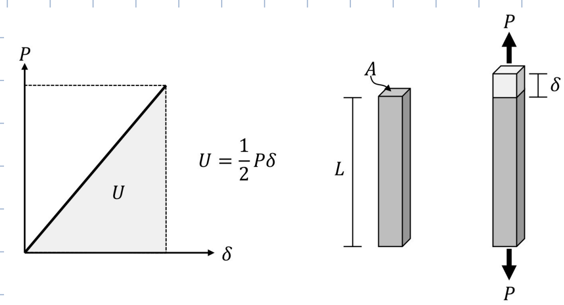
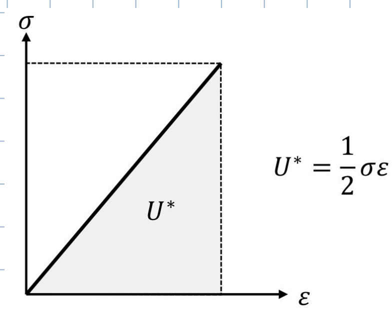
Elastic Strain Energy :

$F - U = 0$, where $F =$ work & elastic strain energy $= U$



Elastic Strain Energy Density : (elastic strain per unit volume of material)



where $\sigma = \frac{P}{A}$, $\varepsilon = \frac{\delta}{L}$, $E = \frac{\sigma}{\varepsilon}$

$$\rightarrow \quad U = \frac{1}{2}P\delta = \frac{\sigma^2}{2E}V = U^*V$$

Toughness:

- We then continue loading until failure, where W is work expended in fracturing material over da :

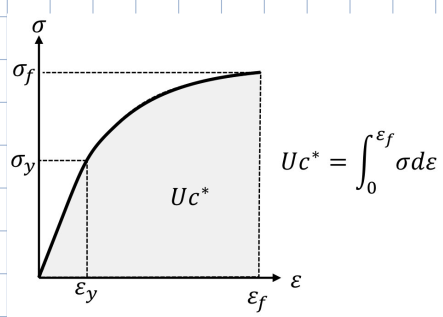
$$\frac{d}{da}(F - U - W) = 0$$

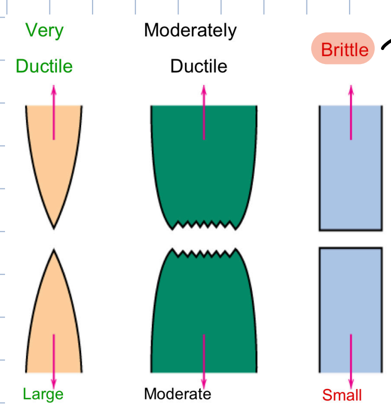
→ energy dissipated per unit volume of material up to failure is toughness.

Ductile vs. Brittle

Ductile - produces non-linear stress, strain response : warning before fracture

→ toughness definition still the same but strain energy changes post elastic limit $(\sigma_y, \varepsilon_y)$



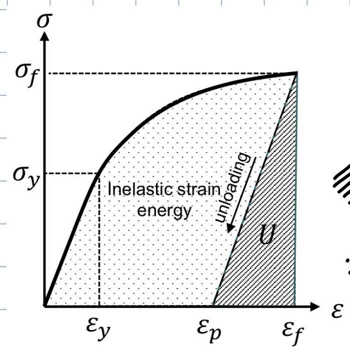


Brittle → no warning before fracture

- Once material has plastically deformed, elastic strain energy is the energy recovered when the material is unloaded.

- Inelastic strain energy is energy absorbed by material through plastic deformation. ($U_{inelastic}$)

- Elastic strain energy (U) can drive crack to grow.

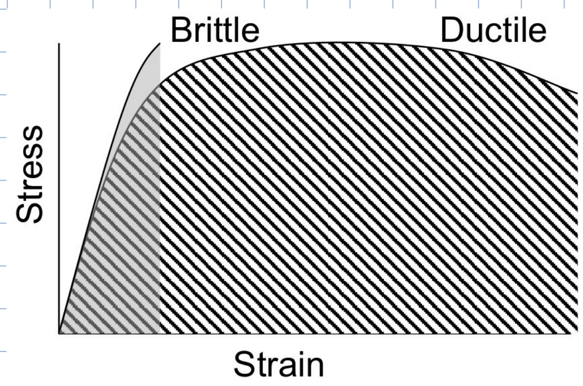


$$Uc^* = \int_0^{\varepsilon_f} \sigma d\varepsilon$$

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

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

- Once a material has failed, area under stress-strain curves indicates level of dissipation / absorption per unit volume.



Imperfections:

- Defects & flaws limit potential elastic strain energy that can be stored by material

- However, extra deformation (strain) prior to failure makes material tougher.

