Chapter 8

Strain Hardening and Annealing

This is a further application of our knowledge of plastic deformation and is an introduction to heat treatment.

Part of this lecture is covered by Chapter 4 of the textbook

The Main Purpose is...

• To study mechanisms of plastic deformation in order to:
  – Predict how easy a material can be permanently deformed
  – Design process to prevent that deformation (if strengthening is required).

Plastic Deformation

• Role of shear stresses
• First in single crystals to understand the deformation mechanisms
• Then in polycrystalline materials to understand the behavior of materials when they work in the plastic region.
Plastic Deformations and Shear Stresses

- Movement of atoms as a result of an applied shear stress.
- The slippage occurs on a high-density (compact) plane and along a high-density (compact) crystallographic direction.
- Examples of compact planes and compact directions in FCC, BCC and HCP crystals?

On which plane is it easier to move atoms? A or B?

On a (111) plane of an FCC metal the slip directions are indicated.

Slip Systems

A slip system is conformed by a slip plane (dense plane) and a slip direction (compact direction). Examples:

<table>
<thead>
<tr>
<th>Structure</th>
<th>Slip plane</th>
<th>Slip direction</th>
<th>Number of slip systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC</td>
<td>(111)</td>
<td>(100)</td>
<td>4 x 3 = 12</td>
</tr>
<tr>
<td>BCC</td>
<td>(110)</td>
<td>(111)</td>
<td>6 x 2 = 12</td>
</tr>
<tr>
<td>HCP</td>
<td>0001</td>
<td>1120</td>
<td>1 x 3 = 3</td>
</tr>
<tr>
<td>Ti (pyramidal planes)</td>
<td>1011</td>
<td>1130</td>
<td>6 x 1 = 6</td>
</tr>
</tbody>
</table>

Remember: A shear stress must align with a slip system to promote plastic deformation.

<table>
<thead>
<tr>
<th>Factor</th>
<th>FCC</th>
<th>BCC</th>
<th>HCP ($\frac{c}{a} = 1.633$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical resolved shear stress (psi)</td>
<td>50–100</td>
<td>5,000–10,000</td>
<td>50–100$^a$</td>
</tr>
<tr>
<td>Number of slip systems</td>
<td>12</td>
<td>48</td>
<td>3$^a$</td>
</tr>
<tr>
<td>Cross-slip</td>
<td>Can occur</td>
<td>Can occur</td>
<td>Cannot occur$^b$</td>
</tr>
<tr>
<td>Summary of properties</td>
<td>Ductile</td>
<td>Strong</td>
<td>Relatively brittle</td>
</tr>
</tbody>
</table>

$^a$For slip on basal planes.

$^b$By alloying or heating to elevated temperatures, additional slip systems are active in HCP metals, permitting cross-slip to occur and thereby improving ductility.
Critical Resolved Shear Stress

The minimum measured value of a shear stress $\tau_{\text{crit}}$ that would start a plastic deformation on a specific direction. Relates to elastic limit.

Tangential Force $= F \cdot \cos \lambda$

Projected Area $= \frac{A}{\cos \phi}$

$$\tau_c = \frac{F}{A} \cdot \cos \lambda \cdot \cos \phi = \sigma \cdot \cos \lambda \cdot \cos \phi$$

Schmid’s Law

Critical Shear Stress in a Cubic System

• An approximation of the needed $\tau_{\text{crit}}$ to move the upper atomic block over the lower one on compact planes:

$$\tau_{\text{crit}} = \frac{Gb}{2\pi h} = \frac{G}{\pi \sqrt{3}}$$

$$\tau_{\text{crit}} \approx \frac{G}{5}$$

• For Fe with low C: $\tau_{\text{crit}} \approx 16 \text{ GPa}$!
The Role of Dislocations in Plastic Deformations

- Theoretical calculations of $\tau_c$ are 1,000 higher than measured values!
- There must be a different deformation mechanism.
- Dislocations are the answer. Look at the dislocation line motion.

Things to consider:

- No atom has been transported more than a fraction of the lattice parameter!
- Only the dislocation line has physically moved.
- Therefore the necessary energy to deform plastically the metal is much lower.
- Therefore the measured $\tau$ values are much smaller!
- Example for Fe with low C: $\tau_p \approx 0.145$ GPa!

\[ \tau_p = 3G \cdot e^{-2\pi} \]
\[ \tau_p \approx \frac{G}{180} \]
One last VERY important conclusion:

- **ANYTHING** that hampers, hinders, stops a dislocation movement is in fact preventing the plastic deformation of the material.
- Therefore, **ANY** obstacle for the dislocation motion **increases** the mechanical strength of the material: both UTS and YS, while reducing the ductility $d$.

Dislocation movements determine why different types of materials have very different formability

- **Metals**: Dislocation motion easier.
  - non-directional bonding
  - close-packed directions for slip.
  - Electron cloud and ion cores
- **Covalent Ceramics (Si, diamond)**: Motion hard.
  - directional (angular) bonding
- **Ionic Ceramics (NaCl)**: Motion hard.
  - Need to avoid $+$ and $-$ neighbors.
Examples of Obstacles to Dislocation Motion

- More dislocation lines → higher number of dislocation per unit volume results in stronger materials.
- Solute atoms, either substitutional or interstitial.
- Impurity particles can pinned down dislocation motion.
- Grain boundaries can stop and pile up dislocation lines → small grain sizes increase YS.

Effect of Grain Boundaries on the Strength of Metals

Experimental Evidence

- Slip lines in a polycrystalline copper sample
- Polycrystalline Specimen
- Single Crystal

Percent Strain

Tensile Strength
Grain Boundary Effect (cont.)

