Lecture 3A

Strengthening of Metals and Alloys

Dr Adeayo Sotayo

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

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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

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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

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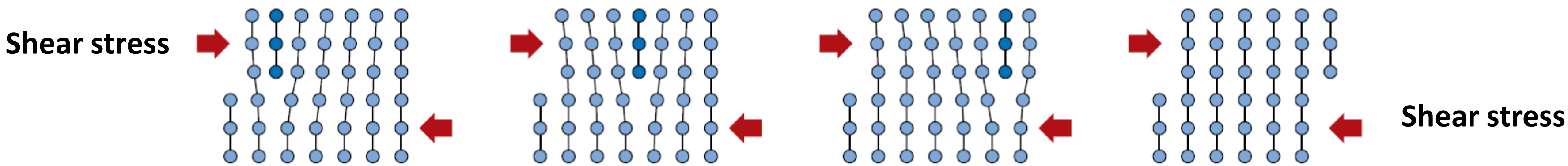
Strengthening

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

Processing → Structure → Properties → Performance

- 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

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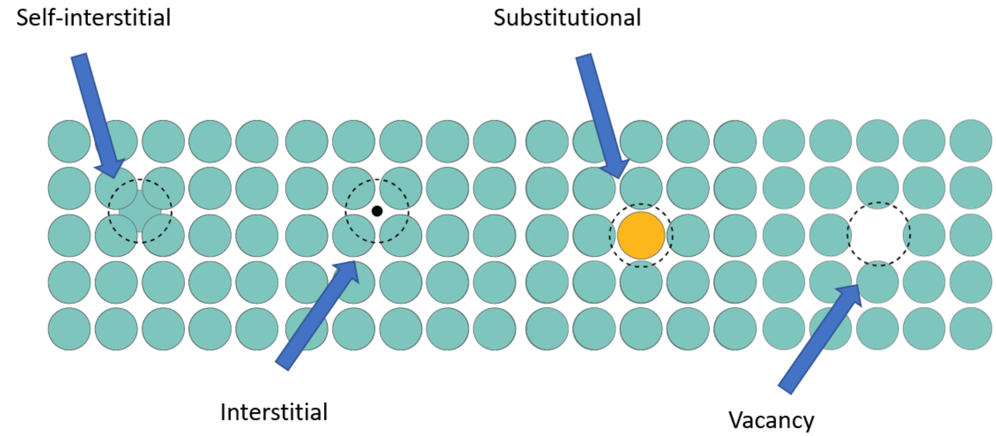
Strengthening

- **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**

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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

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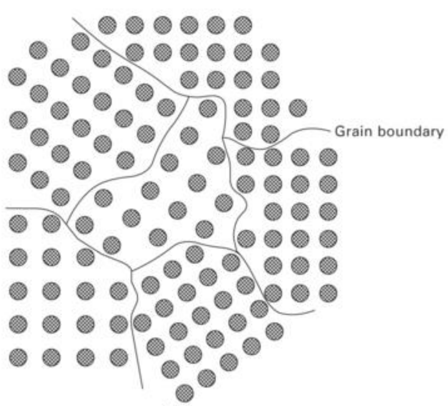
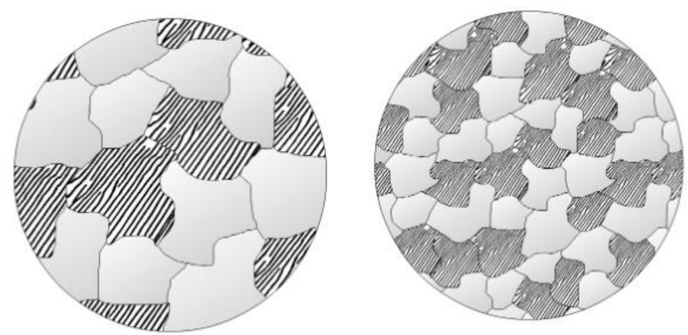
Strengthening by grain size reduction

- 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/

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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**

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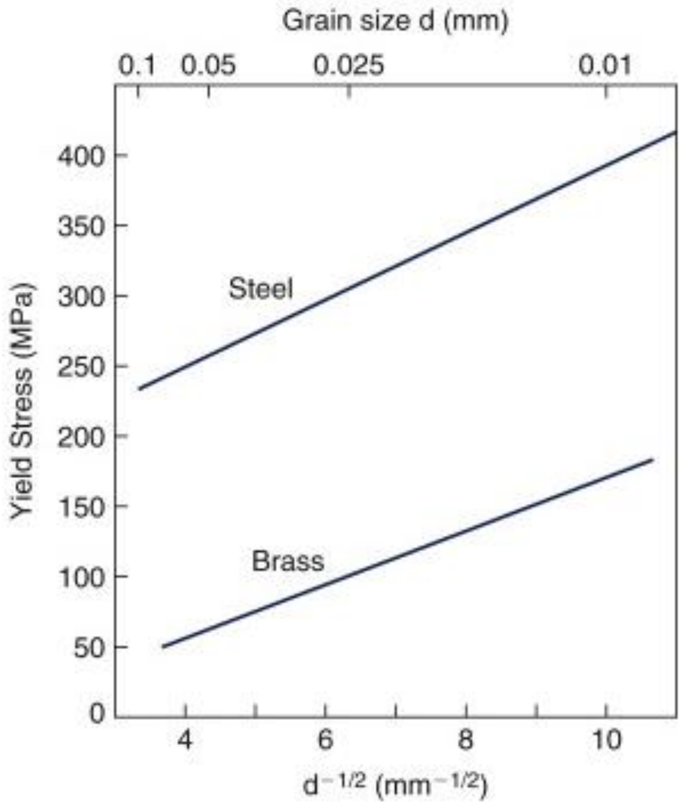
Strengthening by grain size reduction

