Module #16

Obstacle-based Strengthening

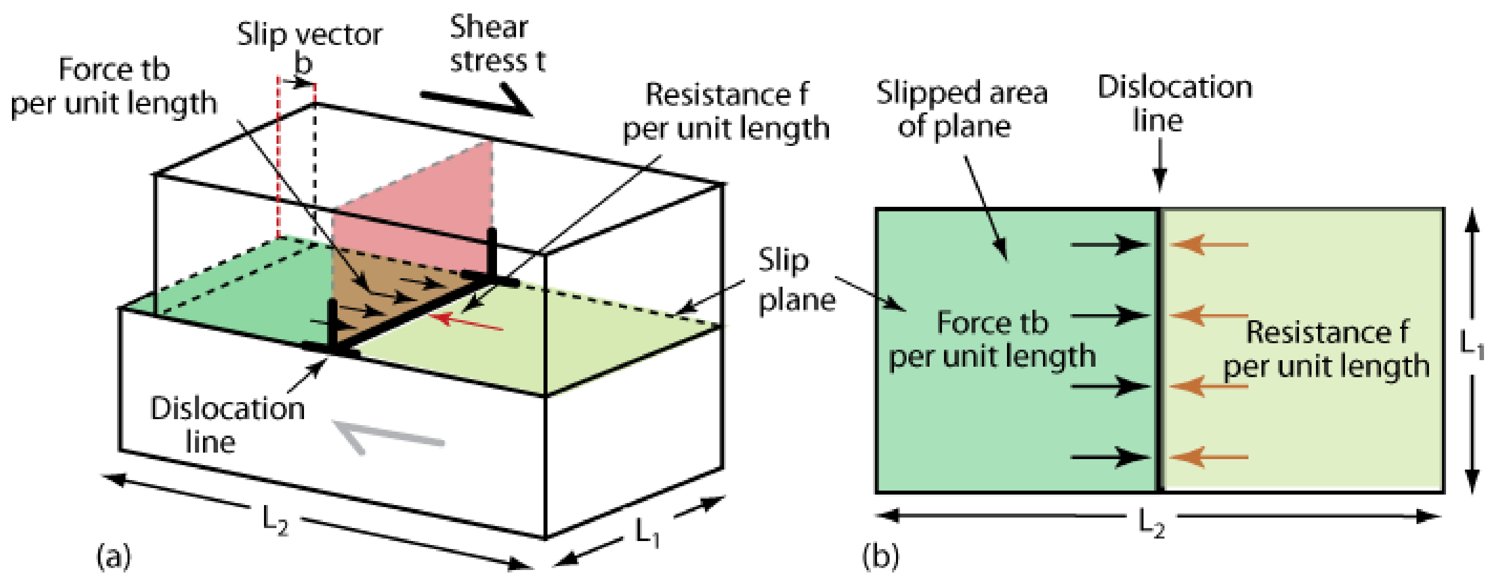
Introduction to Strengthening Mechanisms for Crystalline Materials

READING LIST

COURTNEY: Ch. 5, pages 175-179

RECALL from Module #13
Forces on and between Dislocations

- Crystals resist dislocation motion with a friction-like resistance, f, per unit length (fL_1).



- Applied stress must overcome lattice resistance for ⊥ to move.

Forces on dislocations

- Dislocations shear crystals.
- Shear force: $F_s = \tau L_1 L_2 b$
- Work done by F_s to shear block by b is:

$$W = \tau L_1 L_2 b$$

- Work done against resistance f per unit length L_1 over displacement L_2 is:

$$W = f L_1 L_2$$

$$\therefore$$

$$\tau b = f \longrightarrow$$

Line tension on dislocation

- Atoms near the dislocation core are displaced from their equilibrium positions.

- They have higher potential energy.

- To keep potential energy as low as possible, the dislocation tries to reduce its length.

- Thus it behaves as if it had line tension Γ.

