Advanced Structures and Materials

Lecture 1: Failure of Materials

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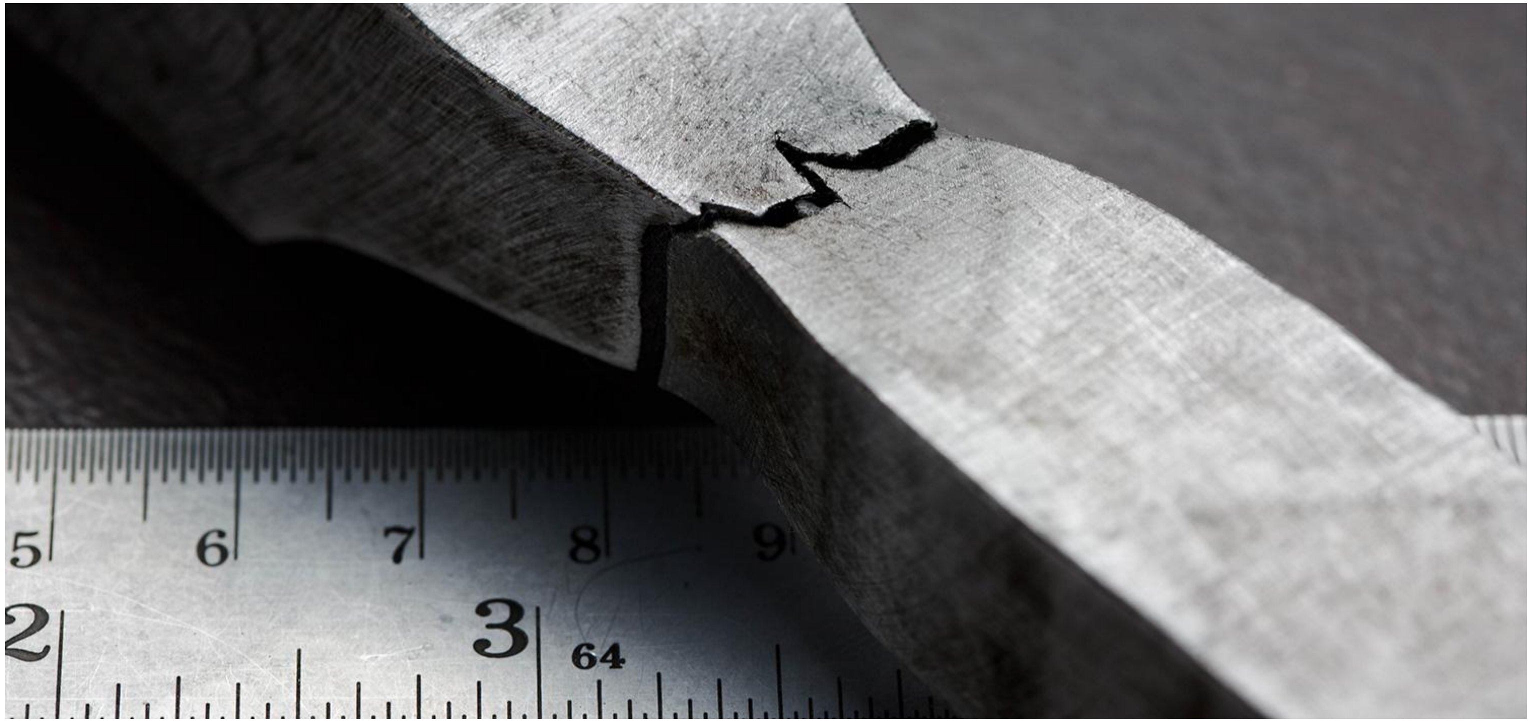
Intended Learning Outcomes

- Understand material failure, how it relates to engineering design and make simple estimates for strength or life prediction.

Course Content

Lecture 1: Modes of failure	Lecture 2: Case studies	Lecture 3: Introduction to fracture mechanics – Part 1	Lecture 4: Introduction to fracture mechanics – Part 2	Lecture 5: Measuring fracture toughness
• Why study failure? • Concept of strain energy and toughness • Ductile, brittle failure • Fractography • Factors affecting ductile to brittle transition	• Historical Examples • Design philosophies	• Introduction to fracture mechanics • Theoretical stress approach to fracture • Stress intensity factor	• Griffith's energy balance approach • Irwin's energy balance approach	• Fracture process zone and geometrical considerations • Measuring toughness • Anisotropic materials

Why Study Failure?

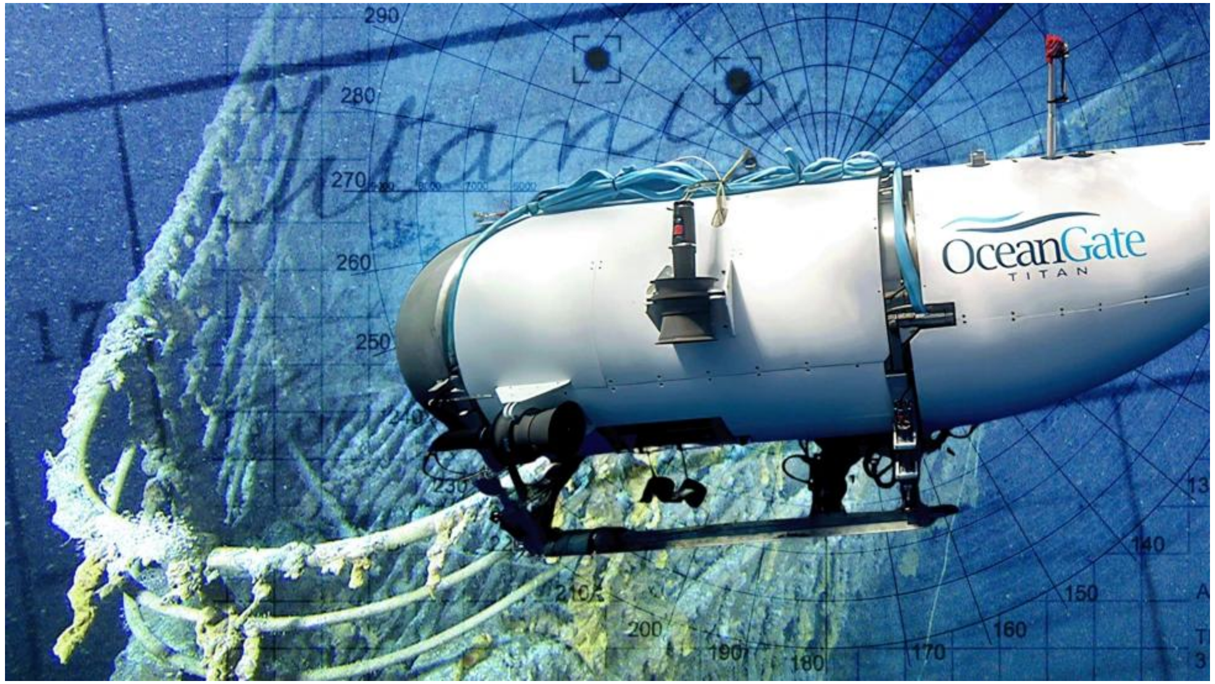


Those who cannot remember the past are condemned to repeat it.
George Santayana

Titan submersible

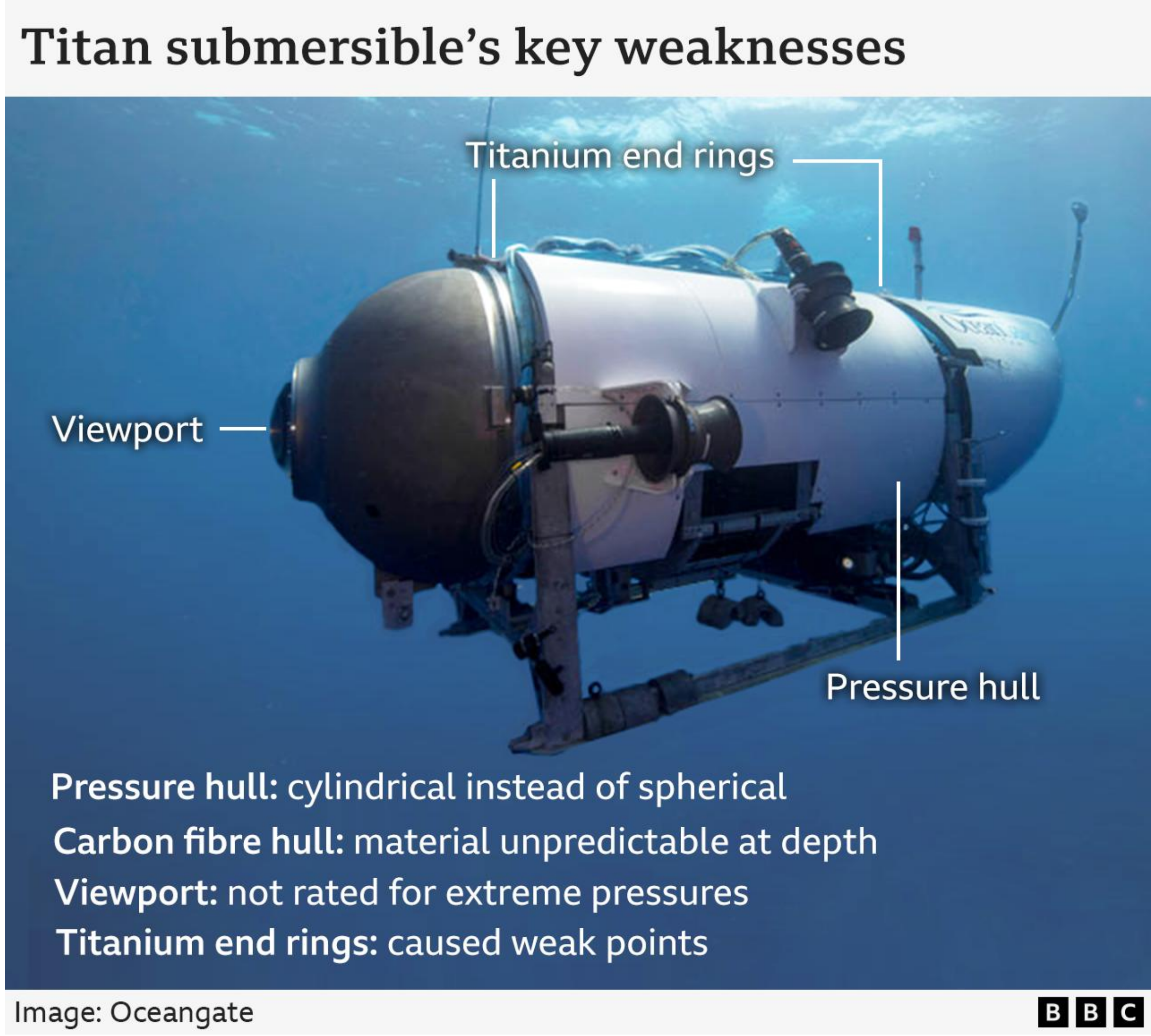
Background: The Titan submersible was designed to explore extreme depths, including the Titanic wreck, but tragically imploded during a 2023 expedition.

Implosion Event: The pressure at 3,800 meters deep (~380 atm) likely caused a catastrophic structural failure, leading to an implosion.

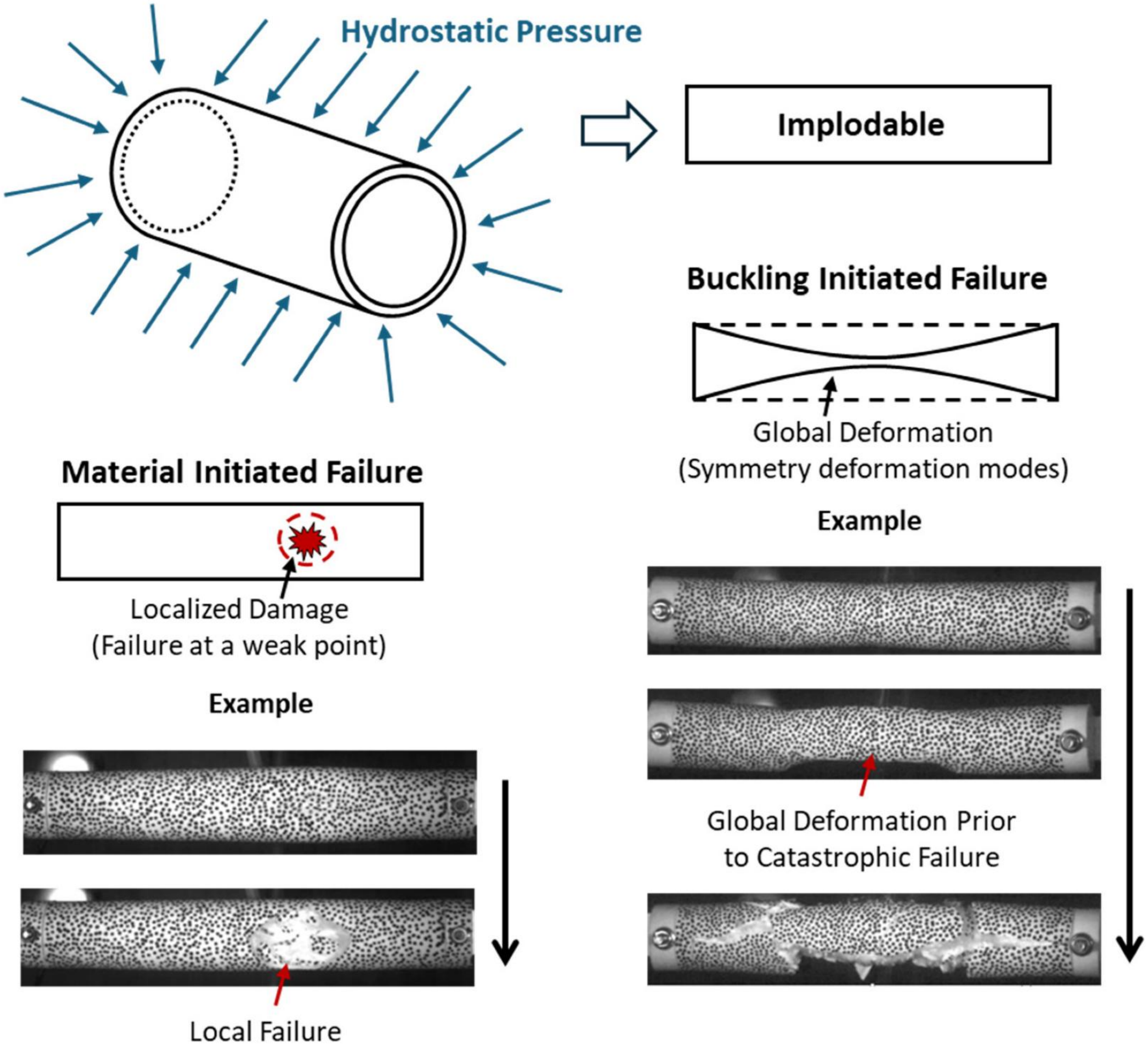


Potential failure causes

- **Material Selection Issues**: The submersible used a **carbon fibre composite hull** rather than traditional all-metal designs (like titanium or steel).
- **Structural Integrity**: Repeated deep-sea dives exposed the hull to extreme pressure fluctuations, likely causing **fatigue** and micro-cracking over time.



