

Lecture 3A



Strengthening of Metals and Alloys

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Monday 16th November 2020

Got a question ?

Please use the “chat” or “raise your hand” functions

Why study how to strengthen metals and alloys

- It is important for engineers and designers to understand:
 - How to modify and tailor the properties of metals and alloys for different applications
 - Strengthening mechanisms used to improve the mechanical properties of metals and alloys

Outline

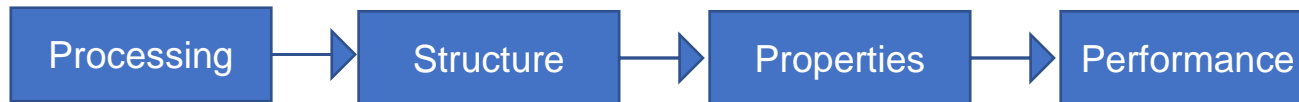
- Strengthening mechanisms of metals
 - Grain size reduction
 - Solid-solution alloying
 - Strain hardening or work hardening or cold working
 - Precipitation hardening or age hardening
- Recovery
- Recrystallization
- Grain growth

Learning Outcomes

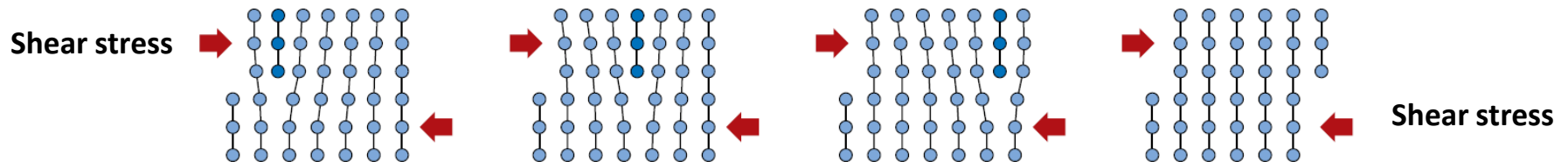
- Describe and explain the following strengthening mechanisms and their effect(s) on Metals and Alloys
 - Grain size reduction
 - Solid-solution alloying
 - Strain hardening or work hardening or cold working
 - Precipitation hardening or age hardening
- Explain the process and effect(s) of **recovery, recrystallization and grain growth** and their effects on the microstructure and mechanical properties of Metals and Alloys

Strengthening

- The processing and structures of Metals and Alloys influence their properties



- Plastic deformation is due to the motion of a large number of dislocations.

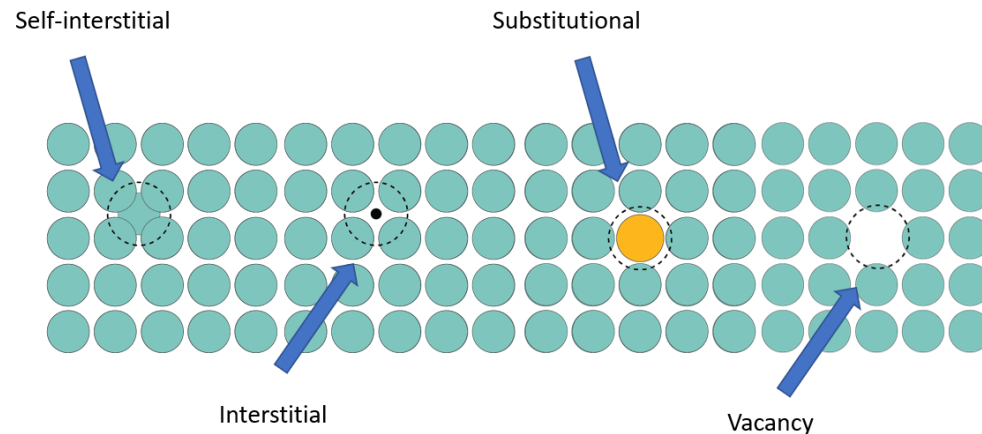


Dislocation motion - Atomic rearrangement in response to applied stress

- Video showing dislocation - https://www.doitpoms.ac.uk/tlplib/dislocations/dislocation_glide.php

Strengthening

- **Restricting or hindering** movement of dislocations makes metals and alloys **stronger and harder**
- **Crystal defects** increase the strength of a metal because they **impede** the movement of dislocations



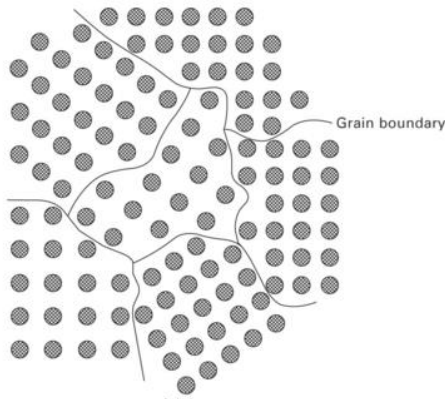
- However, **Strengthening** reduces **ductility**

Strengthening Mechanisms

- How can we **restrict or hinder or limit** movement of dislocations makes metals and alloys stronger and harder ?
 - Grain size reduction
 - Solid-solution alloying
 - Strain hardening or work hardening or cold working
 - Precipitation hardening or age hardening

Strengthening by grain size reduction

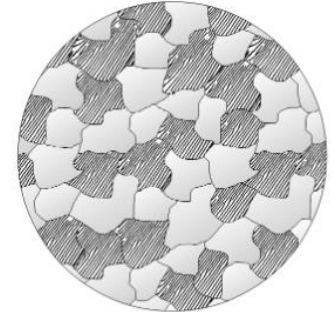
- The size of the grains (or grain diameter) in polycrystalline metals affect their mechanical properties
- Adjacent grains normally have **different crystallographic orientations** and **common grain boundary**
- Grain boundaries act as **barriers/obstacles** to dislocation motion
 - Finer grains → More grain boundaries → More obstacles prevent more dislocation motion → Higher strength



Grain Structure Mouritz (2012) Introduction to Aerospace Materials



Coarse-grained
microstructure



Fine-grained
microstructure

Tec Science (2018) <https://www.tec-science.com/material-science/heat-treatment-steel/annealing-processes/>

Strengthening by grain size reduction

- **Fine-grained** material (one that has small grains) is **harder and stronger** than coarse-grained
- **Fine-grained** has a **greater total grain boundary area** to impede dislocation motion
- **Yield strength** varies with the **grain size** using the **Hall-Petch equation** (shown below)

