Lecture 1B

Mechanical Properties of Metals and Alloys

Dr Adeayo Sotayo

Thursday 5th November 2020

Got a question ?

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

***Quiz time** – Why is it important to study the mechanical properties of Metals and Alloys?*

Website – Sli.do

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Why *study the mechanical properties of metals and alloys*

- It is important for engineers and designers to understand:
  - Design structures or components so that **failure** or **unacceptable deformation** will not occur
  - How various mechanical properties are measured
  - What the mechanical properties represent

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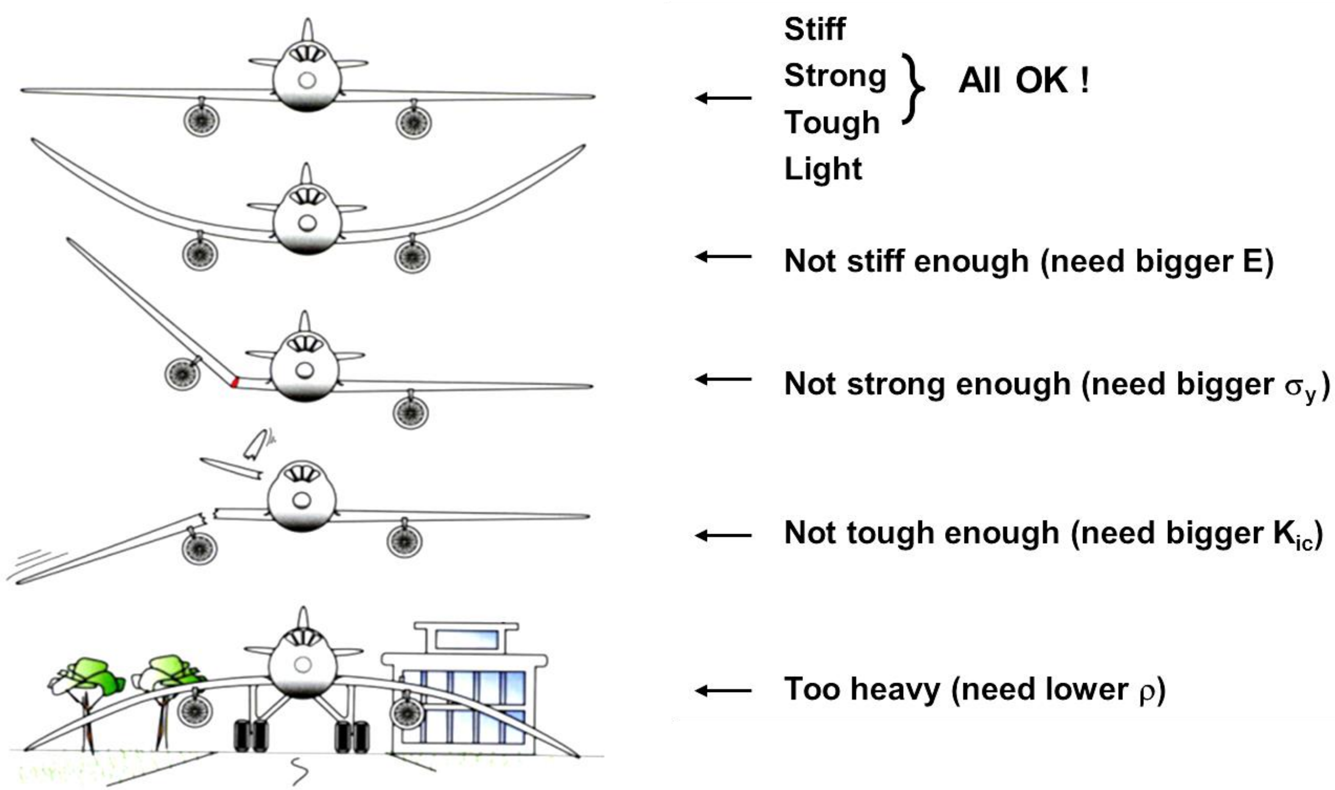
Co-funded by the Erasmus+ Programme of the European Union

Why study the mechanical properties of metals and alloys



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Outline

- Mechanical tests to evaluate mechanical properties
  - Tensile tests
  - Compression tests
  - Shear tests
  - Torsion tests
- Engineering stress and strain
- Elastic and plastic deformation
- Influence of temperature on mechanical properties
- Key mechanical properties
  - Young’s modulus
  - Poisson’s ratio
  - Proportionality limit
  - Yield strength
  - Tensile strength
  - Ductile and brittle behaviour
  - Toughness
  - Hardness
  - Safe stress or working stress

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Learning Outcomes

- List different types of mechanical tests
- Describe the different mechanical properties
- Explain the difference between elastic and plastic deformations
- Explain the effect of temperature on the mechanical properties of metals and alloys

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Mechanical Properties of Metals and Alloys

- The mechanical behaviour of metals and alloys reflects their **response** or **deformation** to an **applied load** or **force**
- Key mechanical properties include
  - Stiffness
  - Strength
  - Hardness
  - Ductility
  - Toughness

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Mechanical Tests

- The type of mechanical test is dependent on the potential in-service conditions
  - Nature of applied load (e.g. tension, compression, shear or torsion)
  - Load duration
  - Environmental conditions

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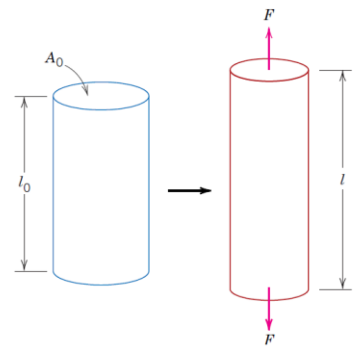
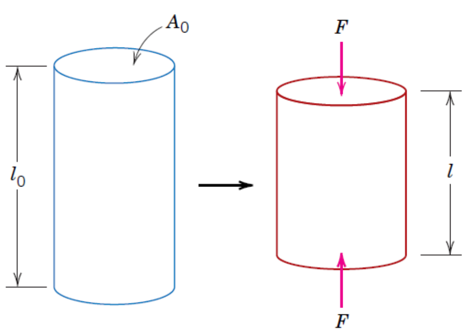
Mechanical Tests

- **Tensile tests**
  - Very common and relatively simple
  - Gradually increase tensile load along the axis of the specimen

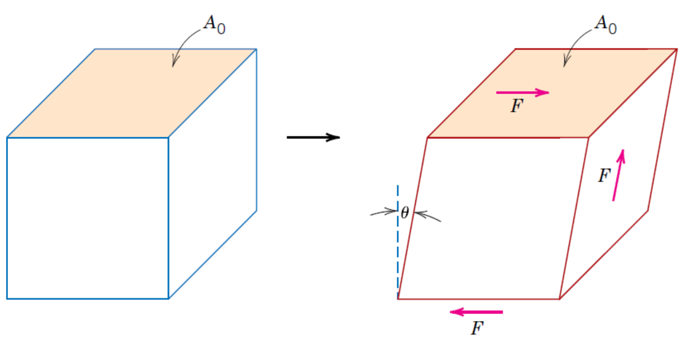


Callister and Rethwisch (2013)