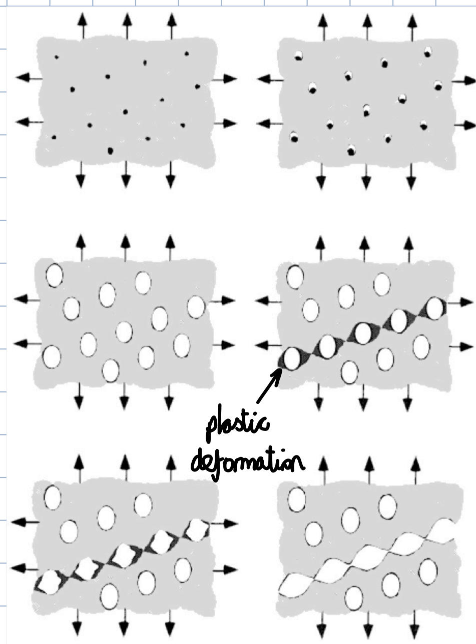
↳ e.g dislocations in crystalline structure results in slip planes

↳ extra energy stored when crystalline structure slides → plastic deformation

Dark lines are dislocations

Microvoid formation, growth & coalescence :

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



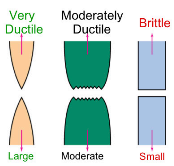
Fractography : Study of fracture surfaces

Ductile fracture

- Accompanied by significant plastic deformation

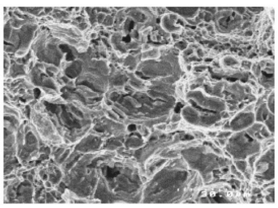
Brittle fracture

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

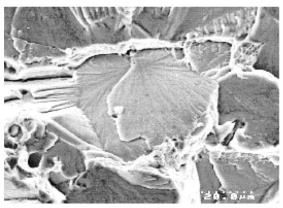


High energy absorbed by microvoid coalescence during ductile failure (high energy fracture mode)

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



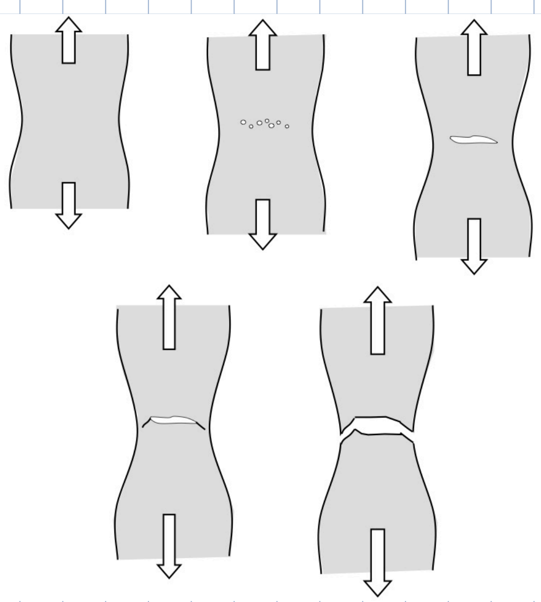
→ Less catastrophic



→ More catastrophic

Ductile Fracture :

- Under uniaxial tensile force in ductile materials :
  → Necking caused by dislocation movements or polymer chain sliding.
  → Atomic bonding and microvoids
    ↳ eventually propagate in direction normal to tensile axis.
      ↳ These coalesce (join) to form larger cracks

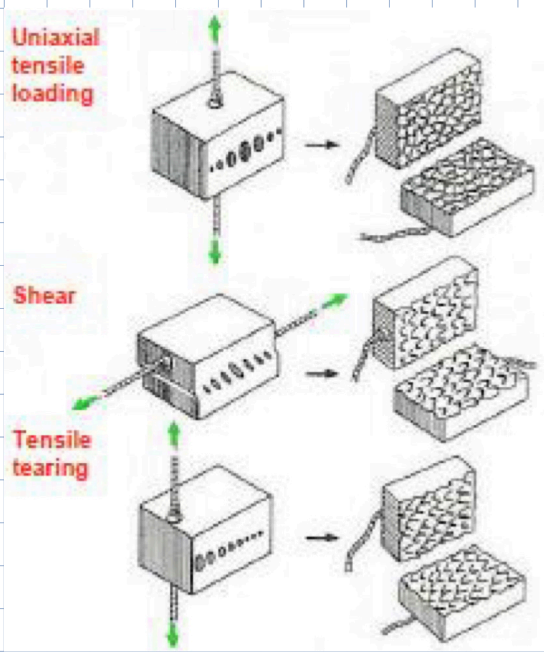


→ Ductile fracture much less critical in engineering

↳ failure can be detected before from observable plastic deformation

→ for round coupons, cracks eventually propagate along shear plane at 45° → cup & cone pattern.

