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Review 4A

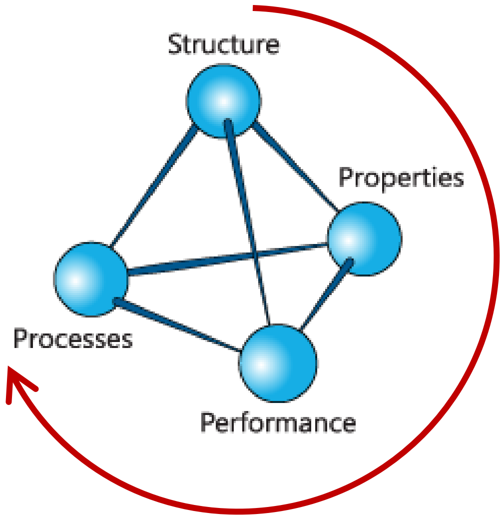
From Processing to Performance

Monday 23rd November 2020

Got a question ?

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

Outline



- Structures and defects of metals
- Phase Diagrams and Microstructures
- Solidification and transformations
- Iron – Carbon Phase Diagram and the Granta EduPack software tool
- Mechanical Properties
- Fracture and Failure
- Strengthening Mechanisms
- SAM project

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Structures and defects

Processing → Structure → Properties → Performance

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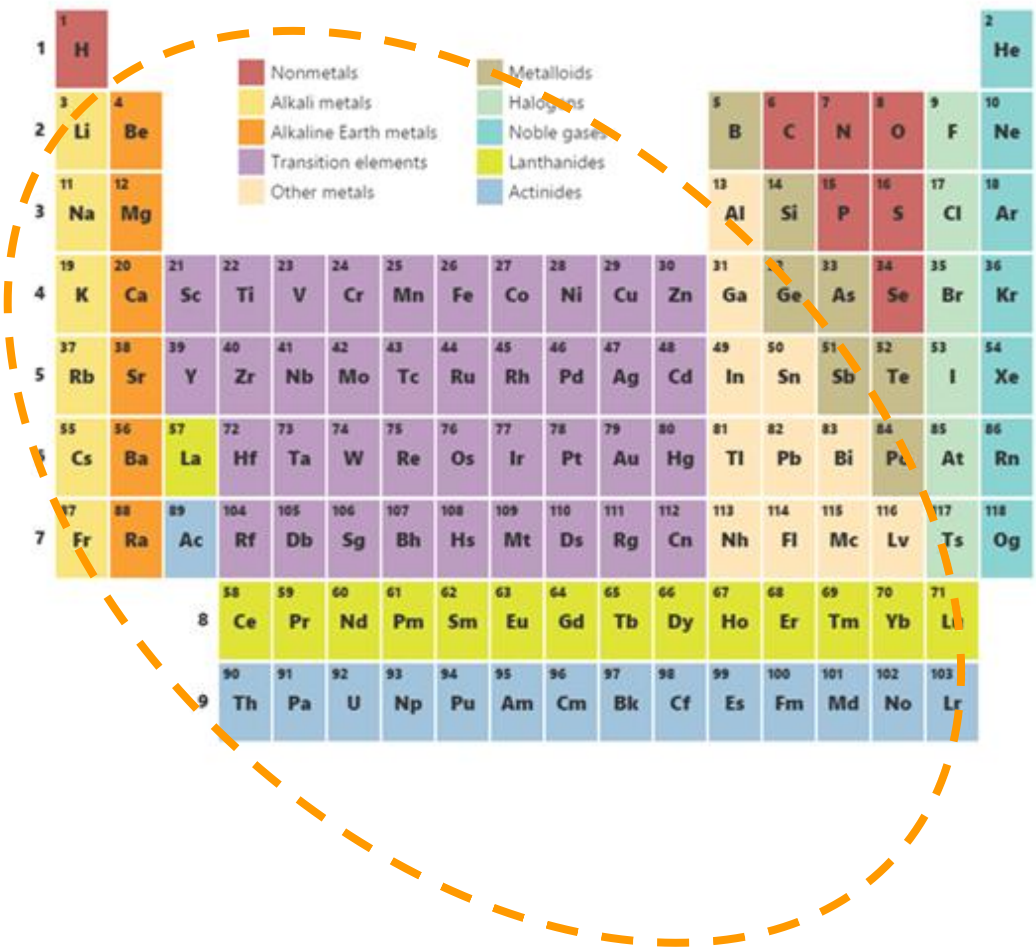
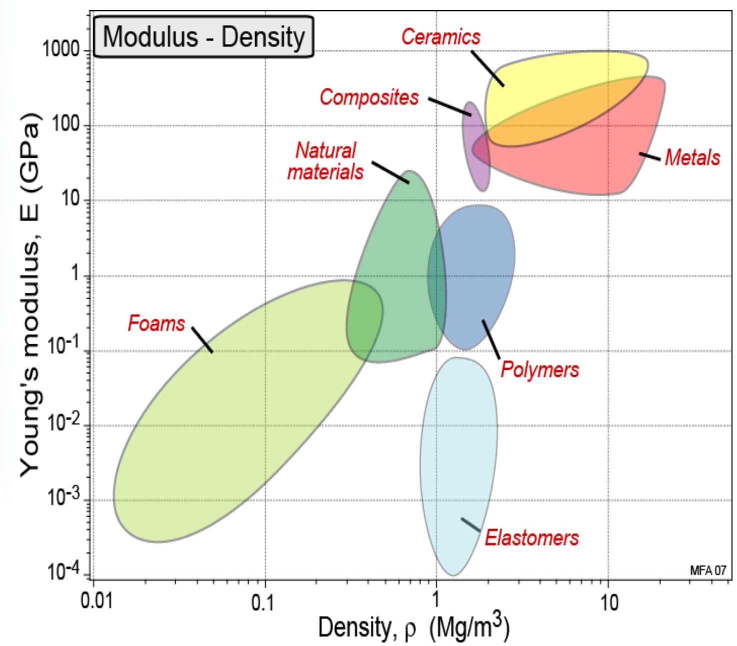
Materials are made from Elements, mostly metals…





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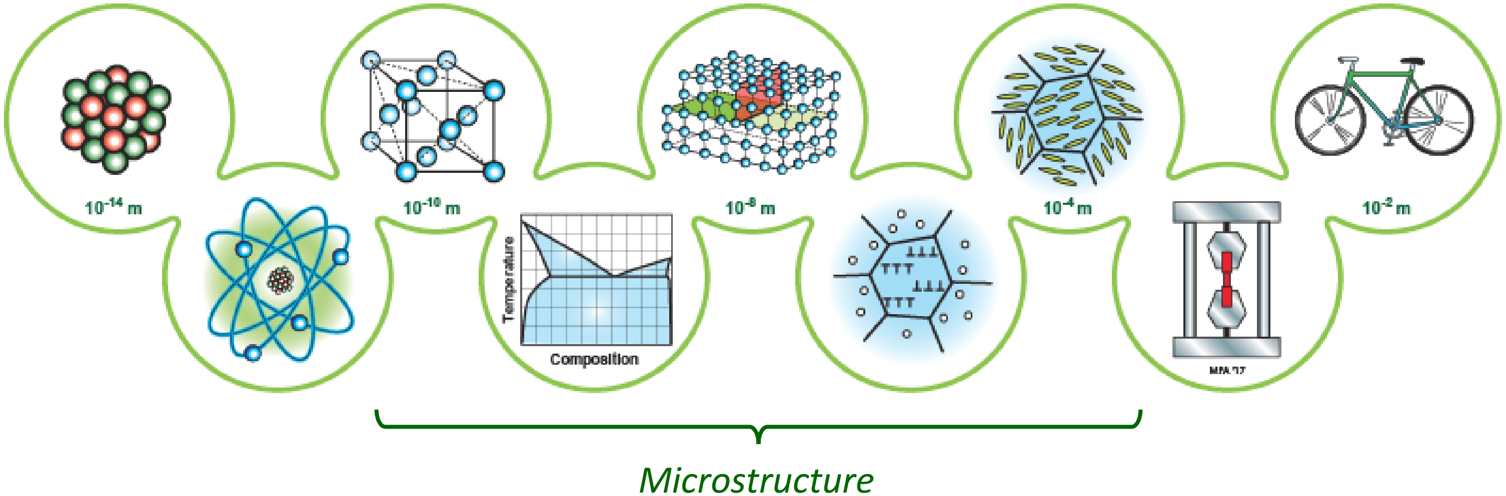
Some Structural Definitions

Most (but not all) solids are *crystalline*. The common engineering metals and ceramics are made up of many small crystals, or *grains.*
These are stuck together at *grain boundaries* to make *polycrystalline aggregates*.
The properties of the material - its strength, stiffness, toughness, conductivity and so forth - are strongly influenced by the underlying crystallinity.
Disordered, or non-crystalline, solids are called *amorphous*



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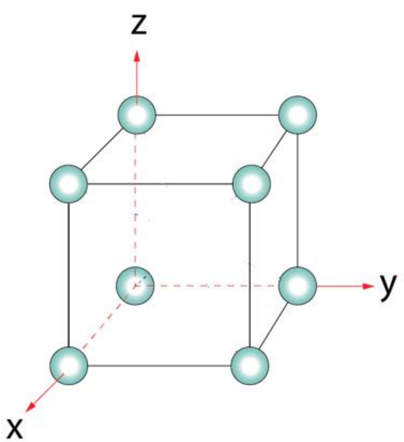
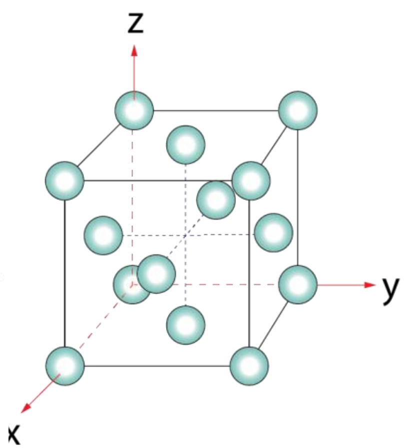
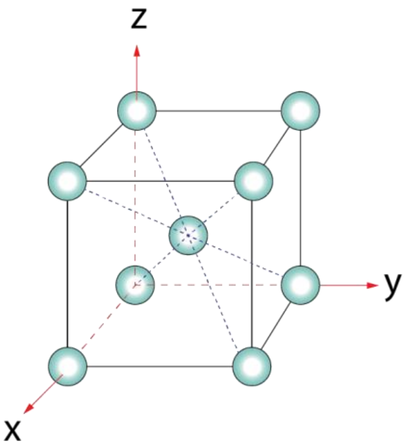
Important Unit Cells of Metals



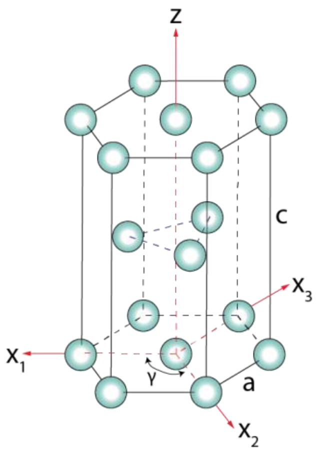
Simple Cubic (SC)



Face-Centered Cubic (FCC)



Body-Centered Cubic (BCC)



Hexagonal Close Packed (HCP)

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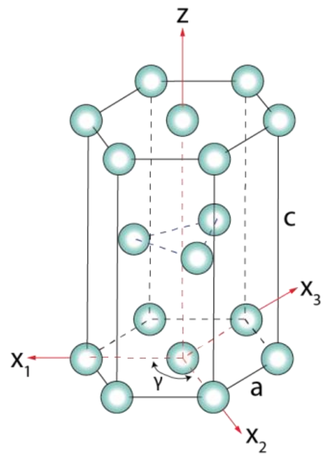
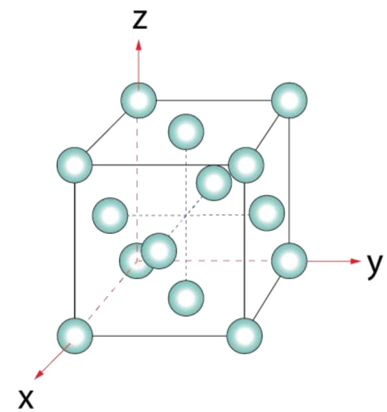
Close Packed Crystal Structures and Crystal Planes