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

σ_y - yield strength

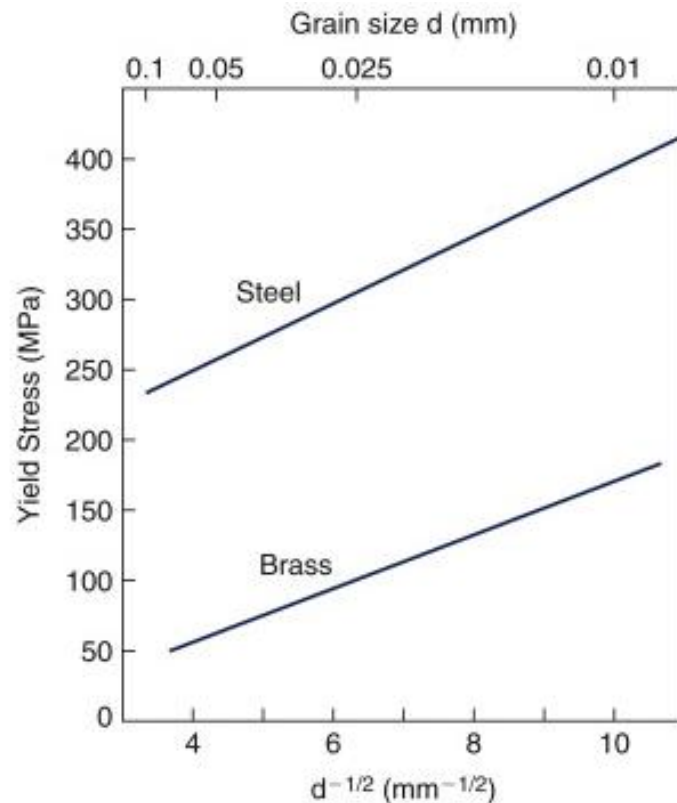
d - average grain diameter

σ_0 and k_y - constants for a particular material

- Typically, **Grain-size reduction** increases **yield strength** and **toughness**

Strengthening by grain size reduction

- Influence of grain size on the yield strength of Steel and Brass



Hall-Petch equation

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

σ_y - yield strength

d - average grain diameter

σ_0 and k_y - constants for a particular material

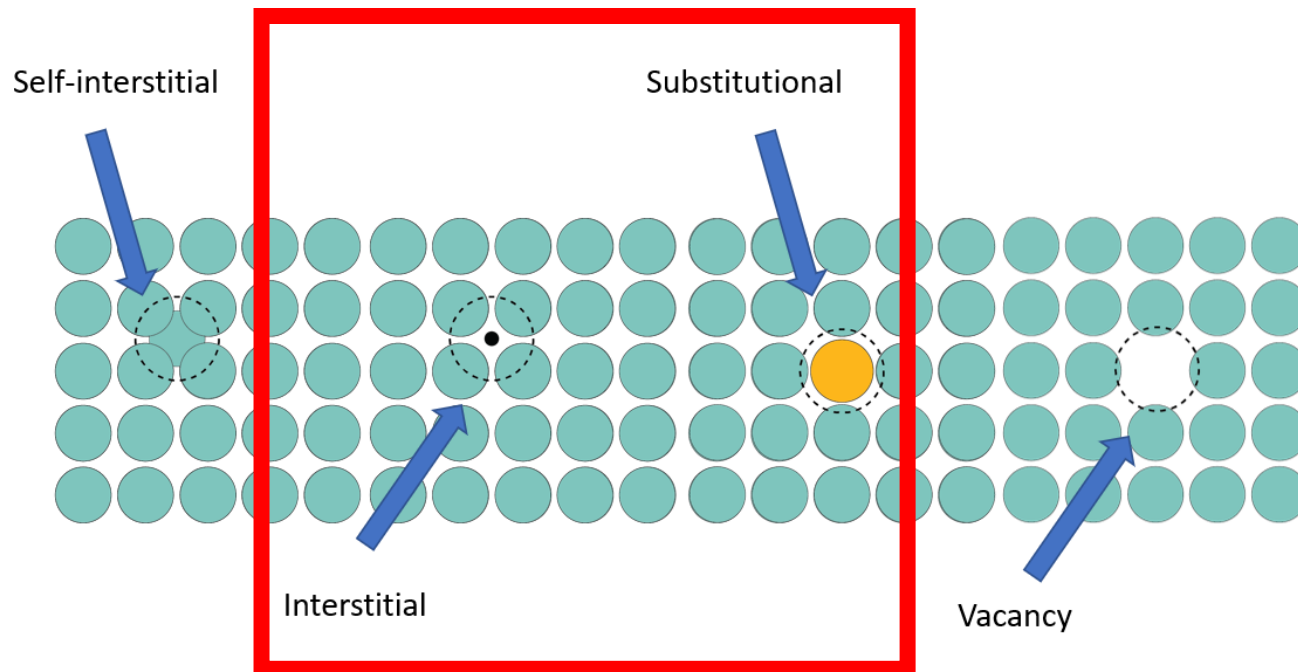
Fisher T (2009) *Materials Science for Engineering Students*

Quiz time – Which of the following mechanical properties of metals is typically reduced by strengthening mechanisms

Website – [Sli.do](#)

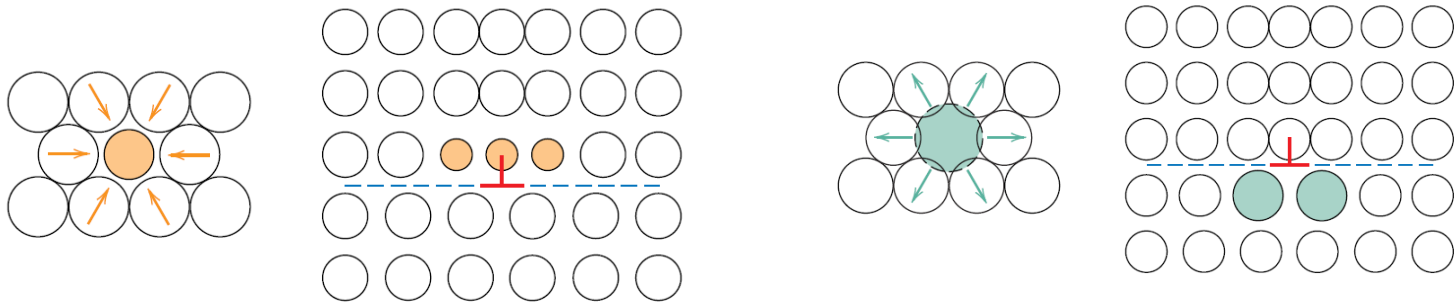
Solid-solution strengthening

- Crystal defects increase the strength of a metal because they impede the movement of dislocations



