Elastic Strain Recovery

\[ \sigma_{y_0} = \text{Yield Strength} \] (typically defined at \( \varepsilon = 0.002 \))
Initial loading

\[ \sigma_{y_i} = \text{Yield Strength} \]
After unloading and reloading

Note: for many metals YS↑ after plastic deformation
Tensile Test
Hardening

• An increase in $\sigma_y$ due to plastic deformation.

![Stress-strain curve with hardening](image)

• Curve fit to the stress-strain response:

$$\sigma_T = C \left( \varepsilon_T \right)^n$$

- hardening exponent:
  - $n=0.15$ (some steels)
  - $n=0.5$ (some copper)

“true” stress ($F/A$)

“true” strain: $\ln(L/L_0)$
CHAPTER 7: DISLOCATIONS AND STRENGTHENING

ISSUES TO ADDRESS...

• Why are dislocations observed primarily in metals and alloys?

• How are strength and dislocation motion related?

• How do we increase strength?

• How can heating change strength and other properties?
Dislocations & Materials Classes

- **Metals**: Disl. motion easier.
  - non-directional bonding
  - close-packed directions for slip.

- **Covalent Ceramics** (Si, diamond): Motion hard.
  - directional (angular) bonding

- **Ionic Ceramics** (NaCl): Motion hard.
  - need to avoid ++ and -- neighbors.
What happens when bonds snap?

Two possible results:
How does plastic deformation happen?

Calculating the shear stress for the mechanism above gives a result of $\sim G/6$ (with $G =$ shear modulus).

Typical experimental values are however $\sim 10^{-4} - 10^{-6} G$

Plastic deformation does NOT happen this way!

**Crystals contain dislocations.**

Most plastic deformation happens by the movement of dislocations across the material.
Dislocation Motion

- Produces plastic deformation,
- Depends on incrementally breaking bonds.

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

Adapted from Fig. 7.1, *Callister 6e*. (Fig. 7.1 is adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976. p. 153.)

Adapted from Fig. 7.8, *Callister 6e*.

Adapted from Fig. 7.9, *Callister 6e*. (Fig. 7.9 is from C.F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

Plastically stretched zinc single crystal.
Dislocation Motion

Edge Dislocation Motion

Screw Dislocation Motion
Dislocation Motion

Dislocation Motion:
Response to shear stress

Analogy between caterpillar motion and dislocation motion
Arrangement of Atoms Around an Edge Dislocation

- **Dislocation “Core”**
  - Region where the bonding is “wrong”
- **Dislocation “Strain Field”**
  - Planes near the dislocation are bent, or strained
    - Bonds are stretched, compressed, or “bent” but not “wrong”
Characteristics of Dislocations

Dislocation repulsion
(same sense of dislocations)

Dislocation attraction
(opposite sense dislocations)
The Tangent Vector or Line Vector

**Line Vector**
Identifies the orientation of the core in the crystal
  Can change along the dislocation
  Dislocations don’t have to be “straight”
Geometry and Nomenclature of Dislocation Glide: Glide Planes

- Glide Plane
  - Definition: a plane on which a specific dislocation can glide
  - Physically: the glide plane must contain $b$ and $t$
  - Mathematically: $n = b \times t$
  (note $b =$ Burgers vector and $t =$ dislocation line tangent vector)

Edge Dislocation

\[ \vec{b} \perp \vec{t} \Rightarrow \]

Only ONE Glide Plane!

Screw Dislocation

\[ \vec{b} \parallel \vec{t} \Rightarrow \]

MANY Glide Planes!

BUT...
“REAL” Glide Planes for Screw Dislocations

• **What Really Happens:**
  - Glide of Screw Dislocations TENDS to occur on Close-Packed Planes

• **Common Glide Planes:**
  - (111) in fcc metals: True Close-packed Plane
  - (0001) in hcp metals: True Close-packed Plane
  - (110) in bcc metals: Closest Packed Plane
Nomenclature for Dislocation Glide

Definitions

**Slip** Deformation of crystalline materials by dislocation *Glide* (also called yielding)

**Slip Direction** is the direction of the shear displacement incurred
  - $\parallel b$, *NOT* the direction of dislocation motion!
  - Burgers vectors like to be as short as possible
    - $\Rightarrow$ TENDS to be a closely-packed direction

**Slip Plane** is the plane on which the dislocations glide

**Slip Systems** are combinations of slip planes and slip directions in which slip can occur by the glide of a dislocation $(b,n)$ pairs
Slip Systems

