# Chapters 5, 6, 7, 9 – Dislocations & Strengthening Mechanisms Outline

**Strengthening mechanisms in metals:**

Grain size reduction
Dislocation density increase (strain hardening, cold work, etc.)
Solid solution additions (interstitial & substitutional)
Precipitation of second phases
Dispersion of secondary particles
Presence of some martensites

**Strengthening mechanisms in other materials systems:**

Ceramics: devitrification, transformation toughening, tempering
Polymers: increase crystallinity, crosslinking, molecular weight, fillers
Composites: reinforcement strengthening

**Deformation modes in crystalline materials:**

Dislocation motion (slip)
Twinning

**Dislocations:**

Dislocations, general:
- edge, screw
- Burgers vector
- energy $\propto Gb^2$
- stress fields $\propto Gb/r$

Mechanisms of motion:
- slip

Dislocation density:
- total length per unit volume
- varies from $10^3$ to $10^{10}$ $mm^{-2}$
- increases dramatically during plastic deformation

Slip systems:
- slip occurs on planes of highest planar density in directions of highest linear density
- slip system: a direction & a plane

**Single crystal dislocation motion:**

Applied stresses are resolved into shear acting on dislocations

$$\tau = F_s / A_s = F \cos \lambda / A / \cos \phi$$

Schmid's law:

$$\tau = \sigma \cos \phi \cos \lambda$$

Resolved shear reaches a critical value resulting in dislocation motion: critical resolved shear stress

Recall dot product & cross product rules for Miller Indices:

$$\cos \theta = \{ h_1h_2 + k_1k_2 + l_1l_2 \} / \{[ h_1^2 + k_1^2 + l_1^2 ] [ h_2^2 + k_2^2 + l_2^2 ]\}^{1/2}$$

$[u_1v_1w_1] \text{ X } [u_2v_2w_2]$ = ………..

**Strengthening mechanisms in metals (partial):**

Grain size reduction:

- dislocation pile-up at grain boundaries
- stress acting on head dislocation $\propto$ number of dislocations: generating dislocation motion in neighboring grain
- Hall-Petch relation observed between grain size d & yield strength $\sigma_y$:

$$\sigma_y = \sigma_o + k_y d^{-1/2}$$

slope: $k_y$
intercept: $\sigma_o$

Solid solution strengthening:

- solute atoms differ from solvent atoms in size, electrical nature, modulus, & chemical nature
- solute interactions with dislocations increase strength with increasing solute content
- solid solution strengthening is concerned with solute atoms that are in *solution*; solute atoms beyond solubility limit segregate as solute-rich phases, e.g., precipitates

Strain hardening (dislocation density increase, cold work):

- increasing amount of dislocations (e.g., via cold work) increases strength
- mechanism: dislocation-dislocation strain field interactions
- recall that the true stress/strain curve above the yield strength (to the point of maximum load) is described by:

$$\sigma = K\varepsilon^n$$

n = strain hardening exponent (coefficient) or work hardening index

$0 \le n \le 1$

initially soft metals tend to work harden more (higher n);
initially hard metals tend to work harden less (lower n)

**Recovery, recrystallization, & grain growth:**

When a crystalline material is heated three phenomena may occur, depending on the temperature & time at temperature & whether sufficient prior cold work has been performed:

- recovery
- recrystallization
- grain growth

Hardness, strength, and ductility change, dependent on annealing temperature & time

Recovery:

- occurs at lower annealing temperatures
- reduction in stored strain energy from reorganization & elimination of dislocations

Recrystallization:

- occurs at intermediate annealing temperatures
- large decrease in hardness & strength & increase in ductility
- associated with formation of new annealed grains (of low dislocation density) from previously deformed grains
- recrystallization temperature is a function of prior cold work amount

Grain growth:

- occurs at high annealing temperatures
- strength normally decreases somewhat (Hall-Petch effect)
- can result in poorer ductility
- associated with the growth of grains to minimize grain boundary interfaces
- normally not a desirable state