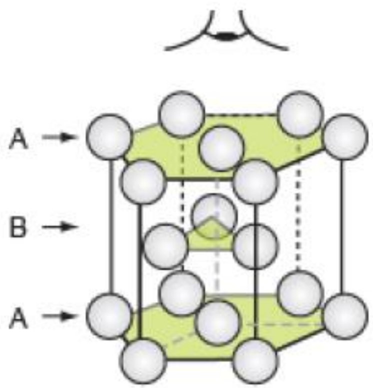


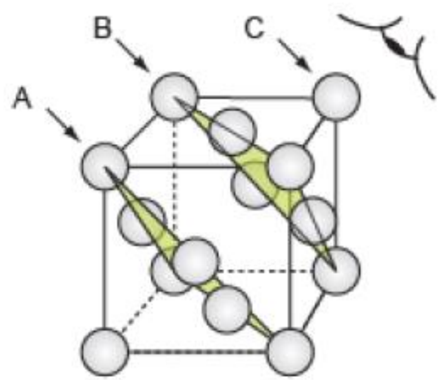
Hexagonal Close Packed (HCP)
Packing density: 74%

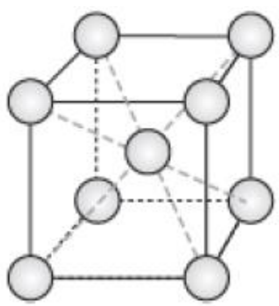


Face-Centered Cubic (FCC)
Packing density: 74%

(No Close Packing in BCC)
Packing density: 68%







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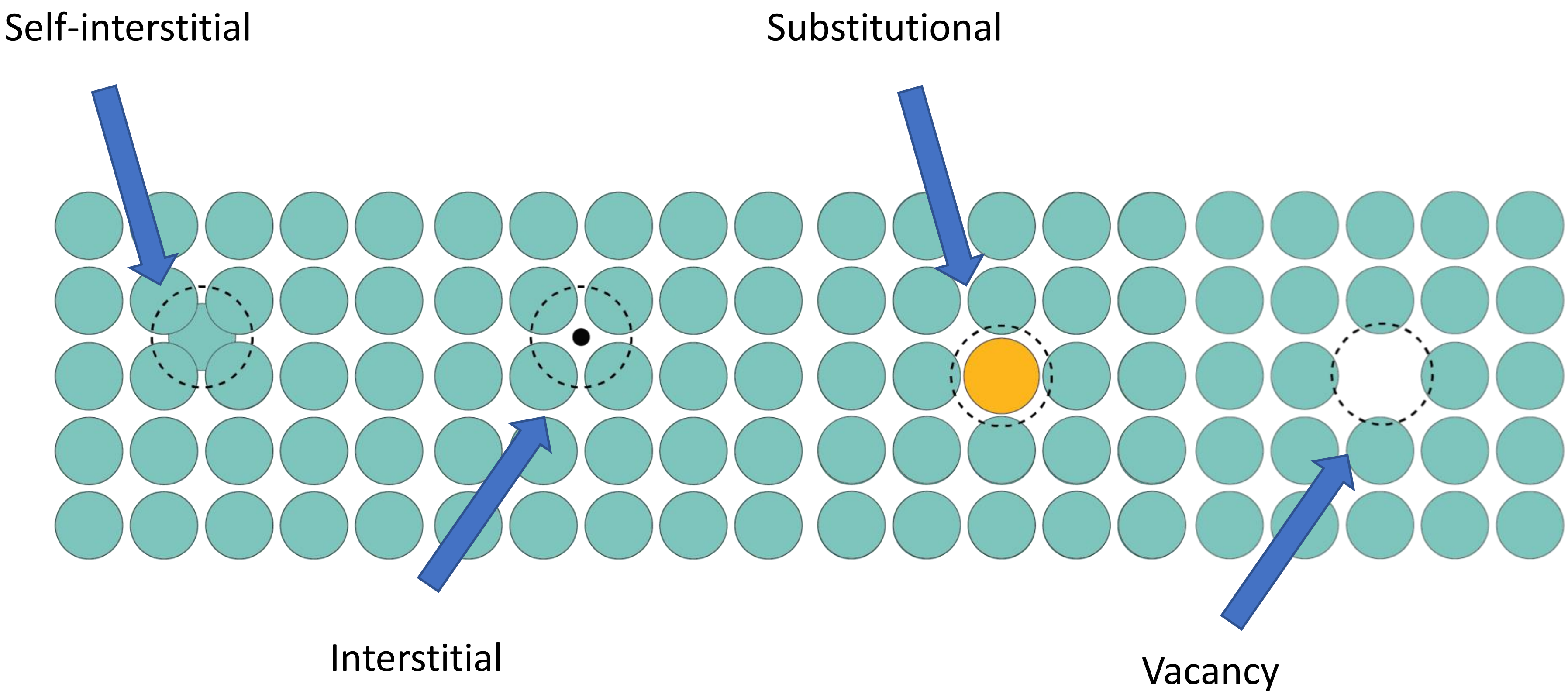
Point Defects



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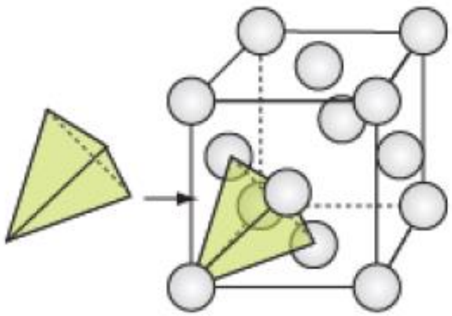
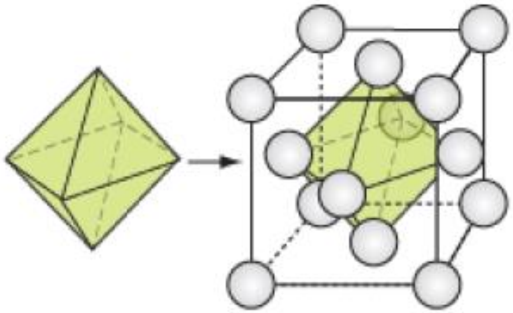
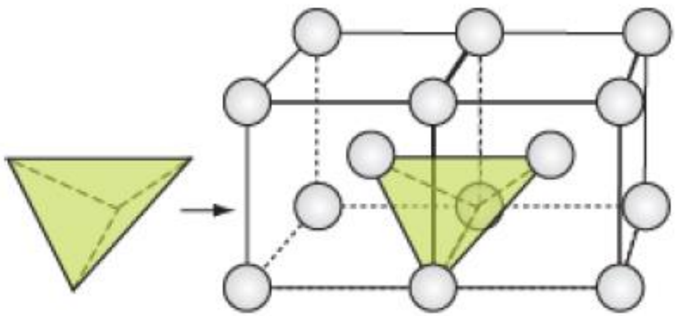
Interstitial holes



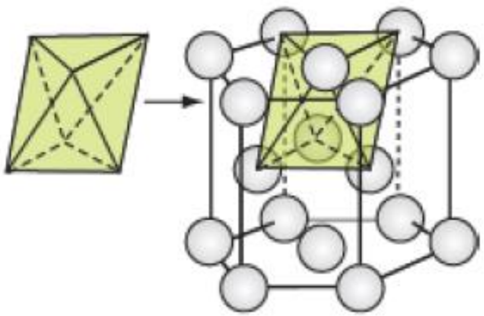
(a) FCC tetrahedral hole



(b) FCC octahedral hole



(c) BCC tetrahedral hole



(d) HCP octahedral hole

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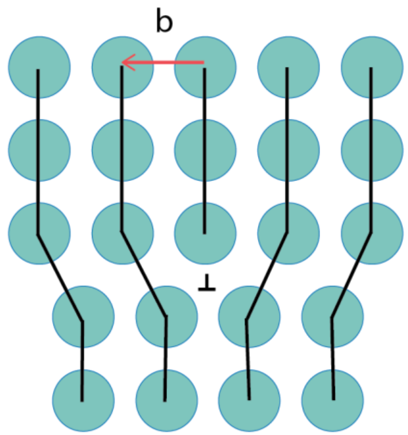
Defects: Dislocations and Grain Boundaries

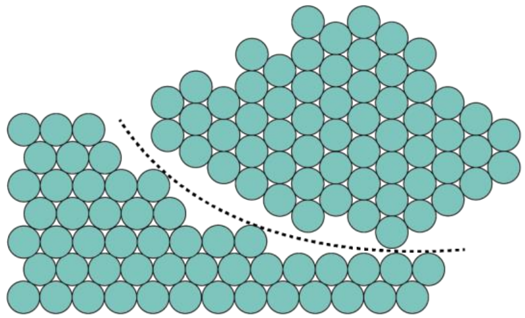
Type of dislocation is defined by the orientation and magnitude of the lattice distortion or the so-called Burger's Vector, b. Grain boundaries are of course, also an interruption of the crystal structure

Edge Dislocation

b ⊥ to the dislocation line



Grain Boundaries



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Phase Diagrams and microstructures

Processing → Structure → Properties → Performance

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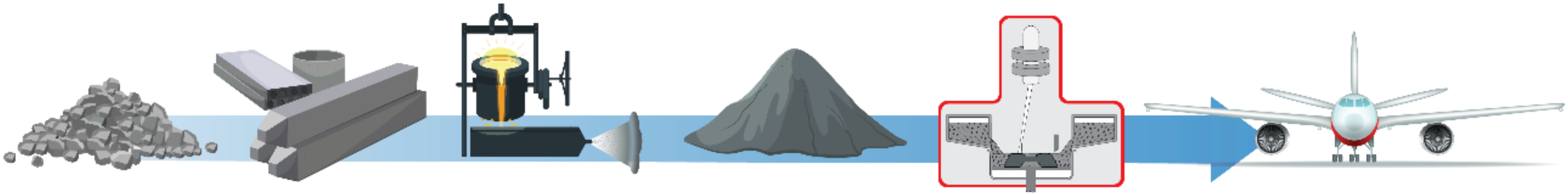
Why do phases matter to manufacture?

Metals are melted and solidified during *casting* and *welding,* but also during *atomization* (metal powder making) and *powder bed fusion* **AM** by *laser* or *electron beam*



Equilibrium ***phase diagrams*** are one step towards understanding metal microstructures and properties after melting or heat treatments. ***Phase transformations*** another.

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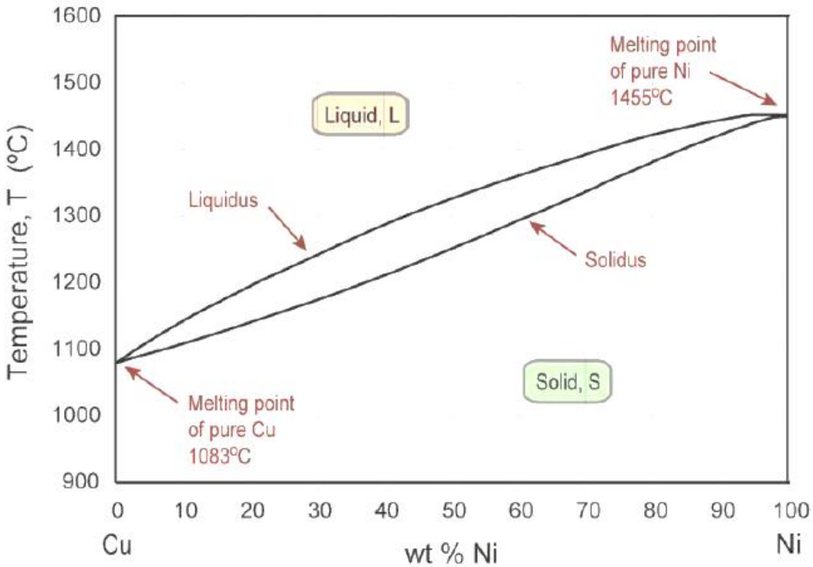
What is a binary metal alloy?

Binary Isomorphous Phase Diagrams



DEF: A *metallic alloy* is a mixture of a metal with other metals or non-metals.

DEF: The *components* are the chemical elements that make up alloys (here, atoms)

DEF: A *binary alloy* contains two components.