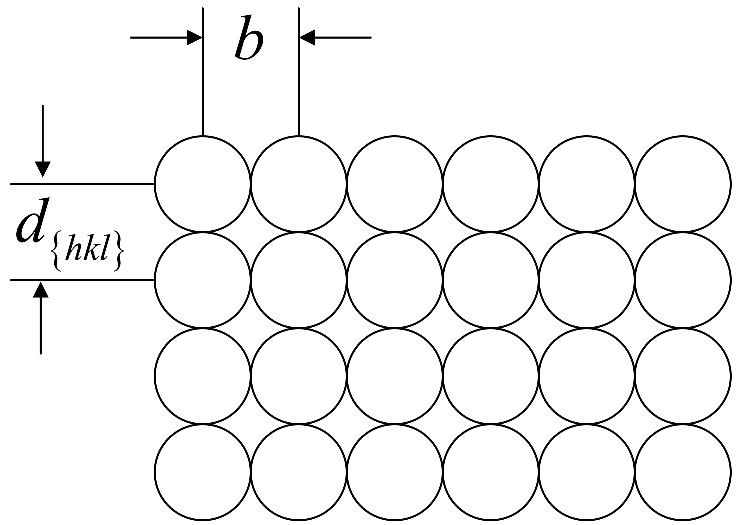
$$\Gamma = \alpha G b^2 \approx G b^2$$

- Has bearing on how $\perp$'s interact with obstacles.

HOW DO WE MAKE

CRYSTALS “STRONG”

Recall: "perfect" crystal



No defects

$$\sigma_{\max} = \sigma_{TCS} = \sqrt{\frac{E\gamma}{d_{\{hkl\}}}} \approx \frac{E}{\pi}$$

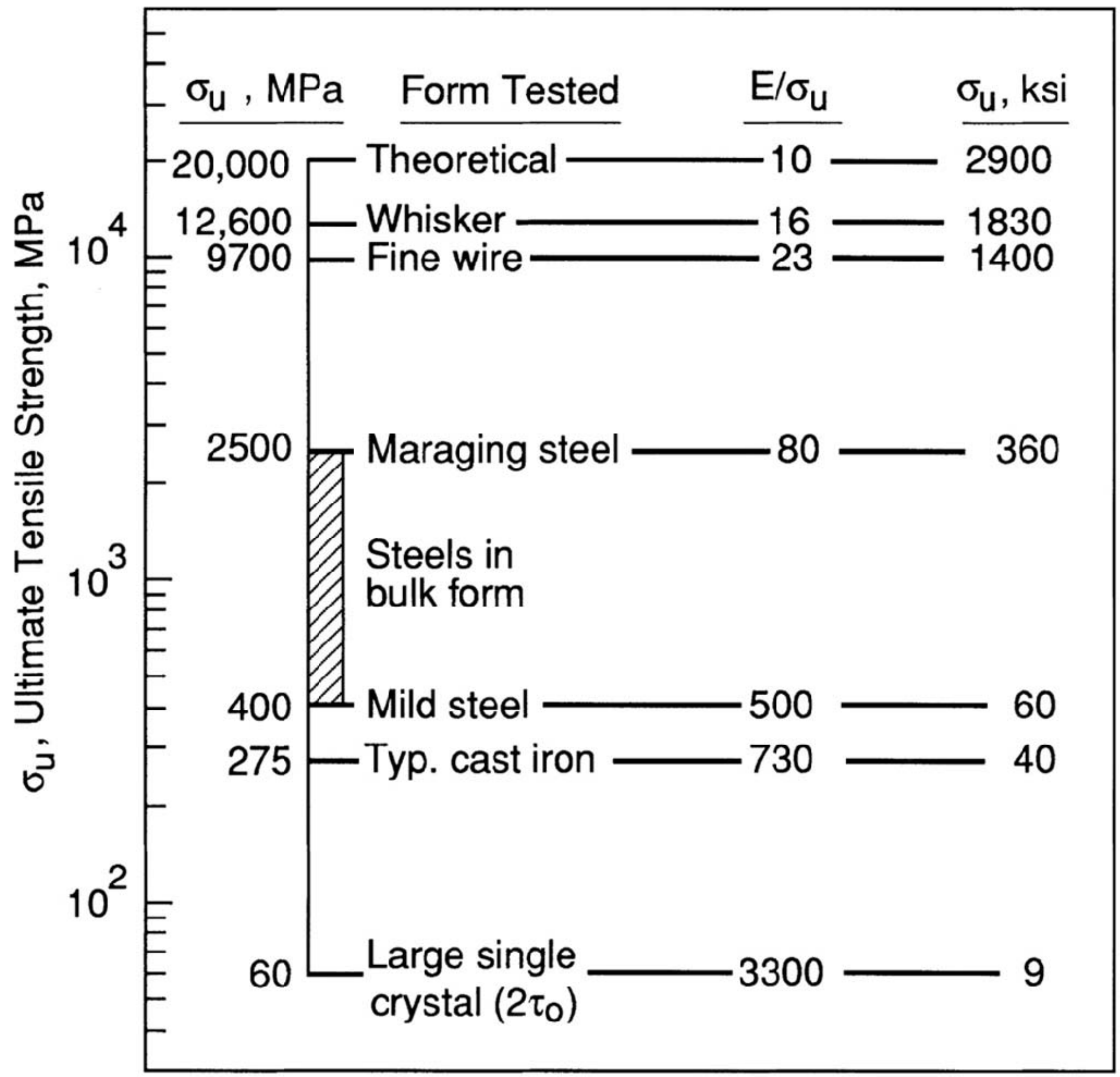
$$\tau_{\max} = \frac{Gb}{2\pi d_{\{hkl\}}} \approx \frac{G}{2\pi}$$