Microvoid Shape :

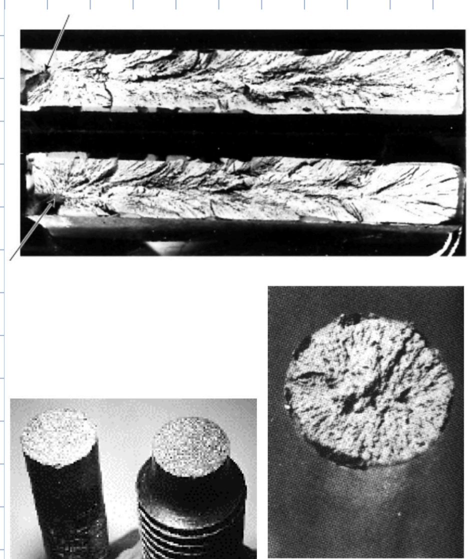


Equiaxed dimples

Elongated & parabolic pointing in opposite directions on matching fracture surfaces

" pointing in same directions

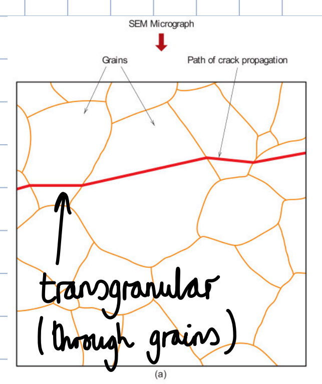
Brittle Fracture :

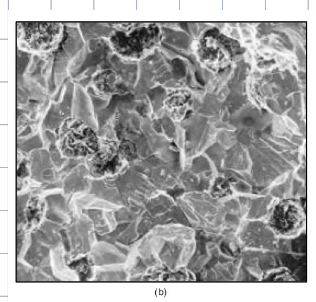


- Process of cleavage fracture : 3 steps
  1. Plastic deformation to produce dislocation pile-ups
  2. Crack initiation
  3. Crack propagation to failure
- Distinct characteristics of brittle fracture surfaces :
  1. Absence of gross plastic deformation
  2. Grainy or faceted texture
  3. River marking or stress lines

Fractography in Metals :

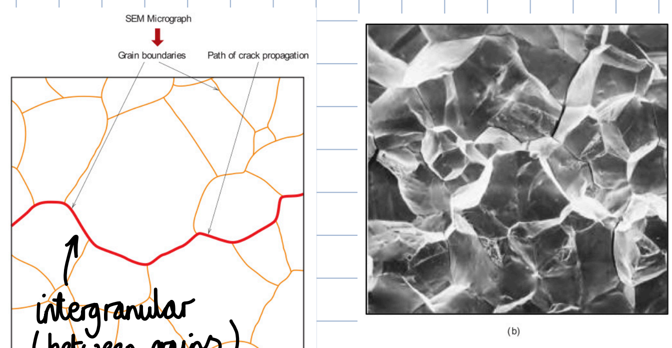
- Cleavage fracture is breaking of atomic bonds along crystallographic planes (transgranular)
  - → Surface : rough & textured, with river & feather patterns
  - → Moderate to high strength brittle fracture mode.





Transgranular fracture

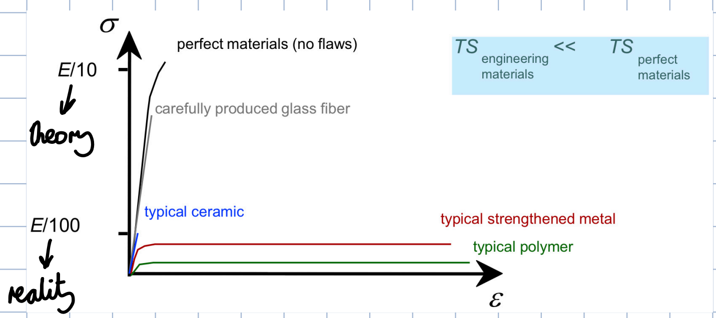
- In some metal alloys, cracks form along grain boundaries (intergranular)
  - → Surface: Sharp & 3D faceted grains
  - → Moderate to low energy brittle fracture mode



Intergranular fracture

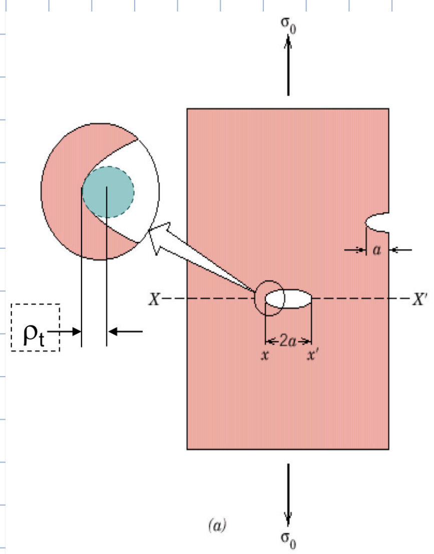
Ideal vs Real Materials:

Strain - stress behaviour (room temp.)