Composite failure



Matos, H et al., 2024. Review of Implosion Design Considerations for Underwater Composite Pressure Vessels. *Journal of Marine Science & Engineering*, *12*(9).

Liberty Ships (1941-1945)

- Liberty Ships were the first all-welded pre-fabricated cargo ships and were mass produced in the United States.
- 4700 ships were built by 1946;
- 1250 of these had suffered brittle fractures by 1953;
- 230 of these fractures were classed as serious;
- 12 of the ships broke in two.

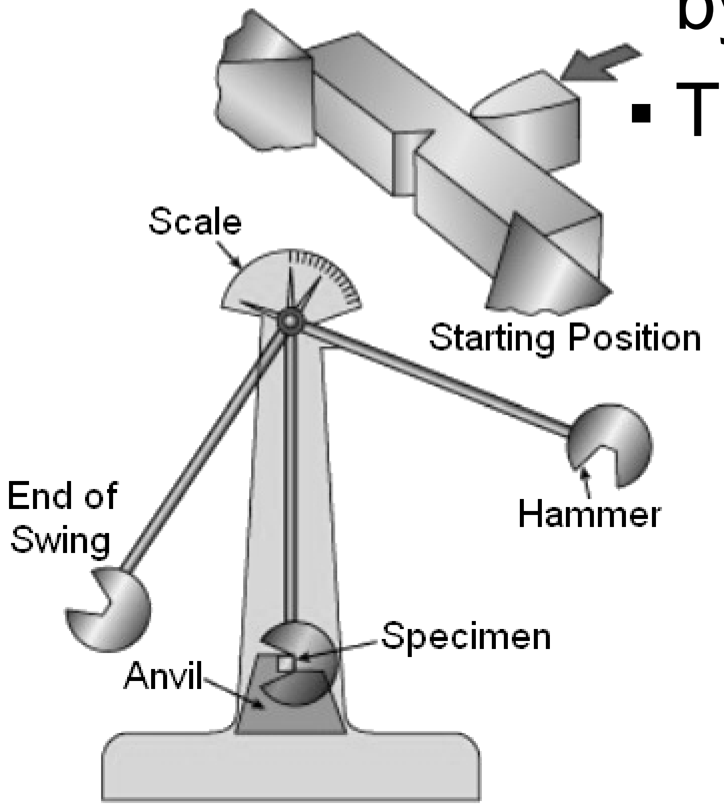
Constance Tipper (1894-1995)

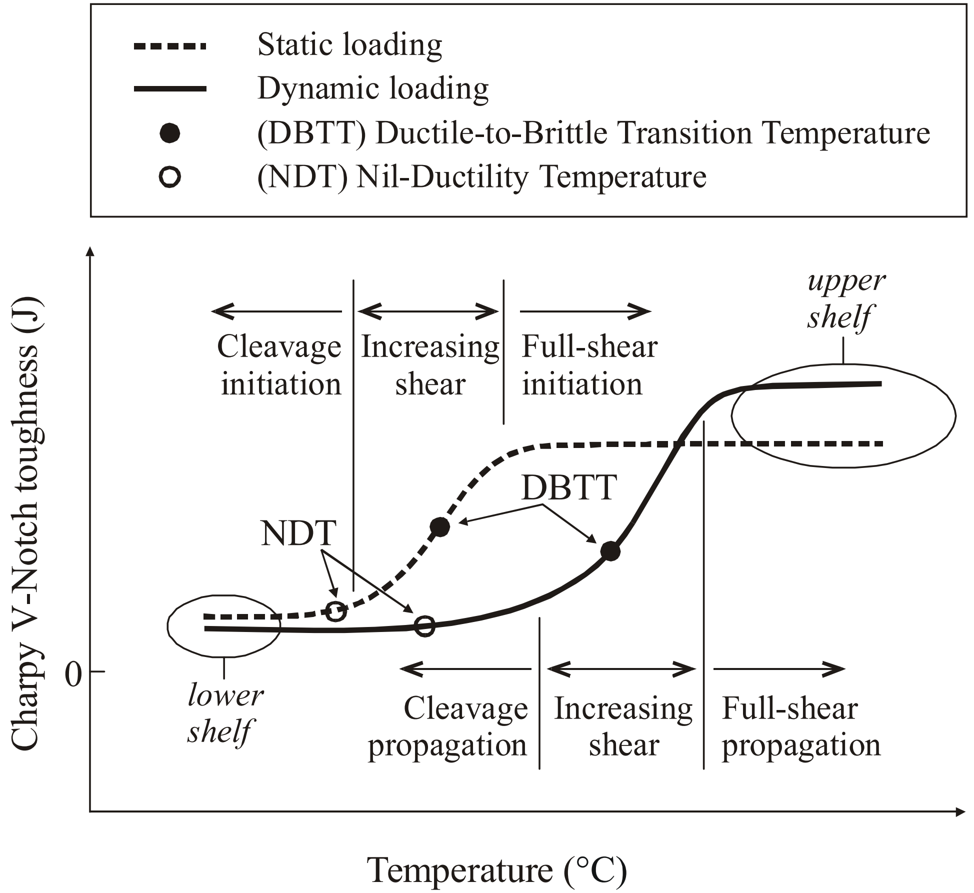
- Her major research contribution was to discover why during the Second World War the Liberty Ships were breaking in two.

http://www-g.eng.cam.ac.uk/125/1925-1950/tipper.html

Liberty Ships: Steel toughness

- The toughness of ship steels is traditionally specified by their Charpy 27 Joule temperature, T27J.
- The lower the T27J, the tougher the steel.





Lessons Learned

- The very high fracture rate in the Liberty ships was due to the use of steel which was unusually brittle even for its date of manufacture.
- Tipper demonstrated that the fractures were caused by the steel used rather than the fact that the ships had been welded, as was first thought.
- She established that there is a critical temperature below which the fracture mode in steel changes from ductile to brittle.
- Ships in the North Atlantic were subjected to such low temperatures that they would have been susceptible to brittle failure.
- Once steel quality was improved in the immediate post war period there was a rapid reduction in the number of ship brittle fractures.

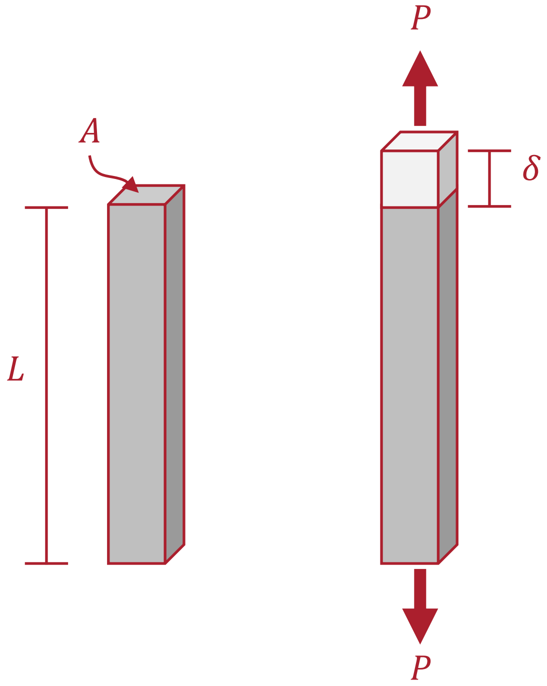
Other types of failure

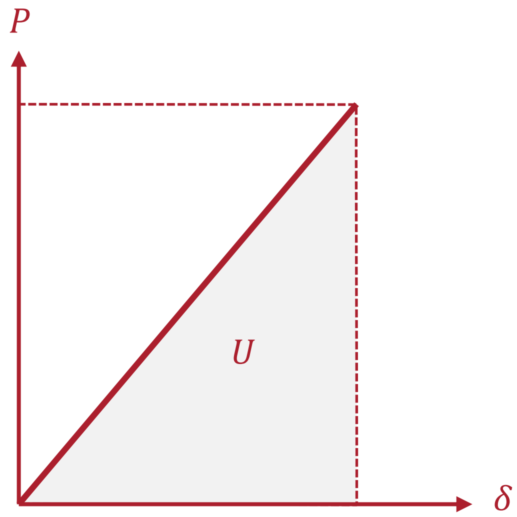
- Fatigue failure
  - Fracture by **slow crack growth**
  - Happens when the part is subjected to **many repetitions** of a stress below that for static crack growth
- Corrosion fatigue failure
  - Combined actions of a cyclic stress and a corrosive environment
  - Fatigue resistance will decrease in the presence of an aggressive chemical environment
    - NB. ‘aggressive’ is a relative term; for some materials plain water has a very significant effect!
- Stress corrosion cracking
  - Similar to corrosion fatigue – combines mechanical and chemical failure processes
  - However in this case the stress is **not cyclic** (but still below the yield stress for a metal)
- Creep and stress rupture failure
  - A result of a static load applied over **long periods of time**

Defining fracture terminology

Elastic Strain Energy

- When the bar is loaded you are inputting energy into the system; this is the elastic strain energy (U)
- This can be done through doing work (W)
- Energy conservation



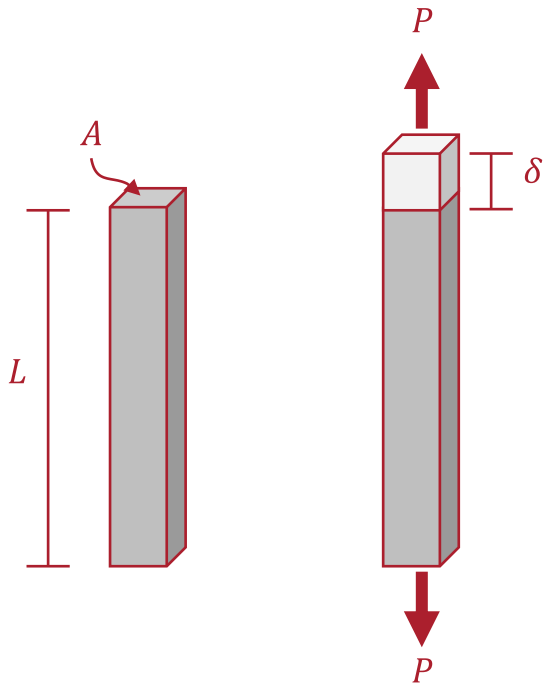


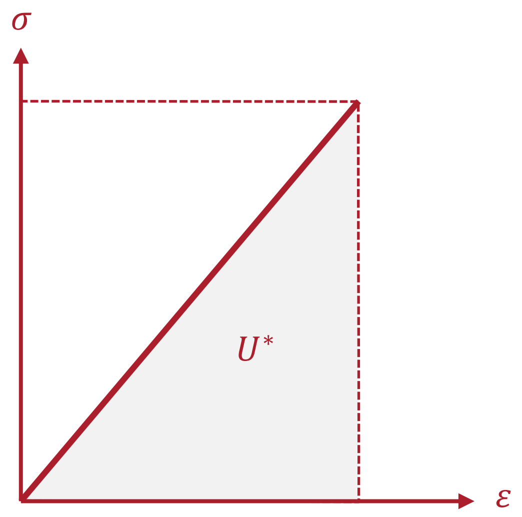
$$W - U = 0$$

$$U = \frac{1}{2} P\delta$$

Elastic Strain Energy Density

- Elastic strain energy density (U^*) is the elastic strain energy per unit volume of material.
- On a stress (σ), strain (ε) plot, strain energy density is the area under the curve.