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



Hall-Petch equation

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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]

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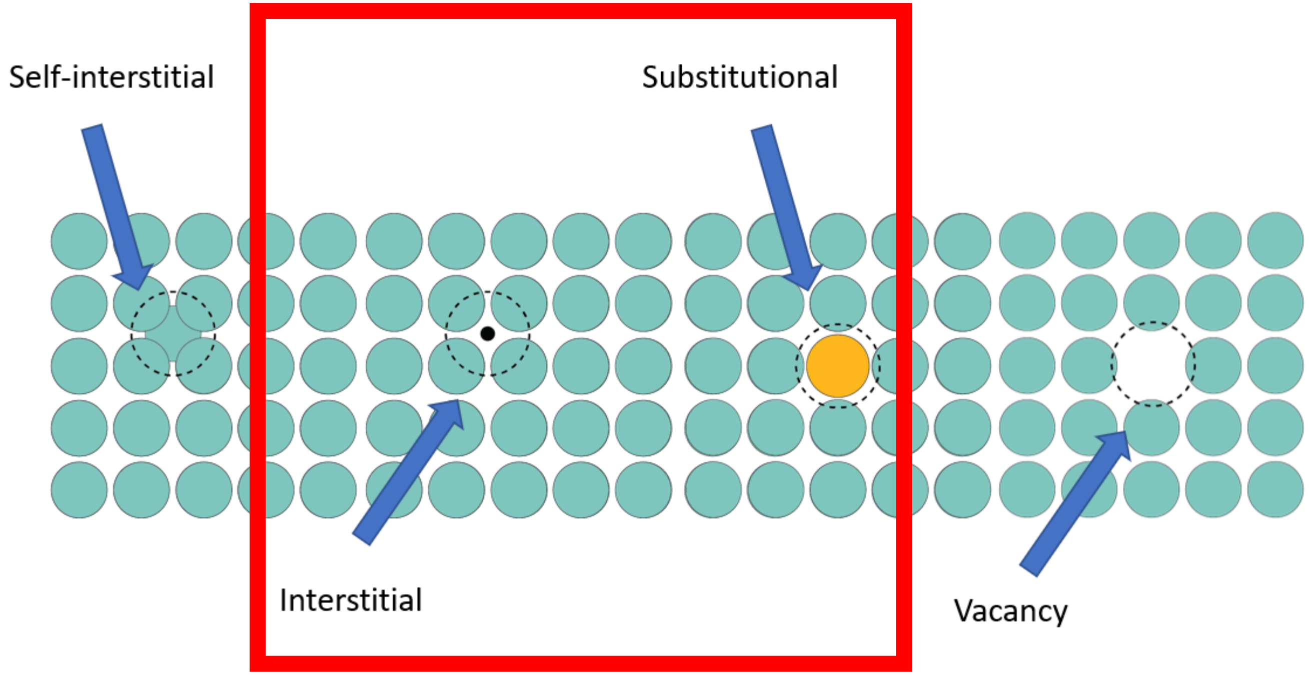
Solid-solution strengthening

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



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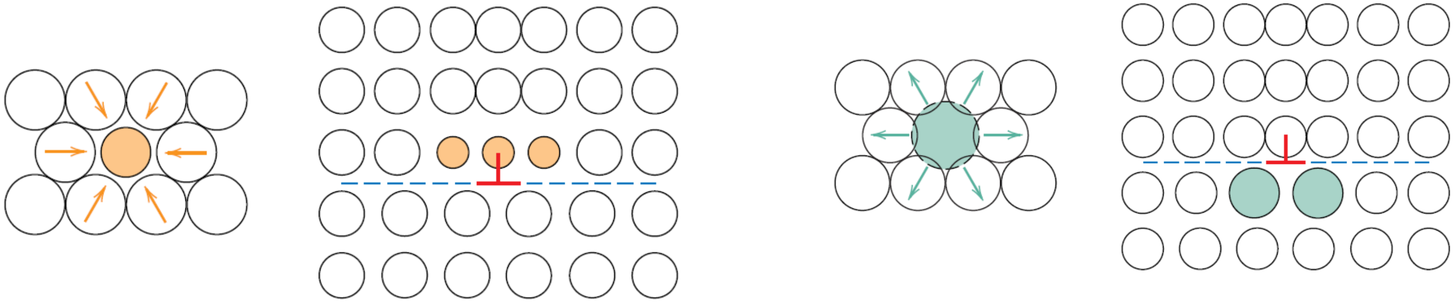
Solid-solution strengthening

- **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)

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Solid-solution strengthening