Solid-solution strengthening

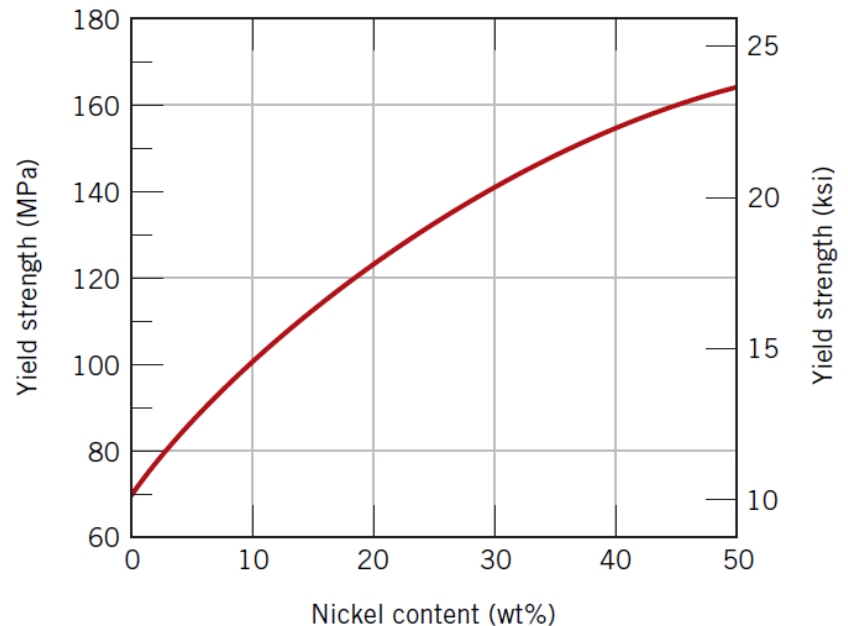
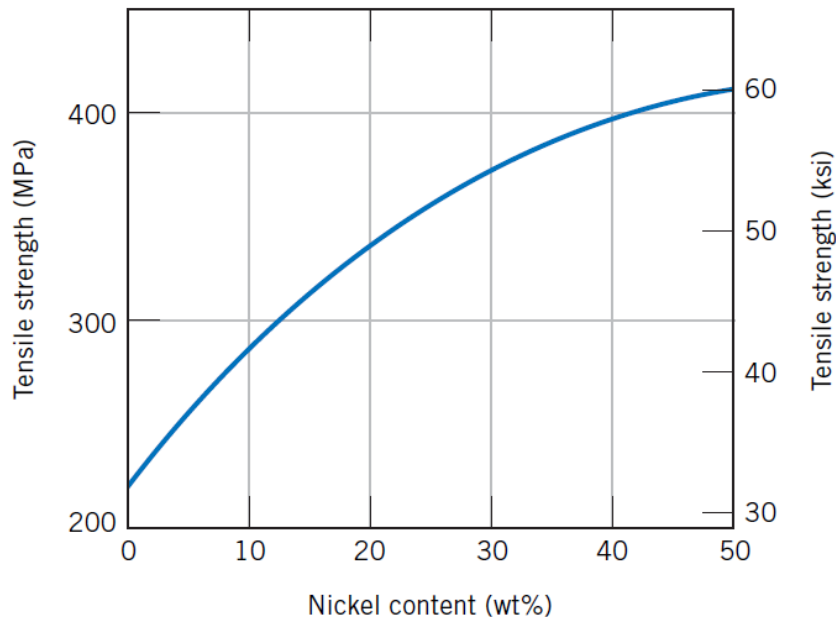
- **Alloys** are stronger than **pure metals**
- Adding **impurity atoms** (e.g. Cu, Ni, C) increase the **Tensile** and **Yield strengths** by:
 - Lattice **strains (tensile and compressive)** around surrounding atoms
 - These strains **hinder/restrict** dislocation motion



Callister and Rethwisch (2013)

Solid-solution strengthening

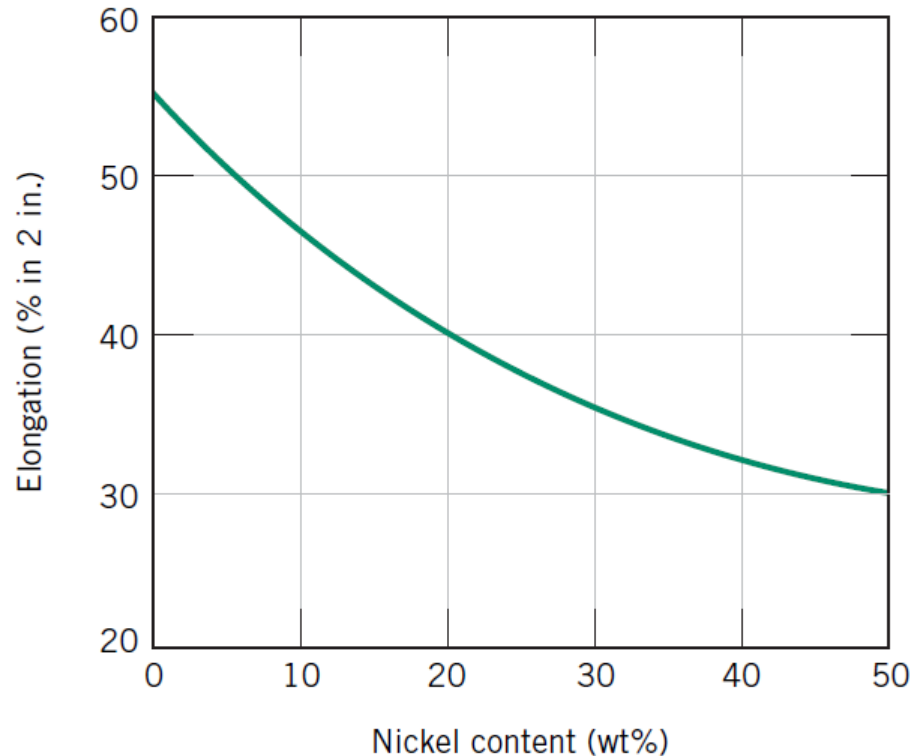
- Impurity atoms (e.g. Cu, Ni, C) increase the **Tensile** and **Yield strengths**



Variation with nickel content (wt%) of tensile strength and yield strength for copper–nickel alloys

Callister and Rethwisch (2013)

