Material Strengthening Mechanisms

Academic Resource Center
Agenda

- Definition of strengthening
- Strengthening mechanisms
- Grain size reduction
- Solid solution alloying
- Cold Working (strain hardening)
- Three steps of Annealing: Recovery, Recrystallization & Grain Growth
Strengthening

• The ability of a metal to deform plastically depends on the ability of dislocations to move.
• Hardness and strength are related to how easily a metal plastically deforms, so, by reducing dislocation movement, the mechanical strength can be improved.
• To the contrary, if dislocation movement is easy (unhindered), the metal will be soft, easy to deform.
Strengthening Mechanisms

1. Grain Size Reduction
2. Solid Solution Alloying
3. Strain Hardening (Cold Working)
4. Annealing
1. Grain Size Reduction

- Grain boundaries are barriers to slip.
- Barrier "strength" increases with misorientation.
- Smaller grain size: more barriers to slip.
Hall Petch Relation

• This equation indicates that the yield strength has an inverse square root relation with grain size (d).

yield = \sigma_0 + k_y d^{1/2}

• Theoretically, a material can be made infinitely strong if the grains are made infinitely small.
2. Solid Solutions

- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

Small substitutional impurity

Large substitutional impurity

Impurity generates local shear at A and B that opposes dislocation motion to the right.

Impurity generates local shear at C and D that opposes dislocation motion to the right.
3. Strain Hardening (Cold Work)

- Room temperature deformation.
- Common forming techniques used to change the cross sectional area:

  - Forging
  - Rolling
  - Drawing
  - Extrusion
Dislocations during Cold Work

- Dislocations entangle one another during cold work.
- Dislocation motion becomes more difficult, which makes the material stronger overall.
Result of Cold Work

- Dislocation density increases, which leads to an increase in yield strength: Materials becomes harder.
- Ductility and tensile strength also increases.
Percentage Cold Work - Definition

\[\% CW = \frac{A_o - A_d}{A_o} \times 100\]

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

Copper Cold work

\[D_o = 15.2\, \text{mm}\]

\[D_d = 12.2\, \text{mm}\]
Isotropic grains are approx. spherical, equiaxed & randomly oriented.

Anisotropic (directional) since rolling affects grain orientation and shape.

Cold Rolling Illustration

(before rolling)

(after rolling)
Annealing

- Process where material is heated to above the recrystallization temperature of the sample and then cooled down.
- Main purpose is to improve Cold work properties by increasing ductility and retaining most of the hardness.
- There are 3 steps involved with annealing: recovery, recrystallization and grain growth.
Recovery

• During recovery, some of the stored internal strain energy is relieved through dislocation motion due to enhanced atomic diffusion at the elevated temperatures.
• Leads to reduction in the number of dislocations.
Recrystallization

• After recovery is complete, the grains are still in a relatively high strain energy state.
• Recrystallization is the formation of a new set of strain-free and uniaxial grains that have low dislocation densities.
• The driving force to produce the new grain structure is the internal energy difference between strained and unstrained material.
• The new grains form as very small nuclei and grow until they consume the parent material.
Recrystallization Illustration

- Cold Worked grains. Not annealed.
- Initial recrystallization after 3 seconds @ 580°C
- Partial replacement of grains, after 4 seconds
- Complete recryst. after 8 seconds
Grain Growth

- After recrystallization, the strain-free grains will continue to grow if the metal specimen is left at elevated temperatures.
- As grains increase in size, the total boundary area decreases, as does the total energy.
- Large grains grow at the expense of smaller grains.
References