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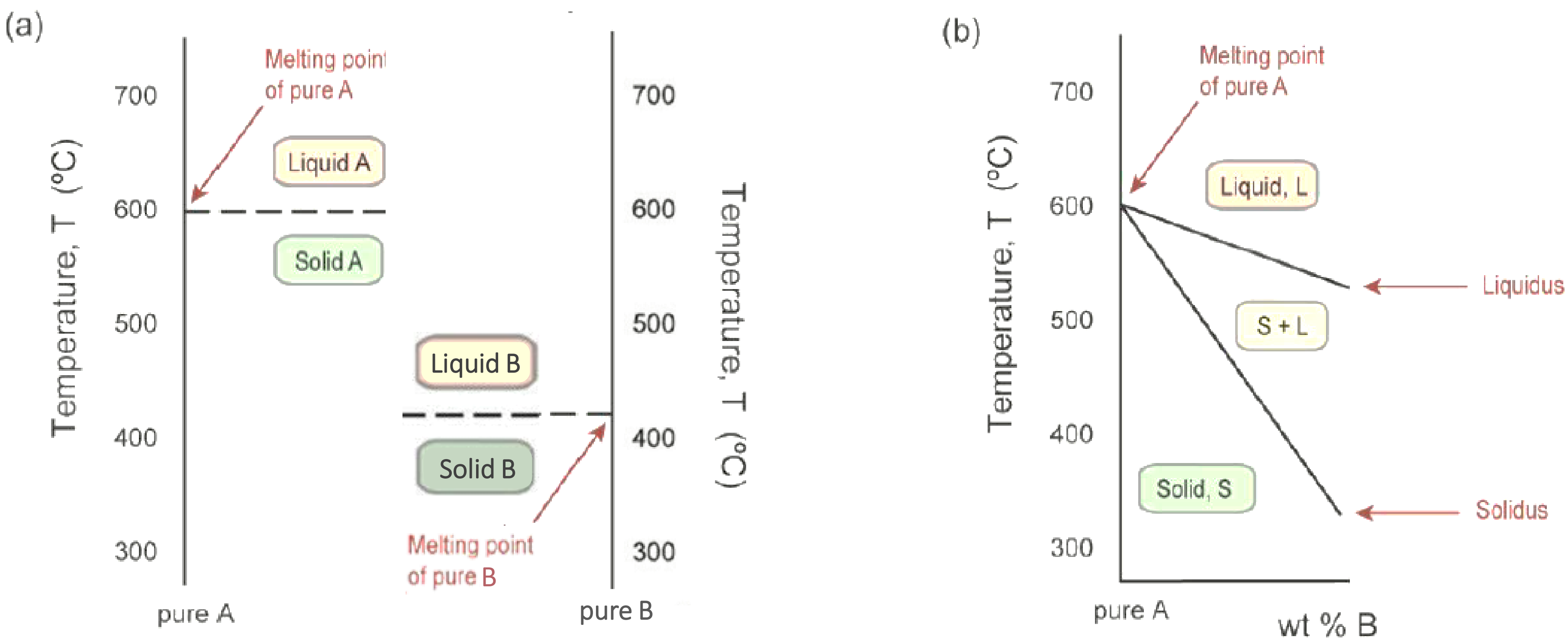
Mixing two metals with different melting point



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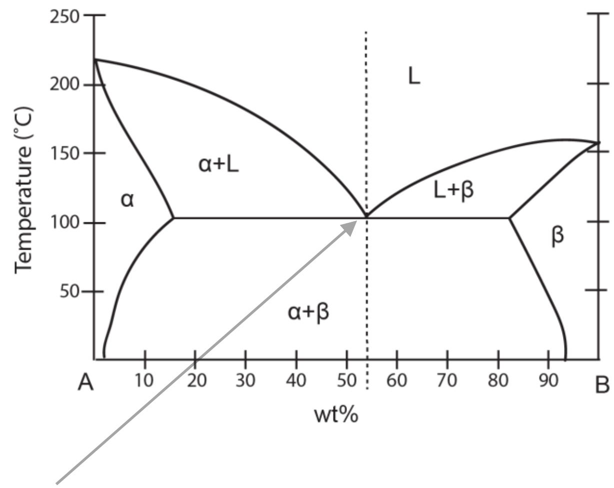
Binary Eutectic Phase Diagram

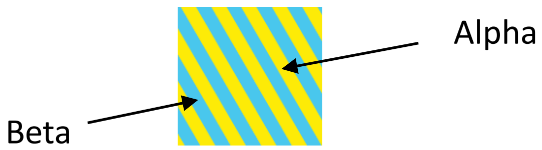
DEF: The lower limit of the single-phase liquid field formed by the intersection of two liquidus lines is called the *eutectic point*.

- Incomplete solubility within the solid phases
- Leads to a *eutectic reaction* at a specific composition and temperature
- Where the liquid solidifies into two unique solids, alpha and beta



Reaction: $L \leftrightarrow \alpha + \beta$

Microstructure:



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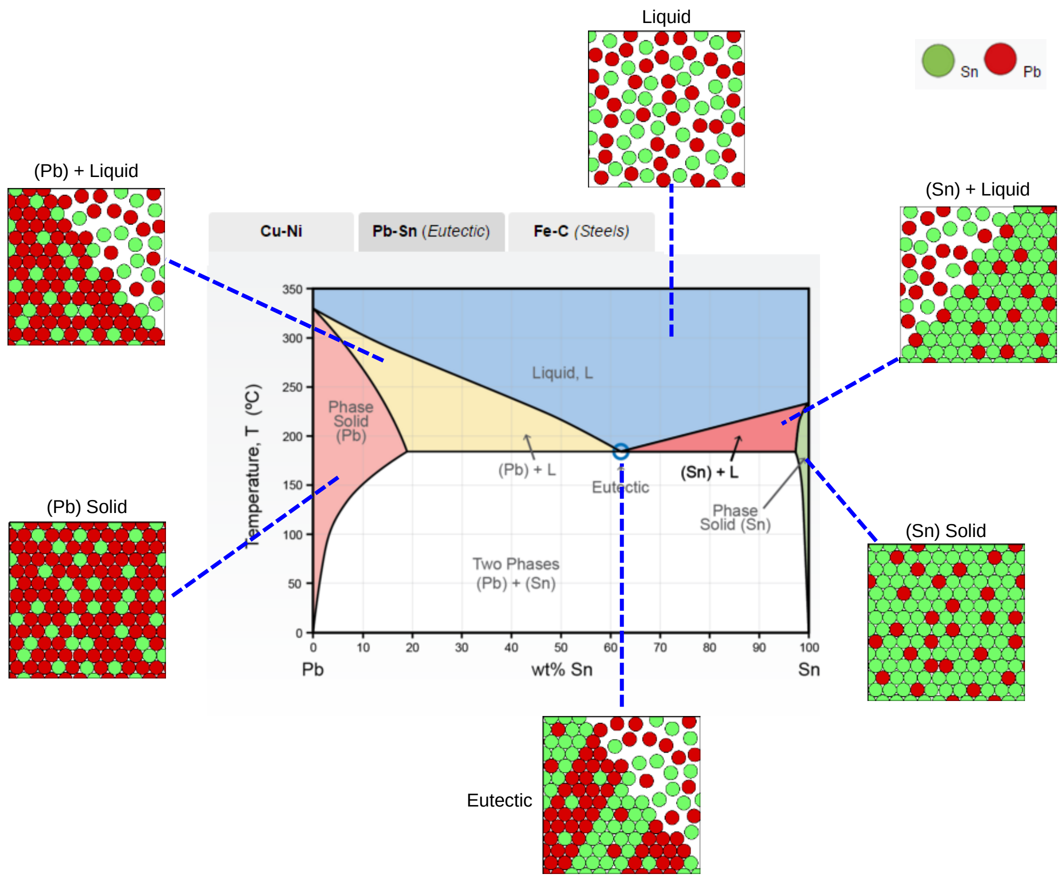
Microstructures and Phase Diagrams

Phase Diagrams

- Phase Diagram glossary
- Lever Rule
- Phases
- Cooling paths
- Phase diagram datatable



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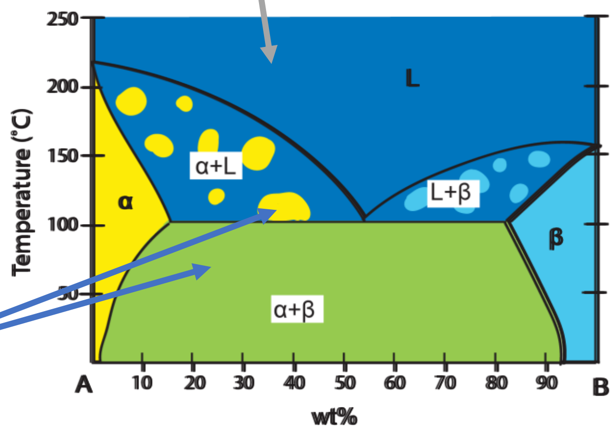
Phase Fractions within Systems

In a single-phase regions, identifying phase fractions is simple

Understanding what phases will be found at specific composition and temperature is incredibly important for alloy development



In two-phase regions, the Lever Rule is needed to calculate the phase fractions

DEF: In a single-phase region, phase and alloy compositions coincide. In a two-phase region the phase compositions lie on the phase boundaries at either end of a horizontal tie-line through the constitution point.

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Lever Rule

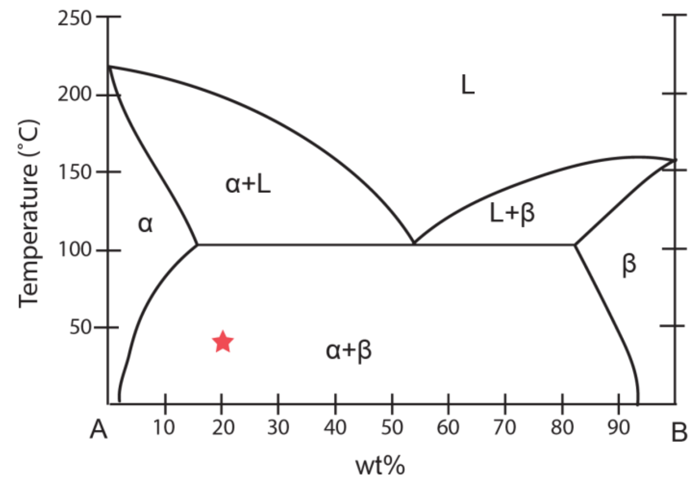
Used to calculate various phase and microconstituent fractions for two phase regions of binary phase diagrams

$$W_\alpha = \frac{C_0 - C_\beta}{C_\alpha - C_\beta} = \frac{20 - 90}{5 - 90} = \frac{-70}{-85}$$

$$= 0.824 = 82.4 \text{ wt\%}$$

$$W_\beta = \frac{C_\alpha - C_0}{C_\alpha - C_\beta} = \frac{5 - 20}{5 - 90} = \frac{-15}{-85}$$

$$= 0.176 = 17.6 \text{ wt\%}$$



Information needed:
composition and temperature of interest.
e.g.: 20 wt.% B and 50 ˚C

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Solidification and transformation

Processing → Structure → Properties → Performance

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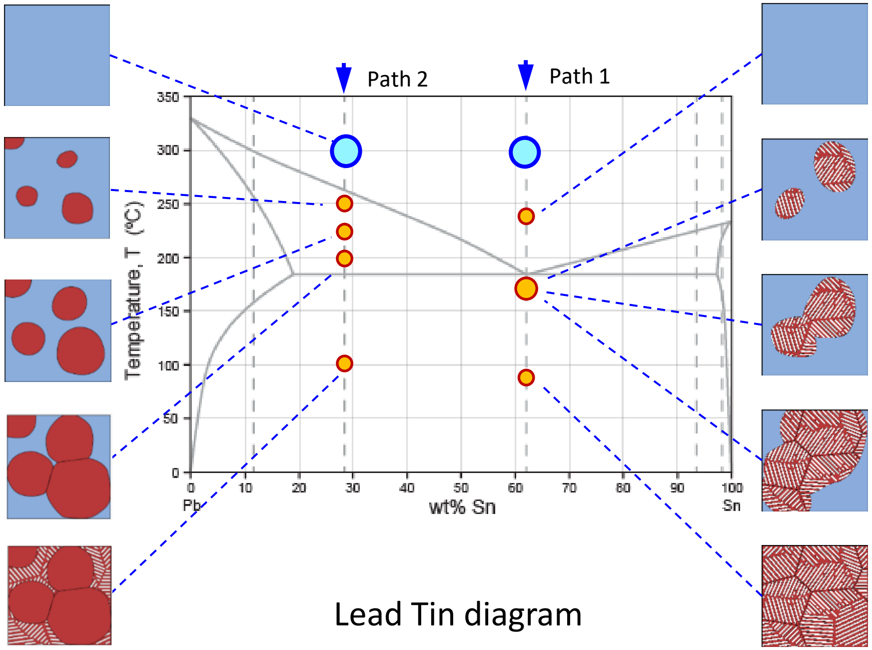
Microstructure Evolution

- As alloys solidify, their microstructure will evolve based on the composition
- Phase diagrams can help give insight as to what microstructure will form



Lead Tin diagram

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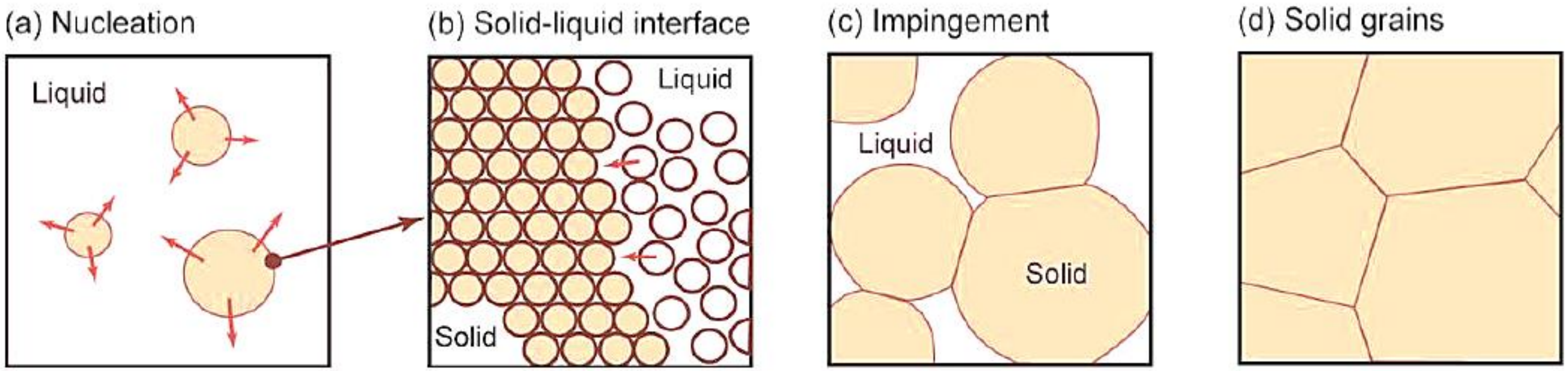
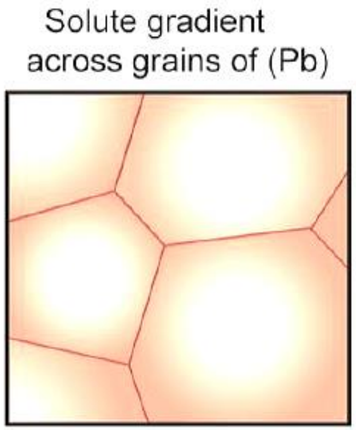
Homogeneous nucleation process and *growth*



- There can also be *Heterogeneous* nucleation and growth from a pre-existing surface
- Grains form due to differences in orientation at impingement.
- Segregation occurs due to gradual change in liquid composition during solidification.