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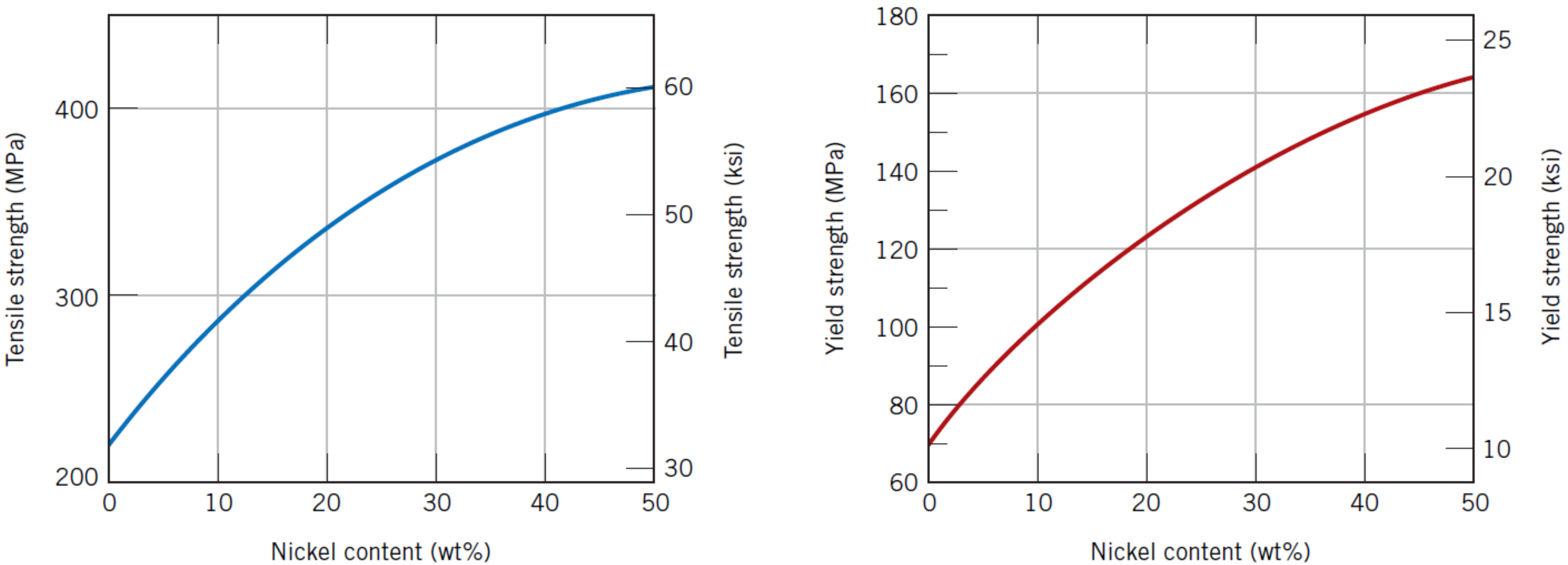

Variation with nickel content (wt%) of tensile strength and yield strength for copper–nickel alloys

Callister and Rethwisch (2013)

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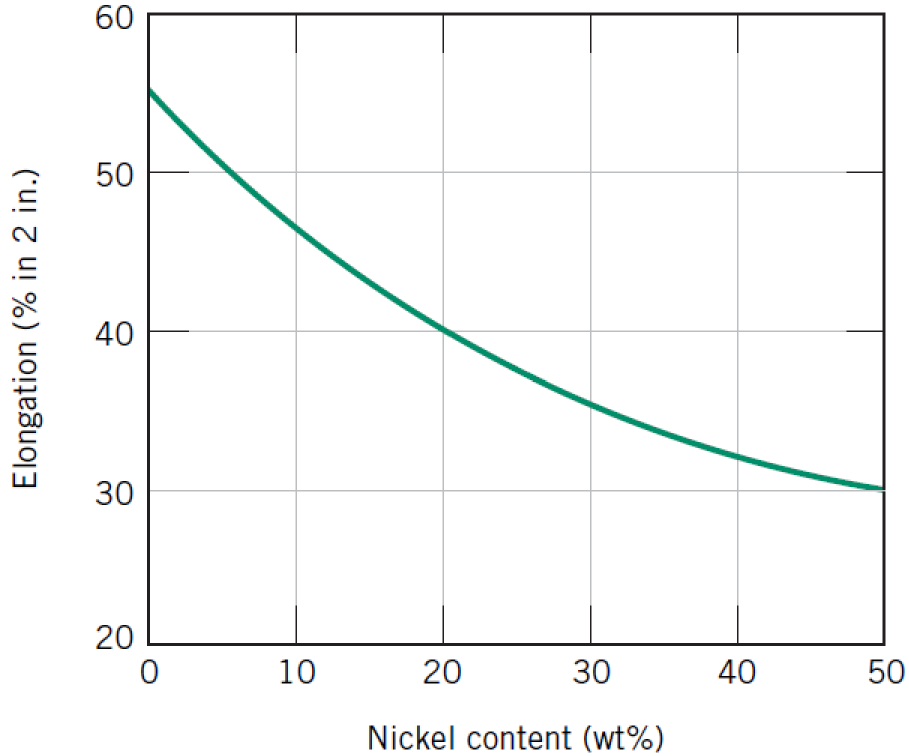
Solid-solution strengthening



Becomes more brittle

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

Callister and Rethwisch (2013)

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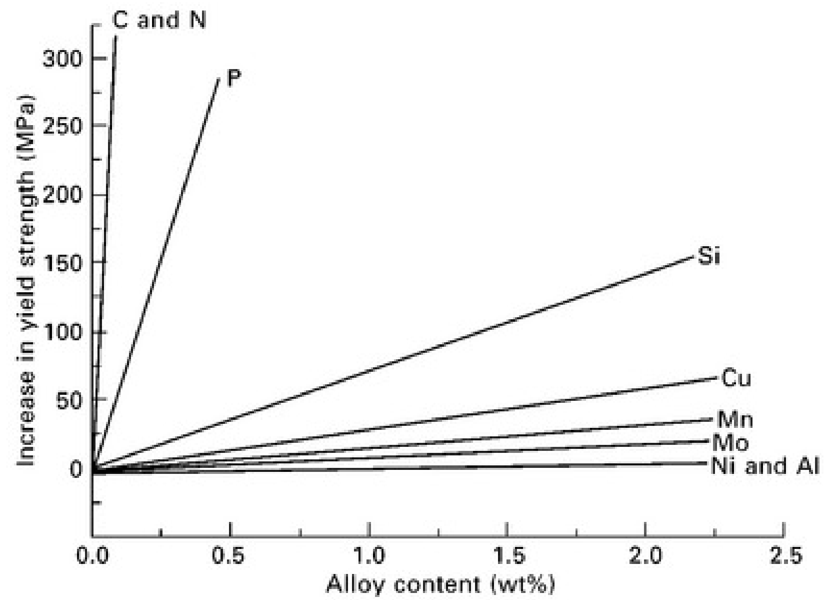
Solid-solution strengthening

