Lecture#14
- Strengthening Mechanisms
- Work Hardening
- RECOVERY, Recrystallization, Grain growth
- Strengthening by grain size reduction

References:
2- Hosford W.F, (2005), Mechanical Behavior of Materials, Cambridge
4- Dieter G.E., (1986), Mechanical Metallurgy, McGraw-Hill

Strengthening Mechanisms
What can we do to increase strength?
• The best way to increase strength in crystals is to do things that decrease the mobility of dislocations.

• GENERAL
  – One simple way 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.

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

Strengthening results from the things that we do to restrict dislocation motion.

□ Effects of bond type on ease of dislocation motion
- Choice of basic material
□ Dislocation- dislocation interactions → immobilized dislocations that block mobile dislocations
- Work hardening
- **Grain boundaries** act as barriers to dislocation motion - Grain-size strengthening and toughening
- Internal stress fields from *dissolved atoms* interact with dislocation stress fields - Solution hardening
- Internal stress fields from *precipitates* interact with dislocation stress fields - Precipitation hardening
- Precipitates or dispersed particles interact with dislocation stress fields - Precipitation hardening or dispersion hardening
- *Phase changes* to produce different microstructures – Transformation hardening or toughening.

<table>
<thead>
<tr>
<th>How does bonding influence strength?</th>
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<tbody>
<tr>
<td><em>Weak</em></td>
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<td>Bonds are essentially nondirectional.</td>
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<tr>
<td>Dislocation motion is easy</td>
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<td>Close-packed metals</td>
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<tr>
<td>Cho, Ni, Ag, etc..</td>
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<tr>
<td>·BCC metals</td>
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<tr>
<td>·W, Fe</td>
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<tr>
<td>·Mo, Nb, etc..</td>
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<tr>
<td>Bonds very directional.</td>
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<tr>
<td>Intermetallics</td>
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<tr>
<td>NiAl, TiAl, Ni3Al, etc..</td>
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**Work Hardening**

Strain hardening is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed. Sometimes it is also called **work hardening**, or, because the temperature at which deformation takes place is “cold” relative to the absolute melting temperature of the metal, **cold working**. Most metals strain harden at room temperature. It is sometimes convenient to express the degree of
plastic deformation as percent cold work rather than as strain. Percent cold work (%CW) is defined as:

\[
\%CW = \left( \frac{A_0 - A_d}{A_0} \right) \times 100
\]

where \(A_0\) is the original area of the cross section that experiences deformation, and \(A_d\) is the area after deformation.

Strain hardening or cold working is an important industrial process that is used to harden metals or alloys that do not respond to heat treatment. The rate of strain hardening can be determined from the slope of the flow curve. This rate is lower for hcp metals than for cubic metals. Increasing temperature lowers the rate of strain hardening.

The strain hardening exponent (n) is a measure of the ability of a metal to strain harden; the larger its magnitude, the greater the strain hardening for a given amount of plastic strain.

The effects of strain hardening may be removed by an annealing heat treatment.

- Cold working produces elongation of the grains in the principal direction of working.
- In addition to the change in tensile properties, cold working produces:
  - small decrease in density
  - small decrease in electrical conductivity
  - small increase in the thermal coefficient of expansion
- because of the increased internal energy of the cold-worked state, chemical reactivity is increased. This leads to a decrease in corrosion resistance and may introduce the possibility of stress corrosion cracking.

During plastic deformation, there is an increase in dislocation density, which leads to work hardening as:-

- Dislocations interact with each other and assume configurations that restrict the movement of other dislocations.
- The situation gets worse as the dislocation density increases leading to an increase in the flow stress.
- The dislocations can be either “hard” or “soft” obstacles depending upon the types of interactions that occur between moving dislocations.
- The number of dislocations in a crystal increases with strain over the number present in the annealed crystal. Dislocation multiplication can arise from existing dislocations (by Frank-Read mechanism or a multiple cross-slip mechanism) or by emission (انبعاث) of dislocations from a high-angle grain boundary.

In a single crystal:

- The $\tau$ vs. $\gamma$ curve for a single crystal oriented for slip on one slip system can be sub-divided into three stages:

  - **Stage I:**
    - After yielding, shear stress for plastic deformation is almost constant. There is little or no work hardening. Very little dislocation interactions, “easy glide” in a single slip system toward the surface

- Dislocations have compressive stress fields above the slip plane and tensile stress fields below the slip plane. These stress fields interact during the early stages of deformation resulting in “weak” drag effects, as a friction force that inhibits glide. This frictional effect will increase as dislocation density increases. In stage I dislocations are “soft”

- **Stage II:**
  - $\tau$ needed to continue plastic deformation begins to increase. This increase is approximately linear “Linear hardening”. This stage begins when slip on multiple systems begins. Work hardening increases due to interactions
between dislocations moving on intersecting planes. This results in the production of jogs.

**Stage III:**
There is a decreasing rate of work hardening due to an increase in the degree of cross slip. Have a parabolic shape to the curve. The stress at which this stage starts depends on temperature.