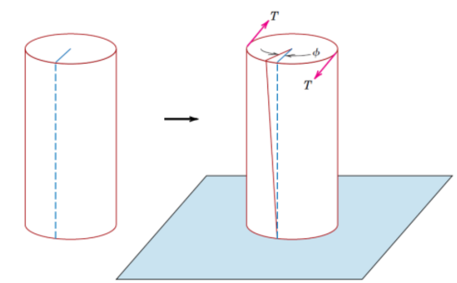
- **Compression tests**



Shear tests



Torsion tests



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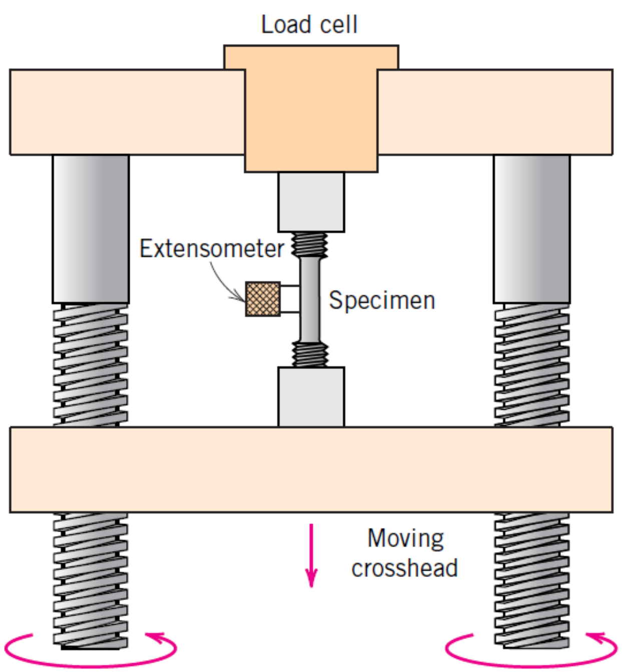
Mechanical Tests

- **Tensile tests**
  - "dogbone" and flat specimens - Standard tensile specimens
  - To ensure deformation and failure in the narrow centre region (**not** near the grips)

Protolabs (2020)

Universal Testing machine

Records the **load (N)** and **elongation (mm)**



Callister and Rethwisch (2013)

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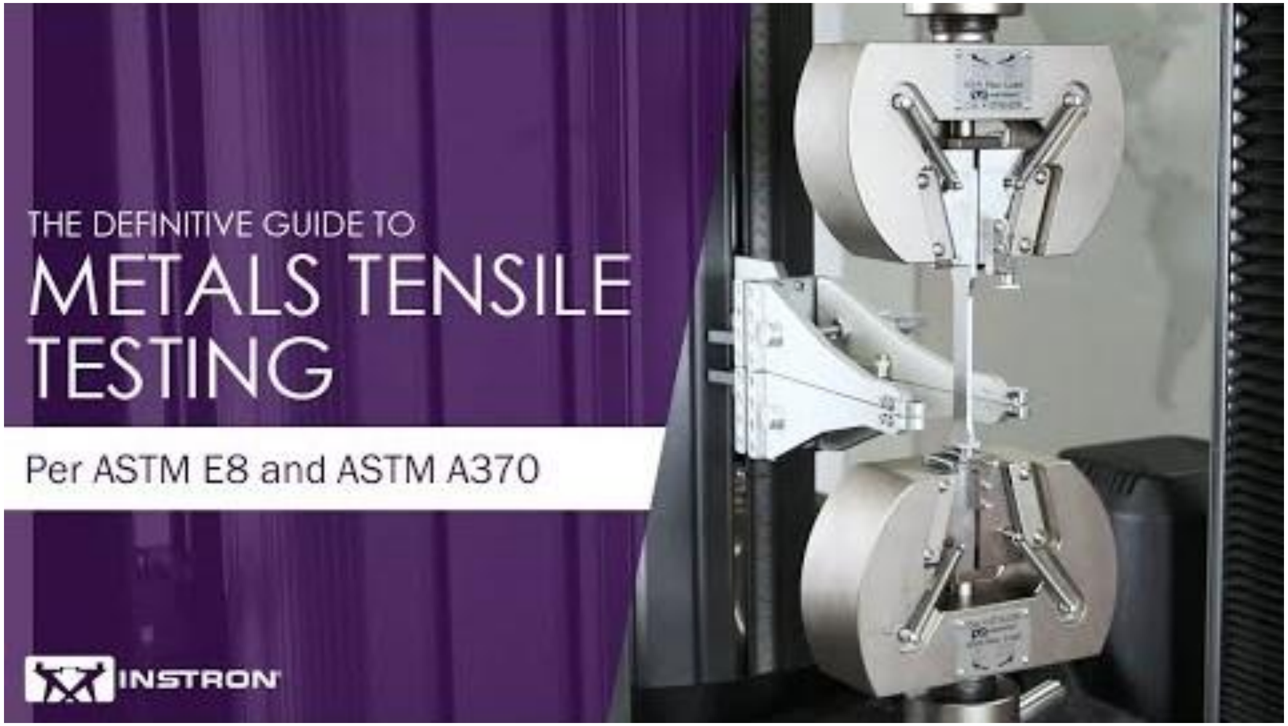
Mechanical Tests

Tensile test on metal



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Mechanical Tests

- Modern universal testing machines
  - Tensile and compression
  - Change of grips and platens

Instron (2020) https://www.plantautomation-technology.com/products/instron/5980-series-universal-testing-system