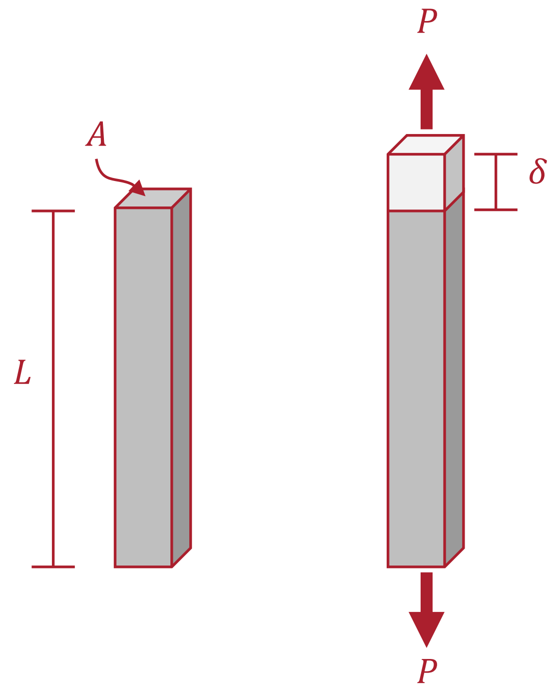


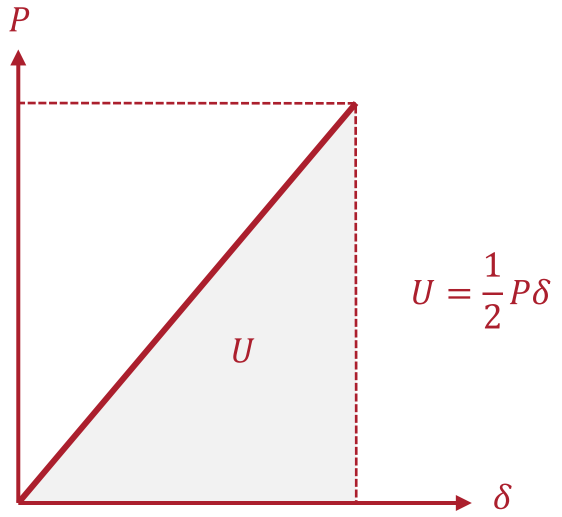


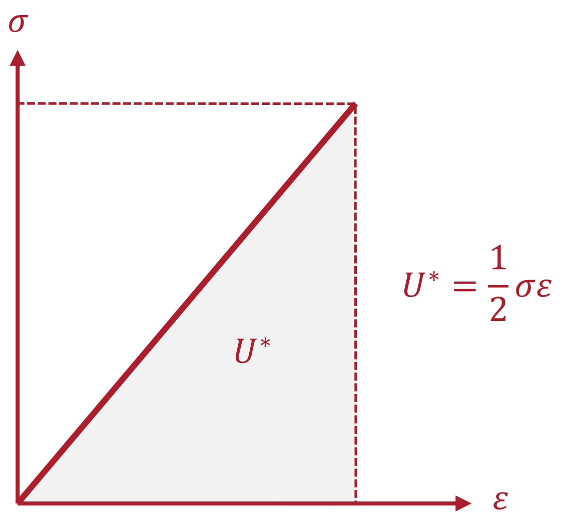
$$U^* = \frac{1}{2}\sigma\varepsilon$$

Elastic strain Energy Density

- The relationship between the input energy U and the strain energy density U^* is:



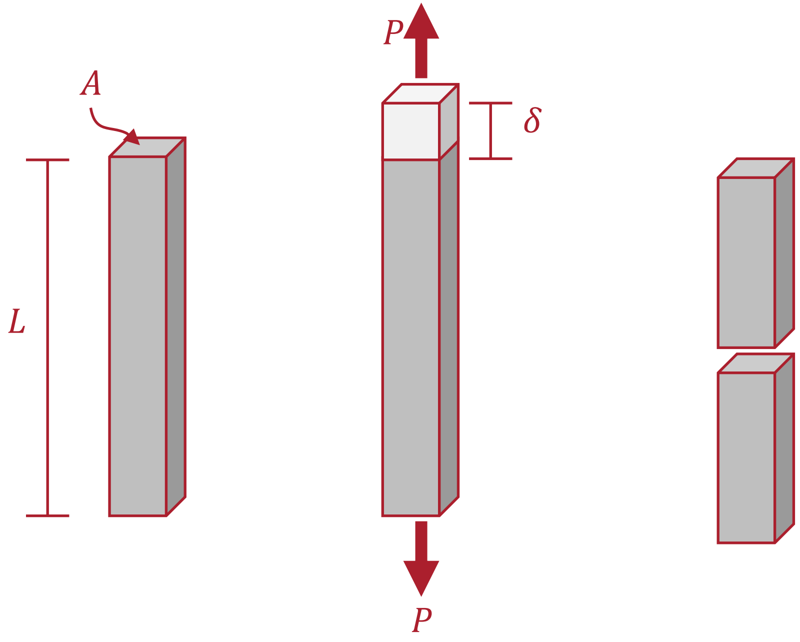


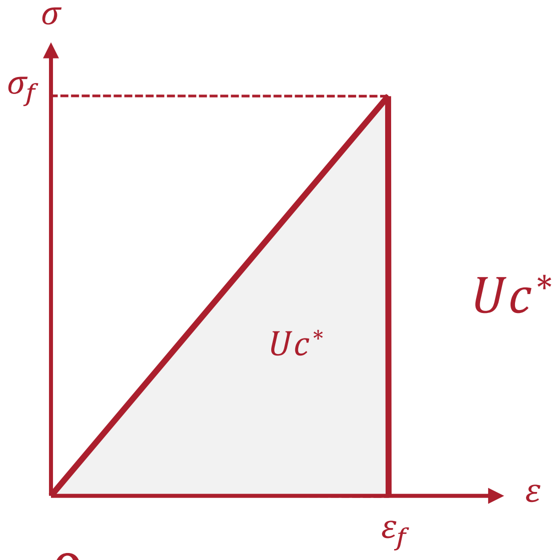


$$\sigma = \frac{P}{A} \qquad \varepsilon = \frac{\delta}{L} \qquad E = \frac{\sigma}{\varepsilon} \qquad U = \frac{1}{2}P\delta = \frac{\sigma^2}{2E}V = U^*V$$

Toughness

- We then continue loading until failure, where *F* is the work expended in fracturing material over da
- The energy dissipated per unit volume of the material **up to** failure is known as **Toughness**



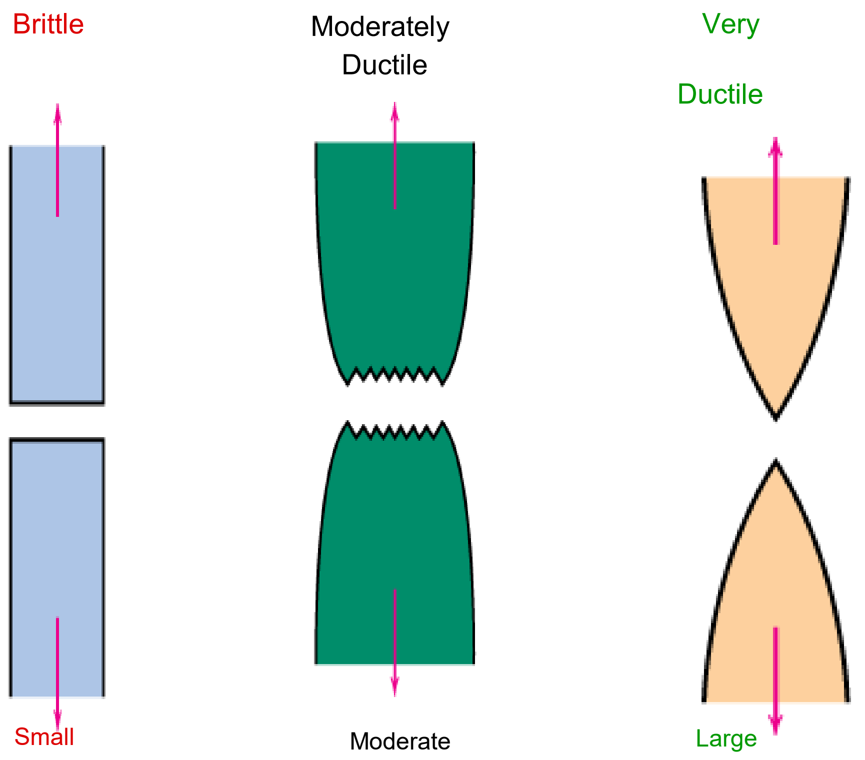


$$Uc^* = \frac{1}{2}\sigma\varepsilon$$

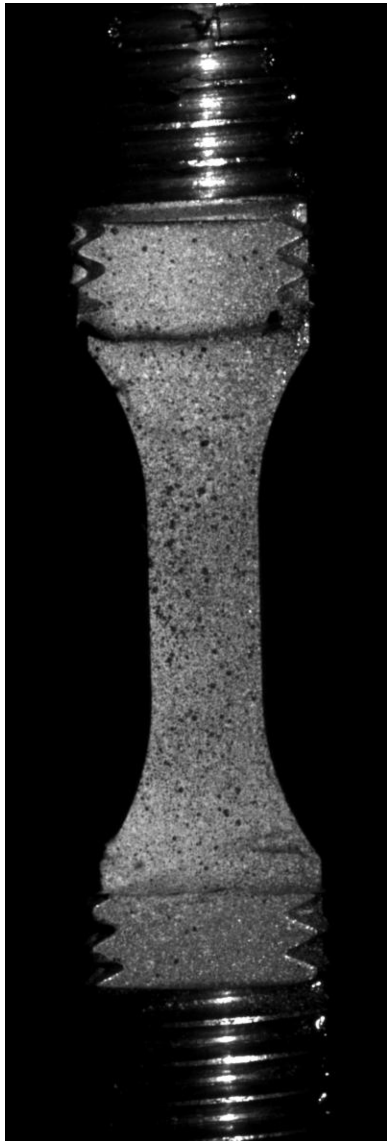
$$\frac{d}{da}(W - U - F) = 0$$

Modes of Failure

- Two general classes of fracture can be seen in engineering materials.
- These are **brittle** and **ductile.** The distinction is based on a material's ability to exhibit plastic deformation