Solid-solution strengthening



Becomes more brittle

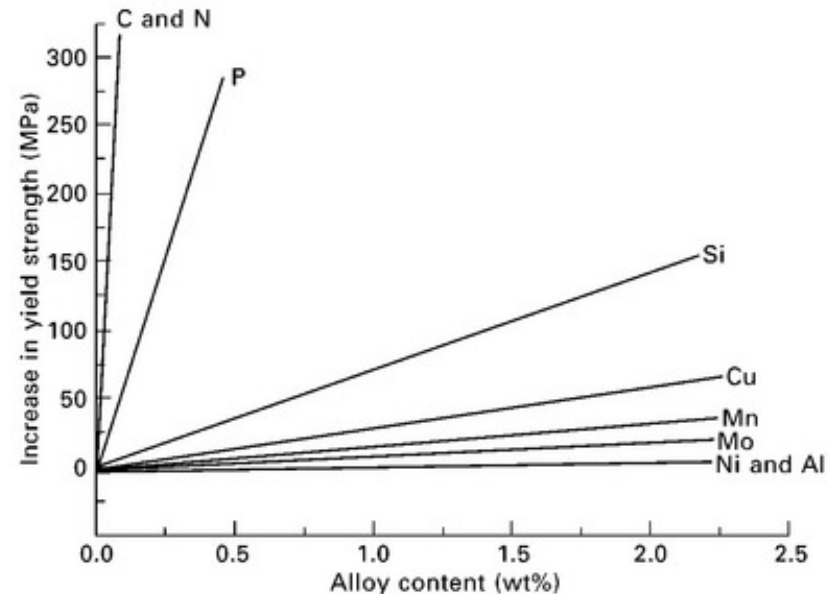
Variation with nickel content (wt%) of ductility for copper–nickel alloys

Callister and Rethwisch (2013)

Solid-solution strengthening

- **Solid-solution strengthening of Iron**

- Carbon and Nitrogen are very effective for strengthening
- Strength increases with increasing alloy content (wt%)



Mouritz (2012) Introduction to Aerospace Materials

Strain hardening or work hardening or cold working

- Strain hardening:
 - Metals become **harder** and **stronger** when they are deformed plastically at temperatures well **below their melting point**
 - Reduction in the distance between dislocations (i.e. dislocations are closer together)
 - Increase in **dislocation density** leads to increased resistance to dislocation motion

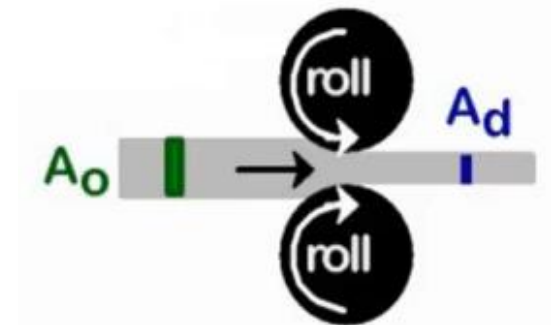
Strain hardening or work hardening or cold working

- Most metals **strain harden** at room temperature
- Often expressed as Percent cold work (%CW)

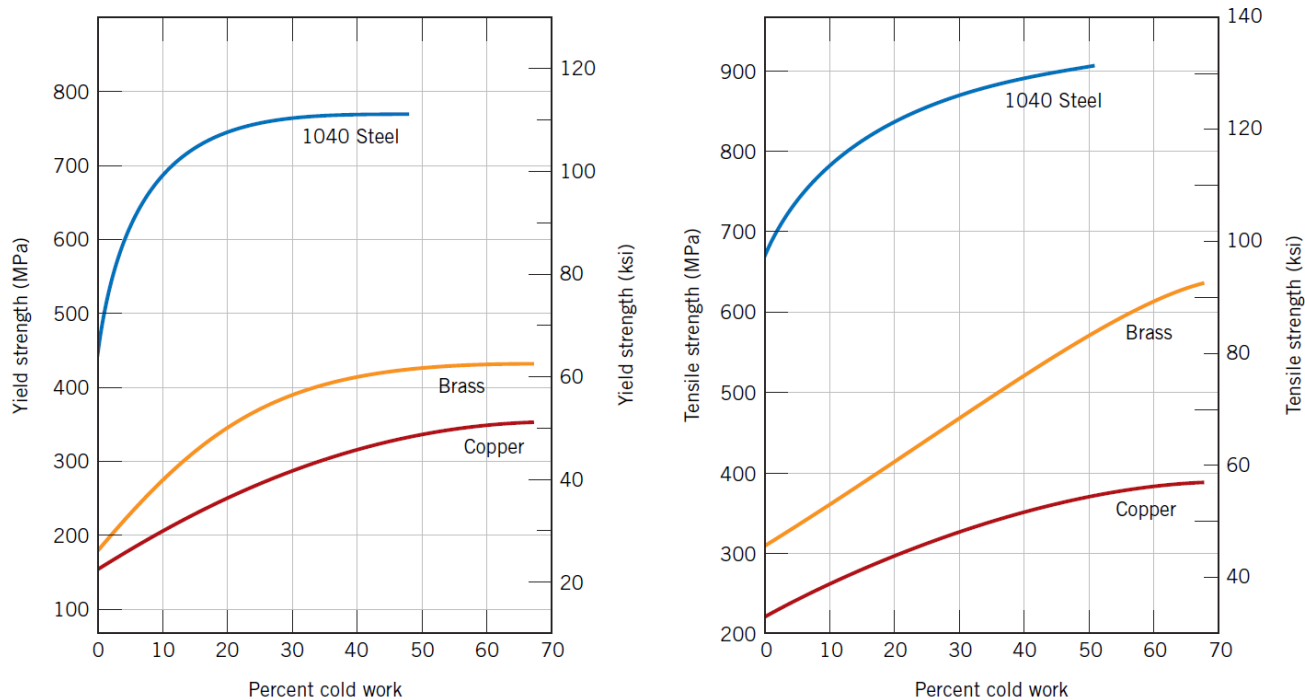
$$\%CW = \left[\frac{A_0 - A_d}{A_0} \right] \times 100$$