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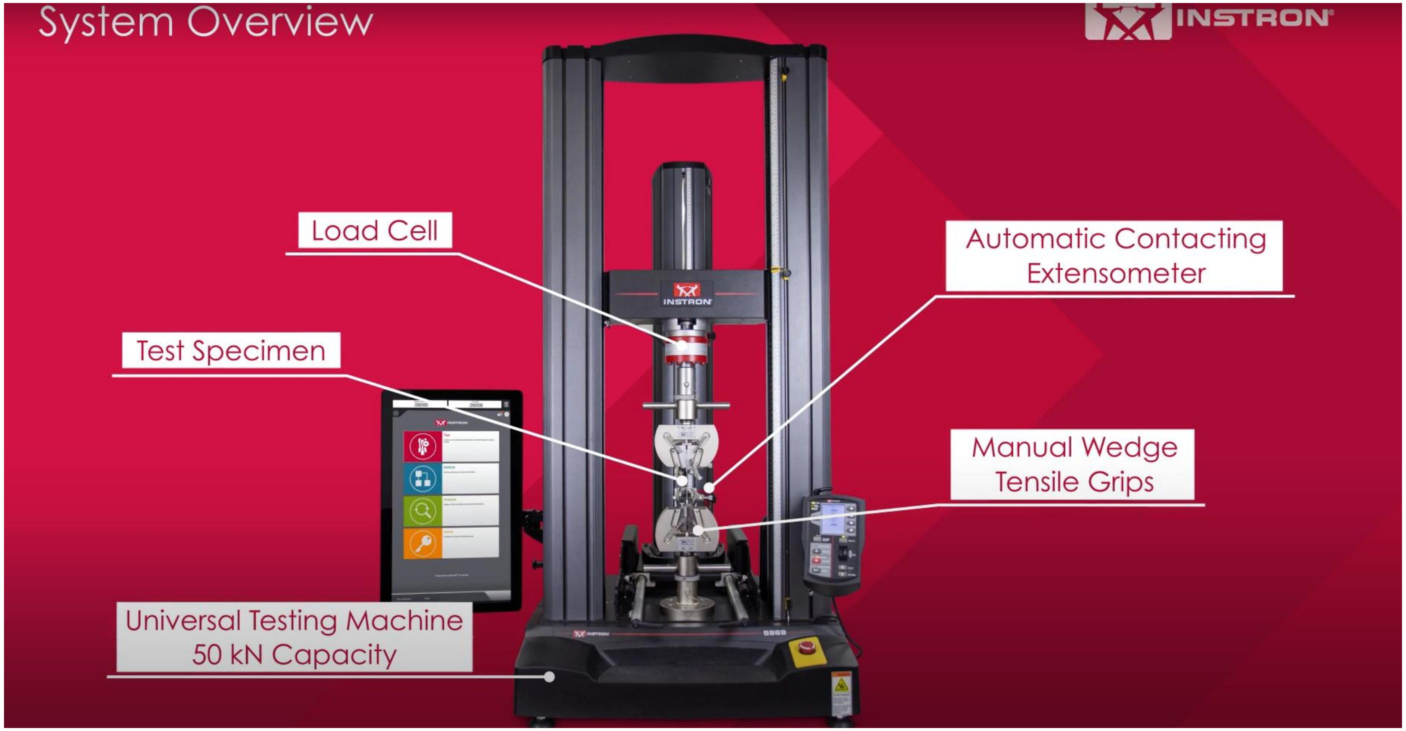
Mechanical Tests

- Modern universal testing machines



Instron (2020)

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Mechanical Tests

- Modern universal testing machines with environmental chambers
  - Simulates different temperatures and in-service conditions

Instron (2020) https://www.instron.us/products/testing-accessories/environmental-chambers-furnaces/environmental-chambers

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Engineering stress and strain

- The universal testing machine gives the **applied load (N)** and **elongation (mm)** values
- To elimінate the **size effect**, these values are converted to the **engineering stress** and **engineering strain**

Engineering stress $$\sigma = \frac{F}{A_0}$$

σ – Engineering stress (N/m^2 or Pa)
F – Load or force (N)
A_0 – Original cross-sectional area (m^2)

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Engineering stress and strain

- The universal testing machine gives the **load (N)** and **elongation (mm)** values
- To eliminate the **size effect**, these values are converted to the **engineering stress** and **engineering strain**

Engineering strain $$\in = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$

$\in$ – Engineering strain (typically unitless or expressed as a percentage)

l_i – Instantaneous length (mm)

l_0 - Original length (mm)

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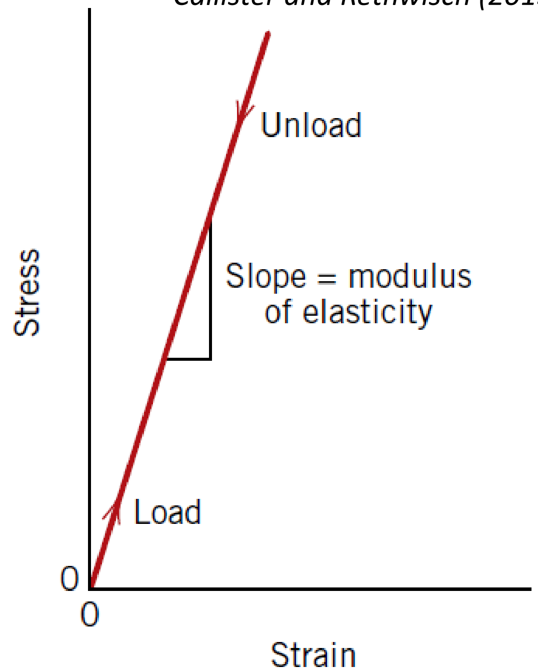
Elastic deformation

- **Elastic deformation**
  - Initial deformation in which stress and strain are proportional
  - Elastic deformation is not permanent
  - Material returns to original shape
- Stress-strain diagram showing elastic deformation
- The gradient/slope of the linear curve is the **modulus of Elasticity**
  - Important property for design and analysis
  - Most structures are designed to ensure that **only elastic deformation** will occur when load or stress is applied
  - Indication of stiffness
  - Material's resistance to elastic deformation
  - The greater the modulus, the stiffer the material

Callister and Rethwisch (2013)



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Engineering stress and strain

- How much a material deforms depends on the magnitude of the applied stress
- At low stress levels, **stress** and **strain** are proportional through a relationship (Hooke's law)

$$\sigma = E \in$$

- E is the **Young's modulus, (also called):**
  - **Modulus of elasticity**
  - **Stiffness modulus**
  - **Modulus**
- E indicates the **stiffness** of the material
- Typical unit of **GPa**

Material	Modulus of Elasticity [GPa]
Magnesium	45
Aluminium	**70**
Brass	97
Titanium	107
Copper	110
Nickel	207
Steel	**210**
Tungsten	407

**at room temperature* *Callister and Rethwisch (2013)*

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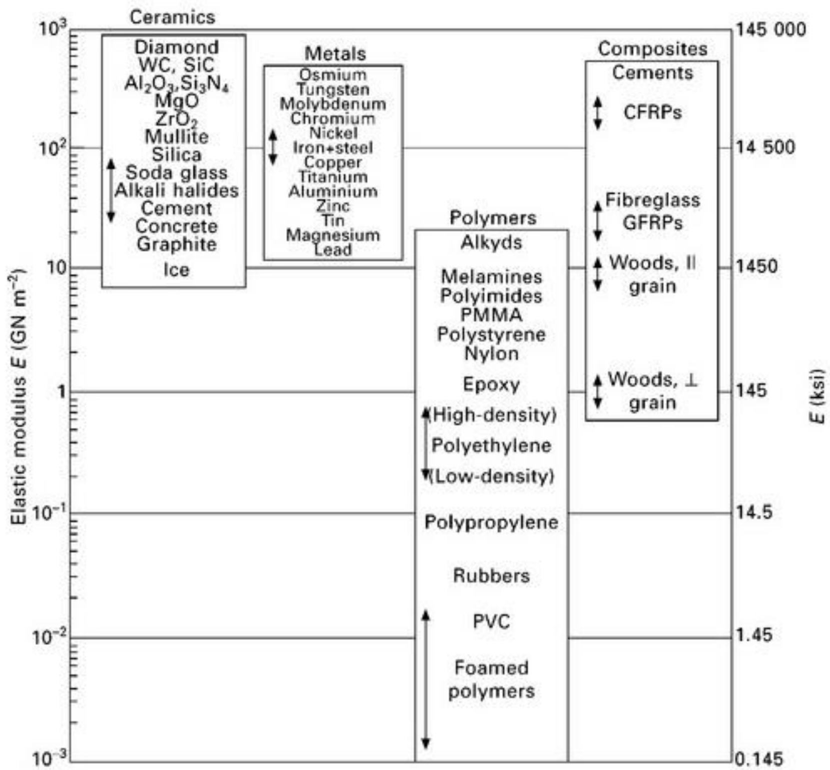
Elastic modulus – Put in context with other materials