Brittle material



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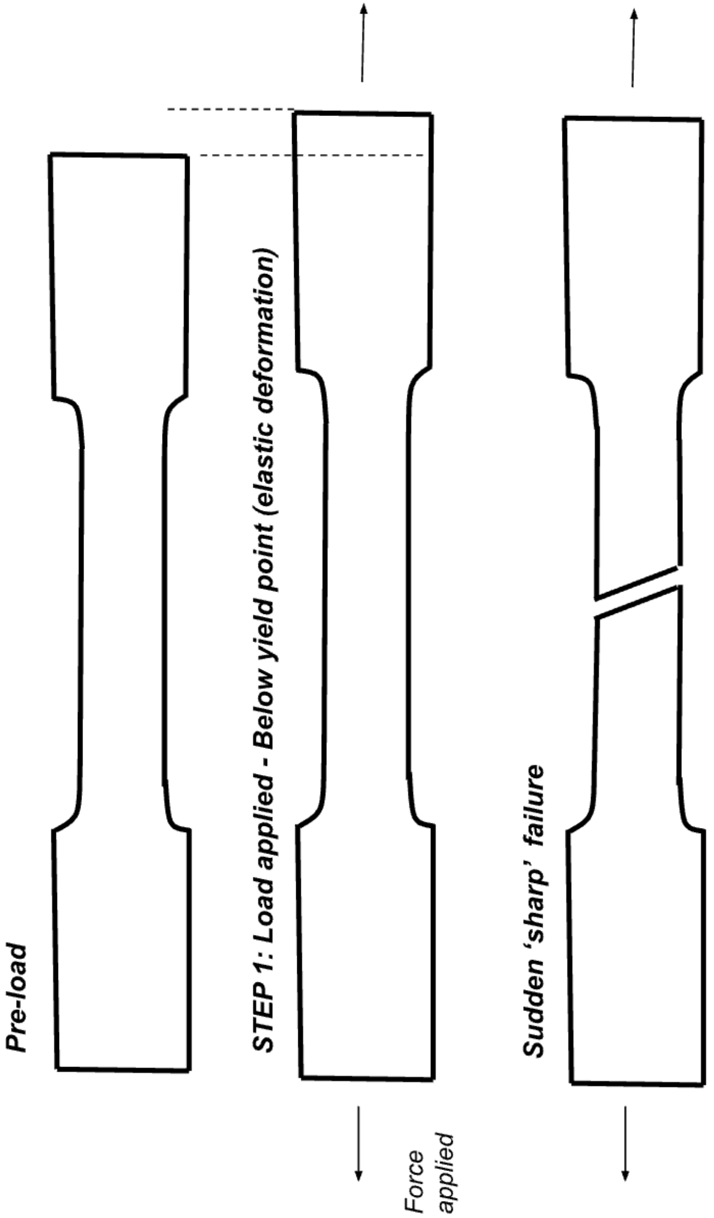
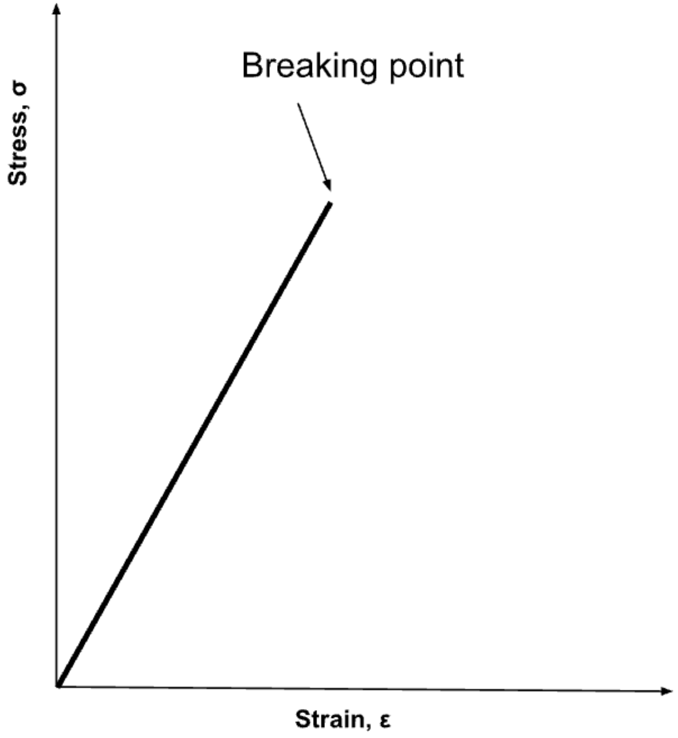
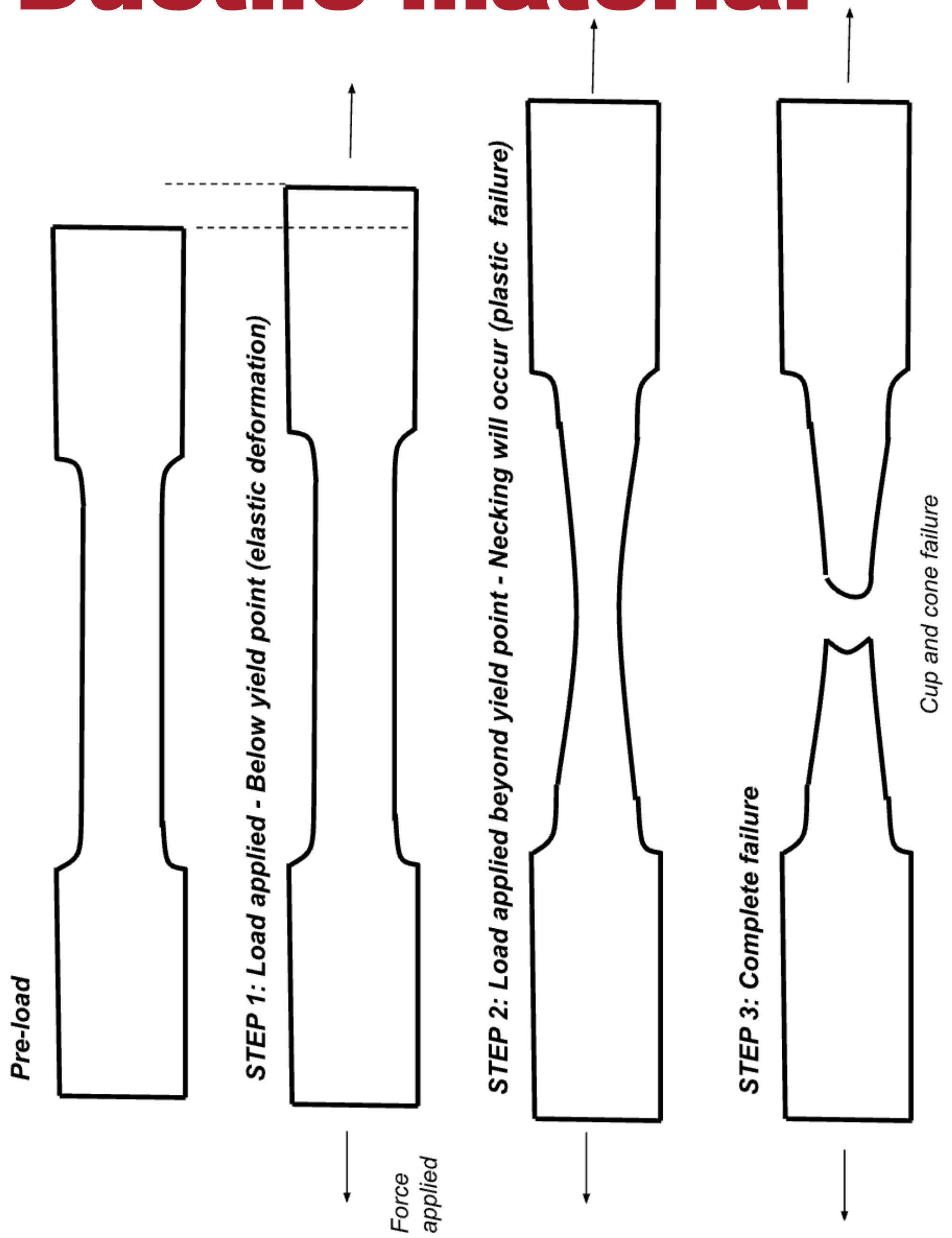
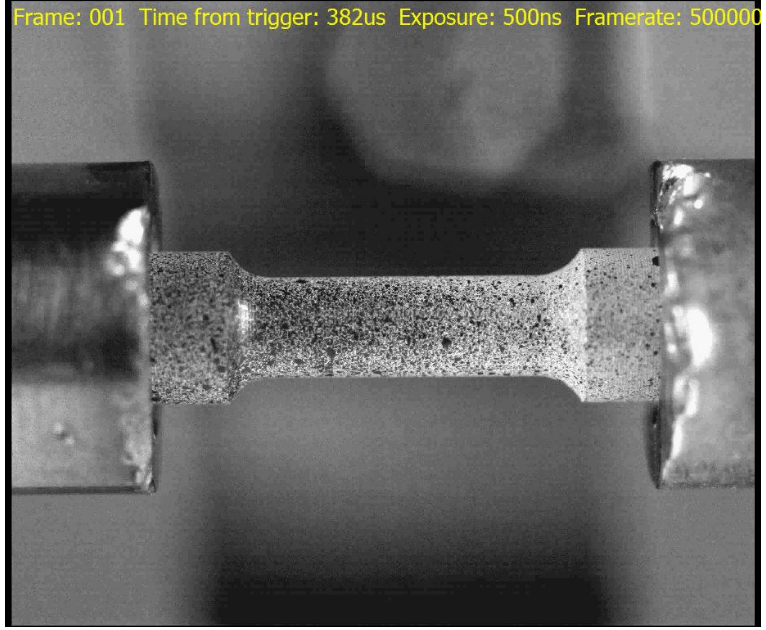
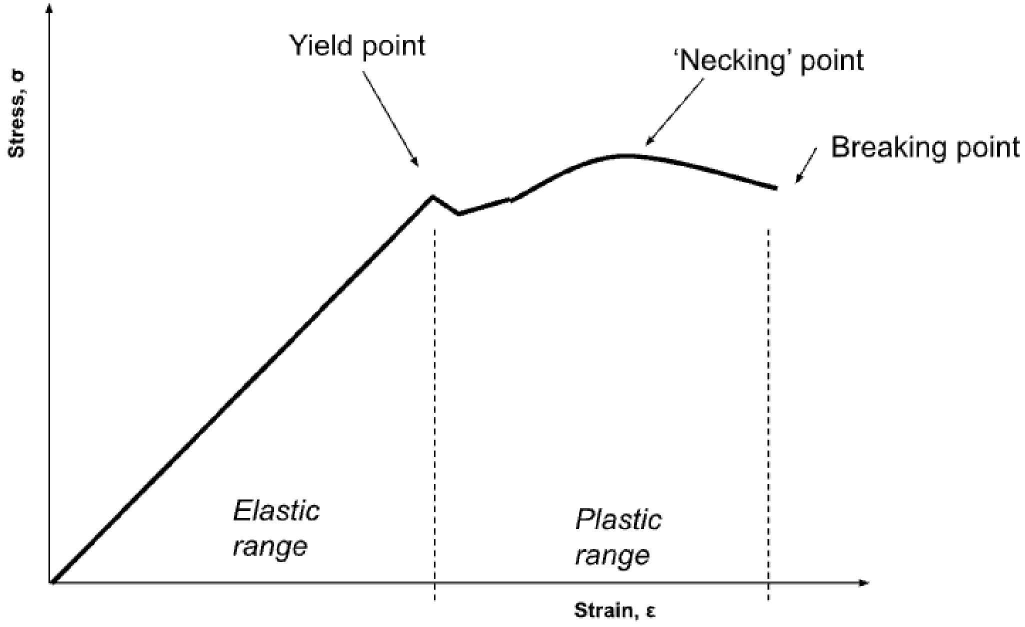




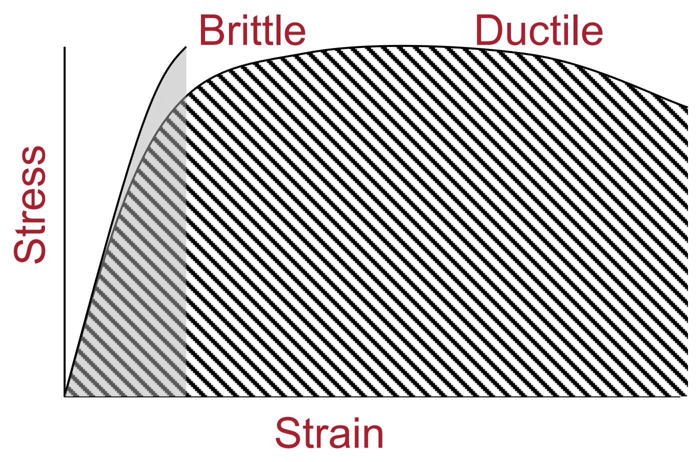
Ductile material







Ductile vs Brittle

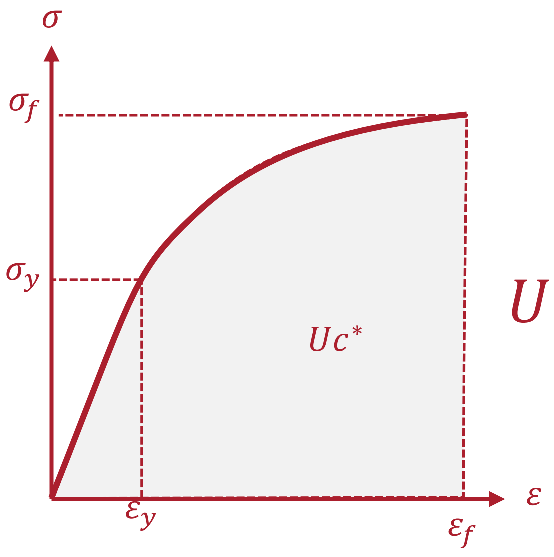


- Once failed, the area under the stress-strain curves indicates the level of energy dissipation or absorption per unit volume
- Brittle materials exhibit little or no plastic deformation and low energy dissipation or absorption
- Ductile materials exhibit extensive plastic deformation and high energy absorption

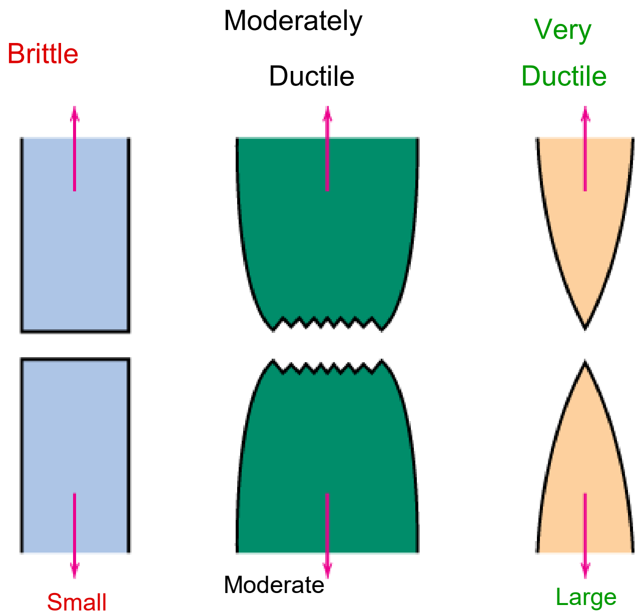
Ductile vs Brittle

- Ductile materials produce a non-linear stress, strain response

- Toughness (strain energy density before failure) definition is still the same but strain energy is no longer the same past the elastic limit (σ_y, ε_y)



$$Uc^* = \int_0^{\varepsilon_f} \sigma d\varepsilon$$



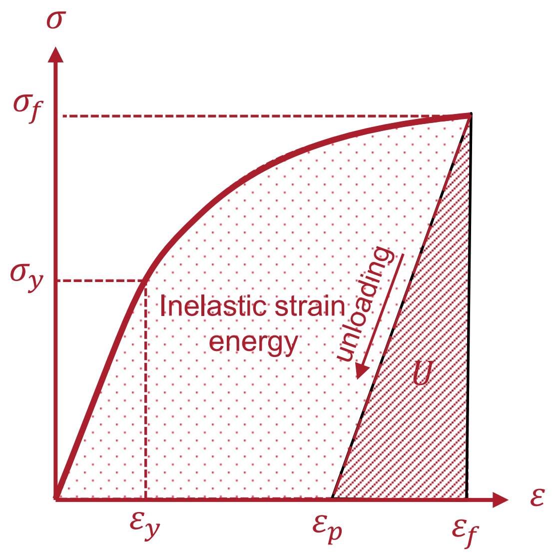
Brittle: No warning

Ductile: Warning before fracture

Ductile vs Brittle

Key slide!