- **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

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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

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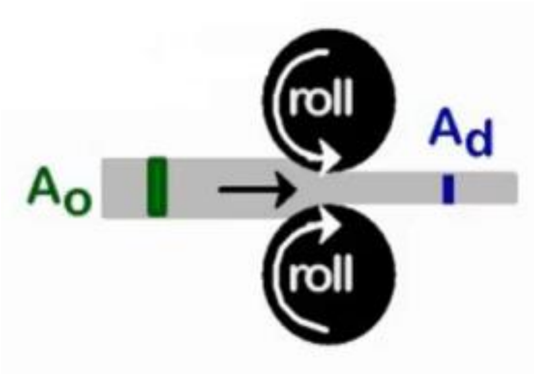
Strain hardening or work hardening or cold working

- 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

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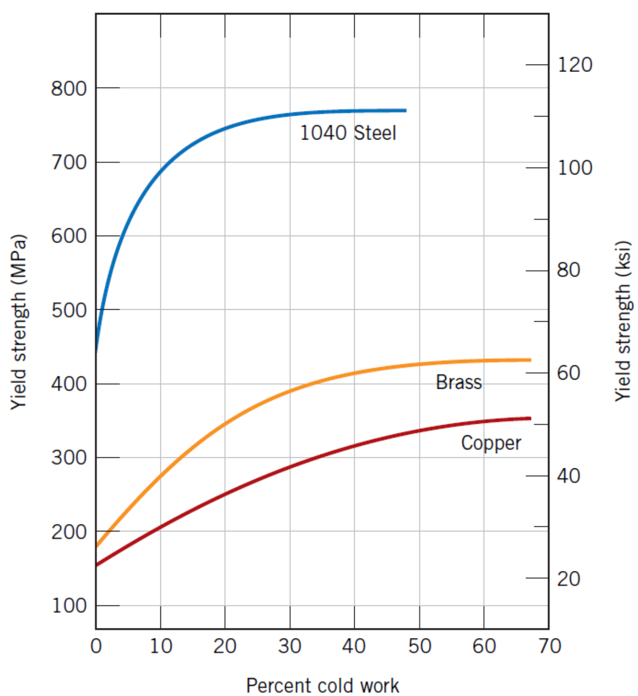
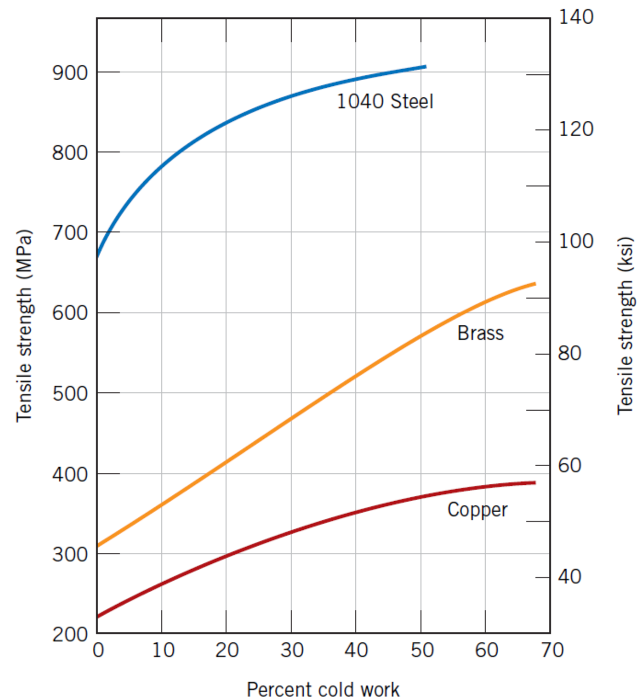
Strain hardening or work hardening or cold working





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

Callister and Rethwisch (2013)

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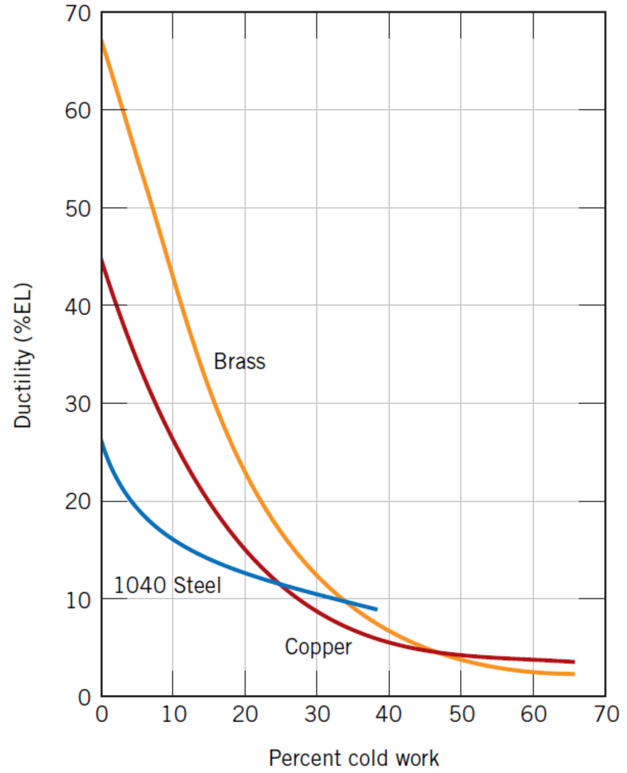
Strain hardening or work hardening or cold working