- Elastic modulus for different engineering materials



M. F. Ashby and D. R. H. Jones, Engineering materials 1, Elsevier, 2005

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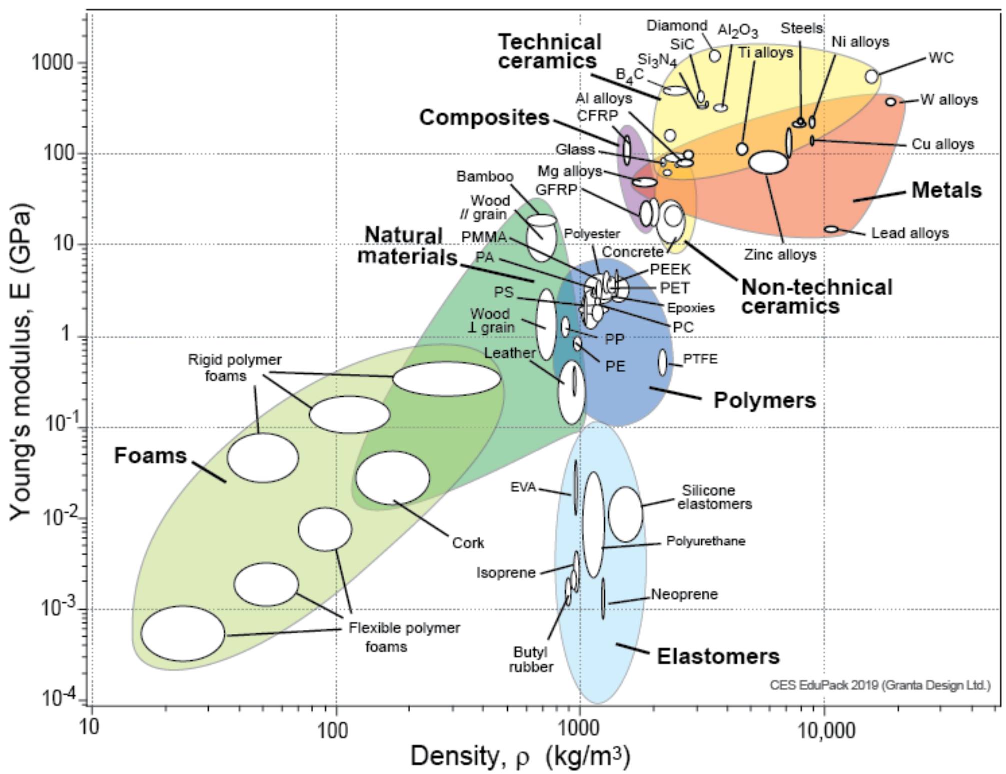
Elastic modulus – Put in context with other materials

- **Elastic modulus** vs **Density** for different engineering materials



Ansys Granta (2019)

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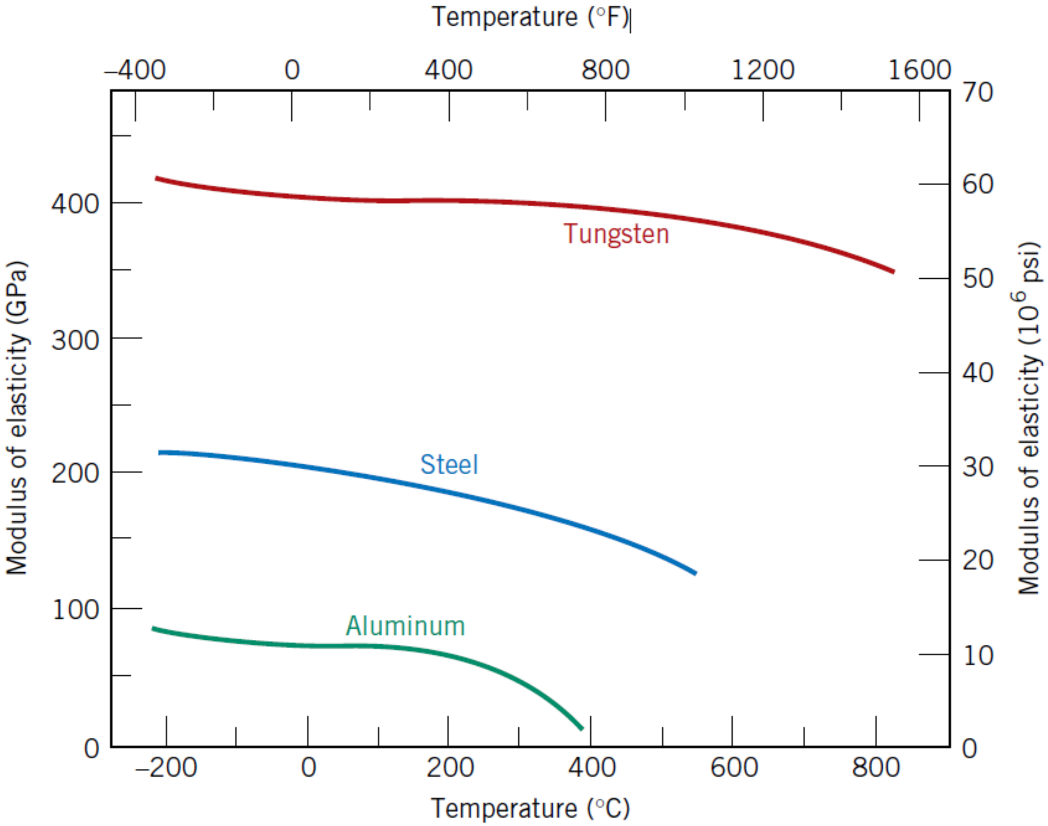
Influence of temperature on modulus of elasticity for metals



Callister and Rethwisch (2013)

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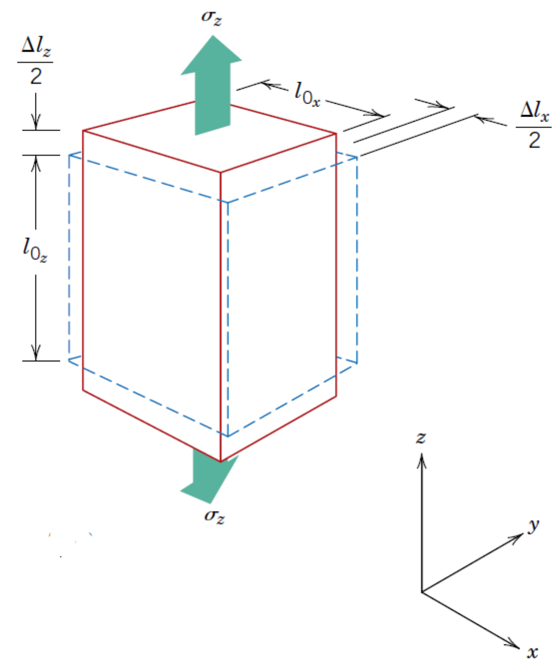
Callister and Rethwisch (2013)