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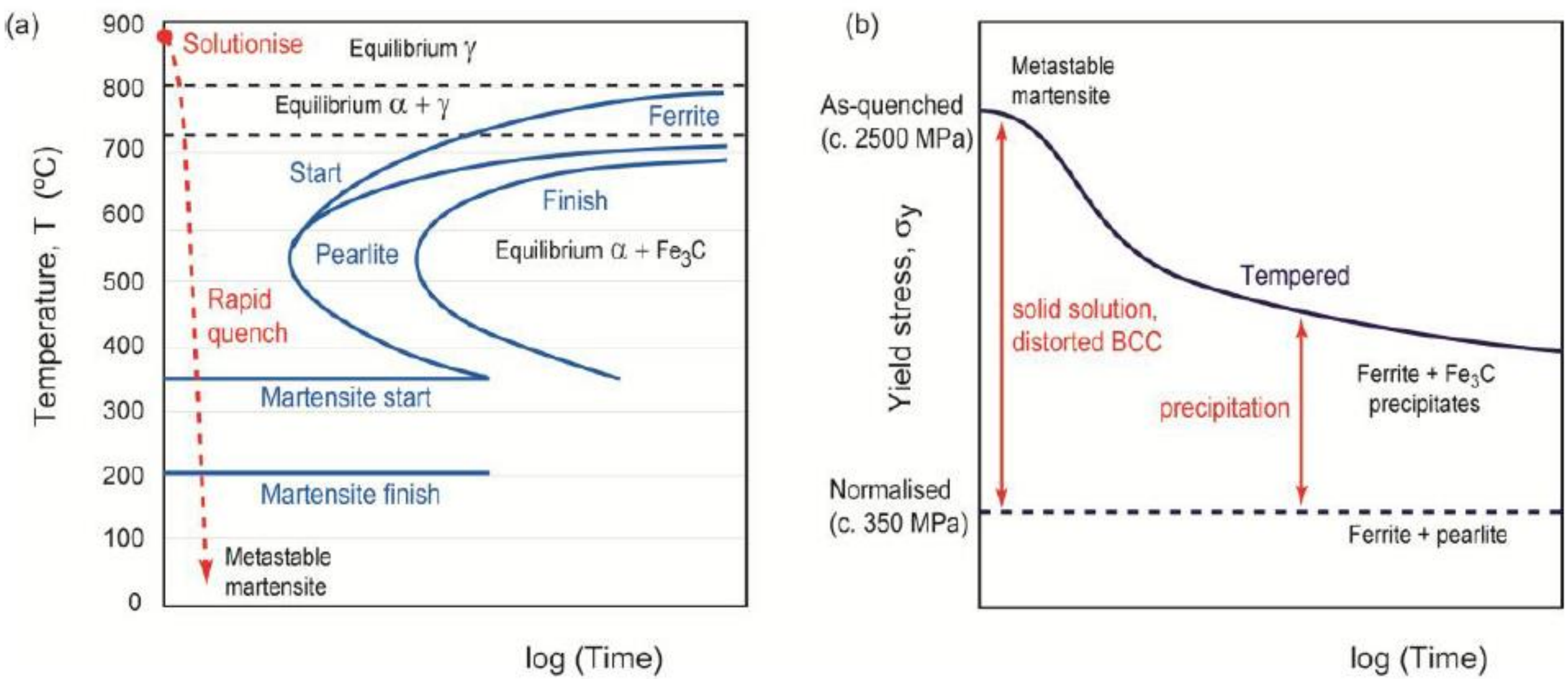
Martensite start and finish on a TTT diagram



Evolution of yield stress during tempering of carbon steels after quenching

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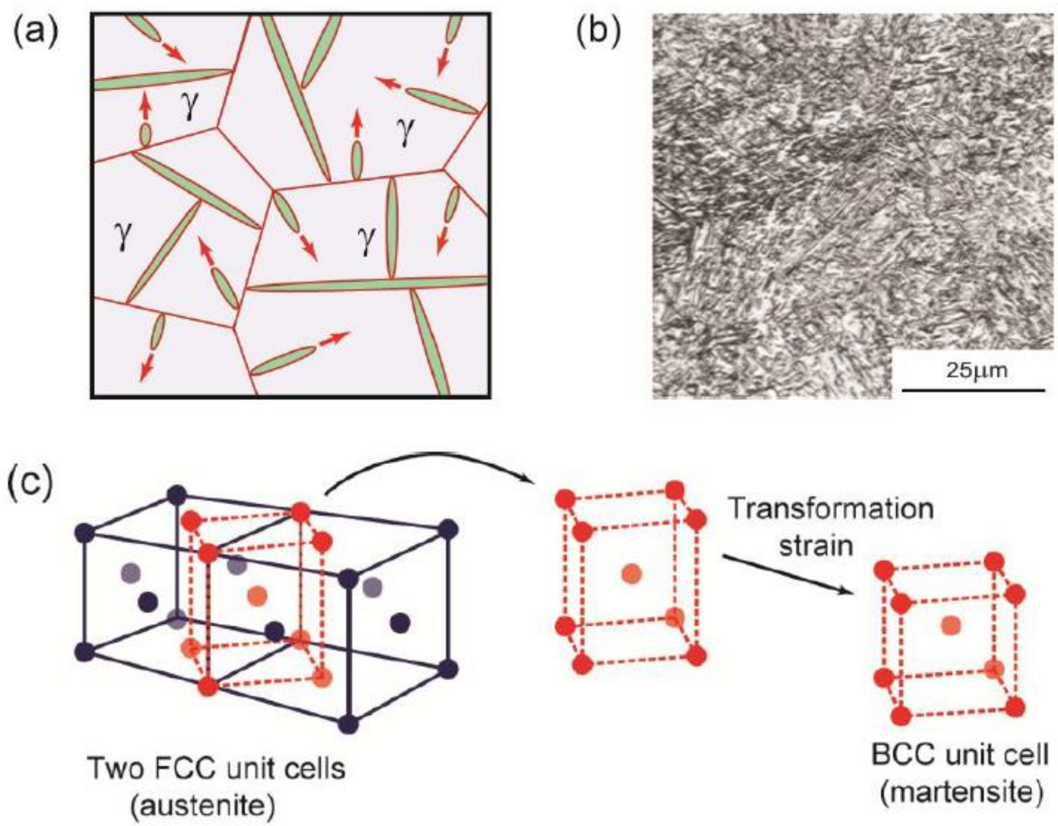
Martensite transformation



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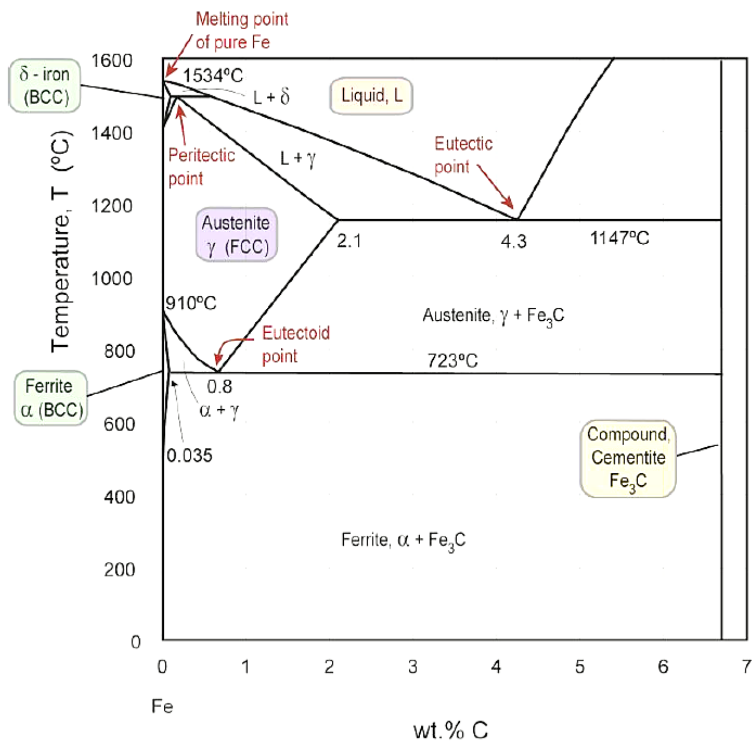
The Iron – Carbon phase diagram: EduPack MS&E



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Mechanical Properties of Metals and Alloys

Processing → Structure → **Properties** → Performance

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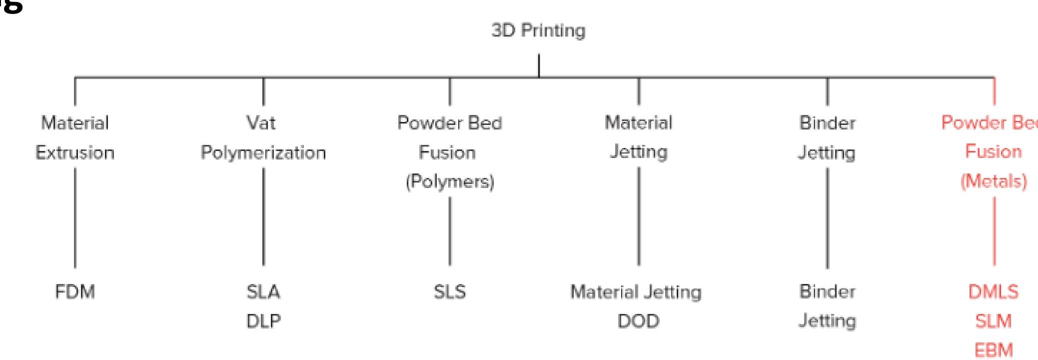
How does Additive Manufacturing compare?

Examples of Metals for Additive Manufacturing

- Aluminium alloys
- Titanium alloys
- Steel



Examples of Powder Bed Fusion processes for metals

- Selective Laser Melting (SLM)
- Direct Metal Laser Sintering (DMLS)
- Electron Beam Melting (EBM)

Source: 3Dhubs.com - https://www.3dhubs.com/knowledge-base/introduction-metal-3d-printing/

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How does Additive Manufacturing compare?

- Excellent properties
- "Almost" isotropic
    - Internal porosity
- Surface quality and roughness
    - Fatigue strength (i.e. imperfection, crack initiation)

	AlSi10Mg (3D printing alloy)	A360 (Die cast alloy)
Yield Strength (0.2% strain) *	XY : 230 MPa Z : 230 MPa	165 MPa
Tensile Strength *	XY : 345 MPa Z : 350 MPa	317 MPa
Modulus *	XY : 70 GPa Z : 60 GPa	71 GPa
Elongation at break *	XY : 12% Z : 11%	3.5%
Hardness **	119 HBW	75 HBW
Fatigue Strength **	97 MPa	124 MPa

* : Heat treated: annealed at 300&#8451 for 2 hours ** : Tested on as-built samples

Source: 3Dhubs.com - https://www.3dhubs.com/knowledge-base/introduction-metal-3d-printing/

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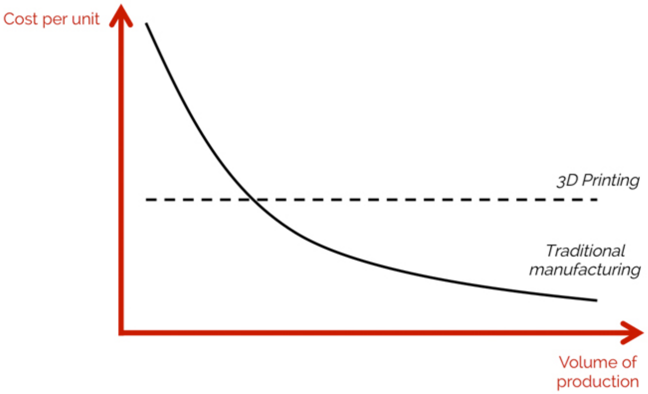
How does Additive Manufacturing compare?

