

Module #18

Strengthening Mechanisms (an introduction)

References

See next viewgraph



Strengthening Mechanisms

Bibliography for Modules 18-22

- ✦ 1. Chapter 5, T.F. Courtney, Mechanical Behavior of Materials, 2nd edition, Waveland Press, Long Grove, IL (2005).
- ★ 2. Chapter 8, W.O. Soboyejo, Mechanical Properties of Engineered Materials, Marcel-Dekker, New York, NY (2002).
- ▲ 3. Chapter 6, G.E. Dieter, Mechanical Metallurgy, McGraw-Hill, Boston, MA (1986).
- ★ 4. Chapters 6 and 10, M.A. Meyers and K.K. Chawla, Mechanical Behavior of Materials, Prentice Hall, Upper Saddle River, NJ (1999).
- 5. A.S. Argon, Strengthening Mechanisms in Crystal Plasticity, Oxford University Press, Oxford (2008).

★ = Provides clear and concise descriptions.

✦ = My favorite basic treatment of the topic. Detailed, yet practical.

▲ = Slightly dated, but a classic. Good fundamental information.

● = New. “Very nice!” Better for graduate students.

What makes crystals strong?

Strengthening in crystals results from the restriction of dislocation motion.

We can restrict dislocation motion by altering, promoting, or adding:

- *Bond type*
 - Choice of basic material

- Dislocation- dislocation interactions
 - Work hardening

- *Grain boundaries*
 - Hall-Petch relationship

- *Solute atoms*
 - Solid solution hardening

- Precipitates or dispersed particles
 - Precipitation hardening or dispersion hardening

- *Phase changes*
 - Transformation hardening or toughening.

How does bonding influence strength?

WEAKER

Strength/Hardness

STRONGER



Directionality of bonds

Close-packed metals	Other metals	Ionic solids	Intermetallics	Covalent solids
<p>Bonds are essentially non-directional.</p>	<p>Bonds are somewhat directional.</p>	<p>Bonds are non-directional but slip is directional due to electrostatic attraction between unlike ions.</p>	<p>Bonds are directional</p>	<p>Bonds very directional.</p>
<p>Dislocation motion is easy</p>	<p>Dislocation motion is relatively easy, but strongly dependent on temperature.</p>	<p>Dislocation motion is difficult</p>	<p>Dislocation motion is difficult</p>	<p>Dislocation motion is difficult</p>
<p><u>Examples:</u> <ul style="list-style-type: none"> •FCC metals •Al, Ni, Ag, etc... </p>	<p><u>Examples:</u> <ul style="list-style-type: none"> •BCC metals •Mo, Nb, W, Fe, etc... </p>	<p><u>Examples:</u> <ul style="list-style-type: none"> •NaCl, CsCl, etc... </p>	<p><u>Examples:</u> <ul style="list-style-type: none"> •NiAl, TiAl, Ni₃Al, etc... </p>	<p><u>Examples:</u> <ul style="list-style-type: none"> •Diamond, Al₂O₃, SiC, Si₃N₄, etc... </p>

What can we do to increase strength?

- GENERAL

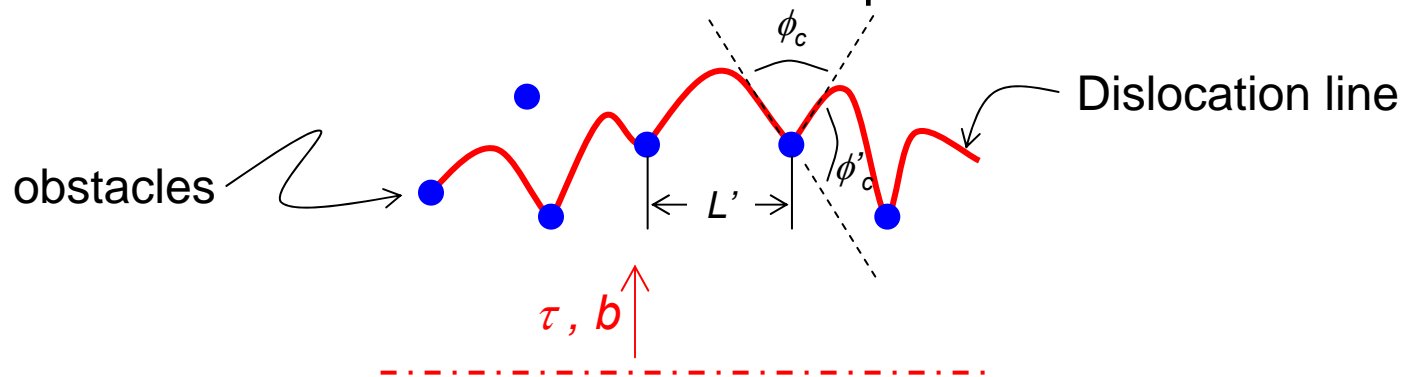
- As I noted before, one simple method is to place obstacles in the path of dislocations that will either slow them down or stop them completely until the stress is high enough to move them further. *This works for crystals!*
- *In non-crystalline materials we must do different things.*

