Outline

- Strengthening Mechanisms in Metals
- Grain Boundaries
- Cold Working
- Annealing
- Recrystallization in Metals
- Grain Growth

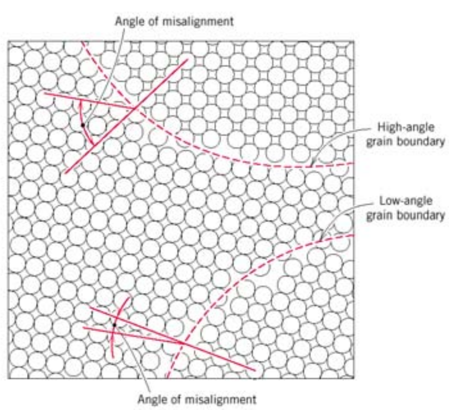
Strengthening Mechanisms in Metals

- Engineering alloys are designed to have maximum strength with some ductility and toughness
- plastic deformation depends on the ability of ……………… to move

- all strengthening mechanisms rely on restricting the motion of dislocations

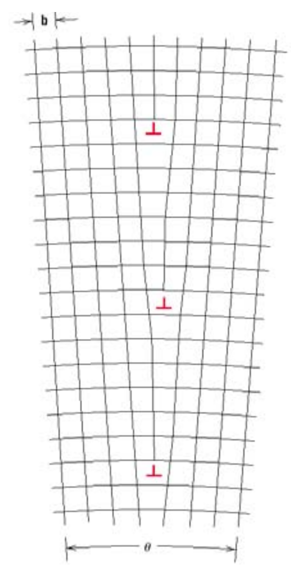
- mechanisms of strengthening are:
  - ....
  - ....
  - ....
  - ....

Grain Boundaries



- Occur due to the crystallographic mismatch when two grains meet.
- When mis-orientation is large → ***……. angle*** *grain boundary.*
- When mis-orientation is small, → ***……. angle*** *grain boundary*
- Atoms are *less bonded* and the atomic packing is lower than in the grain (*lower coordination*).
- The result is an energy difference → *interfacial surface energy or grain boundary energy.*

Grain Boundaries



- Segregation of impurities due to higher energy.
- Grain boundaries are more chemically reactive.
- Total grain boundary area is smaller in *……… grained* than *…….. grained* material.
- Low angle grain boundary is described as an array of dislocations:
  - *tilt boundary* (edge)
  - *twist boundary* (screw)

Strengthening by Grain Size Reduction

- Grain boundaries ………. the motion of dislocations:
  - dislocation changes direction on moving from grain A to B
  - *grain boundary is a discontinuity in the lattice*
- Small grain size → high grain boundary surface area and high yield strength (σ_y) without reducing the *ductility*
- *Hall-Petch* equation:

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

where:

d = average grain diameter and σ_o and k_y are constants

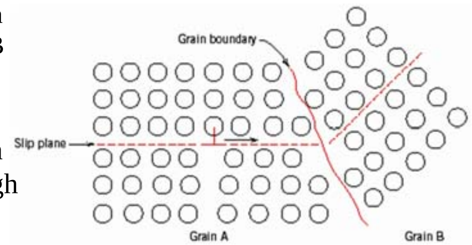


FIGURE 7.14 (Callister) The motion of a dislocation as it encounters a grain boundary, illustrating how the boundary acts as a barrier to continued slip. Slip planes are discontinuous and change directions across the boundary.

Strengthening by Grain Size Reduction

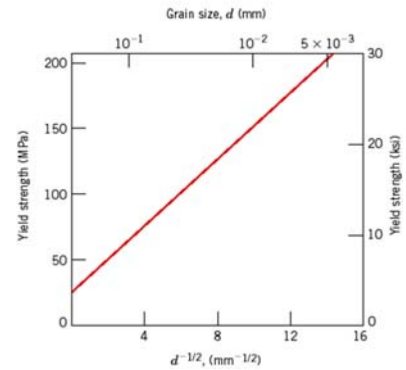


FIGURE 7.15 (Callister) The influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy. Note that the grain diameter increases from right to left and is not linear.

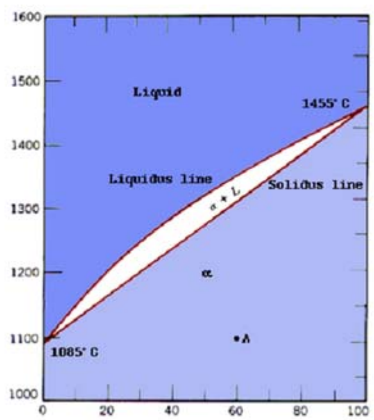
- Brass (Cu-Zn) strengthening through grain size reduction is shown in the figure.
- Grain size is controlled by:
  - rate of solidification during casting
  - plastic deformation followed by ………………
- Small grain size results in higher strength without reducing the …………

➔ *toughness* is also improved.