- Once a material has plastically deformed, the elastic strain energy is the energy that is **recovered** when the material is unloaded
- The inelastic strain energy ($U_{\text{inelastic}}$) is the energy that is **absorbed** by the material through **plastic deformation**
- The elastic strain energy (U) can drive the crack to grow



$$Uc^* = \int_0^{\varepsilon_f} \sigma d\varepsilon$$

$$U = \frac{1}{2}\sigma(\varepsilon - \varepsilon_P)V$$

$$U_{\text{inelastic}} = Uc^*V - U$$

Fractography: Study of fracture surfaces

Brittle fracture

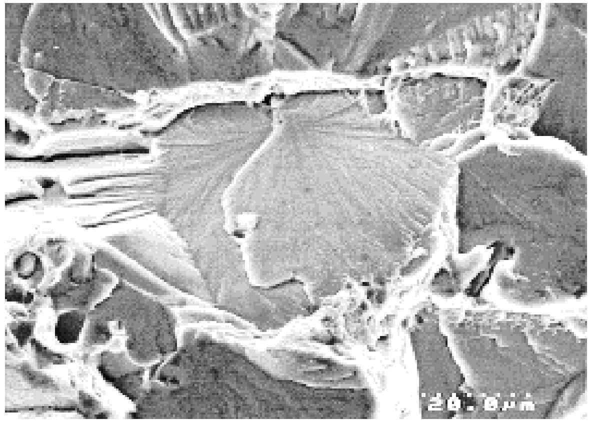
- Little or no plastic deformation
- Catastrophic, usually strain is < 5%

Ductile fracture

- Accompanied by significant plastic deformation

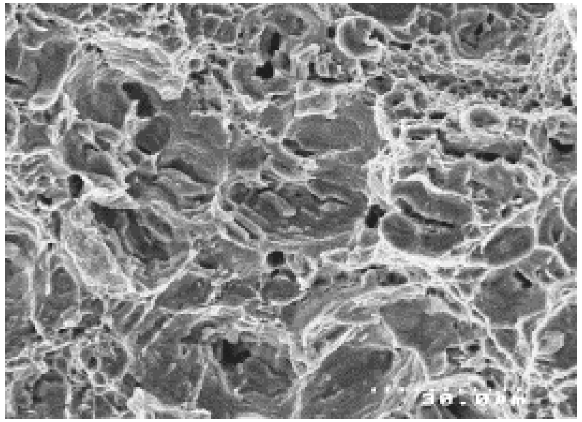
Low energy absorbed during transgranular cleavage fracture (low energy fracture mode)

High energy absorbed by microvoid coalescence during ductile failure (high energy fracture mode)



→ More catastrophic

→ Less catastrophic

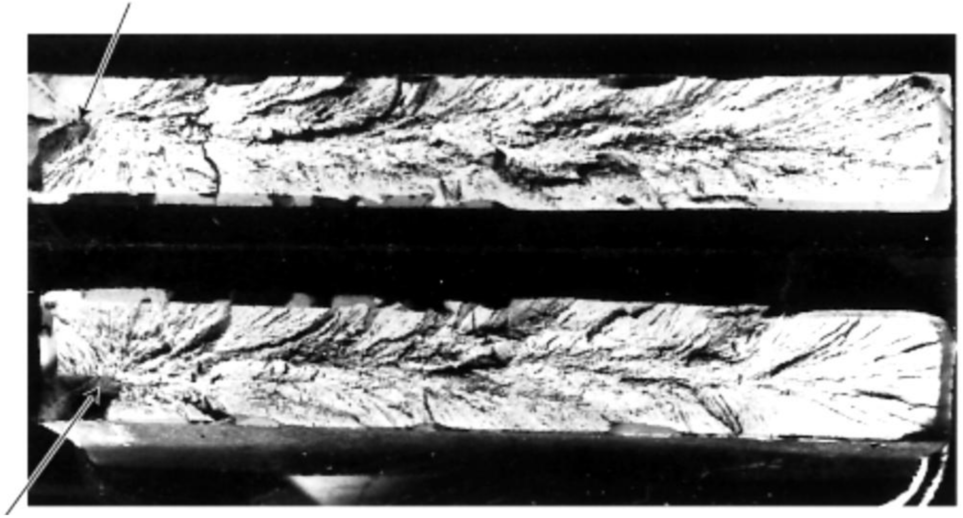


Brittle Fracture

Key slide!

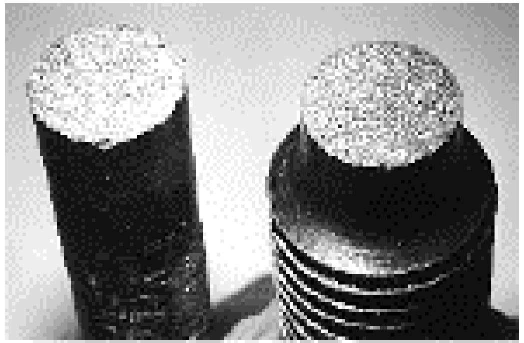
- The process of cleavage fracture consists of three steps:

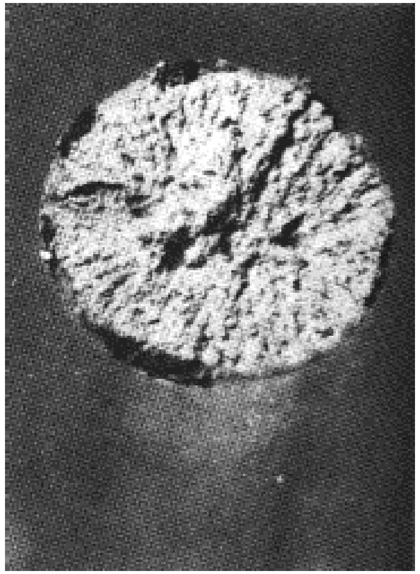
1. Plastic deformation to produce dislocation pile-ups.
2. Crack initiation
3. Crack propagation to failure



- Distinct characteristics of brittle fracture surfaces:

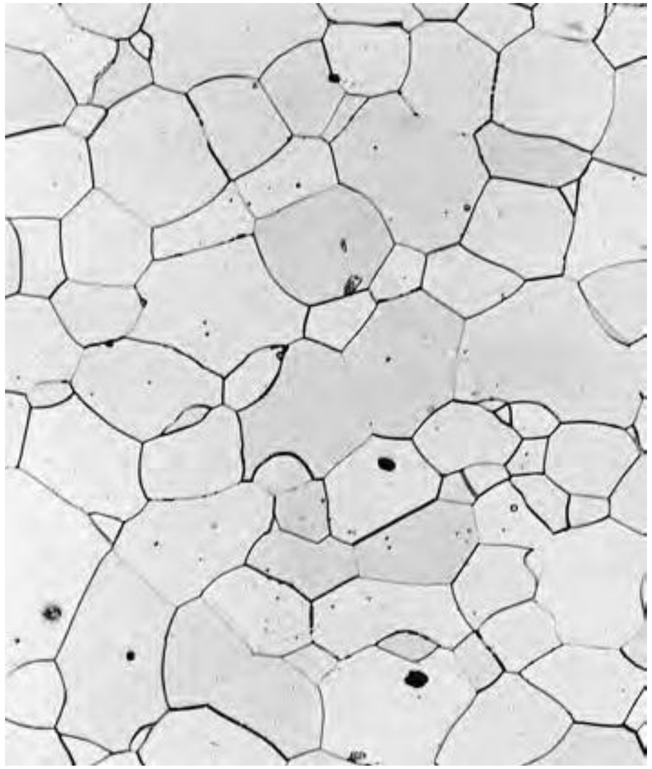
1. The absence of gross plastic deformation
2. Grainy or Faceted texture
3. River marking or stress lines





Atomic bonds and Grain boundaries

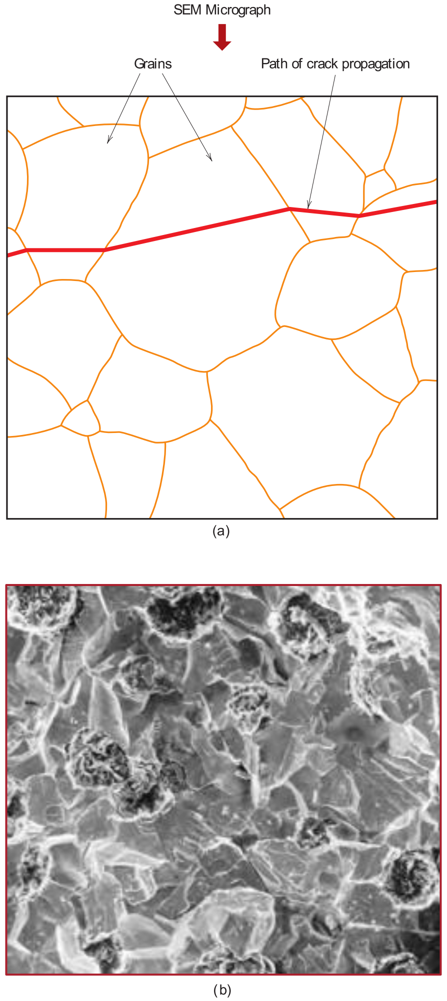
Photomicrograph of a polycrystalline brass specimen.
W. Callister, Materials Science and Engineering



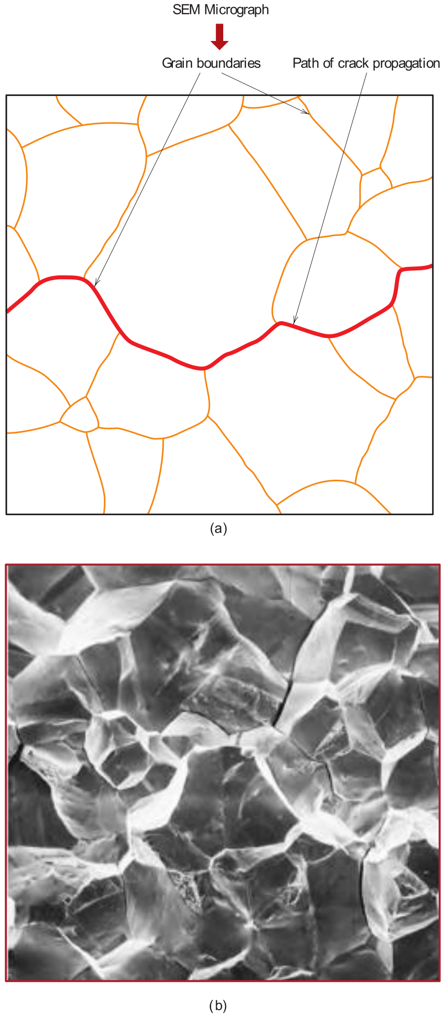
Photomicrograph of the surface of a polished and etched polycrystalline specimen of an ironchromium alloy in which the grain boundaries appear dark.
W. Callister, Materials Science and Engineering

Fractography in metals

- **Cleavage** fracture is the breaking of atomic bonds along crystallographic planes (**Transgranular**)
  - Surface: Rough and textured, with river and feather patterns
  - Moderate to high strength brittle fracture mode
- In some metal alloys cracks form along grain boundaries (**Intergranular**)
  - Surface: Sharp and 3D faceted grains
  - Moderate to low energy brittle fracture mode



Transgranular fracture

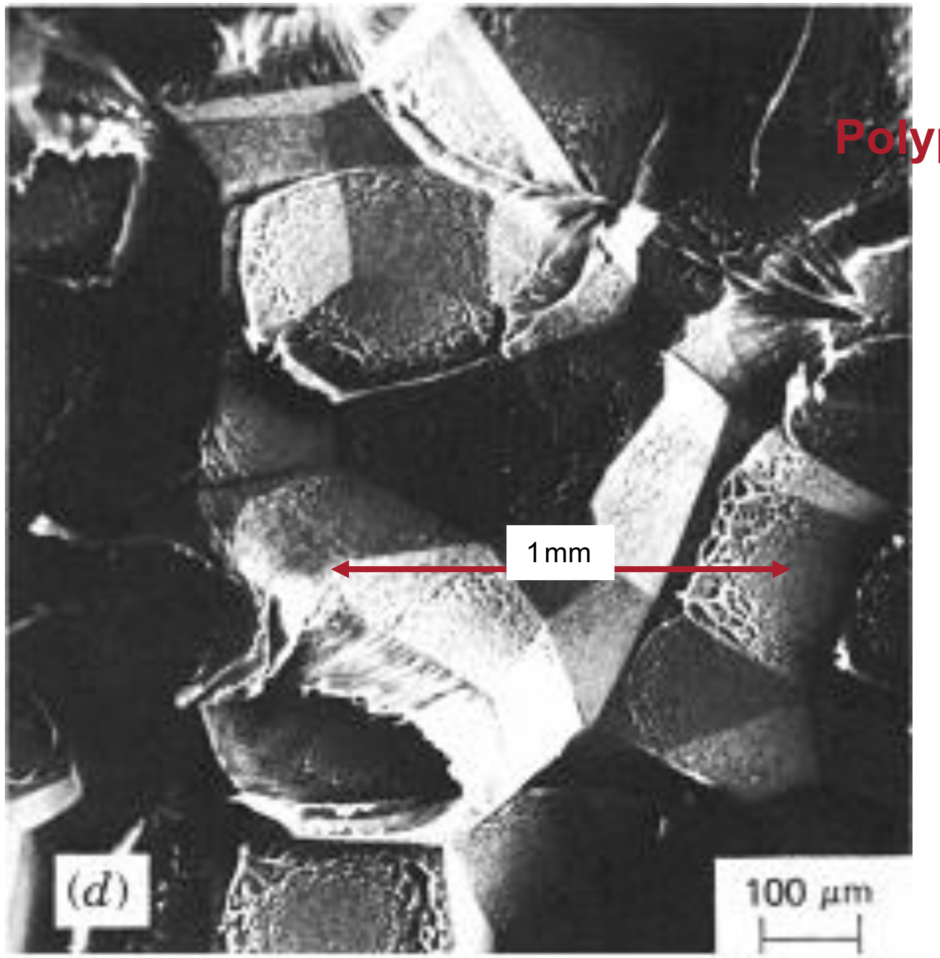


Intergranular fracture

W. Callister, Materials Science and Engineering

Brittle Fracture Surfaces

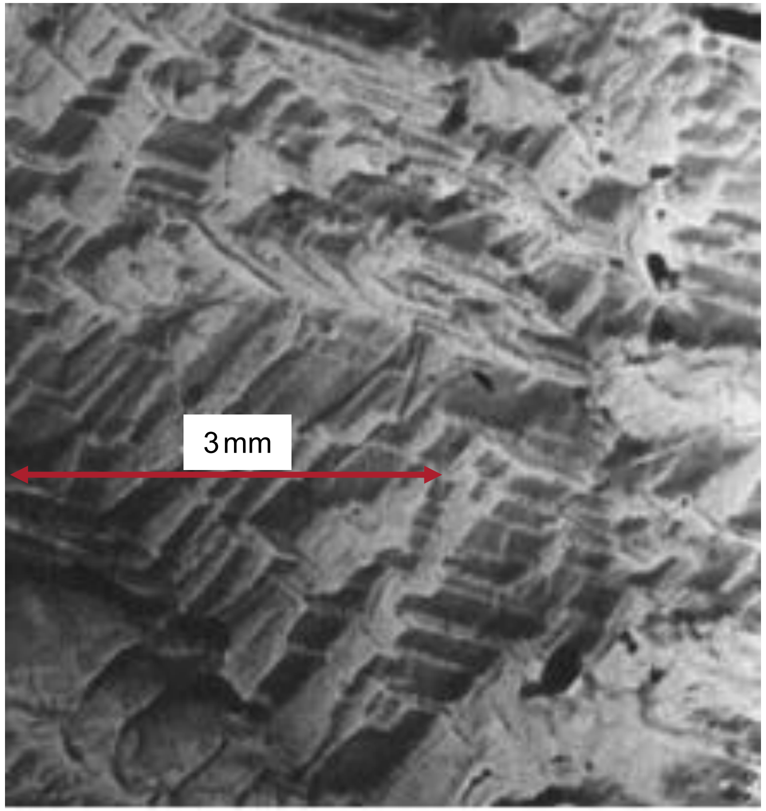
Intergranular (between grains)