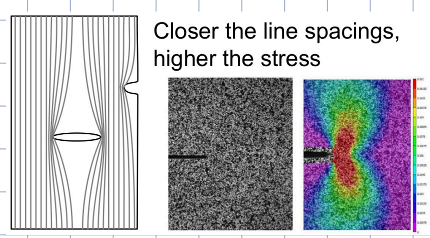
↳ Why? → Size effects: ↑size = ↑ probability of defects

→ Flaws introduce stress concentrations:



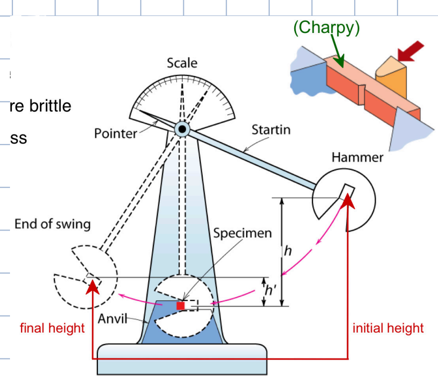
Griffith Crack

a = crack size
ρ_t = radius of curvature
σ_0 = applied stress
σ_m = stress at crack tip

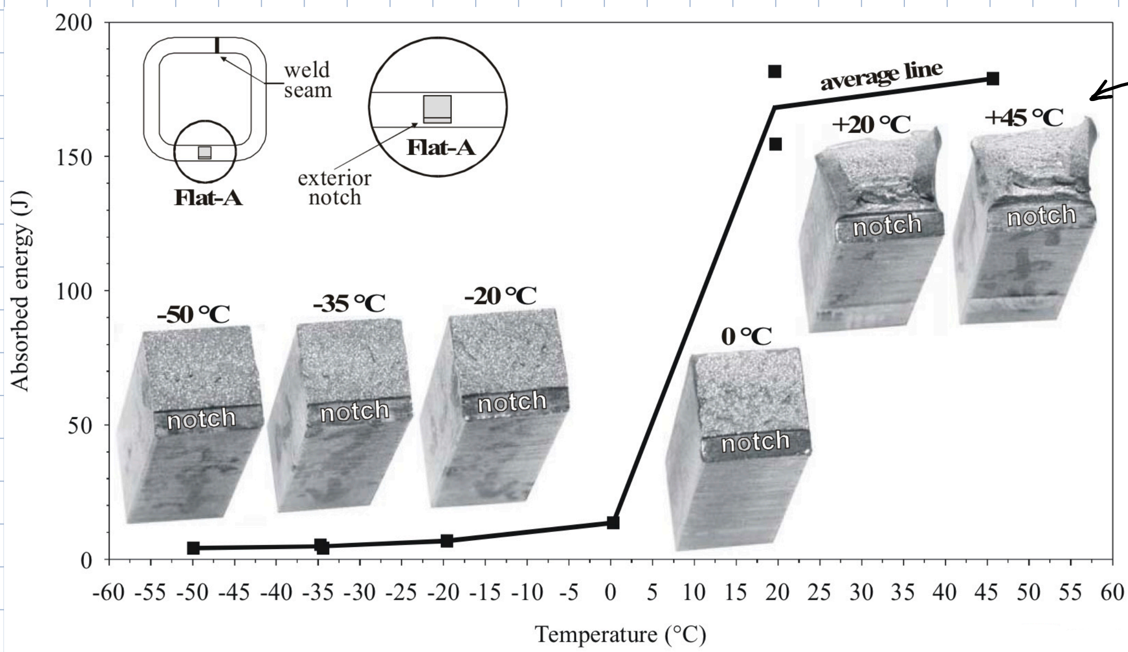


Characterisation of Transition Temp.

- Impact loading under low temperatures:
  - → Severe testing case
  - → Makes material more brittle
  - → Decreases toughness



Ductile → Brittle Transition Behaviour :



↑ temp allows more slip systems to operate, yielding general plastic deformation to occur prior to failure

Other Types of Failure :

- Fatigue failure
  → fracture by slow crack growth
  → when part subjected to many repetitions of stress below that for static crack growth

- Corrosion fatigue failure
  → Combined action of cyclic stress & corrosive environment
  → ↓ fatigue resistance with ↑ chemical env. (even water can have effect)

- Stress corrosion cracking
  → similar to corrosion fatigue : mechanical + chemical failure
  → stress NOT CYCLIC (but below yield stress for metal)

- Creep & stress rupture failure
  → result of static load applied over long periods of time