- Boundaries between different phases (*particles*) have same effect on dislocation motion → ……………………………….

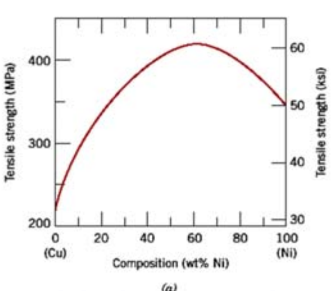
Solid-Solution Strengthening

- Solid-solution alloys are always …………… than pure metals.
- an example of complete solid-solubility is the Cu-Ni system.

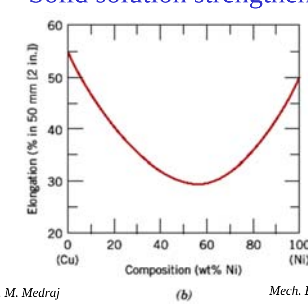


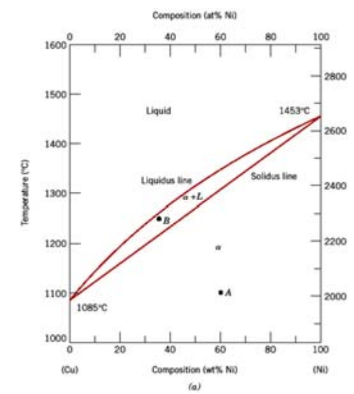
Solid-Solution Strengthening

Mechanical properties of isomorphous alloys



Solid solution strengthening





By making appropriate choices of compositions and alloy elements, we can engineer materials to have specific properties needed for certain applications (mechanical, electrical, thermal, optical).

Solid-Solution Strengthening

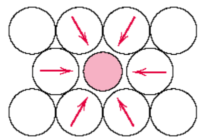


Fig. 7.17 (Callister) (a) Representation of tensile lattice strains imposed on host atoms by a smaller substitutional impurity atom.

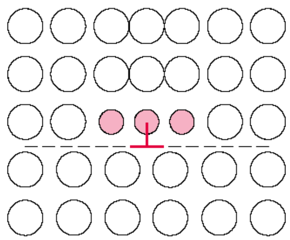


Fig. 7.17 (b) Possible locations of smaller impurity atoms relative to an edge dislocation such that there is partial cancellation of lattice strains.

- Alloying elements impose *lattice strain* in the host lattice due to the difference in size.
- Small atom creates a …………
- Impurity atoms diffuse to positions where they reduce strain in lattice.
- Smaller solute atoms sit at <u>base</u> of edge dislocations
  - ……………………….
- This **nullifies** the effect of strain around dislocations and <u>increases</u> the stress required to move dislocations

→ resistance to slip is **increased**

Solid-Solution Strengthening

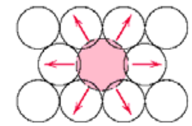


Fig. 7-18 (a) Representation of <u>compressive strains</u> imposed on host atoms by a larger substitutional impurity atom.

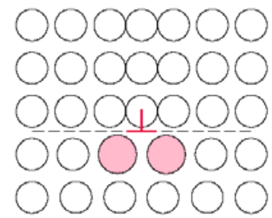


Fig. 7-18 (b) Possible locations of larger impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

- Impurity atoms diffuse to positions where they reduce strain in lattice.
- **<u>Larger</u>** solute atoms sit below edge dislocations - ……………..

By <u>ALLOYING</u> (making pure metal "impure") make material stronger + harder (***almost always***)

Pure metals hardly ever used.
(*gold plating - electronics, platinum*)

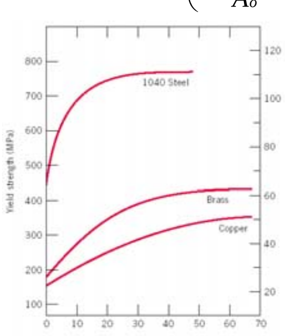
In engineering, nearly always metals with some impurity/**alloying** are used.