A_0 - Original cross-section area

A_d - Area after deformation



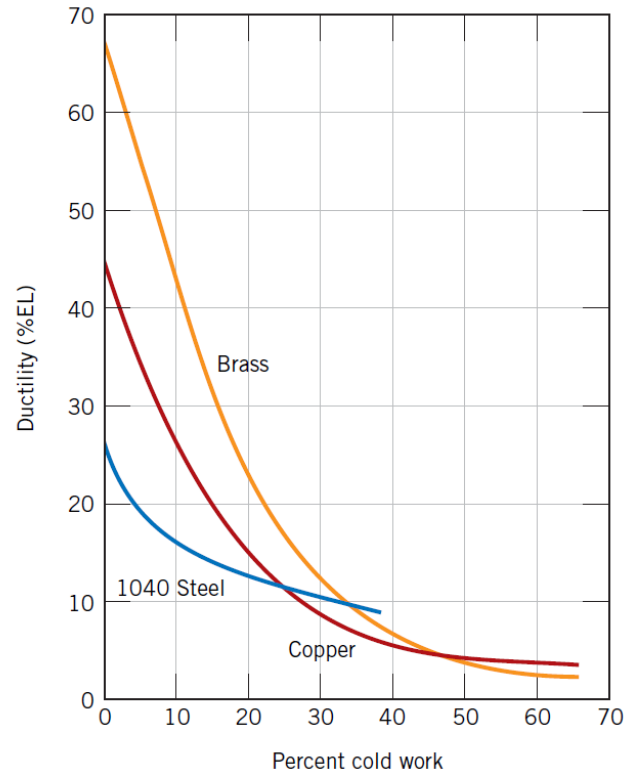
Strain hardening or work hardening or cold working



Increase in Yield Strength and Tensile Strength for Steel, Brass, and Copper with percent cold work

Callister and Rethwisch (2013)

Strain hardening or work hardening or cold working



Becomes more brittle

Decrease in Ductility for Steel, Brass, and Copper with percent cold work

Callister and Rethwisch (2013)

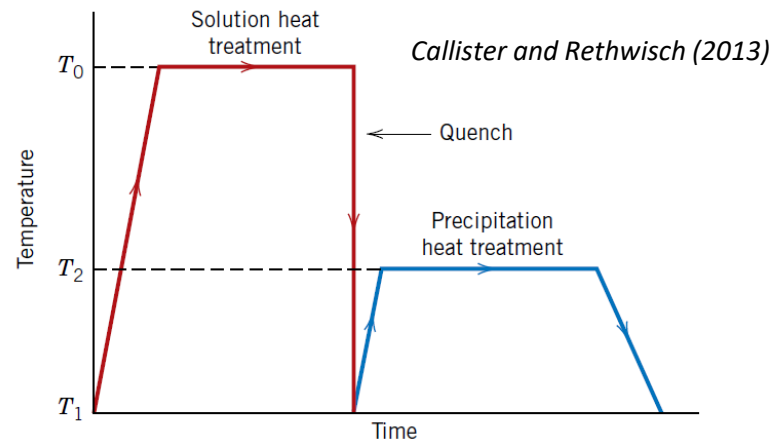
*Quiz time – Which of these statements
are false ?*

Website – [Sli.do](#)

Precipitation hardening or age hardening

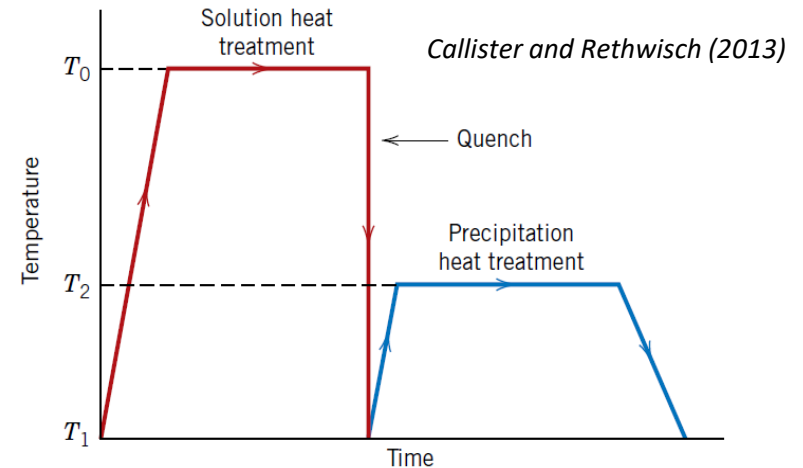
- Strengthening through the formation of **extremely small, uniformly dispersed particles (called precipitates)** of a **second phase (e.g. Cu)** within the **original phase matrix (e.g. Al)**
- Caused by **heat treatments** to improve the strength and hardness of metal alloys (e.g.

Aluminium-copper alloy)



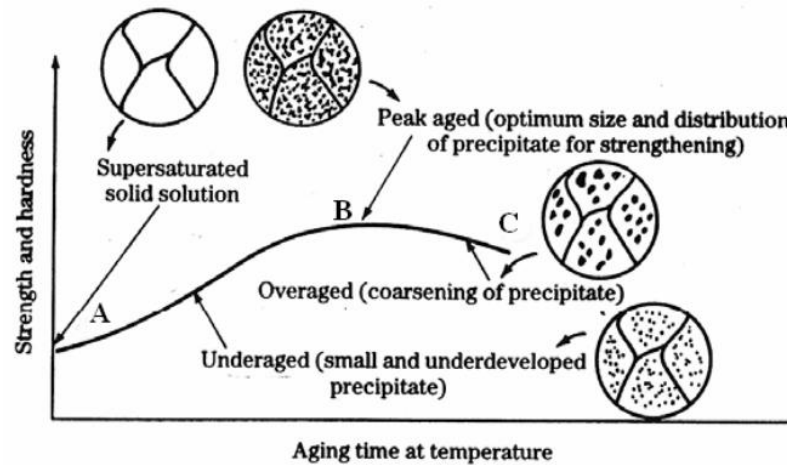
Precipitation hardening or age hardening

- Increased resistance to dislocation motion due to small precipitate particles
 - Solution heat treatment (Stage 1)
 - Solute atoms form a single-phase solution
 - Precipitation heat treatment (Stage 2)
 - Precipitate particles form and grow
- Strength develops with time (hence **age hardening**)

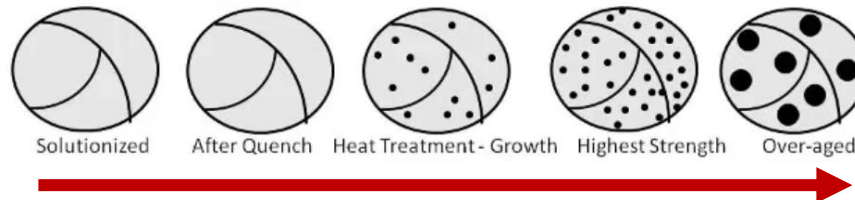


Precipitation hardening or age hardening

- As **time** increases, the **strength** and **hardness increase**, until it reaches a **maximum**, and subsequently **reduces**
- The reduction in strength/hardness after a long time is called **overaging**