How to achieve highest strength - 1

1. Eliminate all defects

- This has been achieved in whiskers. Whiskers are flaw free materials with cross-sections on the order of a few microns. They are some of the strongest materials produced by man. Some representative examples are provided in Appendix 1 of Strong Solids.

  - Fe whiskers: $\sigma_{exp} \approx 12.6$ GPa
  - Patented steel wire: $\sigma_{exp} \approx 3\text{-}4$ GPa
  - Strongest bulk steel: $\sigma_{exp} \approx 2$ GPa (Maraging steel)
  - Most steels have strengths in the MPa regime.



Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue, Third Edition,
by Norman E. Dowling. ISBN 0-13-186312-6.

How to achieve highest strength - 2

2. Create so many defects that they interfere with each other.

- Principle behind primary strengthening mechanisms:
  - Work hardening,
  - Precipitation hardening,
  - Solid solution hardening,
  - Transformation hardening,
  - etc…

} Obstacles to ⊥ motion

General Rule

Strengthening in crystals results from the restriction of dislocation motion.

We can restrict dislocation motion by altering/promoting/adding:

- *Bond type*
  - Selection of 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**
Bonds are essentially non-directional.	Bonds are somewhat directional.	Bonds are non-directional but slip is directional due to electrostatic attraction between unlike ions.	Bonds are directional	Bonds very directional.
Dislocation motion is easy	Dislocation motion is relatively easy, but strongly dependent on temperature.	Dislocation motion is difficult	Dislocation motion is difficult	Dislocation motion is difficult
<u>Examples</u>: •FCC metals •Al, Ni, Ag, etc…	<u>Examples</u>: •BCC metals •Mo, Nb, W, Fe, etc…	<u>Examples</u>: •NaCl, CsCl, etc…	<u>Examples</u>: •NiAl, TiAl, Ni_3Al, etc…	<u>Examples</u>: •Diamond, Al_2O_3, SiC, Si_3N_4, etc…

What can we do to increase strength?

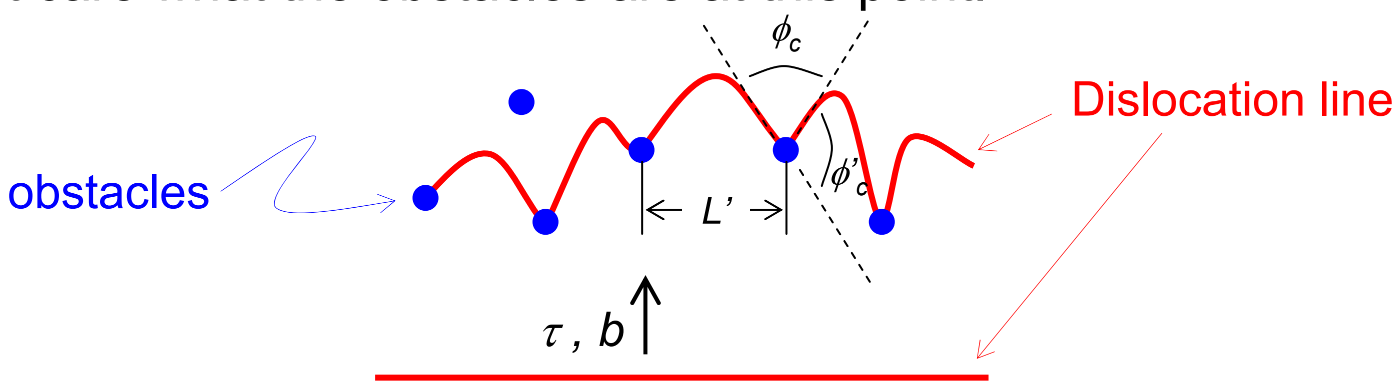
- GENERAL
  - As I noted before, one simple method *for crystals* is to place obstacles in the path of dislocations that will either slow them down or stop them completely until the stress is high enough to move them further.
  - *In non-crystalline materials we must do different things.*

- 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.