Strain or Work Hardening

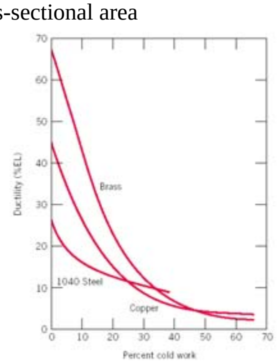
- *Strain hardening* (work hardening) is where a material becomes *less ductile*, *harder* and *stronger* with plastic deformation.
- Encountered during *cold working*.
- Percentage cold work can be expressed as:

$$\%CW = \left(\frac{A_o - A_d}{A_o}\right) \times 100$$

A_o = original cross-sectional area
A_d = deformed cross-sectional area

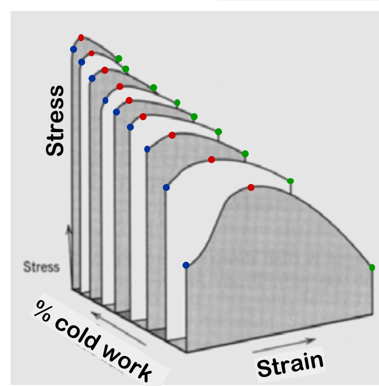


- Ductility ……..…. with cold work
- Yield and tensile strength ……………



Strain or Work Hardening

- Yield strength (σ_y) increases.
- Tensile strength (UTS) increases.
- Ductility (%EL or %AR) decreases.

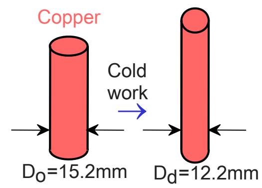


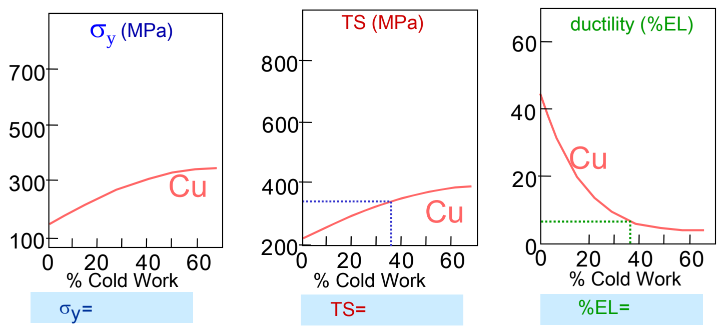
The influence of cold work on the stress–strain behavior for a low-carbon steel.

- Dislocation density *increases* with CW
- Motion of dislocations is *hindered* as their density increases
- *Higher* stress is required to cause further deformation
- Strain hardening is used <u>commercially</u> to improve the yield and tensile properties
  - **cold-rolled low-carbon steel sheet**
  - **aluminum sheet**
- *Strain hardening exponent n* indicates the response to cold work (i.e. larger *n* means greater strain hardening for a given amount of plastic strain)

Example: Cold Work Analysis

- What is the tensile strength & ductility after cold working?





Cold Working

- Performed at room temperature or *slightly* above
- Many cold forming processes are important mass production operations
- Minimum or no machining usually required
  - These operations are *near net shape* or *net shape* processes

Advantages of Cold Forming vs. Hot Working:

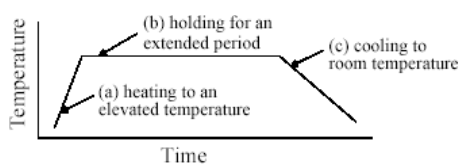
- ……. accuracy, …….. tolerances
- …….. surface finish
- Strain hardening increases strength and hardness
- Grain flow during deformation can cause …………………… properties in product
- No heating of work required (*less …….. energy*)

Cold Working

Disadvantages of Cold Forming:

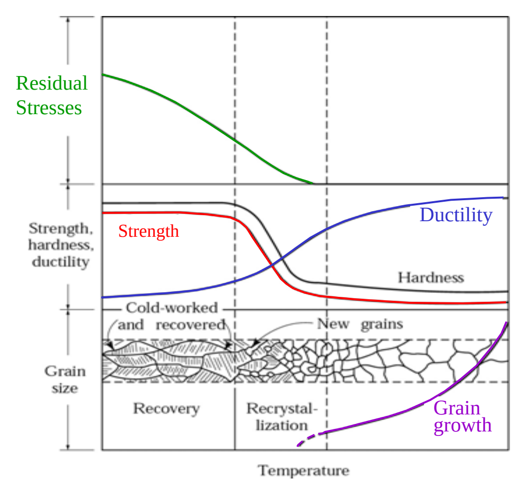
- Equipment of higher forces and power required
- Surfaces of starting workpiece must be free of scale and dirt
- Ductility and strain hardening limit the amount of forming that can be done
  - *In some operations, metal must be annealed to allow further deformation*
  - *In other cases, metal is simply not ductile enough to be cold worked*

Purposes of annealing:
- …………..
- ……………………
- …………………………..