Additional factors

- Complex and bespoke designs
  - Topology optimisation
  - Lightweight design
- Material and Manufacturing Cost
  - Machine cost
  - Time cost
  - Post-processing (powder)



An example of a topologically optimised design with a reduction in weight
Source: 3dnatives - https://www.3dnatives.com/en/why-3d-printing230720184/#!

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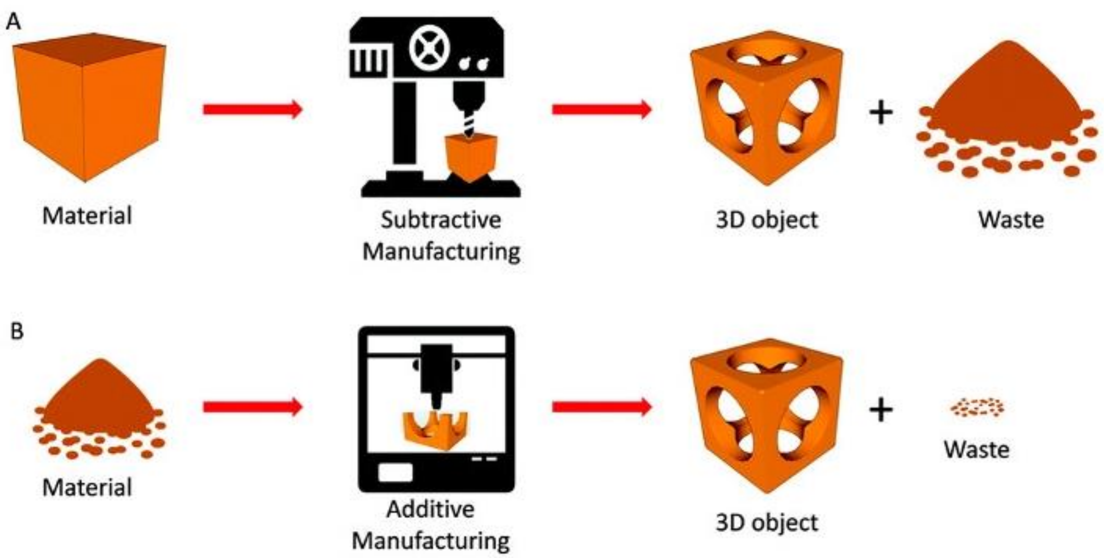
How does Additive Manufacturing compare?

Additional factors

- Waste
- Size limitations (i.e. build platform)



Source: 3dnatives - https://www.3dnatives.com/en/3d-printing-vs-cnc-160320184/

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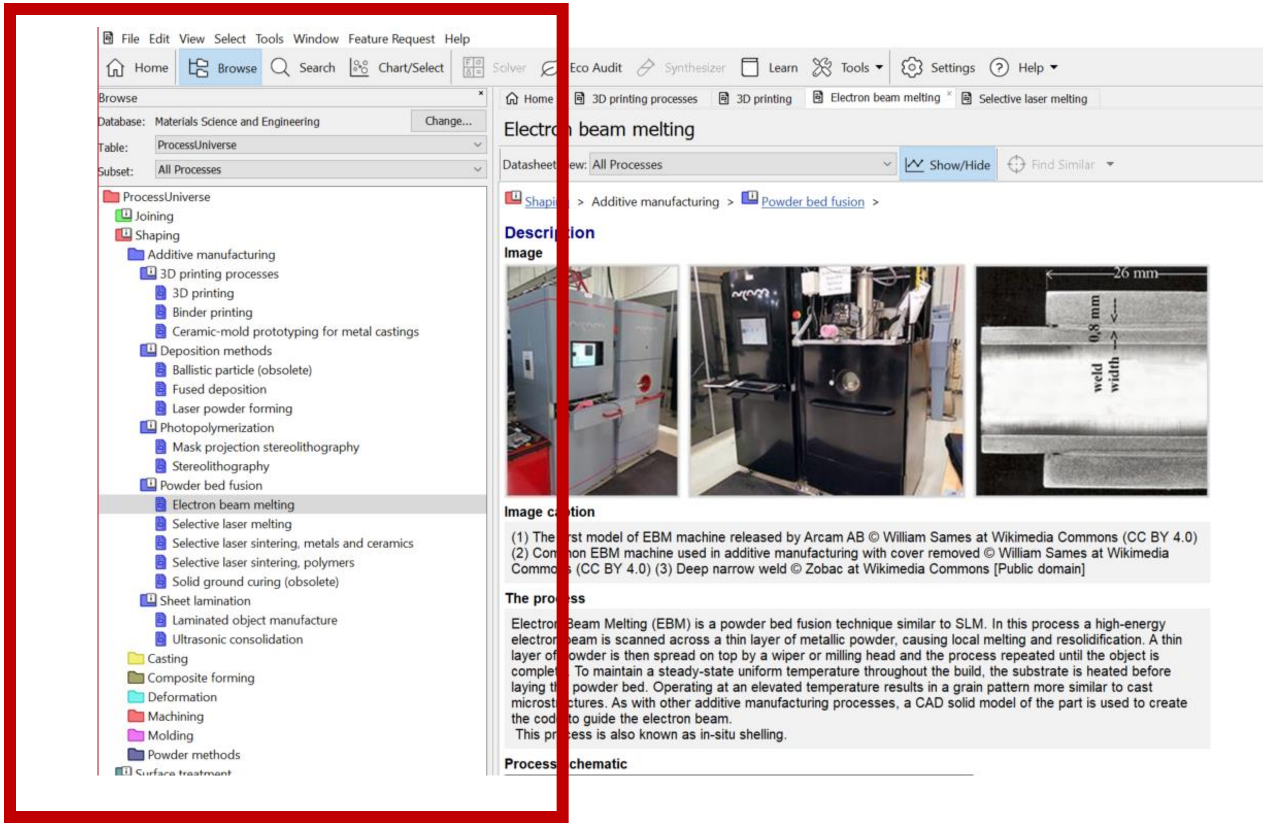
How does Additive Manufacturing compare?

Granta EduPack



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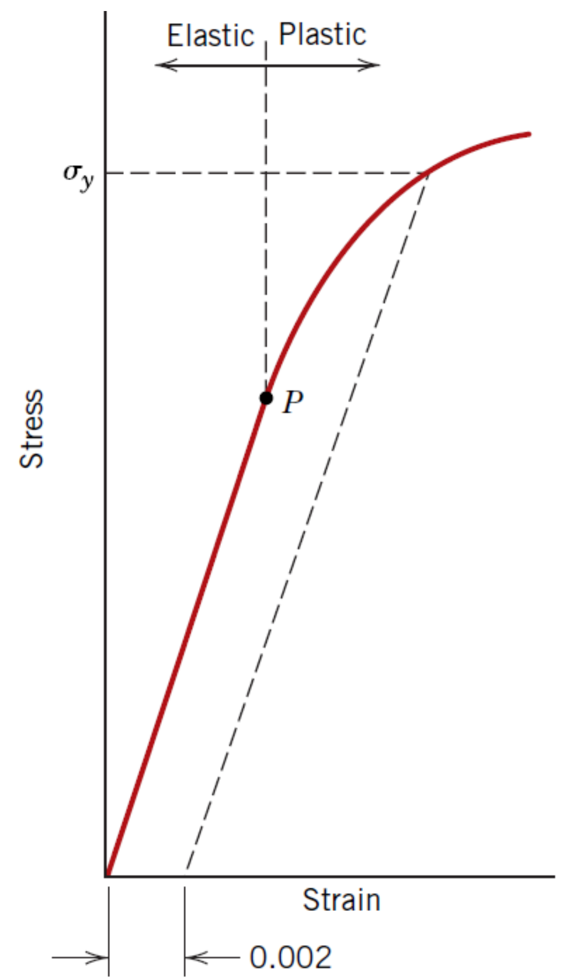
Elastic and Plastic deformation

- **Elastic deformation**
  - **Reversible**: when the stress is removed, the material **returns** to its original dimensions
- **Plastic deformation**
  - **Irreversible**: when the stress is removed, the material **does not return** to its original dimensions
- Most materials and structures are designed to ensure that **only elastic deformation** will occur when loading/stress is applied



Callister and Rethwisch (2013)

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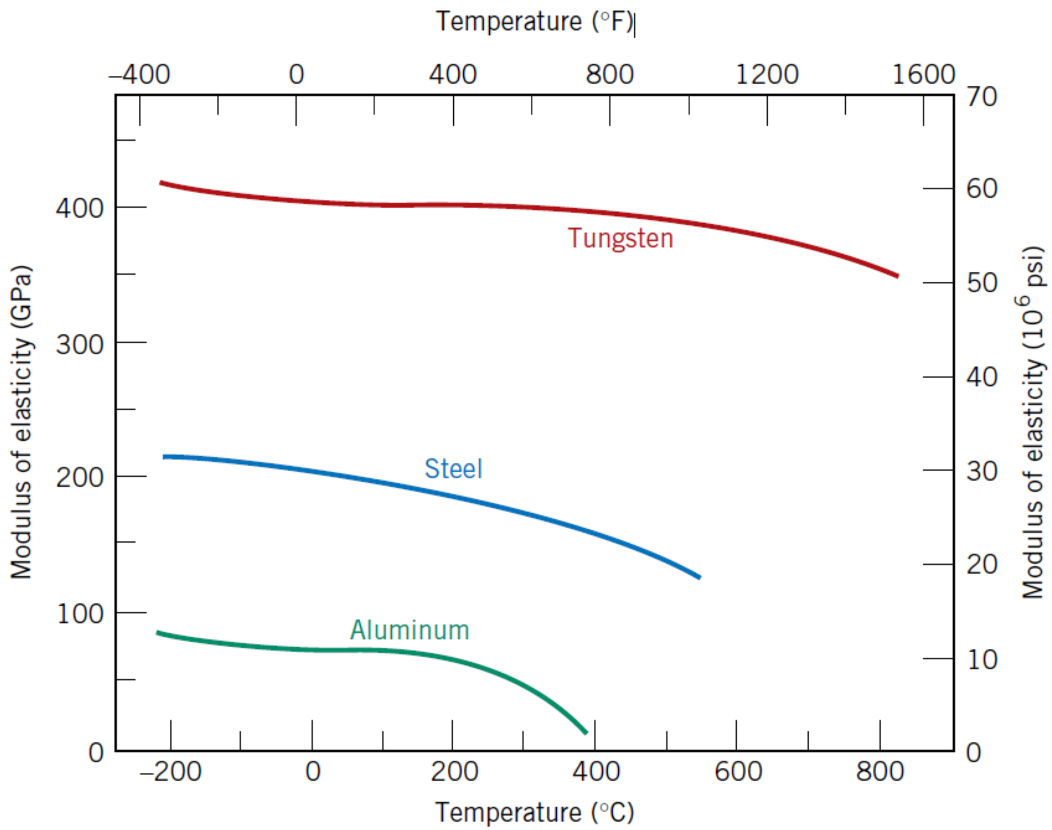
Influence of temperature on modulus of elasticity for metals



Callister and Rethwisch (2013)

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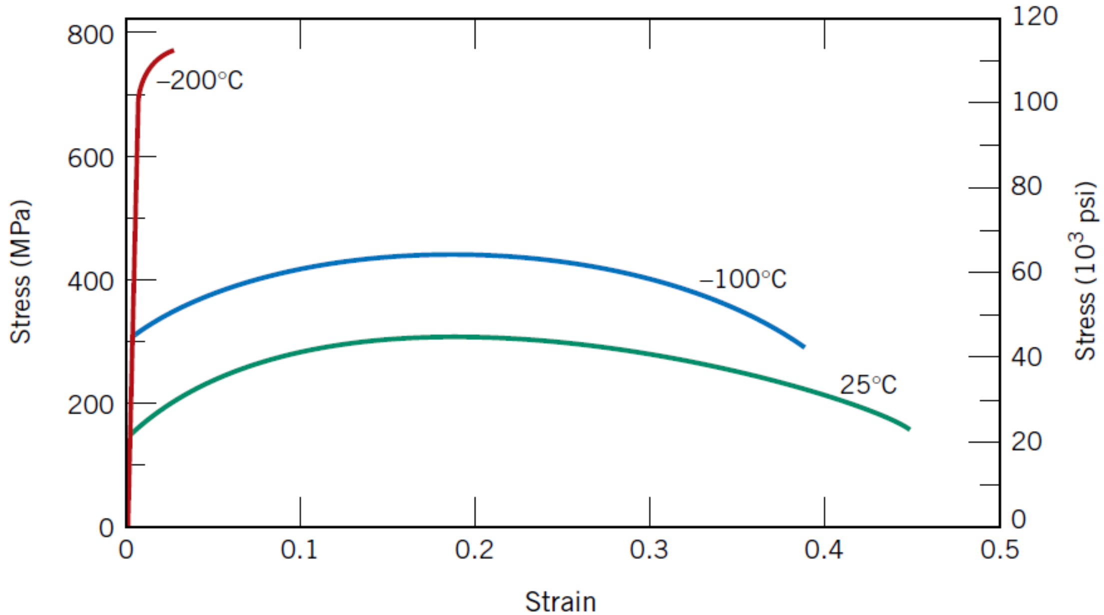
Influence of temperature on Iron