To specify a *slip system*, need:

- Slip plane, \( n \)
  - Usually a closely-packed plane

- A *slip direction* (Burgers vector!), \( b \)
  - Usually a close-packed direction
  - \( b \) lies in the slip plane
    - If \( b \) of a screw dislocation isn’t in the plane, the dislocation isn’t either
    - If \( b \) of an edge dislocation isn’t in the plane, the dislocation can’t glide
Slip Systems in FCC Metals

Slip Directions
Common $b$: $a/2<110>$

Slip Plane
Close-packed planes: $\{111\}$

Slip Systems
$b$ must lie in the slip plane ($b \perp n$)

There are TWO $\{111\}$ planes that contain each possible $<110>$ Direction
∴ Six $<110>$ type directions leads to 12 slip systems!
**Slip Systems in BCC Metals**

**Slip Directions**
- Common \( \mathbf{b} \): \( a/2<111> \)

**Slip Plane**
- Closely-Packed Planes are \{110\}

**Slip Systems**
- \( \mathbf{b} \) must lie in the slip plane (\( \mathbf{b} \perp \mathbf{n} \))

Two \(<111>\) type Directions in Each \{110\} Plane

\[ \therefore \text{Six \{110\} type planes yield 12 slip systems of this type} \]
Slip Systems in HCP Metals

**Slip Directions**
- Common \( \mathbf{b} \): \(<11\text{-}20>\)

**Slip Plane**
- Close-packed planes: \{0001\}

**Slip Systems**
- \( \mathbf{b} \) must lie in the slip plane \( (\mathbf{b} \perp \mathbf{n}) \)

There is only ONE \{0001\} plane!

\[ \therefore \text{ Three most favored slip systems!} \]

AND they all lie in a plane!
Table 7.1  Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

<table>
<thead>
<tr>
<th>Metals</th>
<th>Slip Plane</th>
<th>Slip Direction</th>
<th>Number of Slip Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face-Centered Cubic</td>
<td>{111}</td>
<td>\langle 1\overline{1}0 \rangle</td>
<td>12</td>
</tr>
<tr>
<td>Cu, Al, Ni, Ag, Au</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body-Centered Cubic</td>
<td>{110}</td>
<td>\langle \overline{1}11 \rangle</td>
<td>12</td>
</tr>
<tr>
<td>(\alpha)-Fe, W, Mo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\alpha)-Fe, W</td>
<td>{211}</td>
<td>\langle \overline{1}11 \rangle</td>
<td>12</td>
</tr>
<tr>
<td>(\alpha)-Fe, K</td>
<td>{321}</td>
<td>\langle \overline{1}11 \rangle</td>
<td>24</td>
</tr>
<tr>
<td>Hexagonal Close-Packed</td>
<td>{0001}</td>
<td>\langle 11\overline{2}0 \rangle</td>
<td>3</td>
</tr>
<tr>
<td>Cd, Zn, Mg, Ti, Be</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti, Mg, Zr</td>
<td>{10\overline{1}0}</td>
<td>\langle 11\overline{2}0 \rangle</td>
<td>3</td>
</tr>
<tr>
<td>Ti, Mg</td>
<td>{10\overline{1}1}</td>
<td>\langle 11\overline{2}0 \rangle</td>
<td>6</td>
</tr>
</tbody>
</table>

(\textbf{Red arrow} ← indicates most common slip systems)
Example: Dislocations in Iron

Dislocations are lined up!

Two different grains
Even More on Shear Stress

For uniaxial deformation: maximum shear stress at 45°

But … this does not take crystallography into account!!!
Even More on Shear Stress

- Crystals slip due to a resolved shear stress, $\tau_R$.
- Applied tension can produce such a stress.

\[ \tau_R = F_s / A_s \]

Relation between $\sigma$ and $\tau_R$

\[ \tau_R = \sigma \cos \lambda \cos \phi \]
Critical Resolved Shear Stress

• Condition for dislocation motion: \( \tau_R > \tau_{CRSS} \)

• Crystal orientation can make it easy or hard to move disl.

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

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

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

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

Typically \( 10^{-4} \Gamma \) to \( 10^{-2} \Gamma \)
Dislocation Motion in Polycrystals

- Slip planes & directions \((\lambda, \phi)\) change from one crystal to another.
- \(\tau_R\) will vary from one crystal to another.
- The crystal with the largest \(\tau_R\) yields first.
- Other (less favorably oriented) crystals yield later.

Adapted from Fig. 7.10, Callister 6e.
(Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)