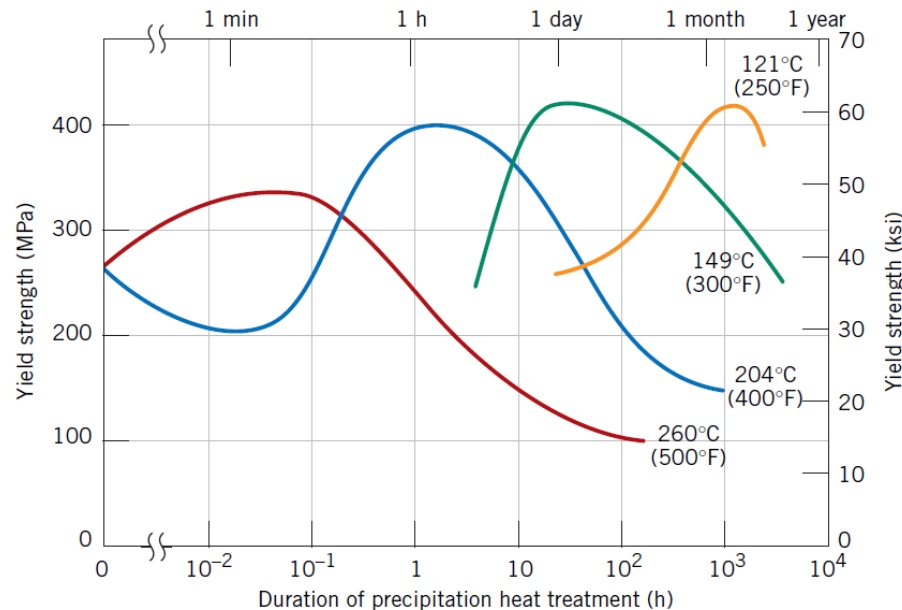


Callister and Rethwisch (2013)



Precipitation hardening or age hardening

Aluminium alloy

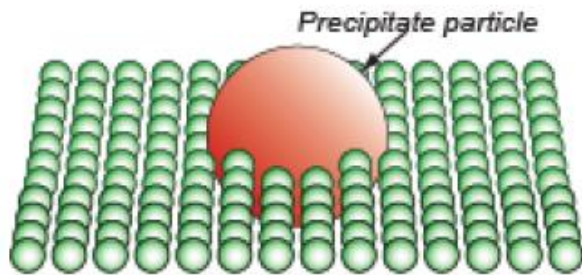


Callister and Rethwisch (2013)

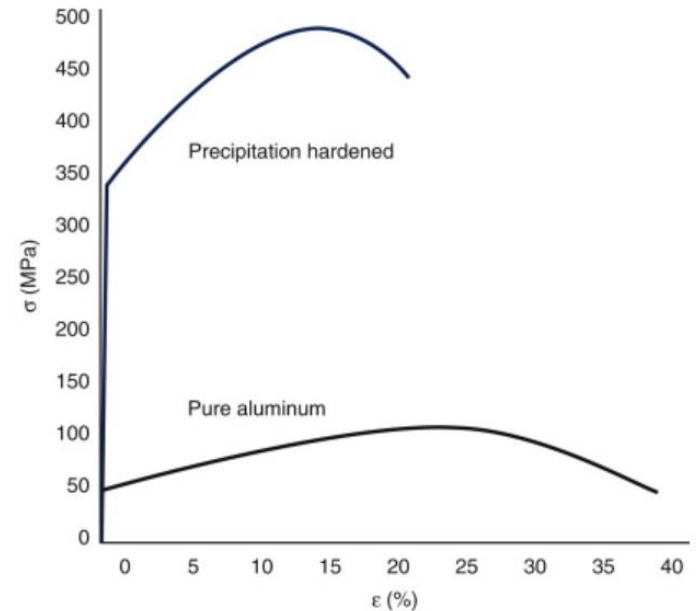
- **Strength or hardness increases**, until it reaches a **maximum**, and subsequently **reduces**
- The process is **accelerated** with **higher temperatures**
- The reduction in strength/hardness after a long time is called **overaging**

Precipitation hardening or age hardening

- Precipitation hardening – very effective for aluminium
- Aluminium-copper alloy (Yield strength increase from **35MPa** to **345 MPa** (factor of 10))
- Precipitates are larger than single atoms
 - Large strains that hinder/restrict dislocation motion



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Fisher T (2009) *Materials Science for Engineering Students*

Strengthening

- **Precipitation hardening** is very effective for strengthening aluminium

Material	Strengthening mechanism	Yield strength	Tensile strength	Ratio of yield strength (alloy/pure metal)
Pure Aluminium	-	20	45	-
Pure Al – 1.2 % Mn	Solid solution strengthening	40	110	2
Pure Al (75% cold worked)	Strain hardening	150	170	7.5
Al (cold-worked and fine-grain structure)	Grain boundary hardening	190	200	9.5
Al – 4% Cu – 1.6% Mg	Precipitation hardening	440	480	22

Mouritz (2012) Introduction to Aerospace Materials

*Quiz time – Which of these statements
is true ?*

Website – [Sli.do](#)

Strengthening

- Strengthening mechanisms can be **combined**
 - For example, a solid-solution strengthened alloy may also be strain hardened
- Grain size reduction and strain hardening can be **eliminated or reduced** by an elevated-temperature heat treatment (i.e. annealing)
- In contrast, **solid-solution strengthening** is unaffected by heat treatment