Callister and Rethwisch (2013)

Higher temperature

- Yield strength ↓
- Tensile strength ↓
- Ductility ↑

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Fracture and Failure mechanisms

Processing → Structure → Properties → Performance

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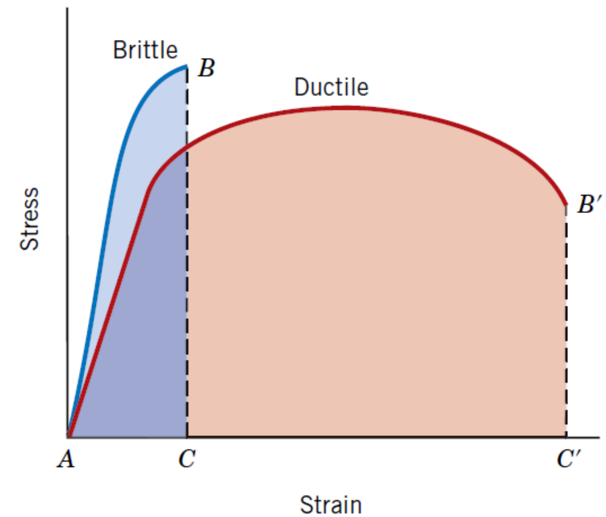
Fracture

- Two major fracture modes of Metals : **Ductile** and **Brittle**
- **Ductile fracture**
  - Substantial plastic deformation before fracture
- **Brittle fracture**
  - Little or no plastic deformation before fracture



Callister and Rethwisch (2013)

Ductile fracture

Cup-and-cone fracture in aluminium
(extensive plastic deformation)

Brittle fracture

Brittle fracture in a mild steel
(rapid crack propagation)

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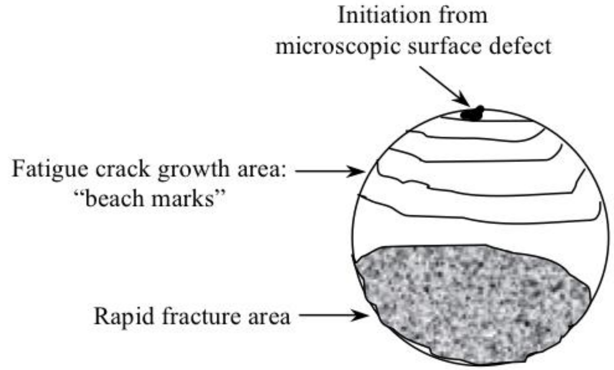
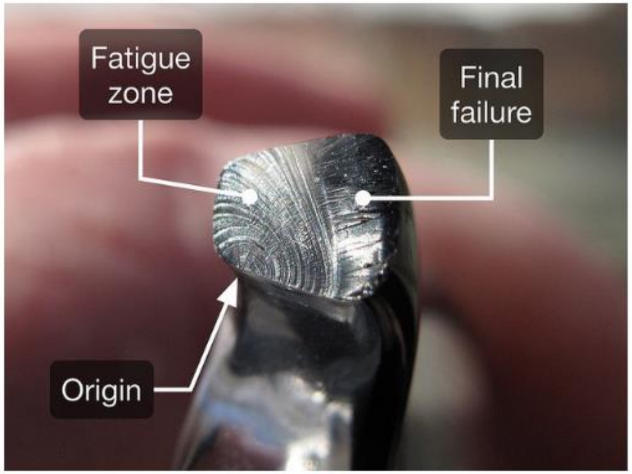
Fatigue

- Fatigue means failure due to <u>repeated</u> (cyclic) stresses or strains

- Causes ~ 90% of all metallic failures

- Three main stages of Fatigue:
    - ➢ Crack initiation
    - ➢ Crack propagation
    - ➢ Final failure



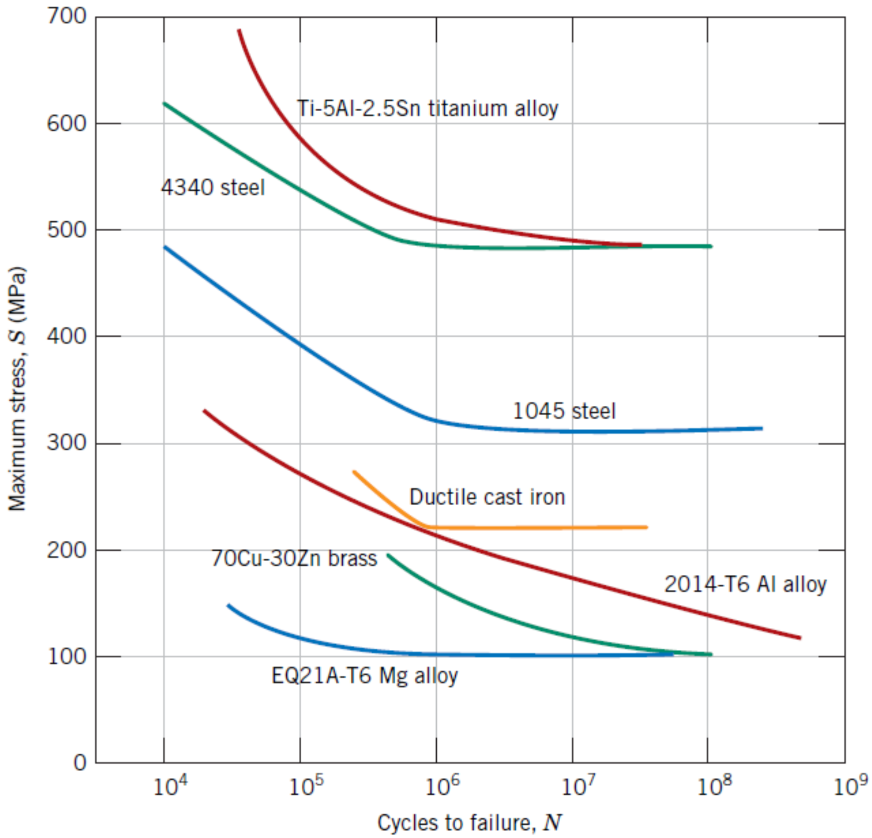


Fatigue Life LLC (2020) https://fatigue-life.com/fatigue-physics/

Fatigue tests (S – N curves)

- **Stress amplitude (S)** versus **Number of cycles (N)**

- **Metals with Fatigue limits**
  - ➢ Titanium alloy
  - ➢ Magnesium alloy
  - ➢ Steel alloy
  - ➢ Cast iron
- **Metals without Fatigue limits**
  - ➢ Brass
  - ➢ Aluminium alloy



Callister and Rethwisch (2013)

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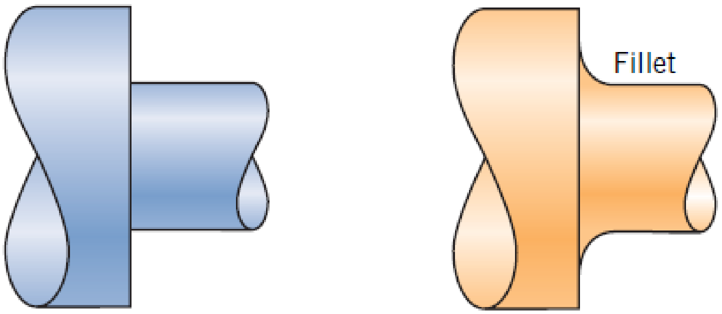
Fatigue

Factors that affect fatigue

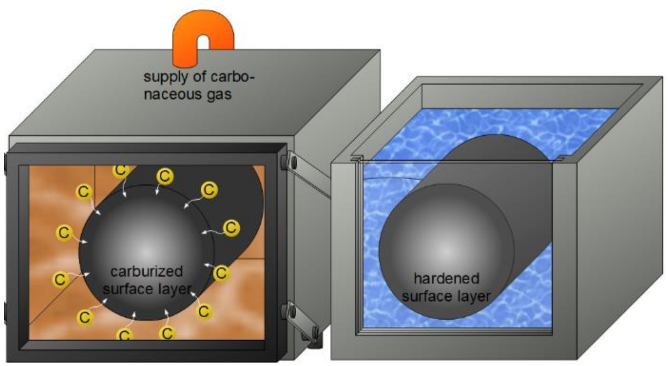
- Stress magnitude
- Surface quality (corners, scratches)



Callister and Rethwisch (2013)

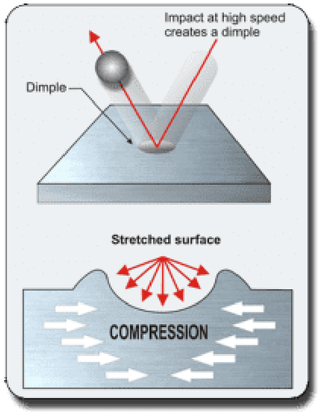
Surface treatment options

- Case hardening



Tec Science (2018) https://www.tec-science.com/

- Shot peening



International Surface Technologies (2020) https://istsurface.com

- Laser hardening

Härterei Gerster AG (2020) https://www.gerster.ch/

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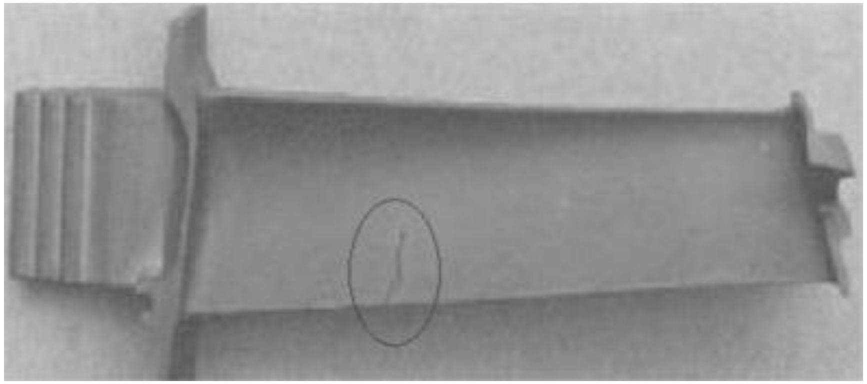
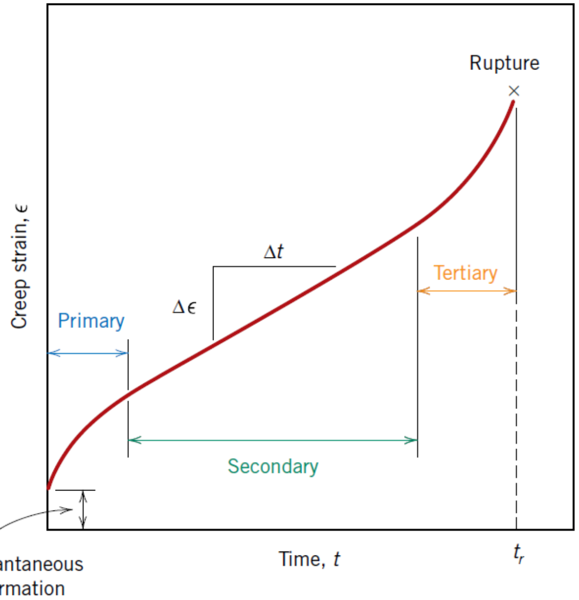
Creep

- Time-dependent and permanent deformation of materials when subjected to constant load or stress at high temperature
- Important for high-temperature applications (e.g. Turbines in jet engines)



Cracked (failed) steam turbine blade due to creep
Mouritz (2012)



Callister and Rethwisch (2013)