Becomes more brittle

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

Callister and Rethwisch (2013)

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

Website – Sli.do

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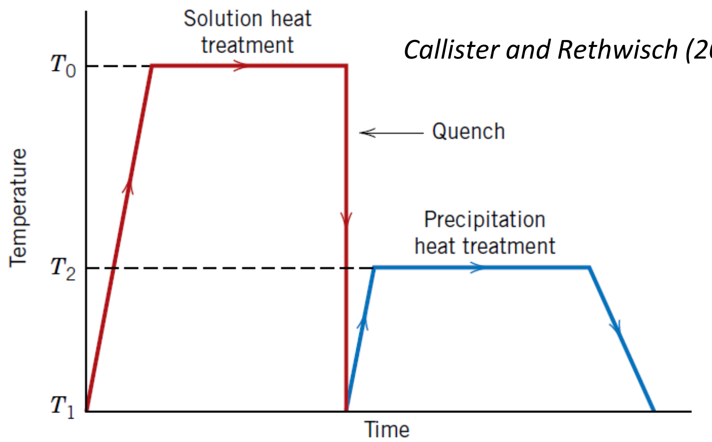
Precipitation hardening or age hardening

- 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)**

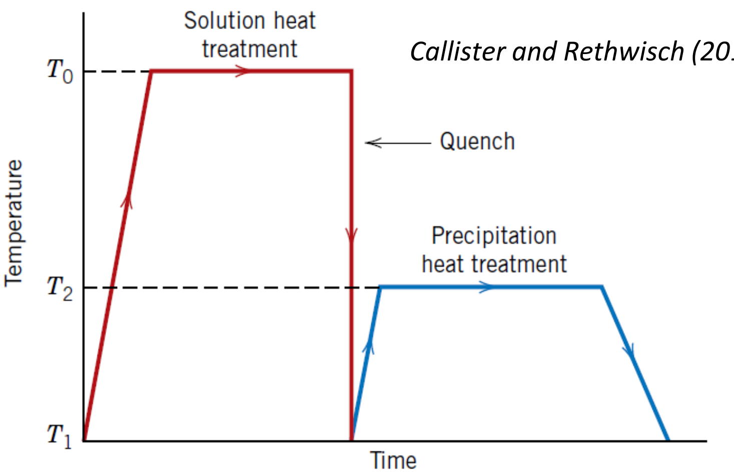
- Caused by **heat treatments** to improve the strength and hardness of metal alloys (e.g. Aluminium-copper alloy)



Callister and Rethwisch (2013)

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**)



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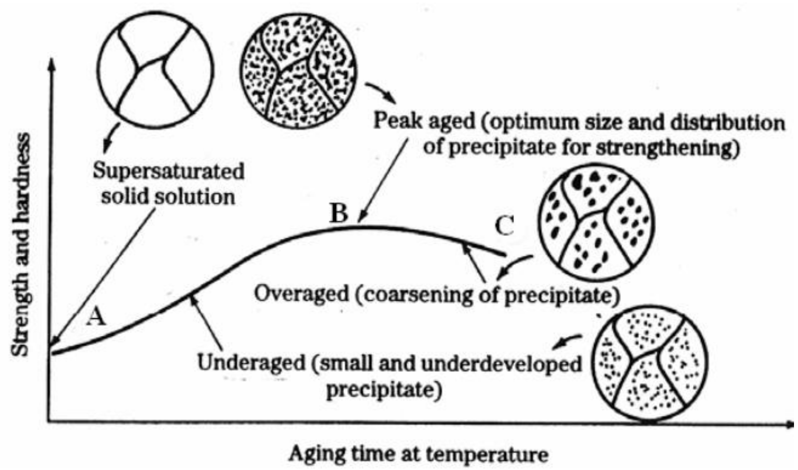
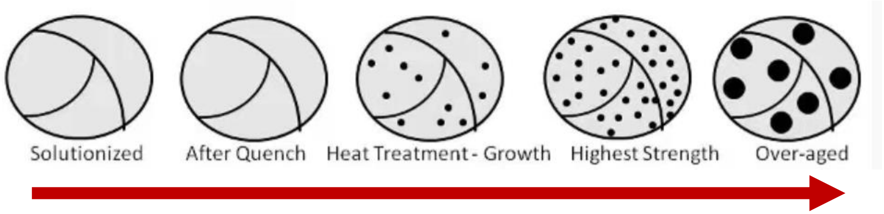
Precipitation hardening or age hardening

- 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)



