Chapter 7
Dislocations & Strengthening Mechanisms

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WHY STUDY Dislocations and Strengthening Mechanisms?

- Understand underlying mechanisms of the techniques used to strengthen & harden metals and their alloys
- Design & tailor mechanical properties of materials

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WHY STUDY Dislocations and Strengthening Mechanisms?

- Strengthening mechanisms will be applied to the development of mechanical properties for steel alloys
- Why heat treating a deformed metal alloy makes it softer & more ductile and produces changes in its microstructure

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Learning Objectives

1. Describe edge & screw dislocation motion
2. Describe how plastic deformation occurs by motion of edge & screw dislocations in response to applied shear stresses
3. Define slip system
4. Describe how grain structure of a polycrystalline metal is altered when it is plastically deformed.
5. Explain how grain boundaries impede dislocation motion & why a metal having small grains is stronger than one having large grains.

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Learning Objectives

5. Describe & explain solid-solution strengthening for substitutional impurity atoms in terms of lattice strain interactions with dislocations.
6. Describe & explain phenomenon of strain hardening in terms of dislocations and strain field interactions.
7. Describe recrystallization in terms of both alteration of microstructure & mechanical characteristics of the material.
8. Describe phenomenon of grain growth from both macroscopic and atomic perspectives.
7.2 BASIC CONCEPTS
Dislocation Motion

Cubic & hexagonal metals - plastic deformation is by plastic shear or slip where one plane of atoms slides over adjacent plane by dislocations motion.
7.3 Characteristics of Dislocations

- When metals are plastically deformed:
  - Around 5% of deformation energy is retained internally
  - Remainder is dissipated as heat
- The major portion of stored energy is strain energy associated with dislocations

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7.3 Characteristics of Dislocations

Figure 7.4: some atomic lattice distortion exists around dislocation line because of presence of extra half-plane of atoms.
7.3 Characteristics of Dislocations

- Atoms immediately above and adjacent to dislocation line are squeezed together.
  - These atoms may be thought of as experiencing a compressive strain relative to atoms positioned in the perfect crystal and far removed from the dislocation.

- Directly below half-plane, lattice atoms sustain an imposed tensile strain.

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7.3 Characteristics of Dislocations

- Shear strains also exist in the vicinity of edge dislocation.
- For a screw dislocation, lattice strains are pure shear only.
- These lattice distortions may be considered to be strain fields that radiate from the dislocation line.
- The strains extend into the surrounding atoms, and their magnitude decreases with radial distance from the dislocation.

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7.3 Characteristics of Dislocations

Strain fields surrounding

- **Figure 7.5 (a):** Two edge dislocations of same sign & lying on same slip plane exert a repulsive force on each other.

- Compressive & tensile strain fields for both lie on same side of the slip plane; there exists between these two isolated dislocations a mutual repulsive force that tends to move them apart.

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7.3 Characteristics of Dislocations

strain fields surrounding

Figure 7.5 (b) Edge dislocations of opposite sign & lying on same slip plane exert an attractive force on each other. Upon meeting, they annihilate each other and leave a region of perfect crystal

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7.4 Slip Systems

- **Slip plane** - plane allowing easiest slippage
  - Wide inter-planar spacing - highest planar densities
- **Slip direction** - direction of movement - Highest linear densities
- FCC Slip occurs on \{111\} planes in <110> directions
  - \( \Rightarrow \) total of 12 slip systems in FCC
- in BCC & HCP other slip systems occur

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Table 7.1: Slip Systems for FCC, BCC, and HCP Metals

<table>
<thead>
<tr>
<th>Metals</th>
<th>Slip Plane</th>
<th>Slip Direction</th>
<th>Number of Slip Systems</th>
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</thead>
<tbody>
<tr>
<td><strong>Face-Centered Cubic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu, Al, Ni, Ag, Au</td>
<td>{111}</td>
<td>⟨110⟩</td>
<td>12</td>
</tr>
<tr>
<td><strong>Body-Centered Cubic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>α-Fe, W, Mo</td>
<td>{110}</td>
<td>⟨111⟩</td>
<td>12</td>
</tr>
<tr>
<td>α-Fe, W</td>
<td>{211}</td>
<td>⟨111⟩</td>
<td>12</td>
</tr>
<tr>
<td>α-Fe, K</td>
<td>{321}</td>
<td>⟨111⟩</td>
<td>24</td>
</tr>
<tr>
<td><strong>Hexagonal Close-Packed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cd, Zn, Mg, Ti, Be</td>
<td>{0001}</td>
<td>⟨1120⟩</td>
<td>3</td>
</tr>
<tr>
<td>Ti, Mg, Zr</td>
<td>{1010}</td>
<td>⟨1120⟩</td>
<td>3</td>
</tr>
<tr>
<td>Ti, Mg</td>
<td>{1011}</td>
<td>⟨1120⟩</td>
<td>6</td>
</tr>
</tbody>
</table>
7.5 Slip in Single Crystals