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Strengthening mechanisms

Processing → Structure → Properties → Performance

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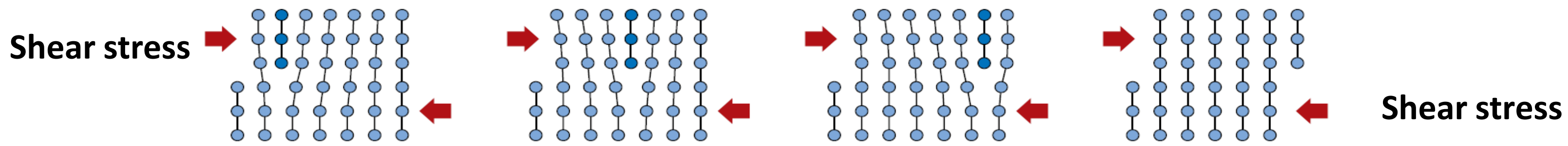
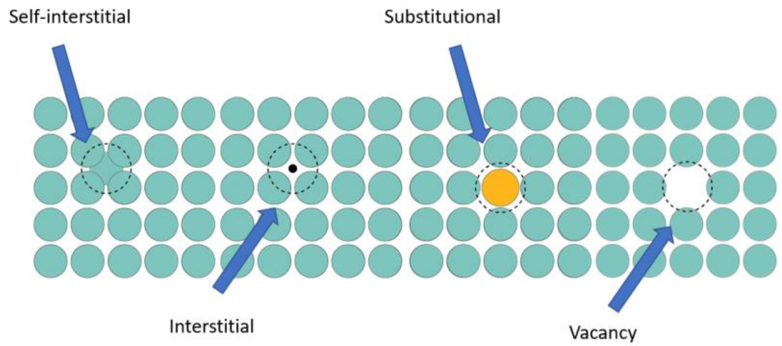
Strengthening

- 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
- **Restricting or hindering** movement of dislocations makes metals and alloys **stronger and harder**



Strengthening Mechanisms

- How can we **strengthen** metals and alloys ?
  - Grain size reduction
  - Solid-solution alloying
  - Strain hardening or work hardening or cold working
  - Precipitation hardening or age hardening

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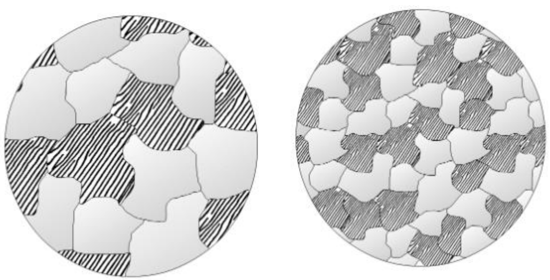
Grain size reduction

- Grain boundaries act as **barriers/obstacles** to dislocation motion
  - ➢ Finer grains → More grain boundaries → More obstacles prevent more dislocation motion → Higher strength



Coarse-grained microstructure

Fine-grained microstructure

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

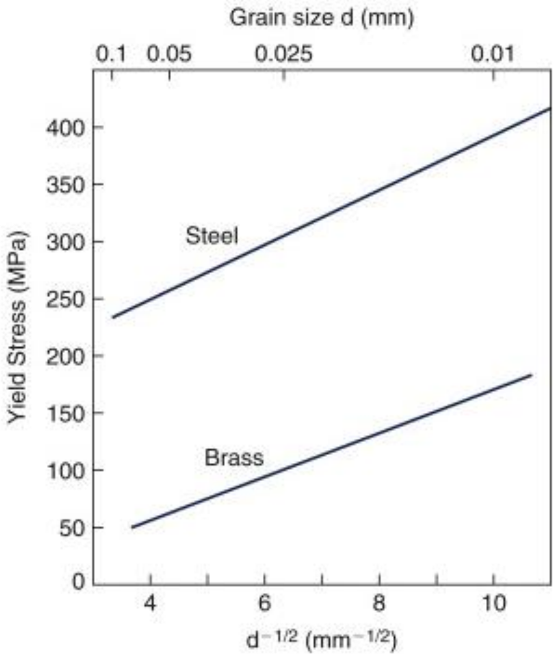
Hall-Petch equation

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

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

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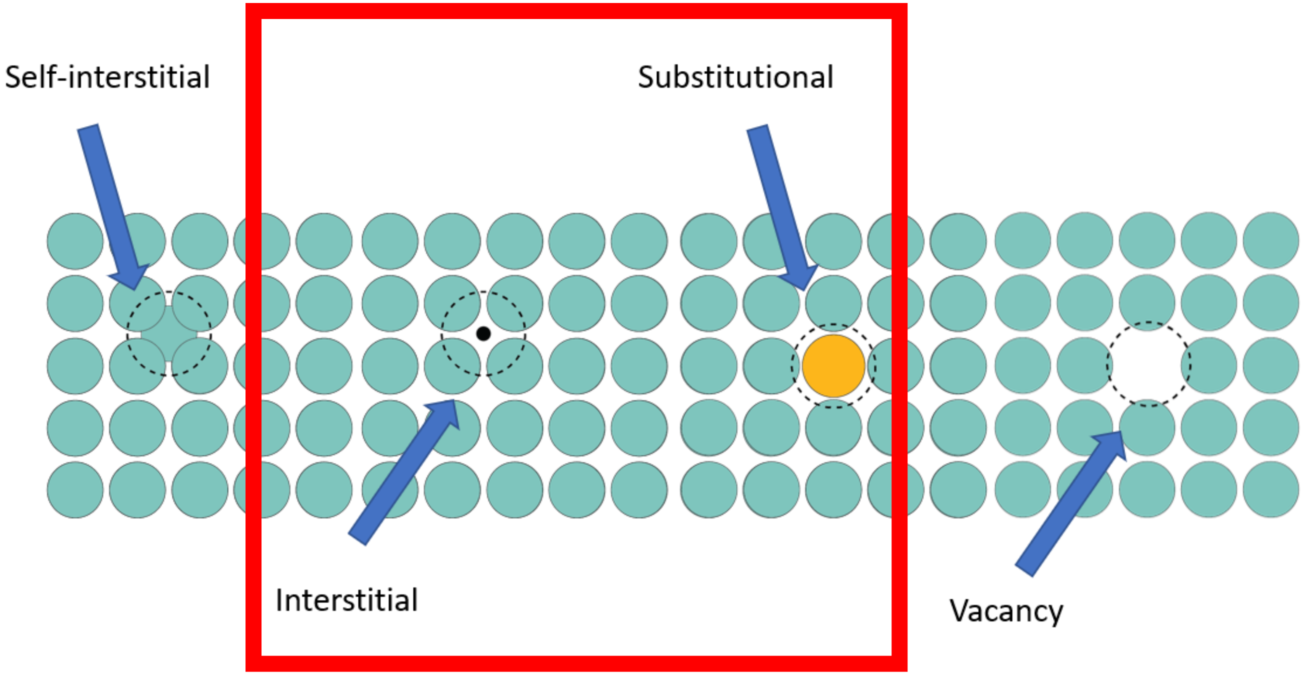
Solid-solution strengthening

- **Alloys** are stronger than **pure metals**
- Adding **impurity atoms** (e.g. Cu, Ni, C) increase the **Tensile** and **Yield strengths** by:



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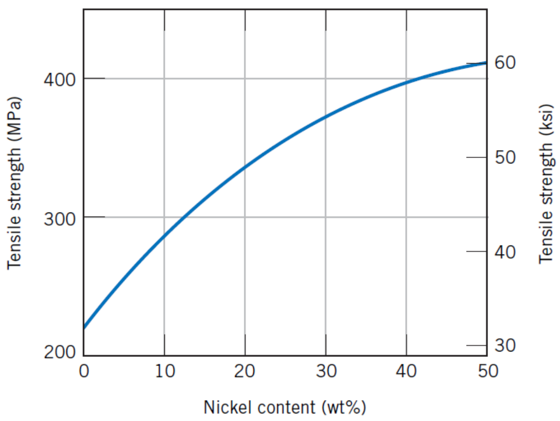
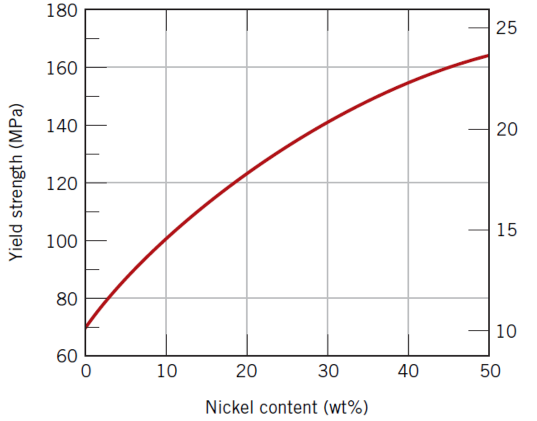
Solid-solution strengthening

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

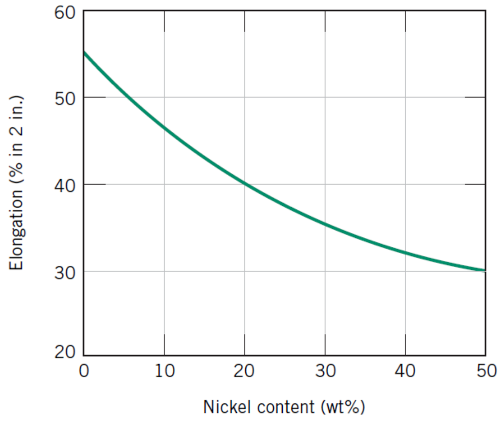
Tensile strength ⬆



Yield strength ⬆



Ductility ⬇



Callister and Rethwisch (2013)

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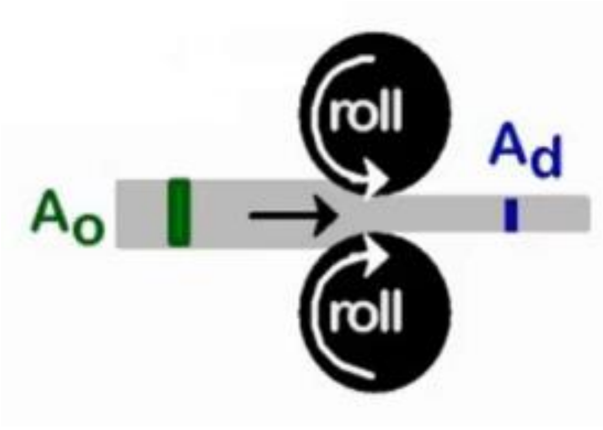
Strain hardening or work hardening or cold working

- Metals become stronger when 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 is often expressed as Percent cold work (%CW)

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

A_0 - Original cross-section area

A_d - Area after deformation



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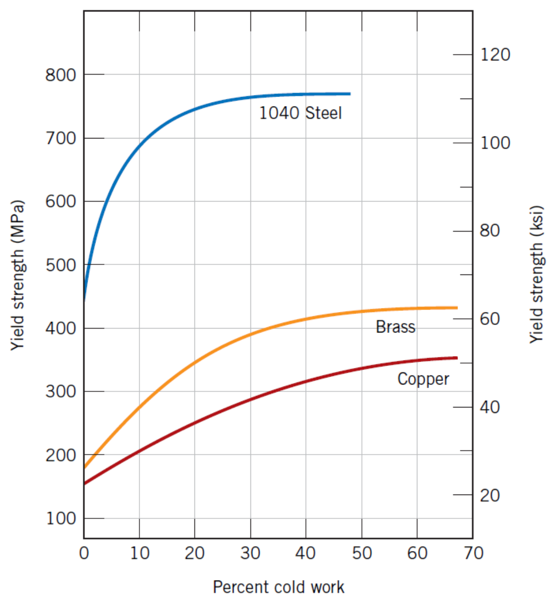
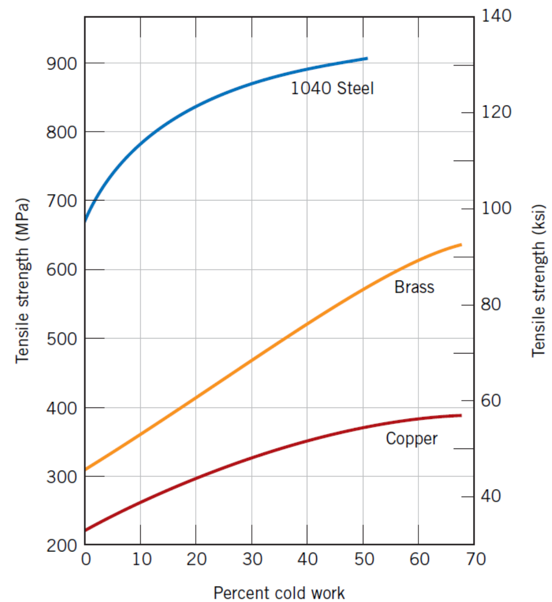
Strain hardening or work hardening or cold working

