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.
 electron cloud
- Covalent Ceramics

 (Si, diamond): Motion hard.
 -directional (angular) bonding
- Ionic Ceramics (NaCI): Motion hard.
 -need to avoid ++ and -neighbors.



(+)

Dislocation motion

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



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.)

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



Stress and dislocation motion

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



Planes and direction relationships

Make a note, we will be using this later

Planes and directions that share the indices are perpendicular

[hkl] is perpendicular to (hkl)

Cosine
$$\theta = \frac{(h.u+kv+l.w)}{(h^2+k^2+l^2)^{1/2}.(u^2+v^2+w^2)^{1/2}}$$

Not true in non-cubic systems!!!



Slip in BCC crystals

In BCC things are a bit more complicated the {110}, {211} and {321} family of planes are potential slip planes - the directions of slip are the <111> directions.

- There are 6 (110) planes and 2 [111] direction per planes, thus
 12 slip systems. (most commonly observed). Others are:
 - There are 12 (211) planes and 1 [111] direction per plane, thus 12 slip systems
 - There are 24 (321) planes and 1 [111] direction per plane, thus 24 slip systems
- Slip is more complicated because not all systems are active in a given BCC metal at any given temperature.

Critical resolved shear stress



Disl. motion in polycrystals

- Slip planes & directions

 (λ, φ) change from one
 crystal to another.
- τ_R will vary from one crystal to another.
- The crystal with the largest τ_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].)

4 Strategies for strengthening:1: Reduce grain size

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



• Hall-Petch Equation:

$$\sigma_{\text{yield}} = \sigma_0 + k_y d^{-1/2}$$

Grain size strengthening: an example

70wt%Cu-30wt%Zn brass alloy

$$\sigma_{\text{yield}} = \sigma_0 + k_y d^{-1/2}$$

• Data:



Adapted from Fig. 7.13, *Callister 6e.* (Fig. 7.13 is adapted from H. Suzuki, "The Relation Between the Structure and Mechanical Properties of Metals", Vol. II, *National Physical Laboratory Symposium No.* 15, 1963, p. 524.)



Adapted from Fig. 4.11(c), *Callister 6e.* (Fig. 4.11(c) is courtesy of J.E. Burke, General Electric Co.

Anisotropy in σ_{vield}

- Can be induced by rolling a polycrystalline metal
 - -before rolling



-after rolling



Adapted from Fig. 7.11, Callister 6e. (Fig. 7.11 is from W.G. Moffatt, G.W. Pearsall, and J. Wulff, The Structure and Properties of Materials, Vol. I, Structure, p. 140, John Wiley and Sons, New York, 1964.)

rolling direction

-isotropic

since grains are approx. spherical & randomly oriented.

-anisotropic

since rolling affects grain orientation and shape.

Strengthening strategy 2: solid solutions

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



 Larger substitutional impurity



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

Impurity generates local shear at C and D that opposes disl motion to the right.

Ex: Solid solution strengthening in copper

• Tensile strength & yield strength increase w/wt% Ni.



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

Strengthening strategy 3: precipitation strengthening

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



Strengthening strategy 4: cold work (%CW)

- Room temperature deformation.
- Common forming operations change the cross sectional area:



Dislocations during cold work

• Ti alloy after cold working:



- Dislocations entangle with one another during cold work.
- Dislocation motion becomes more difficult.

Adapted from Fig. 4.6, *Callister 6e.* (Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)

Result of cold work

- Dislocation density (ρ_d) goes up: Carefully prepared sample: ρ_d ~ 10³ mm/mm³ Heavily deformed sample: ρ_d ~ 10¹⁰ mm/mm³
- Ways of measuring dislocation density:



Dislocation-dislocation trapping

- Dislocation generate stress.
- This traps other dislocations.

Red dislocation generates shear at pts A and B that opposes motion of green disl. from left to right.



Impact of cold work

- Yield strength (σ y) increases.
- Tensile strength (TS) increases.
- Ductility (%EL or %AR) decreases.



Adapted from Fig. 7.18, *Callister 6e.* (Fig. 7.18 is from *Metals Handbook: Properties and Selection: Iron and Steels*, Vol. 1, 9th ed., B. Bardes (Ed.), American Society for Metals, 1978, p. 221.)

σ - ϵ Behavior vs temperature



- σ_y and TS *decrease* with increasing test temperature.
- %EL increases with increasing test temperature.
- Why? Vacancies help dislocations past obstacles.



Effect of heating after %CW

- 1 hour treatment at T_{anneal}... decreases TS and increases %EL.
- Effects of cold work are reversed with annealing!



 3 Annealing stages to discuss...

Adapted from Fig. 7.20, *Callister 6e.* (Fig. 7.20 is adapted from G. Sachs and K.R. van Horn, *Practical Metallurgy, Applied Metallurgy, and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys,* American Society for Metals, 1940, p. 139.)

First stage: Recovery

Dislocations annihilation reduces dislocation density.



2. grey atoms leave by vacancy diffusion allowing disl. to "climb"
 1. dislocation blocked; can't move to the right



 $\tau_{\mathbf{R}}$

Second stage: Recrystallization

0.6 mm

- New crystals are formed that:
 - --have a small disl. density
 - --are small
 - --have low strain energy
 - --consume cold-worked crystals.



Adapted from Fig. 7.19 (a),(b), *Callister 6e.* (Fig. 7.19 (a),(b) are courtesy of J.E. Burke, General Electric Company.)

Further recrystallization

• All cold-worked crystals are consumed.



Adapted from Fig. 7.19 (c),(d), *Callister 6e.* (Fig. 7.19 (c),(d) are courtesy of J.E. Burke, General Electric Company.)

Why (Driving force)?=Strain energy stored in deformed xtals is reduced

Recryst. temp. = Temp. at which recryst. is complete in one hour!

Third stage: Grain growth

- At longer times, larger grains consume smaller ones.
- Why (driving force)? Grain boundary area (and therefore surface energy) is reduced.



Recryst = f(%CW, T, t)

Driving force = difference in strain energy between deformed crystals and recrystallized crystals

(1) Recrystalization rate increases with cold work!!!

Relies on atomic diffusion of atoms, thermally activated process

(2) Recrystalization rate **increases** with temperature

The greater the %CW the less thermal energy required to recrystalize in 1 hour



 (3) Recrystalization temperature (temperature at which the recrystalization is complete in 1 hour) decreases with cold work

Chapter 7-

Summary

- Dislocations are observed primarily in metals and alloys.
- Here, strength is increased by making dislocation motion difficult.
- Particular ways to increase strength are to:
 - -- decrease grain size
 - -- solid solution strengthening
 - -- precipitate strengthening
 - -- cold work
- Heating (annealing) can reduce dislocation density, cause the appearance of new, distortion free, crystals and increase grain size.
- Recovery, recrystallization and grain growth are thermally activated processes

Cold work analysis



Adapted from Fig. 7.17, *Callister 6e.* (Fig. 7.17 is adapted from *Metals Handbook: Properties and Selection: Iron and Steels*, Vol. 1, 9th ed., B. Bardes (Ed.), American Society for Metals, 1978, p. 226; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th ed., H. Baker (Managing Ed.), American Society for Metals, 1979, p. 276 and 327.)

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