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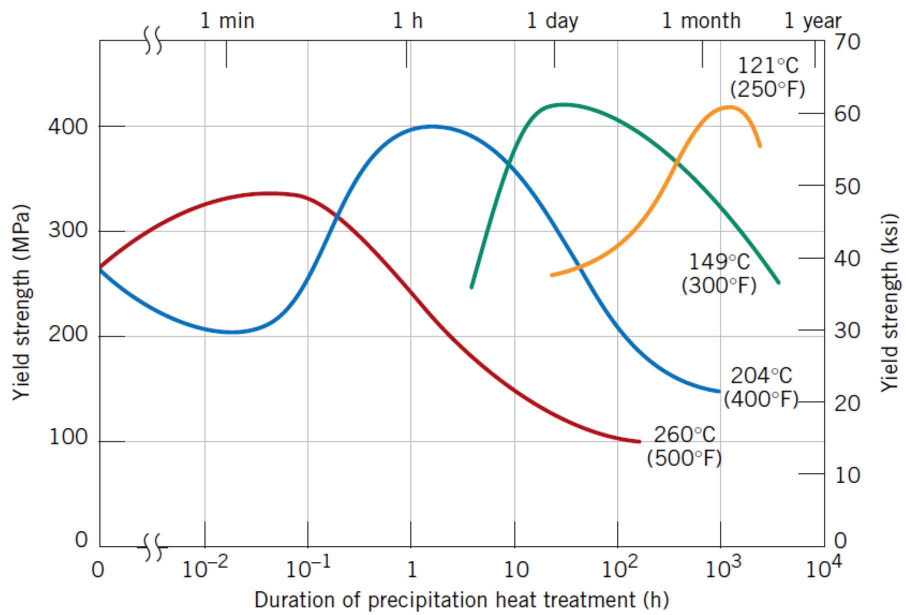
Precipitation hardening or age hardening

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**

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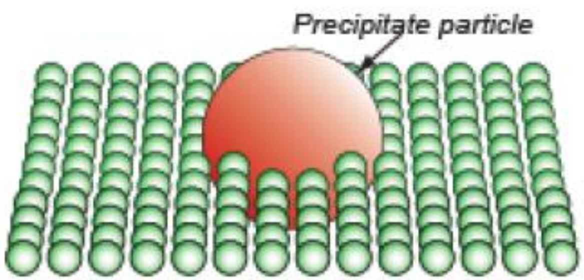
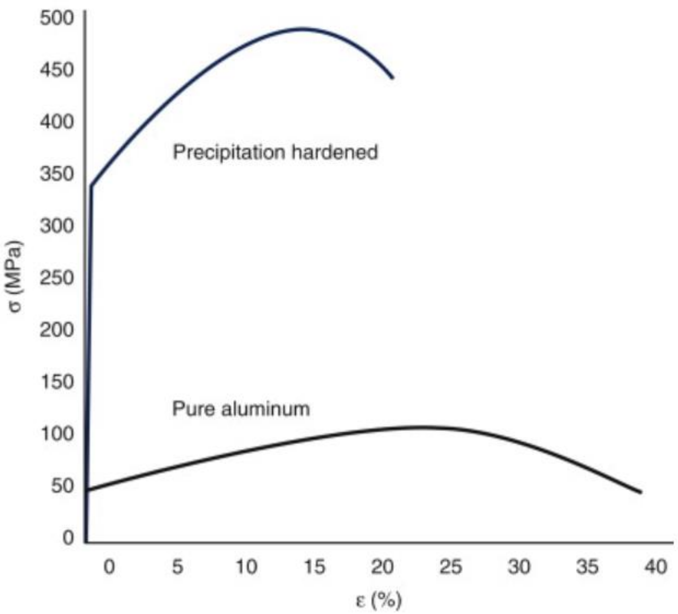
Precipitation hardening or age hardening

- 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



Ansys Granta



Fisher T (2009) Materials Science for Engineering Students

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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

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Quiz time – Which of these statements is true ?

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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

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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

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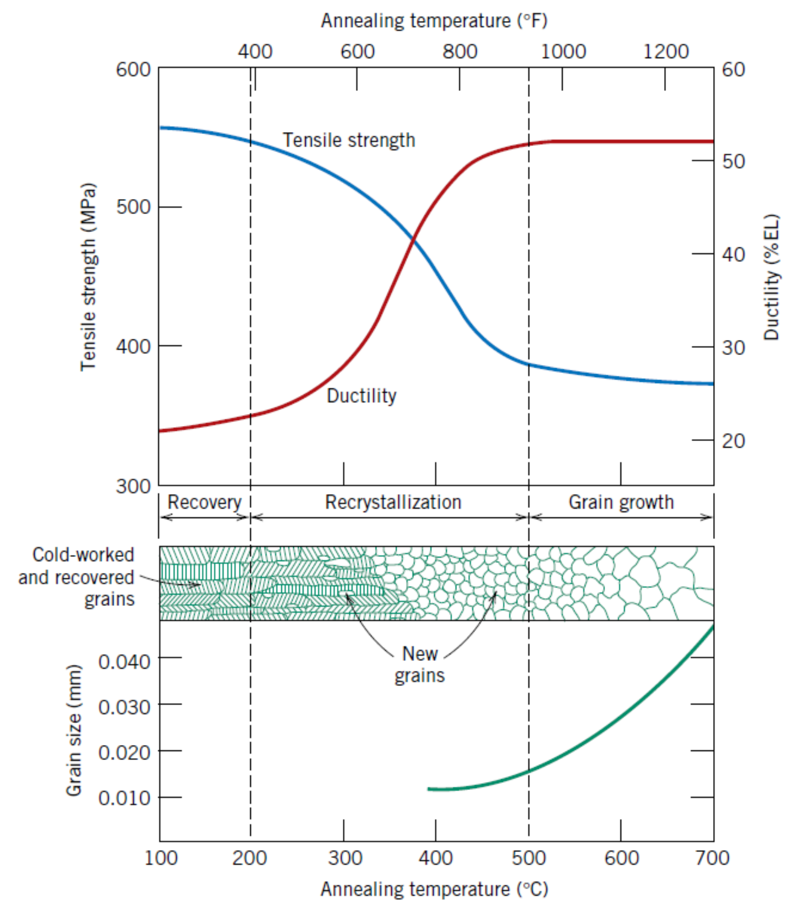
Recovery, recrystallization and grain growth