Poisson's ratio

- **Poisson's ratio** – ratio of the **lateral** to **axial** strain
  - dimensionless
- Axial **elongation** (z) and lateral **contractions** (x and y)
  - Dashed lines = before applied load/stress
  - Solid lines = after applied load/stress



$$\textbf{Poisson's ratio } \nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$$

- Metals and alloys range from **0.25 – 0.35**

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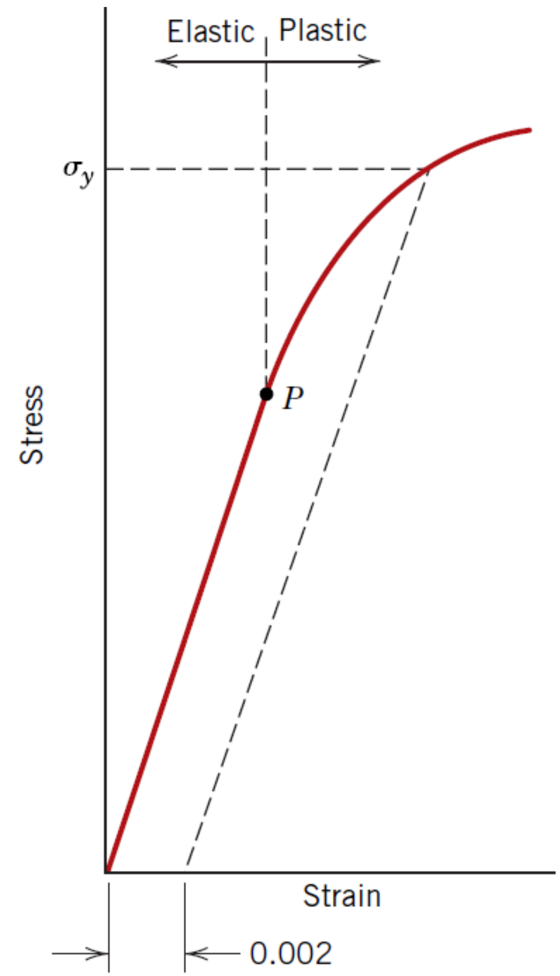
Elastic and Plastic deformation

- **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
- For **most metallic materials**, elastic deformation occurs only to strains of about 0.005 (i.e. 0.5%)
- Most materials and structures are designed to ensure that **only elastic deformation** will occur when loading/stress is applied



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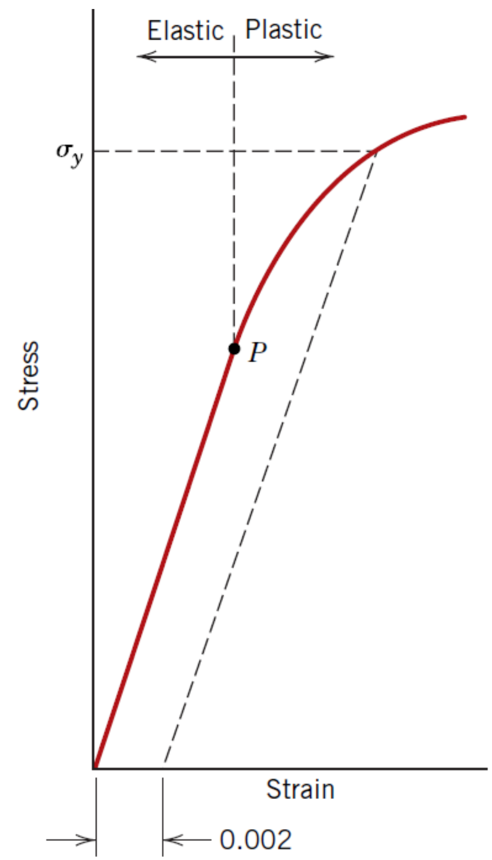
Mechanical Properties of Metals and Alloys

- **Proportionality limit**
  - The elastic-plastic transition
  - Transition point from linearity to non-linearity on the curve (**Point P**)
- **Yield strength , σ_y (MPa)**
  - Straight line parallel to the elastic region at a specified strain offset (usually 0.002 strain) and the intersection on the stress-strain curve
  - **Yield strength** is a measure of the resistance to plastic deformation
- For Metals and Alloys, Yield strengths range from **35 MPa for a low-strength aluminium** to over **1400 MPa for high-strength steels**



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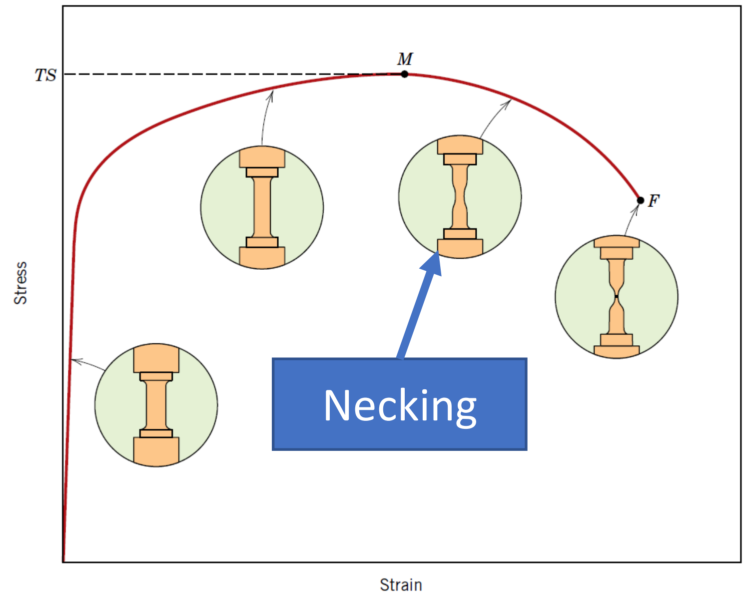
Mechanical Properties of Metals and Alloys

- After **yielding**, the stress required to continue **plastic deformation** increases to a maximum point **(Tensile strength, Point M)** before it decreases, leading to subsequent **fracture (Point F)**

- **Tensile strength** - maximum stress on the stress–strain curve
  - Also called **ultimate tensile strength** or **ultimate strength**

- Tensile strengths range from **50 MPa for aluminium** to over **3000 MPa for high-strength steels**

Typical engineering stress – strain behaviour



Callister and Rethwisch (2013)