- Crystals slip due to a resolved shear stress, $\tau_R$.
- Applied tension can produce such a stress.
  - $\lambda = \text{angle between stress direction & Slip direction}$
  - $\phi = \text{angle between stress direction & normal to slip plane}$

$$\tau_R = \sigma \cos \lambda \cos \phi$$
Critical Resolved Shear Stress

- Condition for dislocation motion:
  \[ \tau_R > \tau_{\text{CRSS}} \]
- Crystal orientation can make it easy or hard to move dislocation

\[ \tau_R = \sigma \cos \lambda \cos \phi \]

- Typically, \(10^{-4} \text{ GPa to } 10^{-2} \text{ GPa}\)

\( \tau_R = 0 \)
- \( \lambda = 90^\circ \)

\( \tau_R = \sigma/2 \)
- \( \lambda = 45^\circ \)
- \( \phi = 45^\circ \)

\( \tau_R = 0 \)
- \( \phi = 90^\circ \)

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7.5 Slip in Single Crystals

Resolved $\tau$ (shear stress) is maximum at $\lambda = \phi = 45^\circ$

And

$\tau_{\text{CRSS}} = \sigma_y/2$ for dislocations to move (in single crystals)
Determining $\phi$ & $\lambda$ angles for Slip in Crystals

For cubic crystals, angles between directions are given by:

$$\theta = \arccos\left[ \frac{u_1u_2 + v_1v_2 + w_1w_2}{\sqrt{(u_1^2 + v_1^2 + w_1^2)} \cdot \sqrt{(u_2^2 + v_2^2 + w_2^2)}} \right]$$
EXAMPLE PROBLEM 7.1

Resolved Shear Stress and Stress-to-Initiate-Yielding Computations

Consider a single crystal of BCC iron oriented such that a tensile stress is applied along a [010] direction.

a. Compute the resolved shear stress along a (110) plane and in a [\( \bar{1}11 \)] direction when a tensile stress of 52 MPa is applied.

b. If slip occurs on a (110) plane and in a [-111] direction, and the critical resolved shear stress is 30 MPa, calculate the magnitude of the applied tensile stress necessary to initiate yielding.
7.6 Plastic Deformation of Polycrystalline Materials

- Stronger since grain boundaries pin deformations
- Slip planes & directions \((\lambda, \phi)\) change from one crystal to another
- \(\tau_R\) will vary from one crystal to another.
- Crystal with largest \(\tau_R\) yields first
- Other (less favorably oriented) crystals yield (slip) later.
7.6 Plastic Deformation of Polycrystalline Materials

- Ordinarily ductility is sacrificed when an alloy is strengthened.

- Relationship between dislocation motion & mechanical behavior of metals is significance to understanding of strengthening mechanisms.

- The ability of a metal to plastically deform depends on the ability of dislocations to move.
7.6 Plastic Deformation of Polycrystalline Materials

- **Strengthening principle**: Restricting or Hindering dislocation motion renders a material harder & stronger.

- We will consider strengthening single phase metals by:
  1. Grain size reduction
  2. Solid-solution alloying
  3. Strain hardening
7.8 Strengthening by Grain Size Reduction

- Grain boundaries are barriers to slip
- Barrier "strength" increases with Increasing angle of mis-orientation.
- Smaller grain size: more barriers to slip
7.8 Strengthening by Grain Size Reduction

**Figure 7.15:** Influence of grain size on yield strength of a 70 Cu–30 Zn brass alloy

**Hall-Petch equation:**

\[ \sigma_{\text{yield}} = \sigma_0 + k_y d^{-1/2} \]
7.8 Strengthening by Grain Size Reduction

Grain Size Reduction Techniques:

- Increase Rate of solidification from the liquid phase
- Perform Plastic deformation followed by an appropriate heat treatment
7.8 Strengthening by Grain Size Reduction

✓ Grain size reduction improves toughness of many alloys.

✓ Small-angle grain boundaries are not effective in interfering with the slip process because of small crystallographic misalignment across the boundary.

✓ Boundaries between two different phases are also impediments to movements of dislocations.
7.9 Solid-solution Strengthening

- 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.