Callister and Rethwisch (2013)

- **Recovery** → High temperature (heating) → increased dislocation motion → reduction in dislocation density → relieve of **some** of the stored internal strain energy

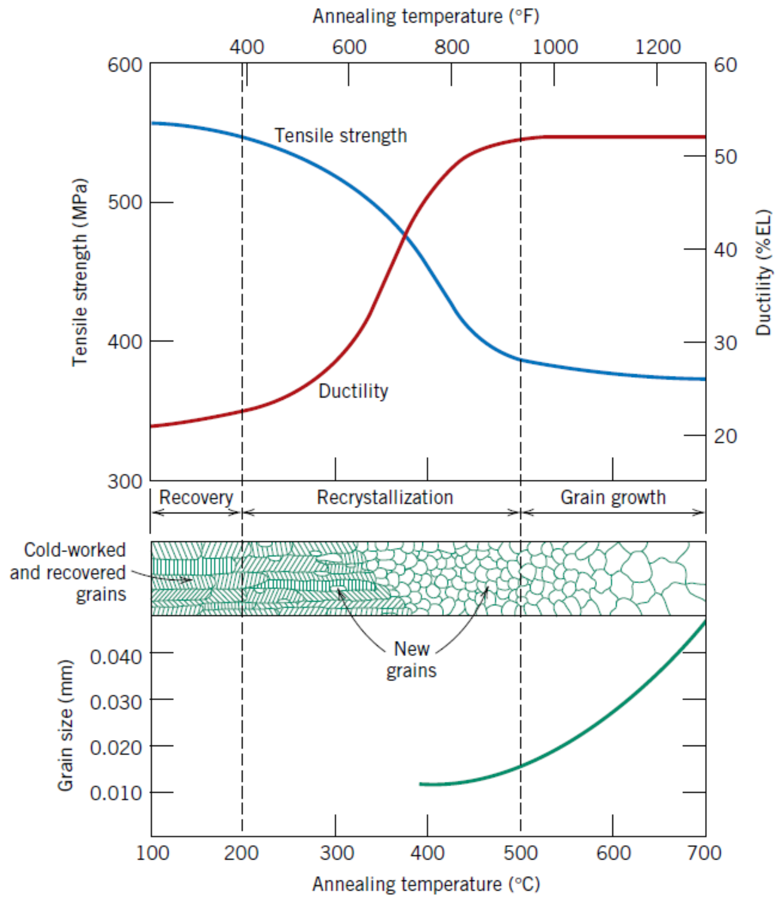
- Even after **recovery**, the grains still have **relatively high strain energy**



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**



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Recovery, recrystallization and grain growth

Callister and Rethwisch (2013)

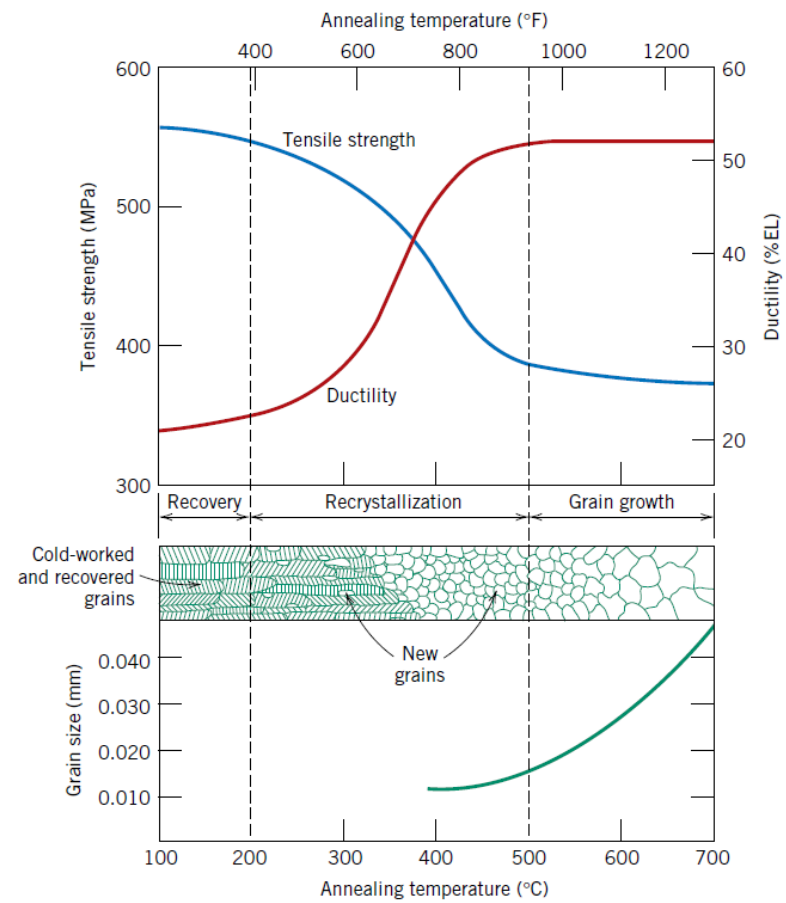
- **Recrystallization temperature** - temperature at which recrystallization reaches completion in one hour