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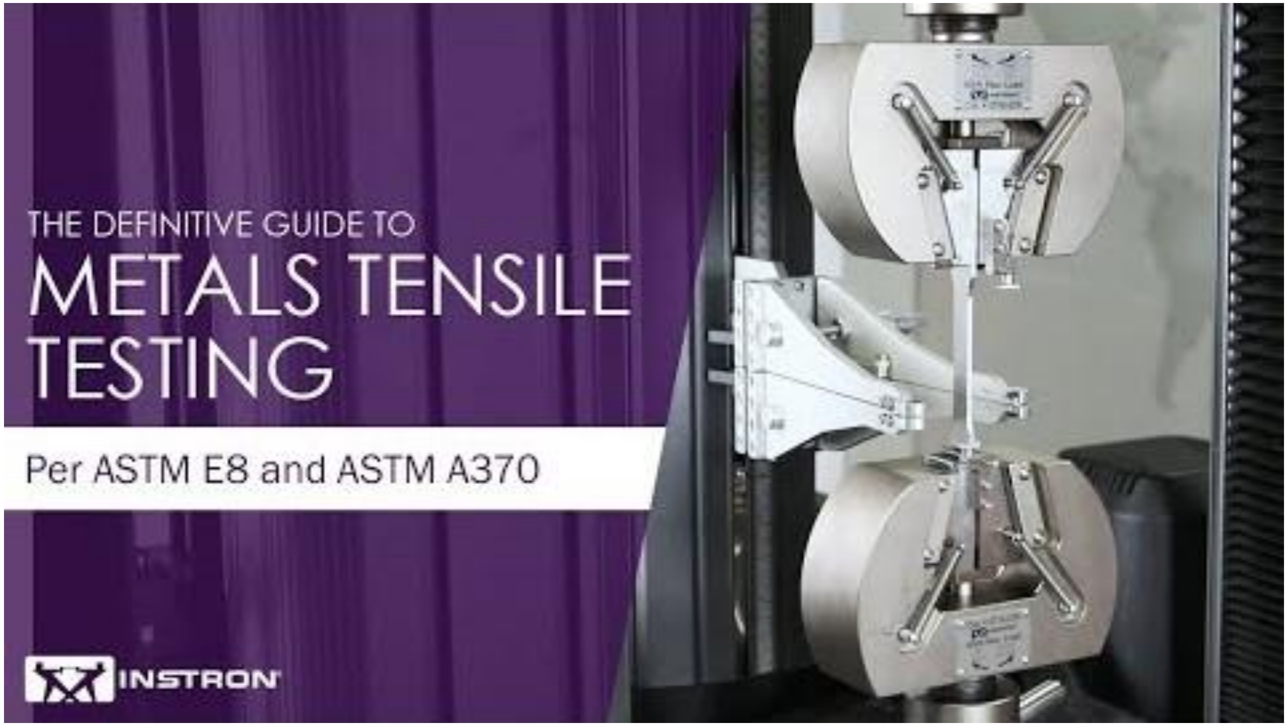
Mechanical Tests

Tensile test on metal



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Mechanical Properties of Metals and Alloys

<u>NOTE</u>

Yield strength is more important than the **Tensile strength**, because once the **yield strength** has passed, the structure has **plastically deformed** beyond acceptable limits

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Quiz time – At which point on the stress-strain curve does the elastic-plastic transition occur ?

Website – Sli.do

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Quiz time – *Which of these statements is true*

Website – [Sli.do]

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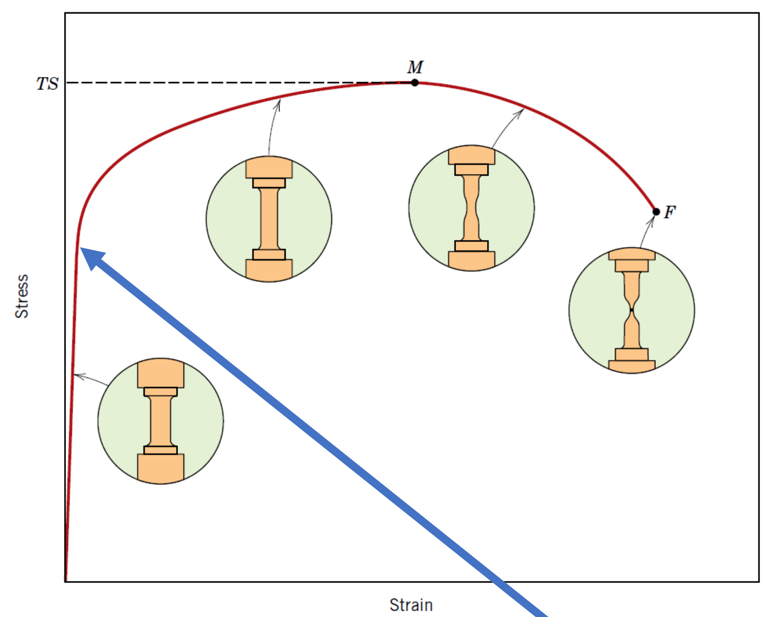
Mechanical Properties of Metals and Alloys

Callister and Rethwisch (2013)

- **Safe stress** is the **yield strength (σ_y)** divided by a **factor of safety (N)**
- For design**, safe Stress or working stress,** σ_w

$$\sigma_w = \frac{\sigma_y}{N}$$

- N can range from 1.2 to 4.0
- **N** depends on economics, experience, accuracy and variation of material properties, consequence of failure (i.e. loss of life or property damage)



In Engineering, the **yield strength** is a vital parameter

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Mechanical Properties of Metals and Alloys

- A metal that has **very little or no plastic deformation** after fracture is **brittle**
- **Ductility -** measure of plastic deformation at fracture
  - Quantified by **percent elongation** or **percent reduction in area**
- **Percent elongation (%EL)**

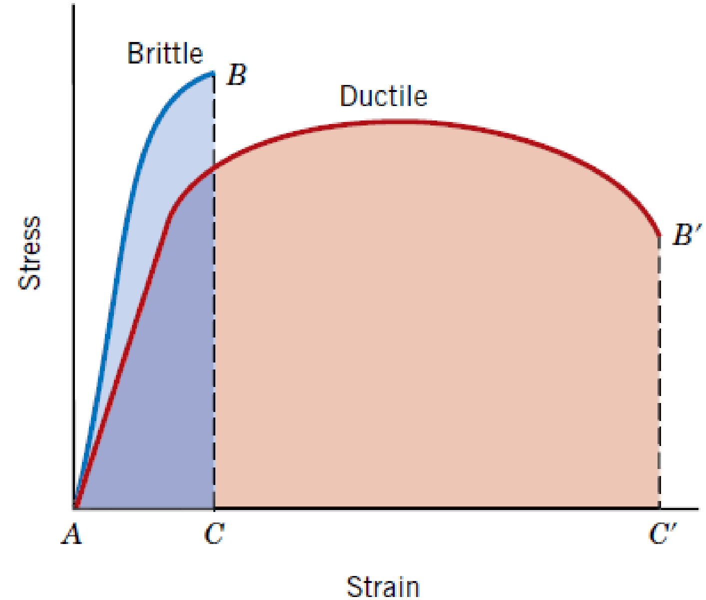
$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

l_f - Fracture length
l_0 - Original length

- **Percent reduction in area (%RA)**

$$\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$$

A_f - Cross-sectional area at fracture
A_0 - Original cross-sectional area



Callister and Rethwisch (2013)