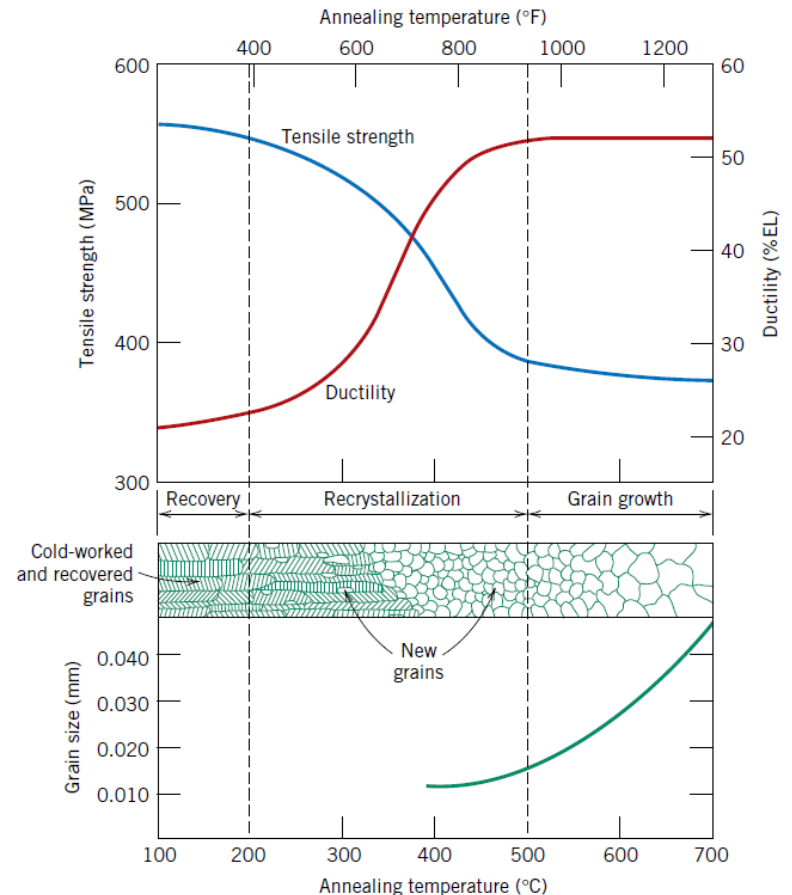
Recovery, recrystallization and grain growth

- Plastic deformation increases dislocation density
- This corresponds to **stored strain energy** in the system
- When applied external stress is removed, the strain energy and dislocations are retained
- Applying appropriate heat treatment (also called **annealing**) can restore the properties and structures back to precold-worked states. These processes include:
 - Recovery
 - Recrystallization
 - Grain growth

Recovery, recrystallization and grain growth

Callister and Rethwisch (2013)

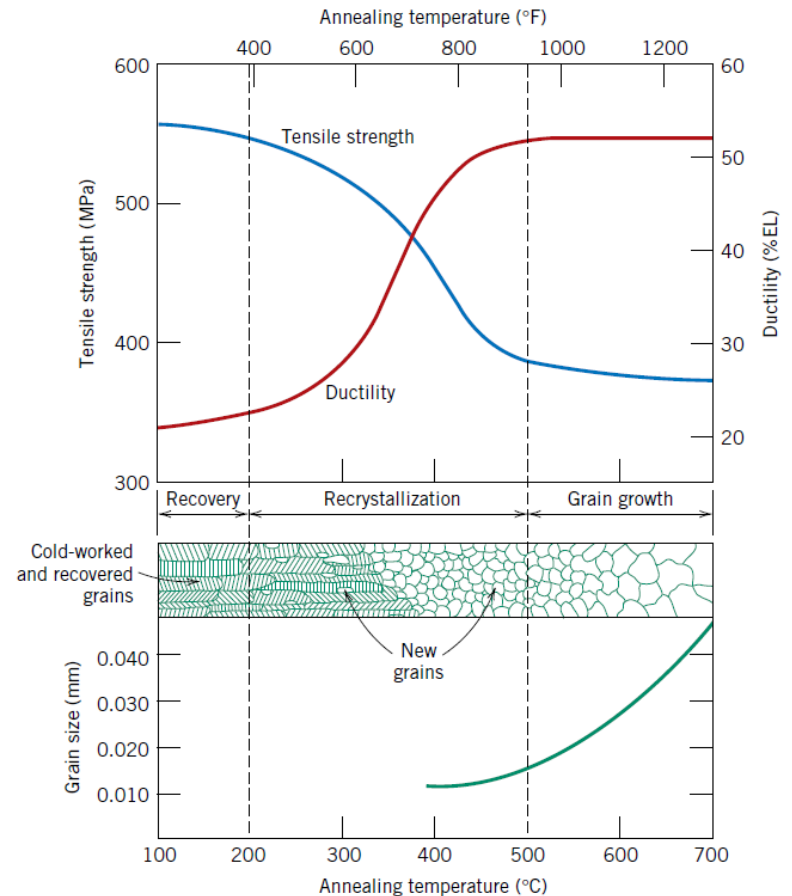
- **Recovery** → High temperature (heating) → increased dislocation motion → reduction in dislocation density → relieve of **some** of the stored internal strain energy
- Even after **recovery**, the grains still have **relatively high strain energy**



Recovery, recrystallization and grain growth

Callister and Rethwisch (2013)

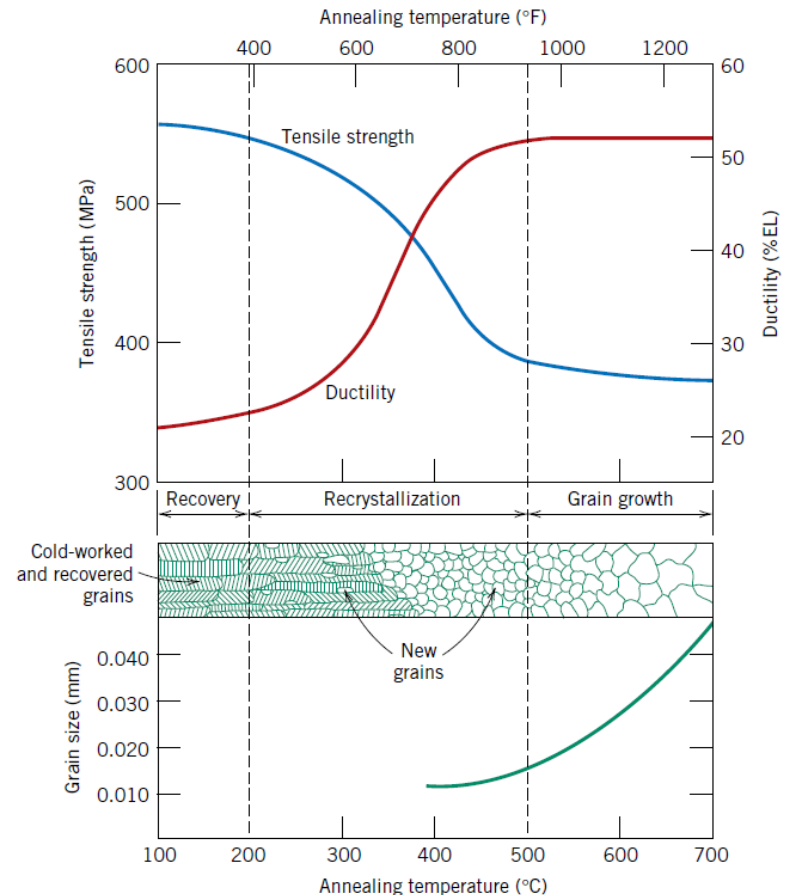
- **Recrystallization** is the formation of new strain-free grains with low dislocation densities
- **Recrystallization** of cold-worked metals may be used to refine the grain structure
- The properties of the metals are restored to their precold-worked values
 - Softer and weaker BUT **more ductile**
- The extent of recrystallization depends on **time** and **temperature**