- The smaller the grain the larger the amount of grain boundaries
- The larger the amount of grain boundaries, the more hurdles the dislocation movement will find
- Therefore the smaller the grain size the higher the strength of the metallic material
- In particular the grain size affects the yield strength $Y_S$

**Hall-Petch Effect**

$$Y_S = \sigma_0 + k \cdot d^{-\frac{1}{2}}$$

- $Y_S$: Yield Strength
- $\sigma_0$: Basic Strength
- $k$: Material constant
- $d$: Grain size equivalent diameter

The Hall-Petch effect is also present at the nanoscale.

**Hall-Petch effect in steels**
Cold plastic deformations affect YS and, thus, hardening. Use dislocations to explain plastic deformations and changes in YS.

After prior plastic deformations what happens to the elastic limit? This explain the **Strain Hardening** phenomenon.

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### Uniaxial vs. Tri-axial Deformations

During tensile test, the materials is preferentially deformed along the vertical axis.

- **Cold rolling of a sheet**
- **Plastic deformations occur along all axes!!**
This is the effect of cold work in the tensile curves of a low carbon steel.

What is the effect of cold work on:

- UTS?
- YS or $\sigma_{0.2}$?
- Toughness?
- Elongation to fracture?
- Area reduction $\psi$?
- E?

Cold work is then another strengthening mechanism:

Examples of cold work in processing:

- Cold Rolling
- Cold Drawing

Amount or percent of cold work:

$$\% \text{Cold Work} = \frac{A_o - A_d}{A_o} \cdot 100$$

$A_o$: initial transverse area

$A_d$: deformed transverse area

Note that this definition is not that different from the area reduction upon fracture in a tensile test:

$$\psi (\%) = (1 - A_{\text{fracture}}/A_o) \cdot 100$$

So what would happen in hot work?
Solution hardening is less effective than cold work

Solute atoms, either substitutional or interstitial

Relative size factor: Effect of solute atoms having a different size than solvent atoms

Short range order: Clustering of atoms that follow certain ordering

Alloys are in general harder than pure metals

Thermomechanical Treatment of Materials

What is heat treatment?
Application of a process under controlled heating and cooling steps to obtain specific mechanical properties.

Examples:
- Annealing
- Normalizing
- Quenching and Tempering
- Solution and Precipitation Hardening (or Aging)
Precipitation/dispersion strengthening

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

- Result: $\sigma_y \sim \frac{1}{S}$

This is a simulation of the strengthening mechanism due to the presence of precipitates

- View onto slip plane of Nimonic PE16 (Ni-Cr superalloy)
- Precipitate volume fraction: 10%
- Average precipitate size: $64 \ b (b = 1 \text{ atomic slip distance})$

Application: precipitation strengthening plays a major role in aerospace materials

Aluminum alloys containing Zn, Cu, Mg, Si, such as AA7075, 6061, 2024, 2014, etc. are strengthened with precipitates formed by alloying elements.
Recovery and Recrystallization of Deformed Metals

What if we need to continue deforming this material?

Permanent deformation

• What if we need to soften the material?
• One choice is by heating it.

For cold worked metals the process involves the following stages:
• Recovery
• Recrystallization
• Grain Growth
The Initial Stage

- Cold Worked Metallic Materials:
  - Higher dislocation density
  - A lot of stored energy as plastic deformation

- Heating up to the “recovery temperature”

Summary of the Thermomechanical Processing

Cu 35% Zn alloy (brass)
Evolution of the Microstructure with Temperature

**Recovery (no microscopic evidence)**
- Large dislocation density

**Recrystallization (small equiaxed grains form)**
- Recrystallized Metal: Small dislocation density

**Grain Growth (larger grains)**
- Grain Growth Onset: No major dislocation lines are observable

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**Let’s analyze each stage individually**

**Recovery**

Start with a large dislocation density shown on slip planes

Increase of internal energy (high temperature) provides energy to “align” dislocations along “low angle grain boundaries”
Recovery (cont.)

Low angle grain boundary in the bubble raft forming a $\theta$ angle. Low angle grain boundary are not effective stoppers for dislocations.

Recrystallization

Nucleus formation follows same basic principles studied before.

In this case all phases are solid.

Need a substrate for heterogeneous nucleation $\rightarrow$ a place with high stored energy.

There is an alternative also:

Both are abundant in the cold worked material. Therefore recrystallization is favored in highly deformed metals.

The effect of prior cold work on recrystallized grain size
If X is the recrystallized fraction by Avrami's equation:

\[ X = 1 - e^{-k \cdot t^n} \]

The "re-crystallization time" \( t_R \) is then measured at 50% or \( X=0.5 \) and plotted as a function of \( 1/T \).

Recrystallization (cont.)

The recrystallization time \( t_R \) also obeys an Arrhenius rate equation:

\[ t_R = C \cdot e^{\frac{Q}{RT}} \]

where: \( t_R \) is the time for full recrystallization at a temperature \( T \) (in degrees Kelvin)

\( Q \) is the activation energy for recrystallization

\( C \) is a constant

For instance, in \( \gamma \)Fe measured values of \( Q \) (~125 kJ/mol) are very close to the values of \( Q \) for self-diffusion. Why?

Note that the exponent is positive in this case!
Grain Growth

Once most grains recrystallize they promptly start to grow. We need to control this growth!

- Large grains grow at the expense of small grains.
- Large grains possess a larger surface area to attach neighbor atoms.
- Those grains seem to “eat” the small ones.

It is evident that grain growth is a diffusion-controlled phenomenon. By the way, what type of diffusion?

Note the relation between concave and convex surfaces in the grains. Any thoughts?

Effect of Annealing Temperature on Mechanical Properties

85wt.%Cu- 15wt.%Zn alloy originally with a 50% cold-rolled section

Given these curves you should be able to indicate the three stages of annealing and recommend the proper treating temperature.