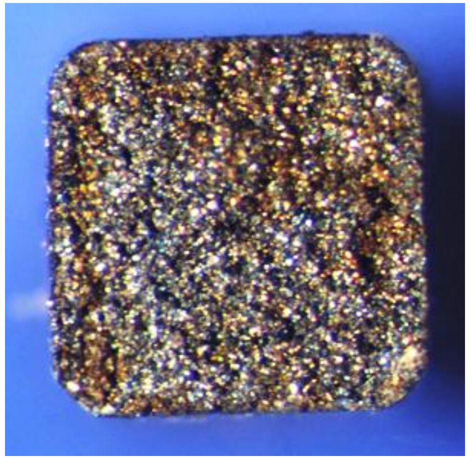
Polypropylene (polymer)

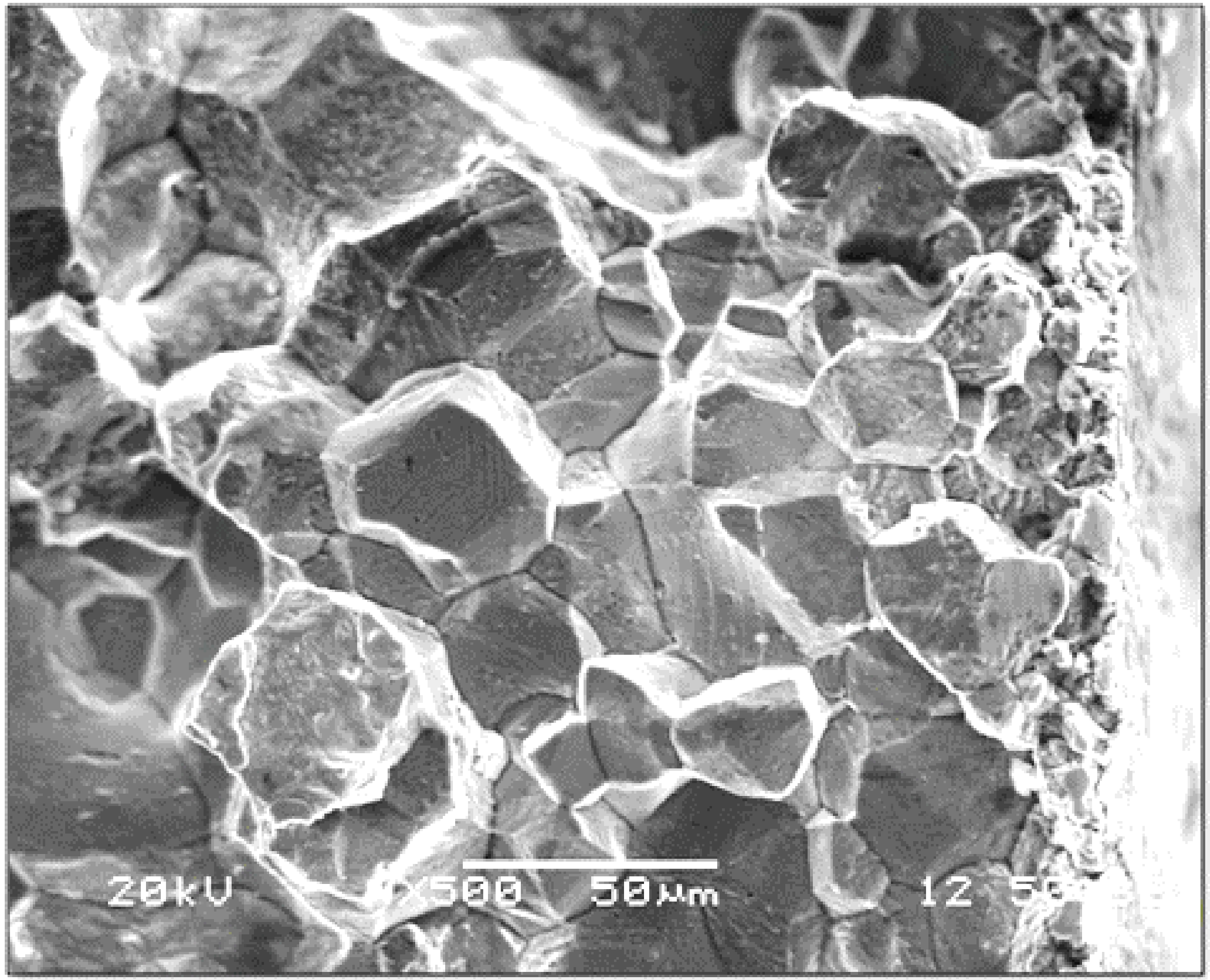
Transgranular (through grains)

Al Oxide (ceramic)

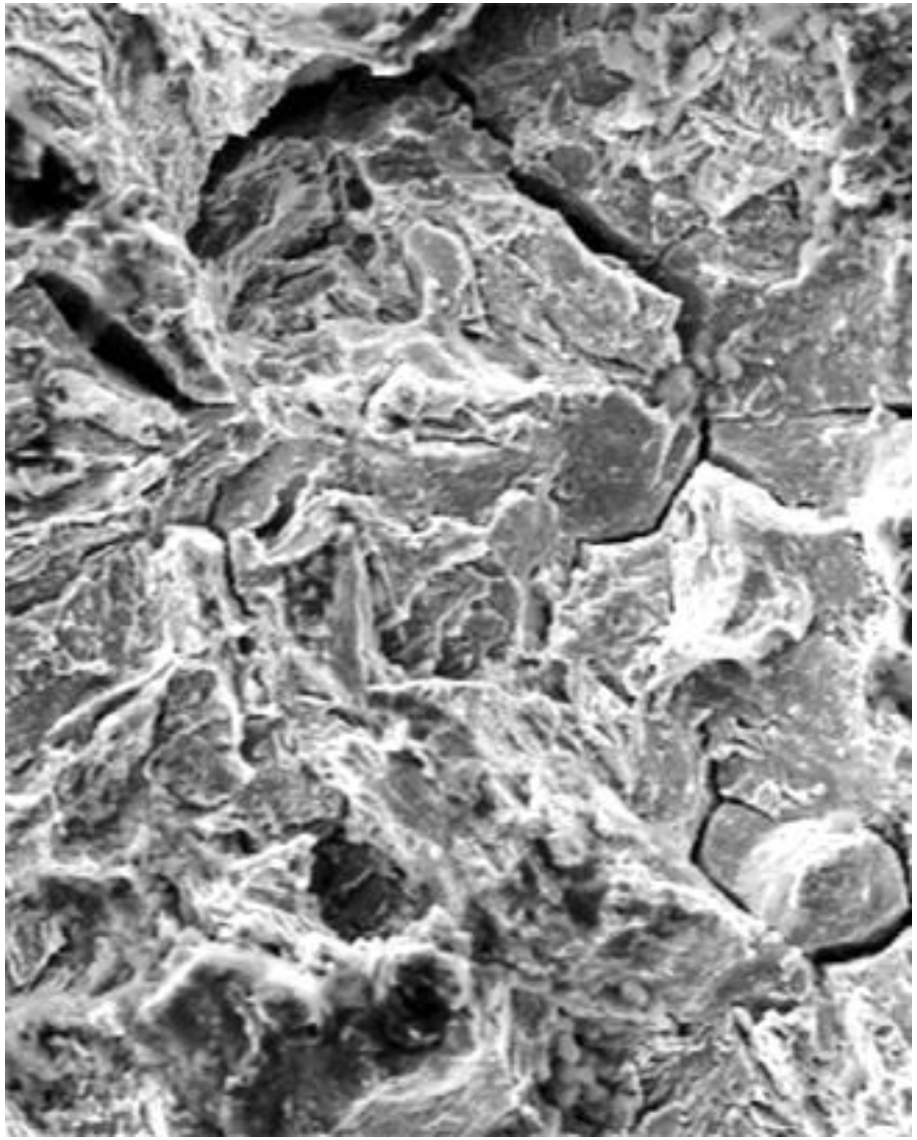


Brittle Fracture Surface - Faceted





Brittle Fracture Surface - Cleavage



Imperfections

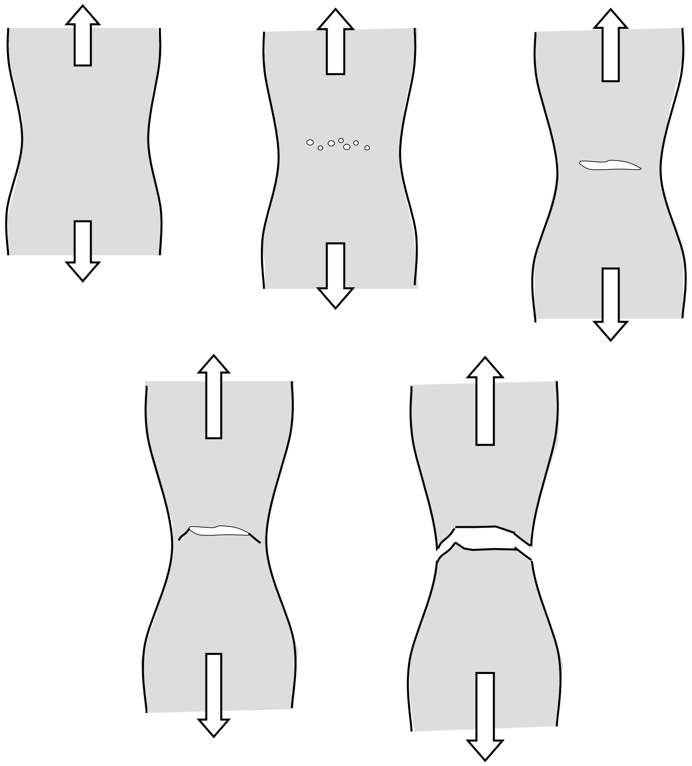
Transmission electron micrograph of a titanium alloy in which the dark lines are dislocations. 51,450×
W. Callister, Materials Science and Engineering

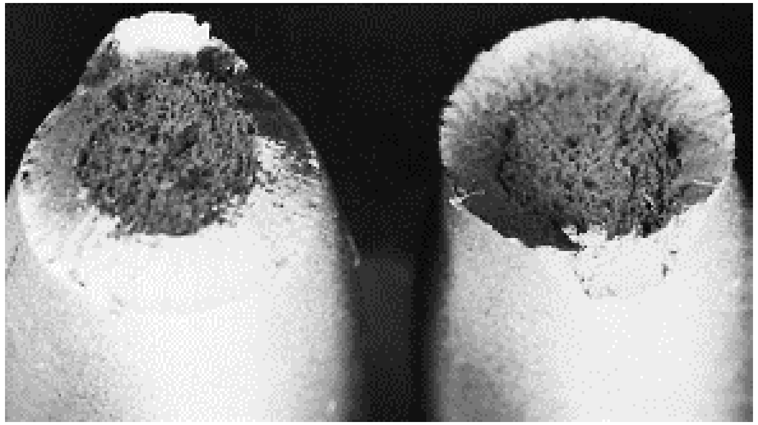
- Defects and flaws limit the potential elastic strain energy that can be stored by the material
- However, extra deformation (strain) prior to failure would mean the material is tougher
- For example, dislocations in crystalline structure results in slip planes
- Extra energy is absorbed when the crystalline structure slides, this is what we refer to as **plastic deformation**

Key slide!