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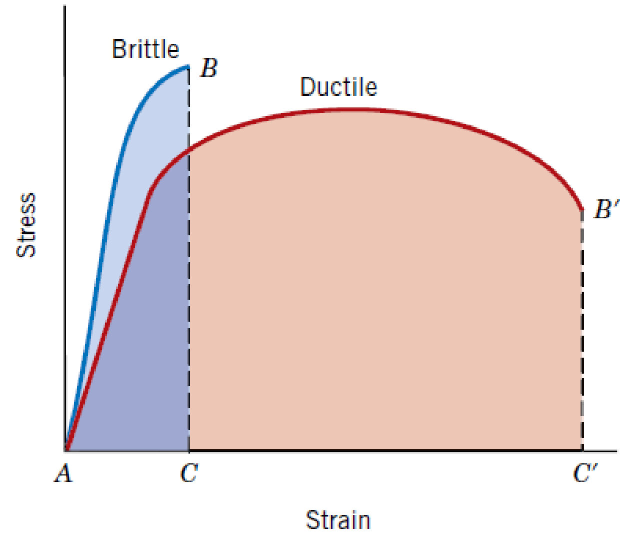
Mechanical Properties of Metals and Alloys

- **Importance of ductility**
  - Engineers/designers need to know how much a material/structure will deform plastically before final fracture
  - **Brittle materials** typically have a fracture strain of less than about 5%



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Mechanical Properties of Metals and Alloys

Ductile fracture

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

Brittle fracture

Brittle fracture in a mild steel
(rapid crack propagation)

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Quiz time – Which of these statements is false

Website – [Sli.do]

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Yield strength, tensile strength and ductility

**at room temperature*

Material	Yield Strength [MPa]	Tensile Strength [MPa]	Ductility [%]
Aluminium	35	90	40
Copper	69	200	45
Brass (70Cu-30Zn)	75	300	68
Iron	130	262	45
Nickel	138	480	40
Steel (1020)	180	380	25
Titanium	450	520	25
Molybdenum	565	655	35

Callister and Rethwisch (2013)

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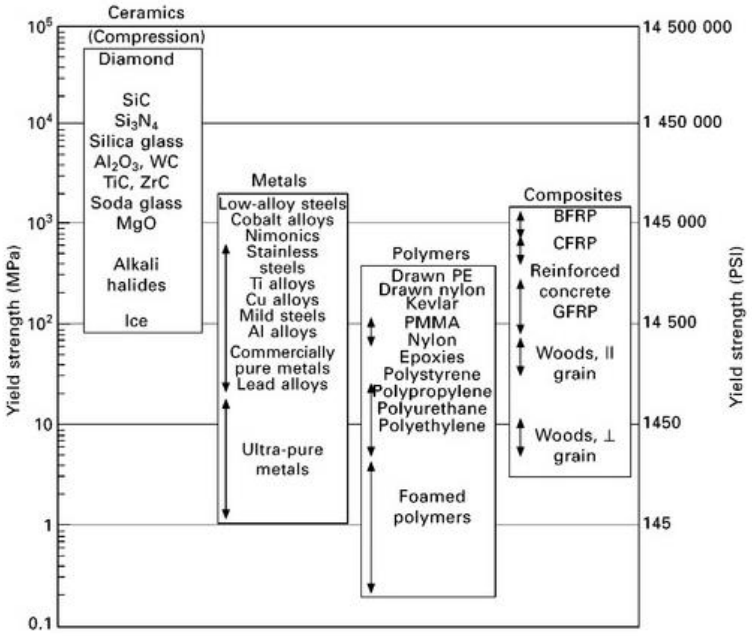
Yield strength – Put in context with other materials

- Yield strength for different engineering materials

- Unlike the **modulus**, the **yield strength** of metals **can be greatly increased,** and is **sensitive** to:
    - ➢ alloy content
    - ➢ type of heat treatment
    - ➢ microstructural features



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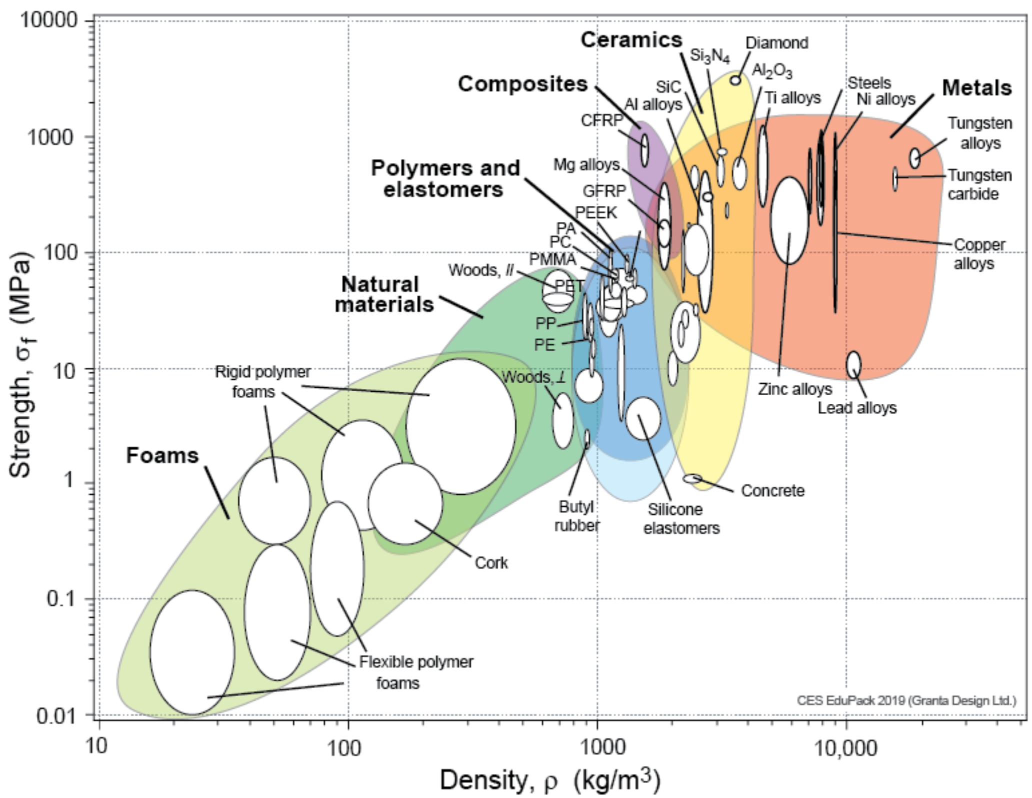
Yield strength – Put in context with other materials