Recovery, recrystallization and grain growth

Callister and Rethwisch (2013)

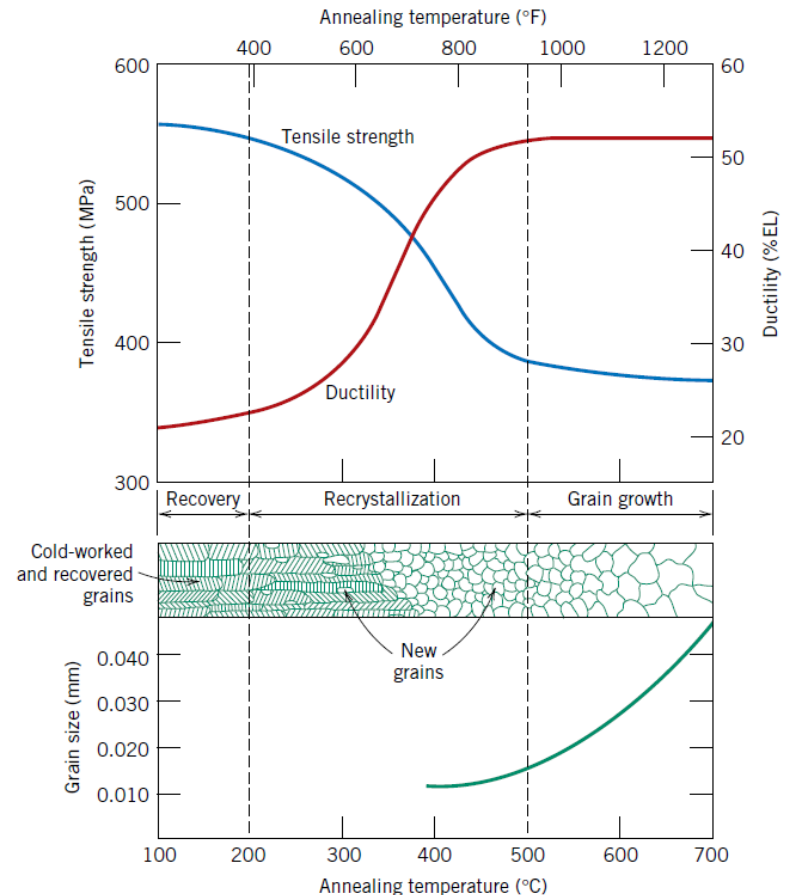
- **Recrystallization temperature** - temperature at which recrystallization reaches completion in one hour
- Typically **one-third** and **half** of the melting temperature of metals or alloys
- Influence of **annealing temperature (for an annealing time of 1 h)** on the **tensile strength** and **ductility** of brass alloy
 - Recrystallization temperature of 450°C
 - Melting temperature of about 900°C
- Grain size as a function of annealing temperature



Recovery, recrystallization and grain growth

Callister and Rethwisch (2013)

- After **recrystallization**, the grains will continue to grow if the elevated temperature is maintained
- This is called **grain growth**
- Increase in grain size leads to:
 - Reduction in the total grain boundary area
 - Reduction in stored total energy
 - Reduction in yield strength
 - Increase in ductility



Recap

- Strengthening mechanisms of metals (**Restricting or hindering movement of dislocations makes metals and alloys stronger and harder**)
 - Grain size reduction
 - Solid-solution alloying
 - Strain hardening or work hardening or cold working
 - Precipitation hardening or age hardening
- Recovery
- Recrystallization
- Grain growth

Quiz time – What does not occur as a result of recovery, recrystallization and grain growth of metals and alloys?

Website – [Sli.do](#)

Further Information



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Materials Science and Engineering

Structure Science

- Solid solution strengthening
- Strain hardening
- Dispersion and precipitation strengthening
- Grain size strengthening
- Toughening
- Electron scattering
- Phonon scattering
- Domain wall pinning

Solid solution strengthening

Solid solutions

Substitutional solid solutions form when atoms of one element replace the more limited is the solid solubility.

- Similar atomic size (to within 15%)
- Similar crystal structure
- Similar electronegativity (energy of ionization) so that covalent bonding is not disrupted
- Similar valence

Thus copper and nickel with the same valence and crystal structure have a high solubility; copper and lead with the same crystal structure have a low solubility of 0.1%.

The mechanism of solution strengthening

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Structure Science

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Strain hardening

Strain hardening

The rising part of the stress-strain curve of a ductile metal is called strain hardening. Metals can be shaped by deformation: rolling, forging, drawing shows the way the stress-strain curve of a metal - here, copper fracture toughness decrease (See also record for Toughening).

The mechanism of strain hardening

The dislocation density, ρ_d , is defined as the length of dislocation line per unit volume. The dislocation density is around 10^{10} m/m^3 , meaning that a 1 m dislocation line. When metals are deformed, dislocations multiply more - 100 million km per cubic centimeter. A moving dislocation intersecting dislocations with an average spacing $L = \rho_d^{-1/2}$.

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Materials Science and Engineering

Structure Science Notes

- Solid solution strengthening
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Dispersion and precipitation strengthening

Precipitation strengthening

An effective way to impede dislocations is to disperse small, strong particles in the matrix. This is the way that metal matrix composites such as Al-SiC are made. An alternative is to use a precipitate. If an alloy with the composition Al-4% Cu is quenched from room temperature, first as nano-scale copper-rich zones ("GP zones") subsequently growing with a little beryllium, similarly treated, gives precipitates of the compound CuBe. Age hardened steels, nickel-based superalloys and high strength titanium alloys all rely on precipitation strengthening.

The mechanism of precipitation strengthening

A shear stress τ exerts a force τb on the dislocation, where b is the dislocation motion. If the particles are small, the force τb pushes the dislocation past the particles.

Any Questions ???

Coffee Break

We will continue at 11:05am GMT

Got a question ?

Please use the “**chat**” or “**raise your hand**” functions