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7.9 Solid-solution Strengthening

- small impurities tend to concentrate at dislocations on the “Compressive stress side”
- reduce mobility of dislocation \( \therefore \) increase strength
7.9 Solid-solution Strengthening

- Large impurities concentrate at dislocations on “Tensile Stress” side – pinning dislocation

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7.9 Solid-solution Strengthening

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

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

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7.10 Strain Hardening

✓ Room temperature deformation
✓ Common forming operations change cross sectional area:

- Forging
- Drawing
- Extrusion
- Rolling

\[ \%CW = \left( \frac{A_o - A_d}{A_o} \right) \times 100 \]
7.10 Strain Hardening

Ti alloy after cold working:
- Dislocations entangle & multiply
- Thus, Dislocation motion becomes more difficult

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7.10 Strain Hardening

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

- Carefully grown single crystal → ca. 10^3 mm^-2
- Deforming sample increases density → 10^9-10^{10} mm^-2
- Heat treatment reduces density → 10^5-10^6 mm^-2

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

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7.10 Strain Hardening

Figure 7.20: influence of cold work on stress strain behavior of a low-carbon steel
7.10 Strain Hardening

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7.10 Strain Hardening

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7.10 Strain Hardening
Cold Work Analysis

What is the tensile strength & ductility after cold working?

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

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Cold Work Analysis

What is the tensile strength & ductility after cold working to 35.6%?

- **Yield Strength (MPa)**
  - 0% Cold Work: 100 MPa
  - 20% Cold Work: 300 MPa (YS = 300 MPa)
  - 60% Cold Work: 700 MPa

- **Tensile Strength (MPa)**
  - 0% Cold Work: 200 MPa
  - 20% Cold Work: 400 MPa
  - 340 MPa (TS = 340 MPa)
  - 60% Cold Work: 800 MPa

- **Ductility (%EL)**
  - 0% Cold Work: 7%
  - 20% Cold Work: 20%
  - 60% Cold Work: 7%

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σ- ε Behavior vs. Temperature

Results for polycrystalline iron:

- $\sigma_y$ & TS decrease with increasing temperature
- %EL increases with increasing temperature
Recovery, Recrystallization, and Grain Growth

- Properties & structures may revert back to the precold-worked states by appropriate heat treatment (annealing treatment).
- Such restoration results from different processes that occur at elevated temperatures:
  1. Recovery
  2. Recrystallization
  3. Grain growth
Recovery, Recrystallization, & Grain Growth

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

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7.11 RECOVERY

- During recovery, some of the stored internal strain energy is relieved by virtue of dislocation motion, due to enhanced atomic diffusion at elevated temperature.
- There is some reduction in number of dislocations, and dislocation configurations are produced having low strain energies.
- Physical properties such as electrical and thermal conductivities are recovered to their precold-worked states.
Even after recovery is complete, the grains are still in a relatively high strain energy state. Recrystallization = formation of a new set of strain-free and equiaxed grains that have low dislocation densities and are characteristic of the pre-cold-worked condition. The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material. The new grains form as very small nuclei and grow until they completely consume the parent material, processes that involve short-range diffusion.
7.12 Recrystallization

33% cold worked brass

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

Figure 7.21

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7.12 Recrystallization

All cold-worked grains are consumed.

After 4 seconds

After 8 seconds

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7.12 Recrystallization

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7.12 Recrystallization

- **Recrystallization temperature** = temperature at which recrystallization just reaches completion in 1 h.

- Recrystallization temperature for brass alloy of Figure 7.22 is about 450°C.

- Typically, between one-third and one-half of absolute melting temperature of a metal or alloy

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$T_R$ = recrystallization temperature

**Figure 7.22:** Annealing temperature influence (for an annealing time of 1 h) on tensile strength & ductility of a brass alloy.
Critical degree of cold work below which recrystallization cannot be made to occur (between 2% and 20% cold work)

Figure 7.23
7.12 Recrystallization

- Recrystallization proceeds more rapidly in pure metals than in alloys.
- During recrystallization, grain boundary motion occurs as the new grain nuclei form and then grow.
- For pure metals, $T_{RC} = 0.4T_m$
### 7.12 Recrystallization

#### Table 7.2  Recrystallization and Melting Temperatures for Various Metals and Alloys

<table>
<thead>
<tr>
<th>Metal</th>
<th>Recrystallization Temperature</th>
<th>Melting Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
<td>°F</td>
</tr>
<tr>
<td>Lead</td>
<td>-4</td>
<td>25</td>
</tr>
<tr>
<td>Tin</td>
<td>-4</td>
<td>25</td>
</tr>
<tr>
<td>Zinc</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Aluminum (99.999 wt%)</td>
<td>80</td>
<td>176</td>
</tr>
<tr>
<td>Copper (99.999 wt%)</td>
<td>120</td>
<td>250</td>
</tr>
<tr>
<td>Brass (60 Cu–40 Zn)</td>
<td>475</td>
<td>887</td>
</tr>
<tr>
<td>Nickel (99.99 wt%)</td>
<td>370</td>
<td>700</td>
</tr>
<tr>
<td>Iron</td>
<td>450</td>
<td>840</td>
</tr>
<tr>
<td>Tungsten</td>
<td>1200</td>
<td>2200</td>
</tr>
</tbody>
</table>
7.13 Grain Growth

