sqrt{\pi a} \]

If specimen thickness >> crack dimensions and stress is applied in mode I,

\[ K_{Ic} = Y\sigma \sqrt{\pi a} \]
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)...**

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

- **Pre-WWII:** The Titanic

  ![Titanic Image]


- **WWII:** Liberty ships

  ![Liberty Ship Image]


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

- **Fatigue limit, \( \sigma_{\text{fat}} \):**
  -- no fatigue if \( \sigma < \sigma_{\text{fat}} \)

- Sometimes, the fatigue limit is zero!

```latex
\begin{align*}
\sigma_a &= \text{stress amplitude} \\
\sigma_{\text{fat}} &= \text{fatigue limit}
\end{align*}
```

Adapted from Fig. 8.19(a), Callister 7e.

```latex
\begin{align*}
N &= \text{Cycles to failure} \\
10^3 &\leq N \leq 10^9
\end{align*}
```

Adapted from Fig. 8.19(b), Callister 7e.
Creep

Sample deformation at a constant stress ($\sigma$) vs. time

**Primary Creep**: slope (creep rate) decreases with time.

**Secondary Creep**: steady-state i.e., constant slope.

**Tertiary Creep**: slope (creep rate) increases with time, i.e. acceleration of rate.

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

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

$$\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

- 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.)