- SPECIFIC

- Dislocations distort the crystal lattice.
- Various obstacles also distort the crystal lattice.
- Stress fields from both will interact with each other, which reduces v (the dislocation velocity).
- This in effect increases the stress required to cause the material to “flow” (i.e., it increases the flow stress) and thus the “strength” of the material.

General model for strengthening (1)

- REFERENCE:
 - L.M. Brown and R.K. Ham, in *Strengthening Mechanisms in Crystals*, edited by A. Kelly and R.B. Nicholson, Wiley, New York, 1971, pp. 9-70.
- Consider a slip plane that contains a random array of obstacles. We don't care what the obstacles are at this point.



L' = Effective particle spacing

ϕ_c = Critical angle to which the \perp bends prior to breaking away from the obstacle.

$\phi'_c = \pi - \phi_c$

- Extra “work” is required to move the dislocation through the array of obstacles. This results in a higher stress to cause “flow”.



$$\tau \cong \frac{Gb}{L'} \cos\left(\frac{\phi_c}{2}\right)$$

$$\tau_{\max} = \frac{Gb}{L}$$

Obstacles to dislocation motion

- ★ • Solute atoms
 - Substitutional
 - Interstitial
- ★ • Other dislocations
- ★ • Grain boundaries
- Twin boundaries
- ★ • Precipitates
- ☆ • Dispersed particles
- Etc.

★ = what we will focus on

☆ = what we say something about

Hardening/strengthening laws

Hardening mechanism	Nature of obstacle	Strong (S) or Weak (W)	Hardening law
Work hardening	Other dislocations	S	$\Delta\tau = \alpha G b \rho^{1/2}$; see ¹
Grain size	Grain boundaries	S	$\Delta\tau = k_y' d^{-1/2}$; see ²
Solid solution	Solute atoms	W (see ³)	$\Delta\tau = G \epsilon_s^{3/2} c^{1/2} / 700$ (see ⁴)
Deforming particles	Small, coherent particles	W (see ⁵)	$\Delta\tau = C G \epsilon^{3/2} (f r / b)^{1/2}$ (see ⁶)
Nondeforming particles	Large particles, incoherent particles	S (see ⁷)	$\Delta\tau = G b / (L - 2r)$

Notes:

¹ α equals about 0.2 for fcc metals, about 0.4 for bcc metals.

² k_y' scales with inherent flow stress and/or shear modulus; therefore k_y' is generally greater for bcc metals than for fcc metals.

³Exception to weak hardening occurs for interstitials in bcc metals; the shear distortion interacts with screw dislocations leading to strong hardening.

⁴Equation apropos to substitutional atoms; parameter ϵ_s is empirical, reflecting a combination of size and modulus hardening.

⁵Coherent particles can be “strong” in optimally aged materials.

⁶Constant C depends on specific mechanism of hardening; parameter ϵ relates to hardening mechanism(s). Equation shown applies to early stage precipitation. Late stage precipitation results in saturation hardening.

⁷Highly overaged alloys can represent “weak” hardening.

Symbols: G = shear modulus; b = Burgers vector; ρ = dislocation density; d = grain size; c = solute atom concentration (atomic fraction); f = precipitate volume fraction; r = precipitate radius; L = spacing between precipitates on slip plane.

Table 5.2

Summary of Hardening Mechanisms in Crystalline Materials

Table from Courtney, *Mechanical Behavior of Materials*, 2nd edition, Waveland Press, Boston, 2000, Long Grove, IL, p. 232.

General form of hardening laws

$$\Delta\tau \text{ (or } \Delta\sigma) = \underbrace{\text{Fcn}(G, \rho, d^n, \text{ etc...})}_{\text{Depends upon the structure of the material}}$$

$$\underbrace{\Delta\tau = \tau - \tau_0}_{\substack{\text{Intrinsic resistance of} \\ \text{lattice to dislocation} \\ \text{motion}}}$$

The next four modules will address strengthening mechanisms relative to the general hardening law