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

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

- exponent typ. ~ 2
- grain dia. At time t.
- coefficient dependent on material & Temp.
- elapsed time

This is: Ostwald Ripening
Coldwork Calculations

A cylindrical rod of brass originally 0.40 in (10.2 mm) in diameter is to be cold worked by drawing. The circular cross section will be maintained during deformation. A cold-worked tensile strength in excess of 55,000 psi (380 MPa) and a ductility of at least 15 %EL are desired. Further more, the final diameter must be 0.30 in (7.6 mm). Explain how this may be accomplished.

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Coldwork Calculations Solution

If we directly draw to the final diameter what happens?

\[
\%CW = \left(\frac{A_o - A_f}{A_o}\right) \times 100 = \left(1 - \frac{A_f}{A_o}\right) \times 100
\]

\[
= \left(1 - \frac{\pi D_f^2/4}{\pi D_o^2/4}\right) \times 100 = \left(1 - \frac{0.30^2}{0.40^2}\right) \times 100 = 43.8\%
\]

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Coldwork Calc Solution: Cont.

- For $\%CW = 43.8\%$
  - $\sigma_y = 420$ MPa
  - $TS = 540$ MPa $> 380$ MPa
  - $\%EL = 6 < 15$

- This doesn’t satisfy criteria…… what can we do?
Coldwork Calc Solution: Cont.

For $TS > 380$ MPa \[\rightarrow > 12 \%CW\]

For $\%EL > 15$ \[\rightarrow < 27 \%CW\]

\[\therefore\text{ our working range is limited to } \%CW = 12 - 27\%\]
This process Needs an Intermediate Recrystallization

- Cold draw-anneal-cold draw again
- For objective we need a cold work of \( \%CW \approx 12-27 \). We'll use \( \%CW = 20 \)
- Diameter after first cold draw (before \( 2^{nd} \) cold draw)? must be calculated as follows:

\[
\%CW = \left(1 - \frac{D_{f2}^2}{D_{s2}^2}\right) \times 100 \quad \Rightarrow \quad 1 - \frac{D_{f2}^2}{D_{s2}^2} = \frac{\%CW}{100}
\]

\[
\frac{D_{f2}}{D_{s2}} = \left(1 - \frac{\%CW}{100}\right)^{0.5} \quad \Rightarrow \quad D_{s2} = \frac{D_{f2}}{\left(1 - \frac{\%CW}{100}\right)^{0.5}}
\]

Intermediate diameter = \( D_{f1} = D_{s2} = 0.30 \sqrt{\left(1 - \frac{20}{100}\right)^{0.5}} = 0.335 \text{ in} \)

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Coldwork Calculations Solution

Summary:
1. Cold work  $D_{01} = 0.40 \text{ in} \Rightarrow D_{f1} = 0.335 \text{ in}$
2. Anneal above  $D_{s2} = D_{f1}$
3. Cold work  $D_{s2} = 0.335 \text{ in} \Rightarrow D_{f2} = 0.30 \text{ in}$

\[
\%CW_1 = \left(1 - \left(\frac{0.335}{0.4}\right)^2\right) \times 100 = 30
\]

\[
\%CW_2 = \left(1 - \left(\frac{0.3}{0.335}\right)^2\right) \times 100 = 20 \Rightarrow
\]

Therefore, meets all requirements

\[\sigma_y = 340 \text{ MPa}\]
\[TS = 400 \text{ MPa}\]
\[\%EL = 24\]

Fig 7.19

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Design Example 7.1

Description of Diameter Reduction Procedure

A cylindrical rod of non-cold-worked brass having an initial diameter of 6.4 mm is to be cold worked by drawing such that the cross-sectional area is reduced. It is required to have a cold-worked yield strength of at least 345 MPa and a ductility in excess of 20 %EL; in addition, a final diameter of 5.1 mm is necessary. Describe the manner in which this procedure may be carried out.
Dislocations are observed primarily in metals and alloys.

Strength is increased by making dislocation motion difficult.

Particular ways to increase strength are to:

1. decrease grain size
2. solid solution strengthening
3. precipitate strengthening
4. cold work

Heating (annealing) can reduce dislocation density and increase grain size. This decreases the strength.
HomeWork Assignment

- 7, 12, 17, 24, 29, 41, D6
- Due Tuesday 26/11/2013
- Quiz is on Tuesday 3/12/2013