Ductile Fracture

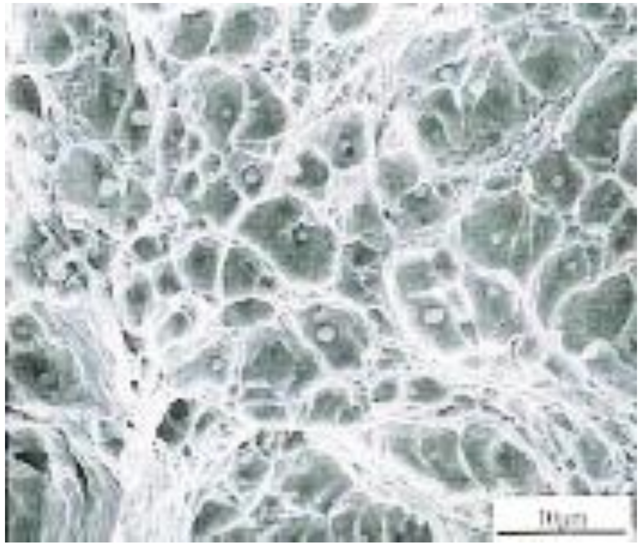
- Under uniaxial tensile force in ductile materials:
  - **Necking** caused by dislocation movements or polymer chain sliding
  - **Atomic debonding** and **microvoid init**
  - These **coalesce**(join) to form larger cracks
  - Eventually propagate in the direction normal to the tensile axis.
- **Ductile fracture** is much less critical in engineering
- Failure can be detected beforehand due to observable **plastic deformation**
- For round coupons: a crack eventually propagates through the periphery along the shear plane at 45º, leaving the typical **cup and cone** pattern



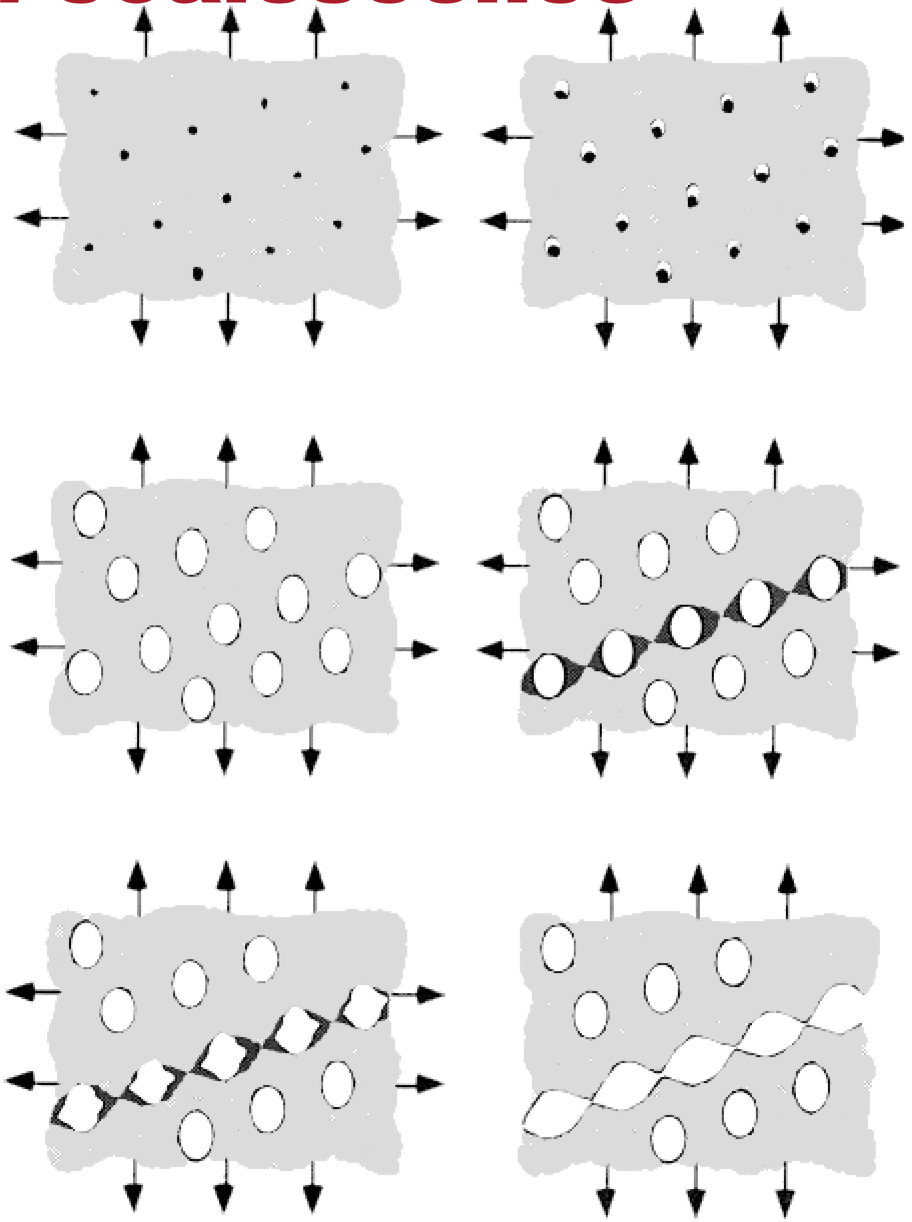


Microvoid formation, growth and coalescence

- Microvoids are easily formed at inclusions, intermetallic or second-phase particles and grain boundaries
- These are simply pockets of air or foreign particles with little to no bond strength
- Growth and coalescence of microvoids progress as the local applied load increases

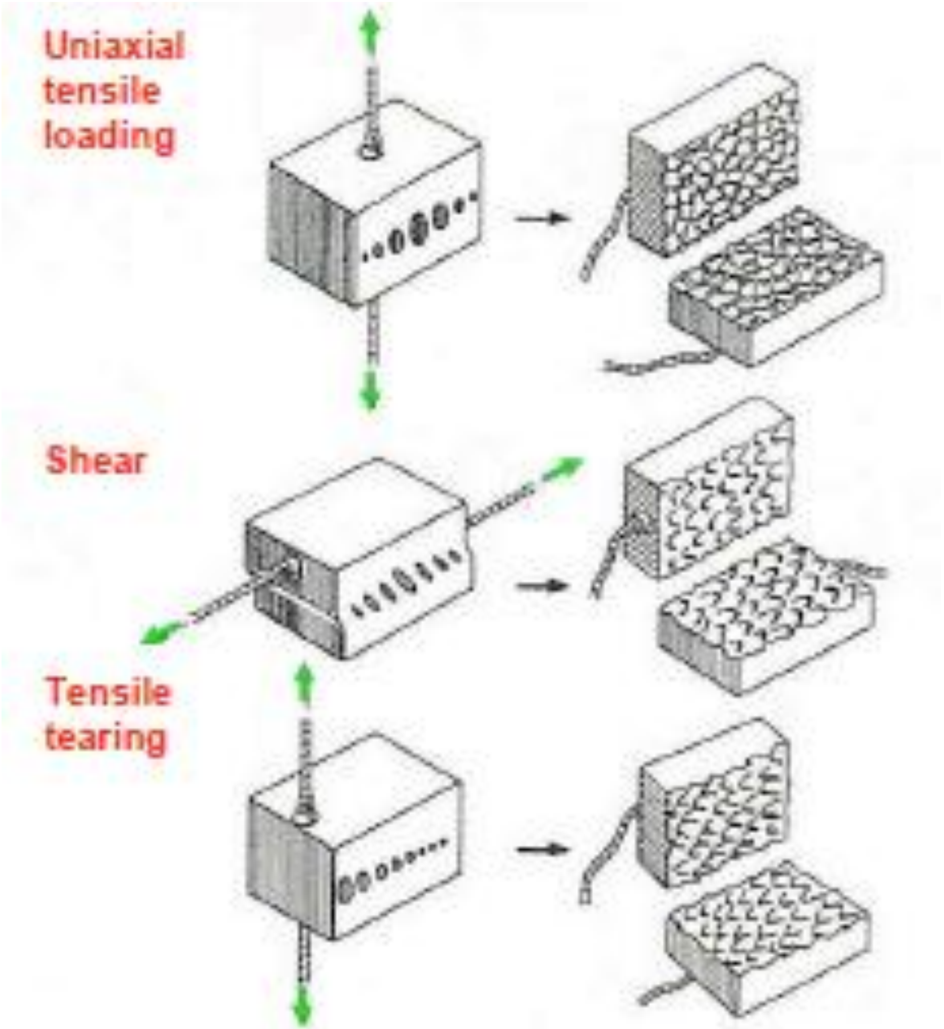


Ductile dimples centre on spherical particles



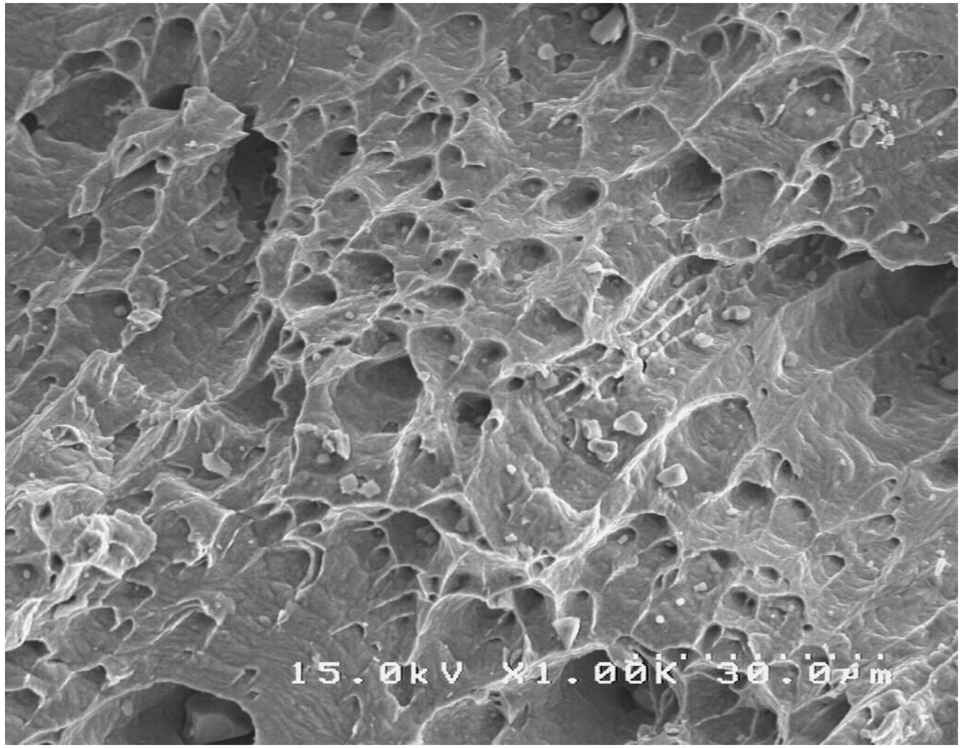
Micro-void shape

- Microvoid shape is strongly influenced by type of loading

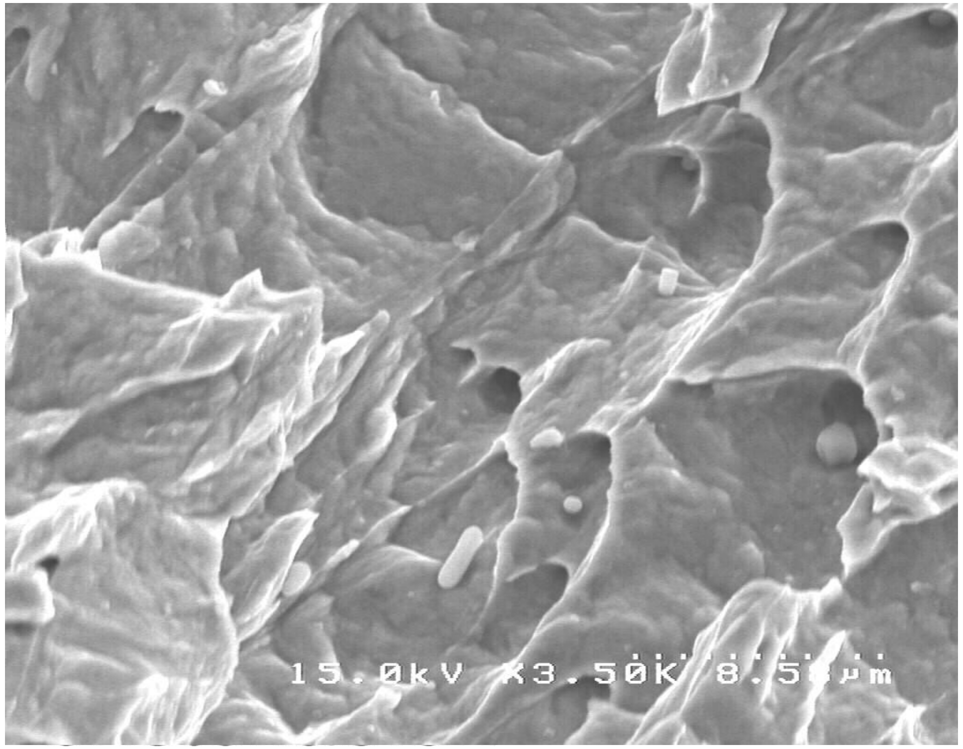


- Uniaxial tensile loading
  - Equiaxed dimples
- Shear loading
  - Elongated and parabolic dimples pointing in the opposite directions on matching fracture surfaces
- Tensile tearing
  - Elongated dimples pointing in the same direction on the matching fracture surface