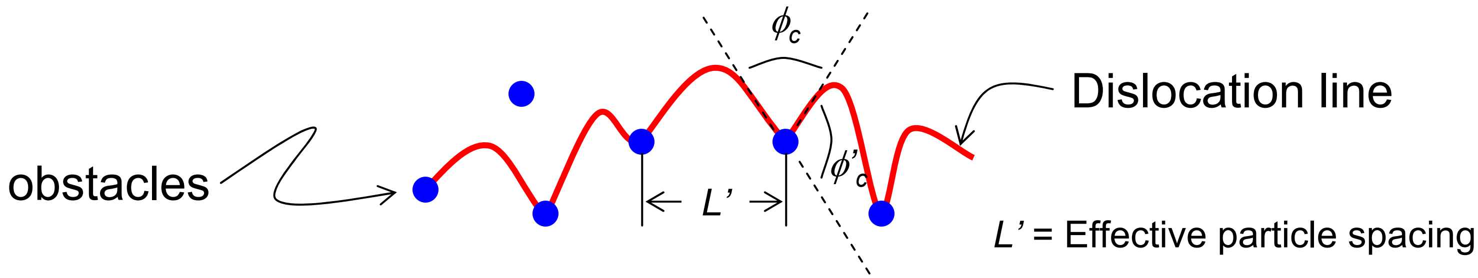
- Consider a slip plane that contains a random array of obstacles. We don't care what the obstacles are at this point.



L' = Effective particle spacing
ϕ_c = Critical angle to which the ⊥ 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".

General model for strengthening (2)



- Let τ equal the flow stress required to move the dislocation through the array of obstacles.

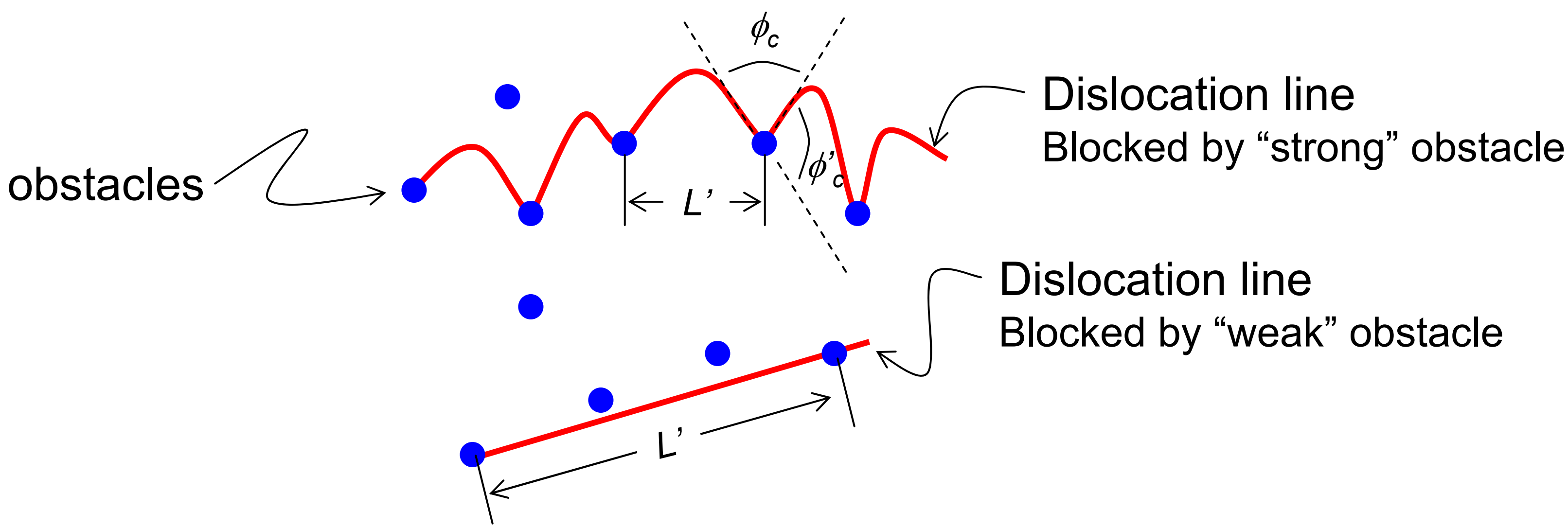
- This allows us to define stress in terms of the strength of the obstacle that is inhibiting dislocation motion.