- **Yield strength** vs **Density** for different engineering materials



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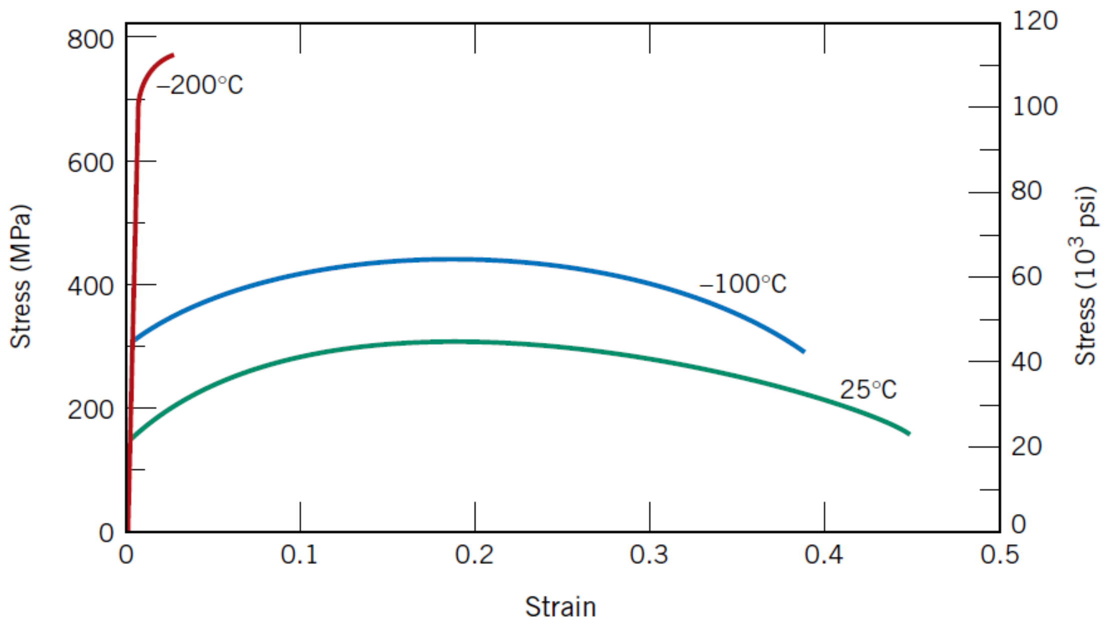
Influence of temperature on yield strength for Iron



Callister and Rethwisch (2013)

Higher temperature

- Yield strength ↓
- Tensile strength ↓
- Ductility ↑

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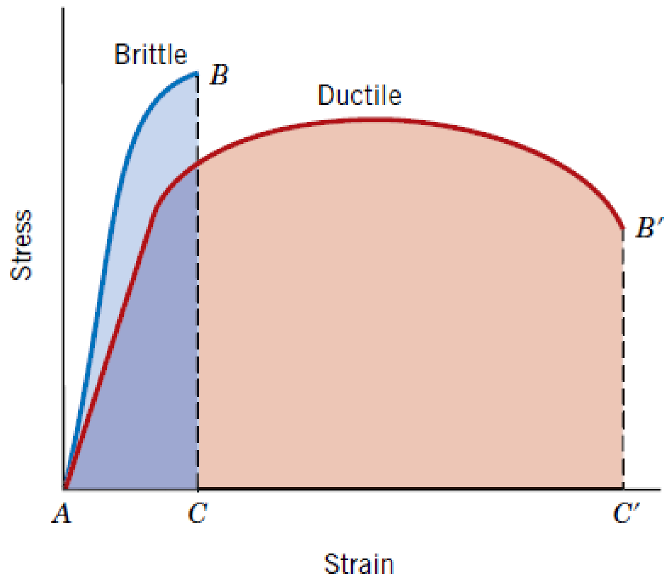
Toughness

- **Toughness** - Ability to absorb energy until fracture
- **Toughness** is the area under the engineering stress–strain curve
- Unit is **Joules per m³ (J/m³)**
- Ductile metals have **higher toughness** than brittle ones



Callister and Rethwisch (2013)

Hardness

- **Hardness** is a measure of the material's resistance to localised plastic deformation (e.g. a small dent or a scratch)
  - simple and inexpensive (no sample preparation and the testing apparatus is relatively inexpensive)
  - Non-destructive test (just a small indentation)
- A qualitative hardness indexing scheme (called the Mohs scale) ranges from 1 to 10
  - **1 for talc (soft)** to **10 for diamond (hard)**

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Hardness

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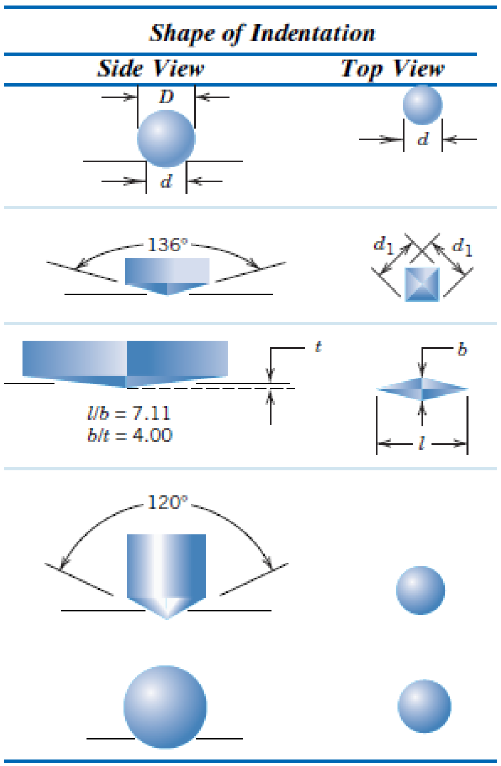
Hardness

- Different types of hardness tests
  - Rockwell, Brinell, Vickers and Knoop hardness tests
- Small indenter (sphere, cone, or pyramid) is forced into the surface of the material
  - The depth or size of indentation is measured
  - The softer the material, the larger and deeper the indentation
  - Vice-versa - the harder the material, the smaller the indentation
  - Measured hardness values **are only relative (rather than absolute**)



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Quiz time *– Which of these mechanical properties is determined by calculating the area under the stress-strain curve ?*

Website – [Sli.do]

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Quiz time – *Which of these typically occur due to an increase in the temperature of metals (e.g. Iron) and alloys ?*

Website – [Sli.do]

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Recap

- Mechanical tests to evaluate mechanical properties
  - ➢ Tensile tests
  - ➢ Compression tests
  - ➢ Shear tests
  - ➢ Torsion tests
- Engineering stress and strain
- Elastic and plastic deformation
- Influence of temperature on mechanical properties

- Key mechanical properties
  - ➢ Young's modulus
  - ➢ Poisson's ratio
  - ➢ Proportionality limit
  - ➢ Yield strength
  - ➢ Tensile strength
  - ➢ Ductile and brittle behaviour
  - ➢ Toughness
  - ➢ Hardness
  - ➢ Safe stress or working stress

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Any Questions ???

Coffee Break

We will continue at **<u>11:15am</u>**

Got a question ?

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

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