- 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



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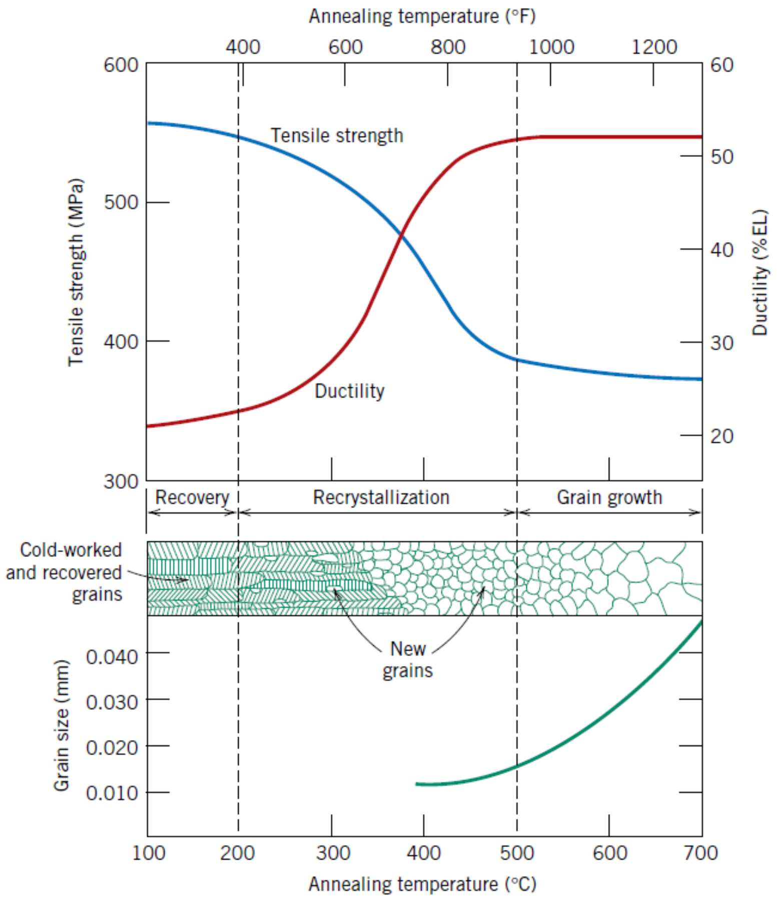
Recovery, recrystallization and grain growth

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



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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

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

Website – [Sli.do](Sli.do)

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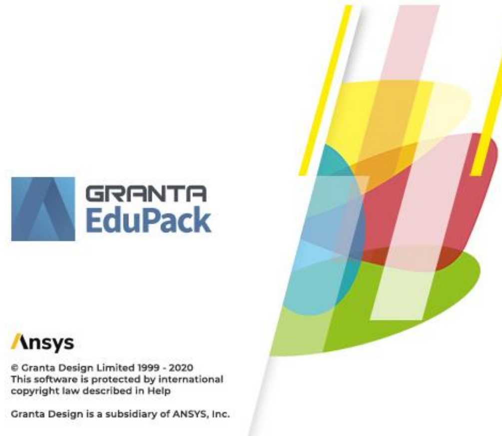
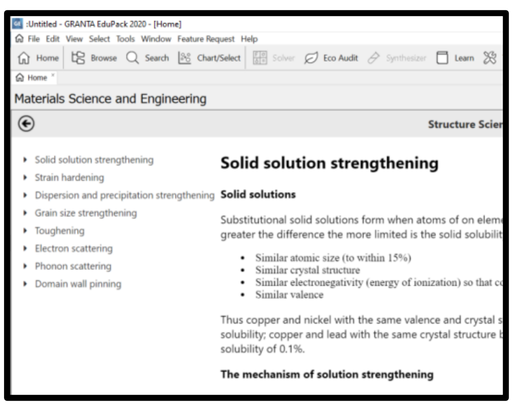
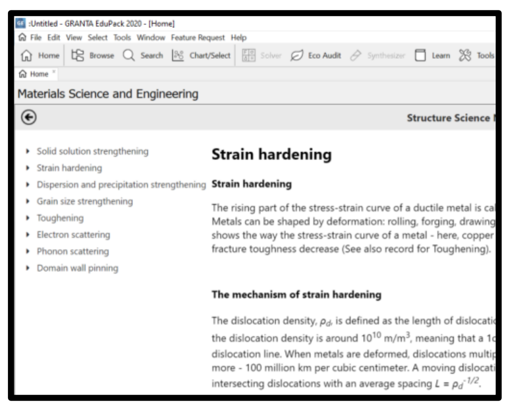
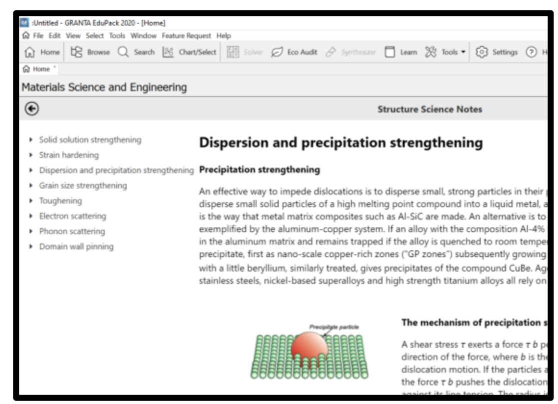
Further Information



Granta Edupack > Materials Science and Engineering > Science Notes > Structure







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Any Questions ???

Coffee Break

We will continue at **<u>11:05am GMT</u>**

Got a question ?

Please use the "**chat**" or **"raise your hand"** functions

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