- “Strong” obstacles resist ⊥ motion

- “Weak” obstacles provide little resistance to ⊥ motion.

General model for strengthening (3)

- "Strong" obstacles:
  - $\phi_c \rightarrow 0°$ and $L' = \underline{\lambda}$ = mean obstacle spacing
- "Weak" obstacles:
  - $\phi_c \rightarrow 180°$ and $L' >> \underline{\lambda}$



WHAT IS τ?

- As we increase τ, *line tension* increases leading to *increased bowing* and a decreased bowing angle (ϕ).

- When τ reaches a high enough level, $\phi \rightarrow \phi_c$ and ⊥'s can "break free" from obstacles.

- This "breakaway" occurs in a number of ways (e.g., climb, cross slip, etc.).

$$\boxed{\tau = \frac{Gb}{L'}\cos\left(\frac{\phi_c}{2}\right)}, L' \geq L$$

- Maximum strengthening will occur when:

$$\phi_c = 0 \text{ and } L' = L \rightarrow \tau_{\max} = \frac{Gb}{L}$$

- **Maximum strengthening** will occur when:

$$\phi_c = 0 \text{ and } L' = L \rightarrow \tau_{\max} = \frac{Gb}{L}$$

- When **obstacles** are **“strong”**:

$$\phi_c > 0 \qquad \tau = \frac{Gb}{L}\cos\left(\frac{\phi}{2}\right)$$

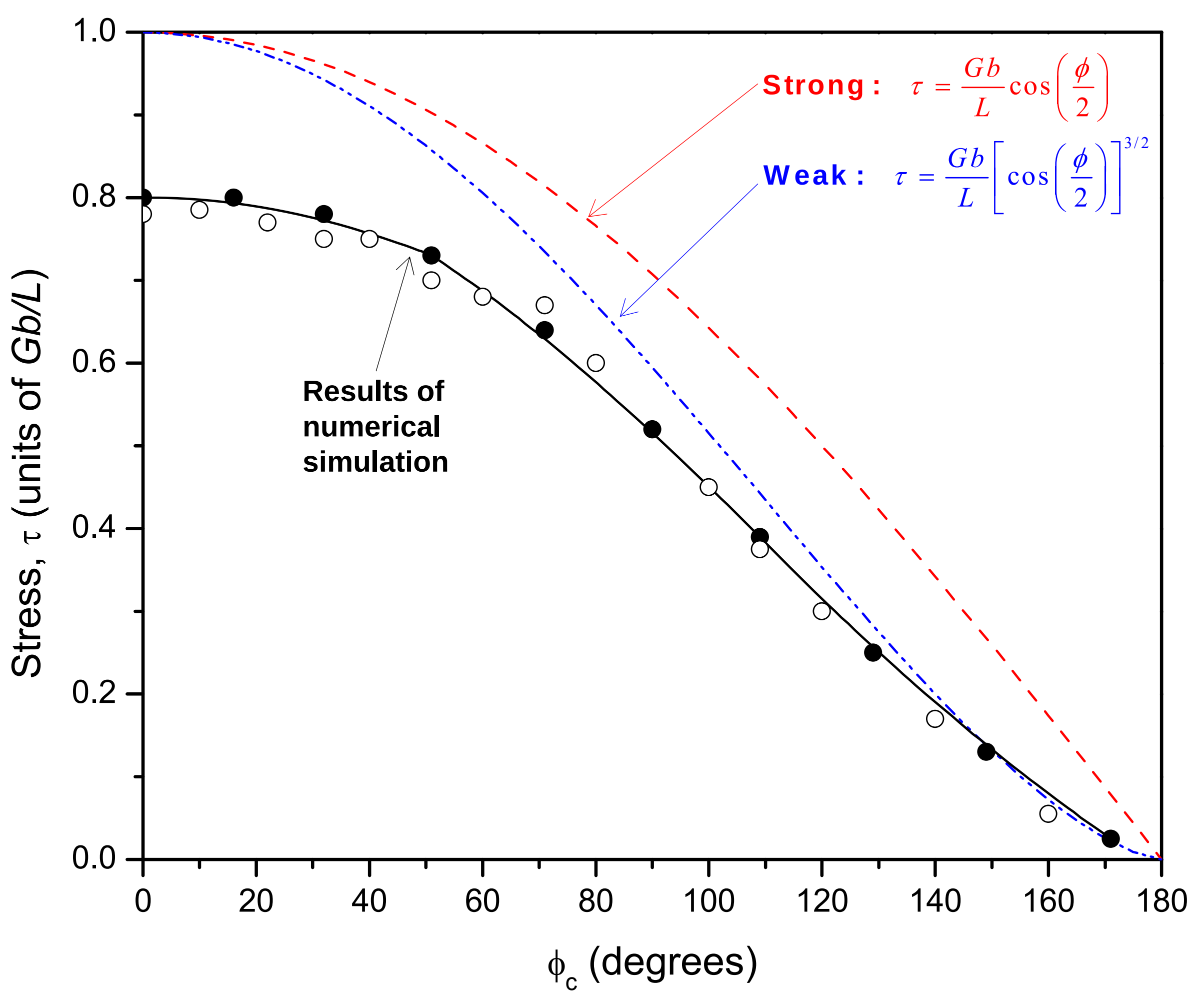
- When **obstacles** are **“weak”**:

$$\phi_c \rightarrow 180° \text{ and } L' = \frac{L}{\sqrt{\cos(\phi/2)}}, \qquad \tau = \frac{Gb}{L}\left[\cos\left(\frac{\phi}{2}\right)\right]^{3/2}$$

This is known as the Friedel relation

The shear stress, in units of *Gb*/*L*, that is required to overcome obstacles on the slip plane. The upper curve corresponds to the equation for "strong" obstacles. The intermediate curve corresponds to "weak" obstacles. The lower curve corresponds to the results of computational simulations.

Adapted from L.M. Brown and R.K. Ham, in Strengthening Mechanisms in Crystals, edited by A. Kelly and R. Nicholson, Wiley, New York (1971) pp. 10-135.



For the equations to work, you must know ϕ_c, which is difficult to determine. It is usually assumed that $\phi_c = 0°$ for strong and $\phi_c = 180°$ for weak. Then for strong obstacles the added strength is always on the order of Gb/L. For weak obstacles everything depends critically on ϕ_c.

Obstacles to dislocation motion

- Examples of weak obstacles:
  - Solid-solution elements,
  - voids,
  - deformable particles
  - Etc.
- Examples of strong obstacles:
  - Other dislocations,
  - grain boundaries,
  - phase boundaries,
  - non-deforming particles,
  - Etc.

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

General form of hardening laws

$$\Delta\tau \ (\text{or } \Delta\sigma) = \text{Fcn}(G, \rho, d^n, \text{etc...})$$

Depends upon the structure of the material

$$\Delta\tau = \tau - \tau_o$$

Intrinsic resistance of lattice to dislocation motion

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

Summary of hardening/strengthening mechanisms for crystalline solids

Hardening Mechanism	Nature of Obstacle	Strong or Weak	Hardening Law
Work hardening	Other dislocations	Strong	$\Delta\tau = \alpha G b \sqrt{\rho}$ (see [1])
Grain size / Hall-Petch	Grain boundaries	Strong	$\Delta\tau = k'_y / \sqrt{d}$ (see [2])
Solid solution	Solute atoms	Weak (see [3])	$\Delta\tau = G\varepsilon_s^{3/2} c^{1/2} / 700$ (see [4])
Deforming particles	Small, coherent particles	Weak (see [5])	$\Delta\tau = CG\varepsilon^{3/2}\sqrt{\frac{fr}{b}}$ (see [6])
Non-deforming particles	Large, incoherent particles	Strong (see [7])	$\Delta\tau = \frac{Gb}{(L-2r)}$

[1] α equals about 0.2 for FCC metals and 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.

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

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

[5] Coherent particles can be "strong" in optimally aged materials.

[6] Constant 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.

[7] Highly overaged alloys can represent "weak" hardening.

SYMBOLS : $G =$ shear modulus; $b =$ Burgers vector; $\rho =$ dislocation density ; $d =$ grain size; $c =$ solute atom concentration (at.%); $f =$ precipitate volume fraction; $r =$ precipitate radius; $L =$ spacing between precipitates on slip plane.

Table adapted from Courtney, *Mechanical Behavior of Materials*, 2nd edition, p. 232.