**Stage II:**
- Dislocation tangles (immobile dislocation segments) form strong obstacles to dislocation motion.
- Interactions produce immobile dislocation configurations (Jogs).
- Work hardening depends strongly on dislocation density:
  \[ \rho_\perp \propto \frac{\text{line length}}{\text{unit volume}} = \frac{L}{L^3} \]
- The average separation distance between dislocations is:
  \[ L = \frac{\alpha}{\sqrt{\rho}} \]

But \( \tau_{\text{max}} = \frac{Gb}{L} \) the shear flow stress will be:
\[ \tau = \tau_0 + \alpha Gb \sqrt{\rho} \]

where:
\( \tau_0 \) – shear stress required to move a dislocation in the absence of other dislocations
\( \alpha \) - constant (0.2 for FCC, 0.4 for BCC)
\( b \) – the displacement of crystal planes above and below the slip plane relative to each other.
- The strengthening increment derived from work hardening can be approximated as:
  \[ \Delta \tau = \alpha Gb \sqrt{\rho} \quad \text{or} \quad \Delta \sigma = m \alpha Gb \sqrt{\rho} \quad (m\text{- Schmid factor}). \]

**RECOVERY, Recrystallization, Grain growth:**
Plastically deforming a polycrystalline metal at low temperatures produces microstructural and property changes that include:
1- a change in grain shape 2- strain hardening and 3- an increase in dislocation density, and 4- stored energy.
Some fraction of the energy expended in deformation is stored in the
metal as strain energy, which is associated with tensile, compressive, and shear zones around the newly created dislocation. Furthermore, other properties such as electrical conductivity and corrosion resistance may be modified as a consequence of plastic deformation. These properties and structures may revert back to the precold-worked states by appropriate heat treatment (sometimes termed an annealing treatment). Such restoration results from two different processes that occur at elevated temperatures: recovery and recrystallization, which may be followed by grain growth.

**During recovery**, some of the stored internal strain energy is relieved by virtue of dislocation motion (in the absence of an externally applied stress), as a result of enhanced atomic diffusion at the elevated temperature. There is some reduction in the number of dislocations, and dislocation configurations are produced having low strain energies. In addition, physical properties are recovered to their precold-worked states. So after recovery
- Ductility increases
- Hardness decreases slightly
- Toughness increases
- Change in thermal and electrical conductivity ignored
- No apparent change in the microstructure of the deformed metal
- Even 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 equiaxed grains (i.e., having approximately equal dimensions in all directions) that have low dislocation densities and are characteristic of the precold-worked condition. The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material. The new grains form as very small nuclei and grow until they completely replace the parent material. Also, during recrystallization, the mechanical properties that were changed as a result of cold working are restored to their precold-worked values; that is, the metal becomes softer, weaker, yet more ductile. Recrystallization is a process the extent of which depends on both time and temperature.

There exists some critical degree of cold work below which recrystallization cannot be made to occur, this is between 2 and 20% cold work. Recrystallization proceeds more rapidly in pure metals than in alloys. Thus, alloying raises the recrystallization temperature, sometimes quite substantially. For pure metals, the recrystallization temperature is normally $0.3T_m$, where $T_m$ is the absolute melting temperature; for some commercial
alloys it may run as high as $0.7T_m$. The amount of cold working also affect the recrystallization temperature.

Plastic deformation operations are often carried out at temperatures above the recrystallization temperature in a process termed hot working. The material remains relatively soft and ductile during deformation because it does not strain harden, and thus large deformations are possible.

**Strengthening by grain-size reduction:**

The size of the grains, or average grain diameter, in a polycrystalline metal influences the mechanical properties. Adjacent grains normally have different crystallographic orientations and, of course, a common grain boundary. During plastic deformation, slip or
dislocation motion must take place across this common boundary. The grain boundary acts as a barrier to dislocation motion for two reasons:

1. Since the two grains are of different orientations, a dislocation passing will have to change its direction of motion; this becomes more difficult as the crystallographic misorientation increases.

2. The atomic disorder within a grain boundary region will result in discontinuity of slip planes from one grain into the other. It should be mentioned that, for high-angle grain boundaries, it may not be the case that dislocations traverse grain boundaries during deformation; rather, a stress concentration ahead of a slip plane in one grain may activate sources of new dislocations in an adjacent grain.

A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained, since the former has a greater total grain boundary area to impede dislocation motion. For many materials, the yield strength $\sigma_y$ varies with grain size according to

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

In this expression, termed the **Hall-Petch equation**, $d$ is the average grain diameter, and $\sigma_0$ and $k_y$ are constants for a particular material. It should be noted that this equation is not valid for both very large (i.e., coarse) grain and extremely fine grain polycrystalline materials.

Grain size may be regulated by the rate of solidification from the liquid phase, and also by plastic deformation followed by an appropriate heat treatment.

It should also be mentioned that grain size reduction improves not only strength, but also the toughness of many alloys. Small-angle grain boundaries are not effective in interfering with the slip process because of the slight crystallographic misalignment across the boundary. On the other
hand, twin boundaries will effectively block slip and increase the strength of the material. Boundaries between two different phases are also impediments to movements of dislocations; this is important in the strengthening of more complex alloys. The sizes and shapes of the constituent phases significantly affect the mechanical properties of multiphase alloys.

![Graph showing the influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy. Note that the grain diameter increases from right to left and is not linear.](image)