Mechanical properties for Steel, Brass, and Copper with percent cold work

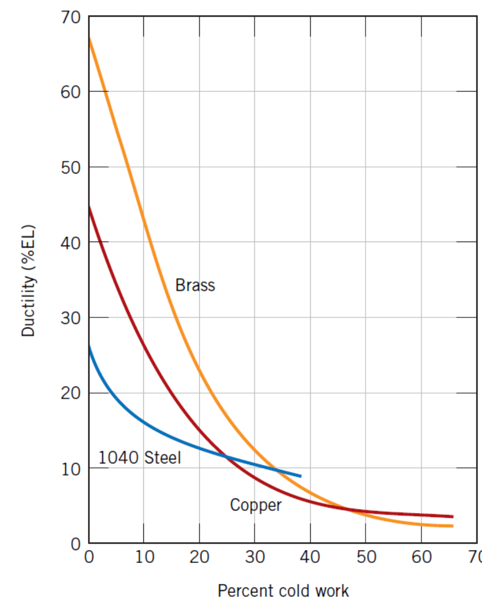
Yield strength



Tensile strength



Ductility



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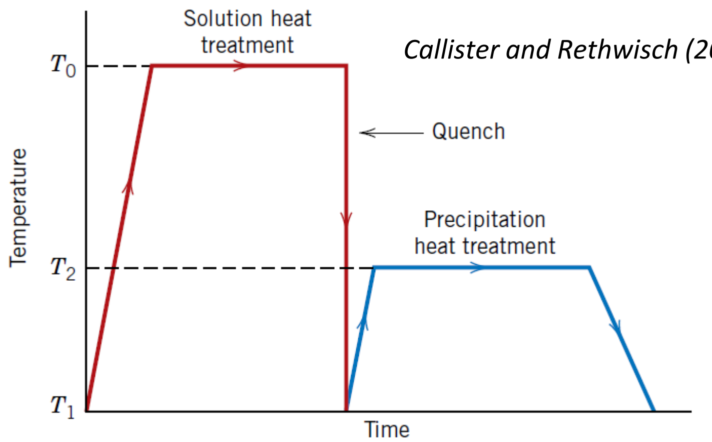
Precipitation hardening or age hardening

- 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)

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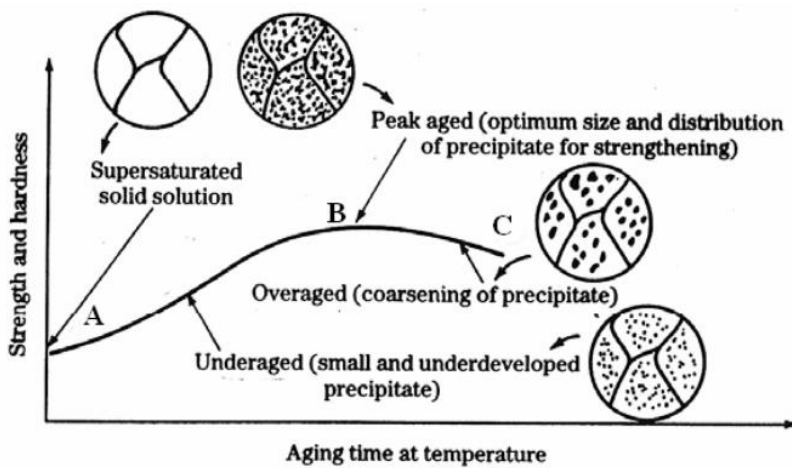
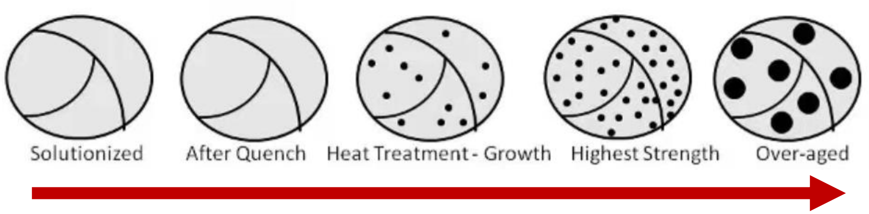
Precipitation hardening or age hardening

- 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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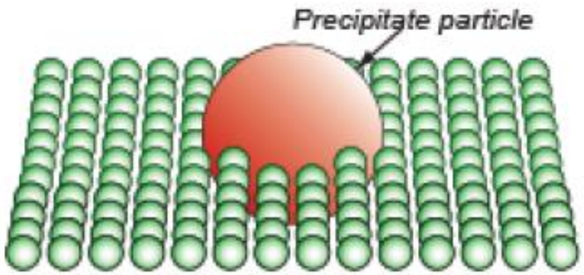
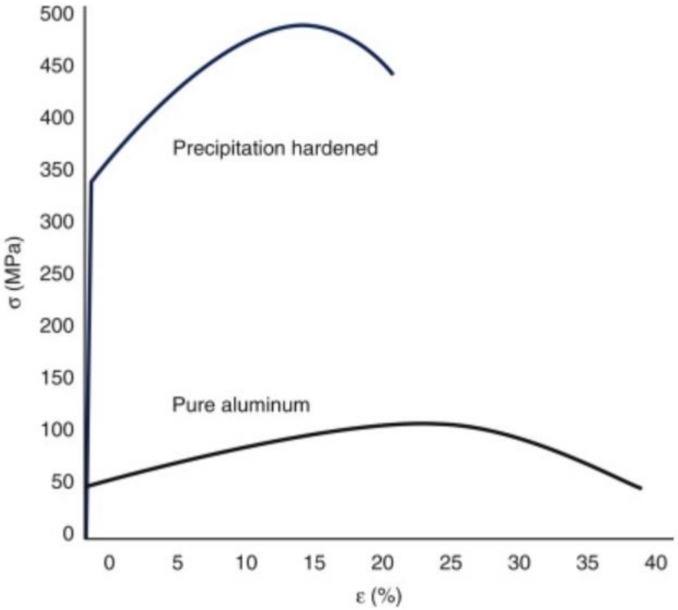
Precipitation hardening or age hardening

- 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



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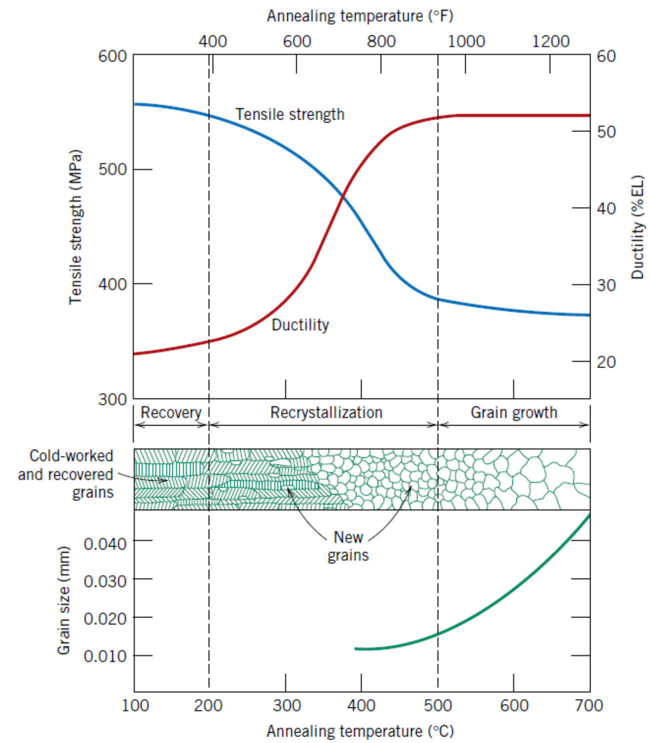
Recovery, recrystallization and grain growth

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

- Recrystallization is the formation of new strain-free grains with low dislocation densities



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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

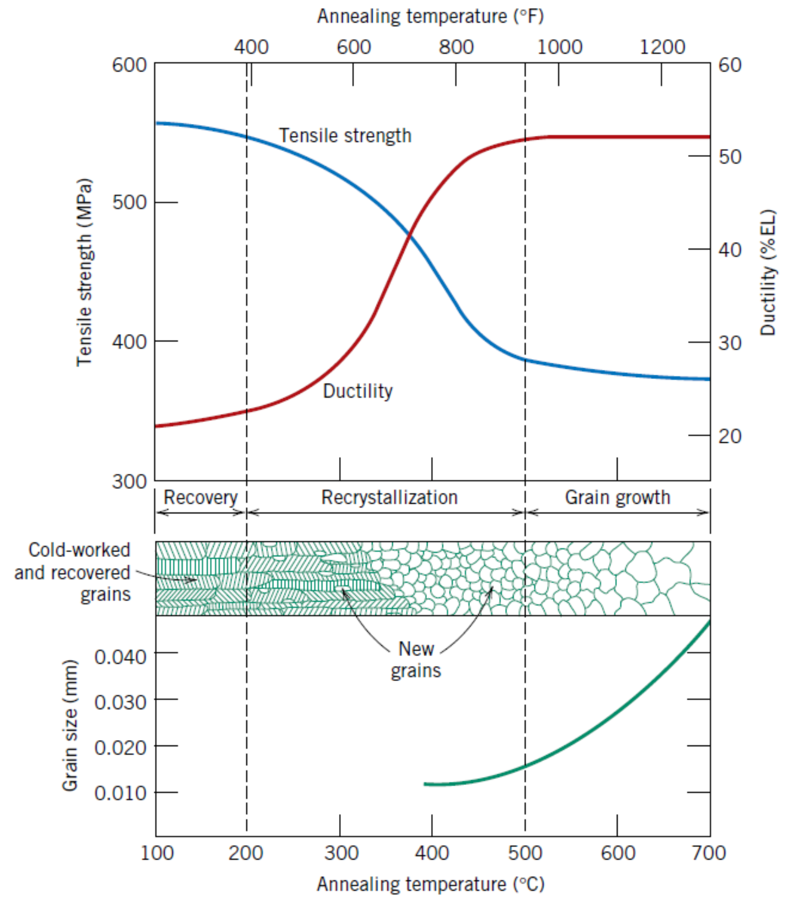
- Increase in grain size leads to:

  - ➢ Reduction in the total grain boundary area

  - ➢ Reduction in stored total energy

  - ➢ Reduction in yield strength

  - ➢ Increase in ductility



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SAM Project

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Introduction to Materials (Metals and Alloys)

Week	Topic	Instructor
1A Monday 2nd November 2020 ***2hr lecture (10am – 12pm GMT)***	**Introduction to Materials – Structures and Properties**	AS and CF
1B Thursday 5th November 2020 ***2hr lecture (10am – 12pm GMT)***	**Mechanical Properties of Metals and Alloys**	AS
2A Monday 9th November 2020 ***2hr lecture (10am – 12pm GMT)***	**Phase Diagrams and Microstructures**	CF
2B Thursday 12th November 2020 ***2hr lecture (10am – 12pm GMT)***	**Phase Transformations and TTT Diagrams**	CF
3A Monday 16th November 2020 ***2hr lecture (10am – 12pm GMT)***	**Strengthening of Metals and Alloys**	AS
3B Thursday 19th November 2020 ***2hr lecture(10am – 12pm GMT)***	**Fracture and Failure mechanisms of Metals and Alloys**	AS
4A Monday 23rd November 2020 ***2hr (10am – 12pm GMT)***	**Summary and recap and QnAs**	AS and CF
4B Thursday 26th November 2020 ***2hr (10am – 12pm GMT)***	**Assessment week**	AS

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Introduction to Materials (Metals and Alloys)

- This pilot course is organised under the scope of the **Sector Skills Strategy in Additive Manufacturing (SAM) Project**
- Running from 1st Jan 2019 – 31st Dec 2022
- European-wide consortium with 17 partners comprising:
  - Industries
  - Education and Training Providers
- Brunel University London – Work Package Leader

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Stay in touch

- **Sector Skills Strategy in Additive Manufacturing (SAM) Project**

Website: http://www.skills4am.eu/

Twitter: https://twitter.com/skills4am

YouTube: https://www.youtube.com/channel/UCO-PfDXv5ReiELtkvyVbtHA

Facebook: https://www.facebook.com/SectorSkillsStrategyinAdditiveManufacturing/

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Stay in touch

- **Sector Skills Strategy in Additive Manufacturing (SAM) Project**

LinkedIn

SAM general group on LinkedIn:
https://www.linkedin.com/groups/12231279/

Students, Trainees & Jobseekers in AM
https://www.linkedin.com/groups/8918566/

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Feedback Survey

Takes less than five minutes

https://freeonlinesurveys.com/s/lkd5smq1

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(optional)

Switch on your camera for a few photographs

The images/screenshots will be shared will be used for reporting, shared on social media platforms, blogs and websites

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Assessment

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Assessment

- Multiple choice questions
  - 14 questions (Based on the lecture content, learning outcomes and learning resources)
- Assessment via **Teams** and **Forms** platforms
  - Camera will need to be turned on
  - 1 minute per question (***Forms records the duration for each participant***)
  - External invigilator on the day from the lead partner – EWF
  - Exam will begin at about 10:15am GMT (i.e. UK TIME).
  - It should be straightforward, but we can use the chat function in Teams for any questions.
  - Results (within one week of the assessment)
  - Score at least 60% to pass (to receive SAM's certificate)
  - If lower, you get one more opportunity with another new assessment (new date TBC)

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Any Questions ???

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