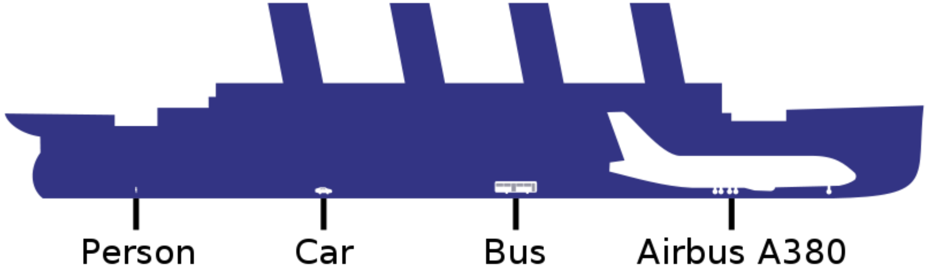
Fracture Surfaces – 304 Stainless Steel

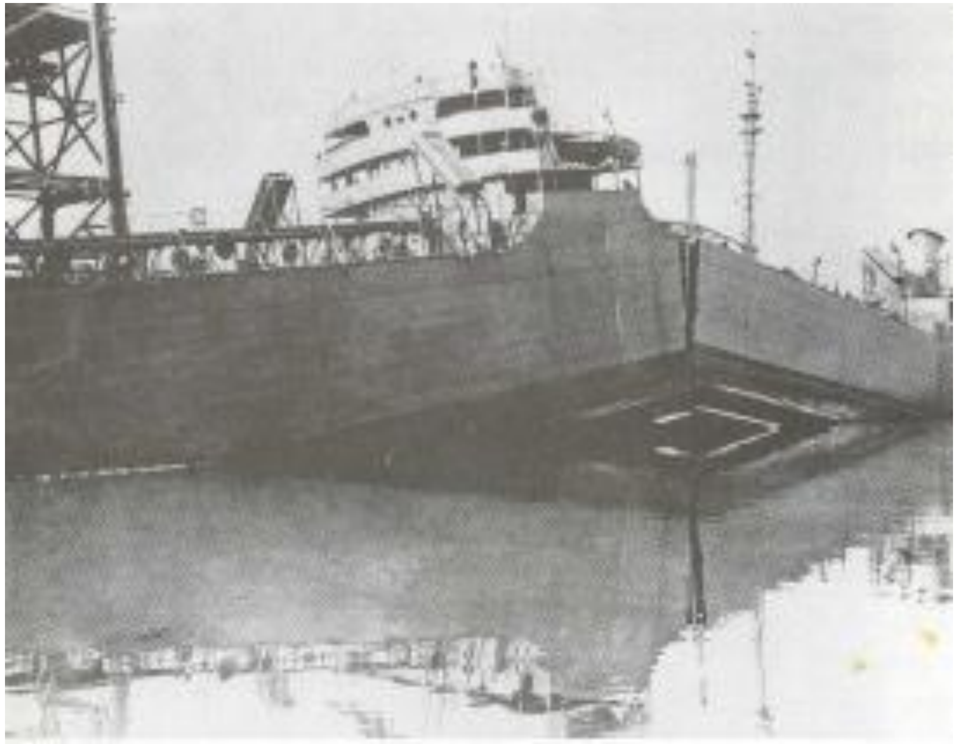


Ductile Fracture of 304 Stainless Steel



Effect of Temperature

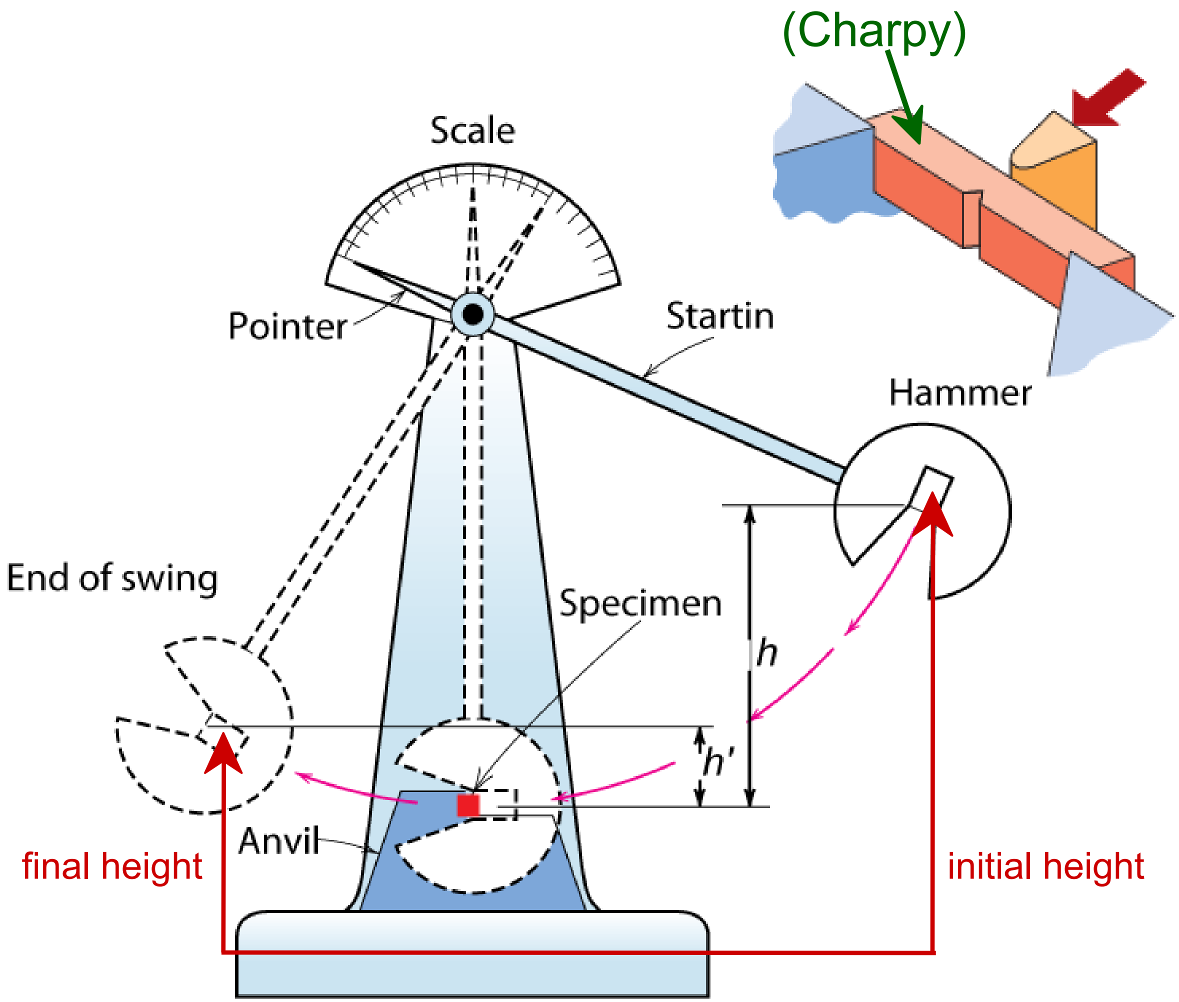




Characterisation of transition temperature

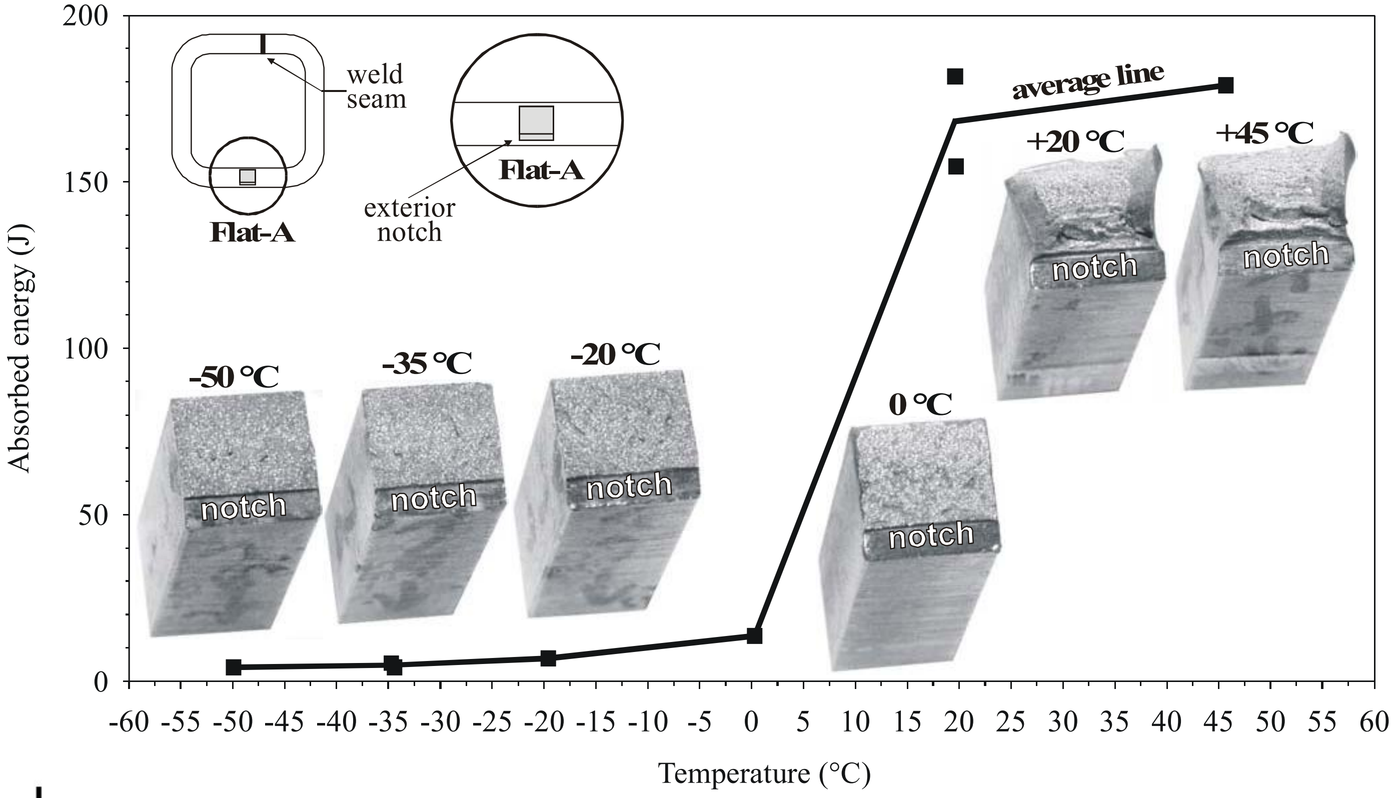
Charpy Impact Testing

- Impact loading under low temperatures:
  - severe testing case
  - makes material more brittle
  - decreases toughness



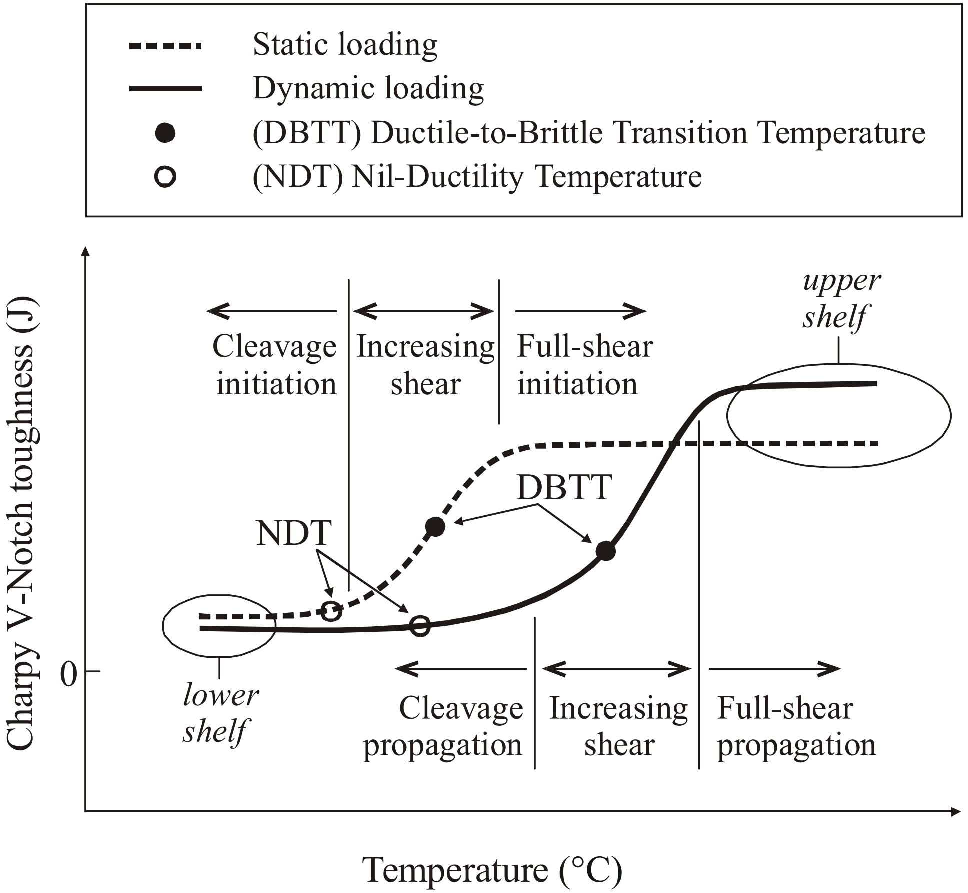
Ductile to brittle transition behaviour

- Absorbed energy versus temperature behaviour of steel
- Increasing temperature allows more slip systems to operate, yielding general plastic deformation to occur prior to failure



Liberty Ships: Steel toughness

- The toughness of ship steels is traditionally specified by their Charpy 27 Joule temperature, T27J.
- The lower the T27J, the tougher the steel.



Concluding Remarks

- We've learned the concept of failure
- We've learned that the presence of defects, cracks or flaw is associated with a loss of potential strain energy
- We've seen how defects and flaws may result in ductile failure
- Fractography is an important method to analyse fracture surfaces
- The effects of temperature, stress concentrations and other factors on the failure

Next week: What can history tell us?

Issues to address:

- How do cracks that lead to failure form?
- How is fracture resistance quantified?
- How does the fracture resistances of different material classes compare?
- How do we estimate the stress to fracture?
- How do loading rate, loading history, and temperature affect the failure behaviour of materials?