Involves three steps

Annealing-Recrystallization in Metals



Schematic illustration of the effects of recovery, recrystallization, *and* grain growth *on mechanical properties and on the shape and size of grains.*

- Formation of new strain-free grains is called *recrystallization*
- Recrystallization takes time - the **recrystallization temperature** is specified as the temperature at which new grains are formed in about …………
- Recrystallization can be exploited in manufacturing
- Heating a metal to its recrystallization temperature prior to deformation allows a greater amount of straining, and lower forces and power are required to perform the process

Recovery, Recrystallization and Grain Growth

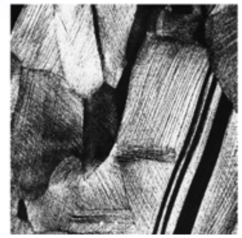
Recovery

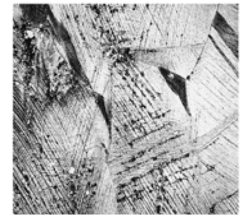
- Occurs during heating at elevated temperatures below the recrystallization temperature
- Dislocations reconfigure due to diffusion and relieve the *lattice strain energy*
- Electrical and thermal properties are recovered to their pre-cold worked state

Recrystallization

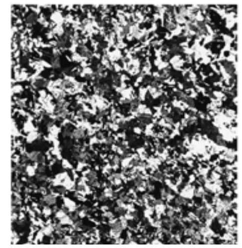
- Recrystallization results in the nucleation and growth of new *strain-free, equiaxed* grains
- Low dislocation density equivalent to the pre-cold worked condition → ………….. state
- Restoration of mechanical properties → ……………

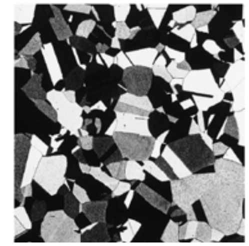
Recrystallization in Metals


Cold-worked (33%CW)


Initial stage of rec. after heating 3 s at 580°C

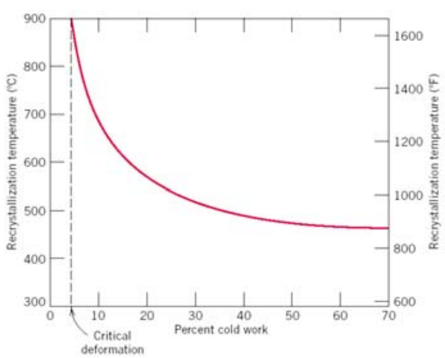

Partial replacement of cw grains by rec. ones 4 s.


Complete recrystallization (8 s at 580°C).


Grain growth after 15 min at 580°C


Grain growth after 10 min at 700°C

Recrystallization in Metals

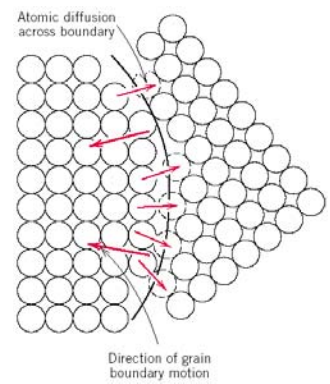


*The variation of recrystallization temperature with percent cold work for iron. **For deformations less than the critical (about 5%CW), recrystallization will not occur.***

- Rate of recrystallization ……….. with amount of cold work
- It requires a ………….. amount of cold-work to cause recrystallization (2-20%)
- Recrystallization is ……… in pure metals than alloys and occurs at lower temperature
  - $0.3T_m$ versus $\sim 0.7T_m$
- …………… involves deformation and concurrent recrystallization at high temperature

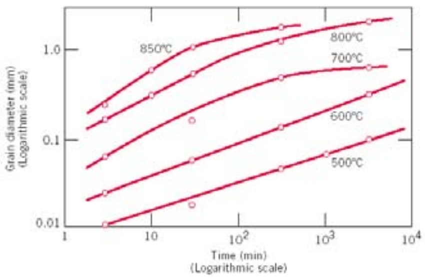
Grain Growth

- Growth of new grains will continue at high temperature.
- ………. require recovery and recrystallization.
- Occurs in both metals and ceramics at elevated temperature.
- Involves the migration of grain boundaries.
- Large grains grow at expense of small ones.
- Reduction of grain boundary area (*driving force*).



Schematic representation of grain growth via atomic diffusion.

Grain Growth Kinetics



The logarithm of grain diameter versus the logarithm of time for grain growth in brass at several temperatures.

- Variation of grain size (d) with time is:

$$d^n - d_o^n = Kt$$

where d_o = initial grain size at $t = 0$, and K and n are time-independent constants, n is ≥ 2

- *Log d* versus *log t* plots give linearity at ……………………….
- Grain size increases with temperature.
- *Toughness* and *strength* are superior in ……. *grained* materials.

Next time:

Two Phase Strengthening