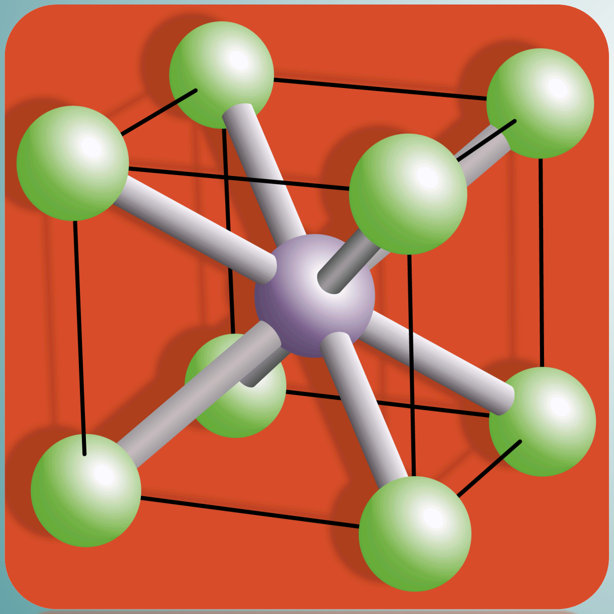
Materials

Topic 6. Fast fracture, brittle fracture and toughness



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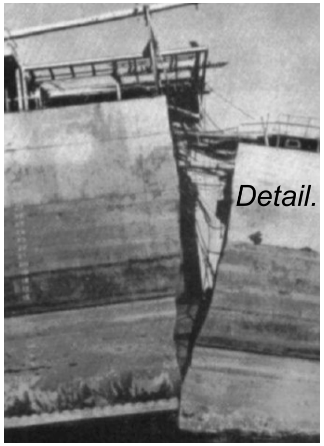
6.1. FRACTURE MECHANICS

Liberty ships (1941-45)

Constructed ships:	*2700.*
Ships with breaks:	*400.*
Serious breaks:	*90.*
Total failure:	*20 (10 of them broken in two).*

Liberty ship which was broken in two halves along the welds.



Detail.

- **There are three main factors of brittle fracture in material:**
  1. High strain rate, that is, rapid rate deformation.
  2. Stress concentration.
  3. Triaxial stress state, which may be introduced by the pre-sence of a notch.

«Alexander Kielland», Platform (1980)

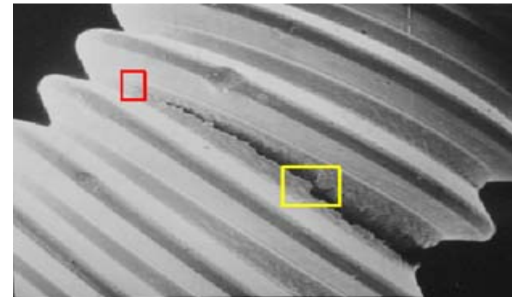
«Challenger», space shuttle (1986)

«Aloha Airlines», Boeing 737 (1988)

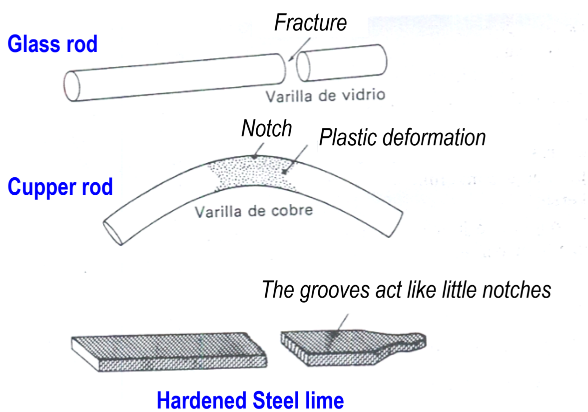
«Prestige», oil tanker (2002)

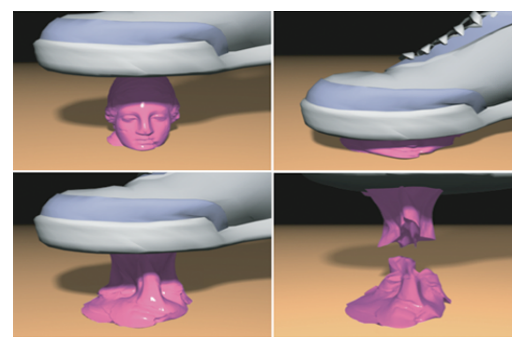
BASIC CONCEPTS

- **Fracture:**
  - **Separation of a body in 2 or more parts after mechanical stress.**
  - **The fracture process consists of 2 stages: crack formation and crack propagation.**



- **Types of Fracture:**
  - **DUCTILE: with plastic deformation prior to breakage.**
  - **BRITTLE: without plastic deformation, sudden and catastrophic, with rapid propagation of crack.**

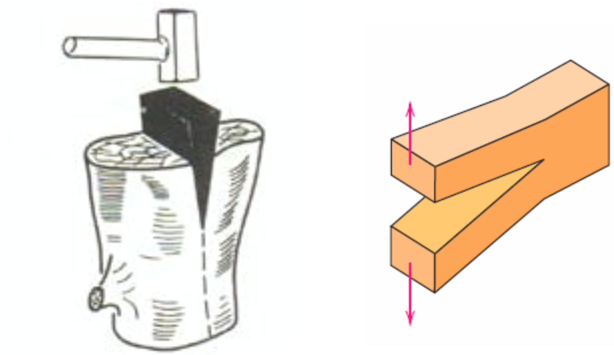




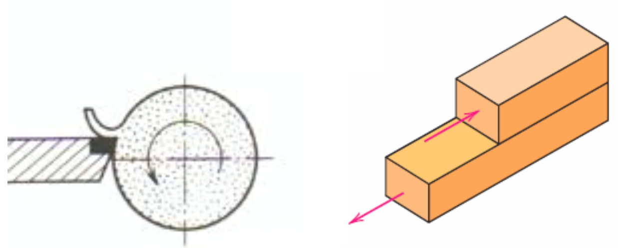
- **Fracture Mechanics:**
  - **Discipline that studies the behavior of the material in the presence of defects.**

6.2. FRACTURE MODES

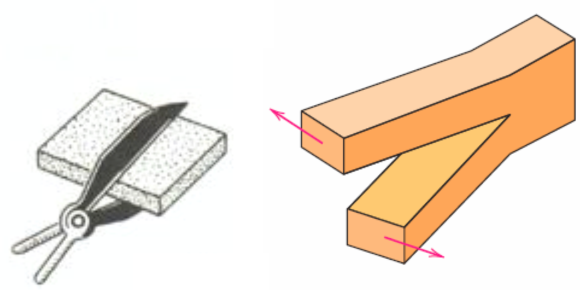
The three modes of crack Surface displacement



Mode I. **Opening or tensile mode.**



Mode II. **Sliding mode.**

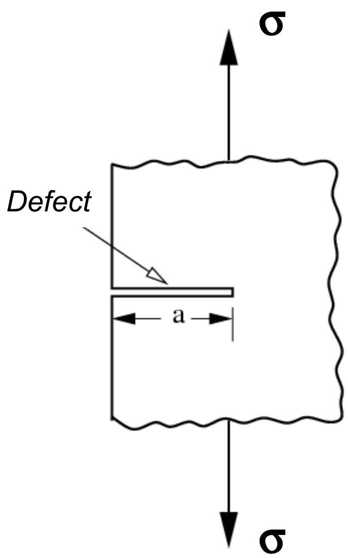


Mode III. **Tearing mode.**

6.3. FRACTURE TOUGHNESS

Fast Fracture condition

$$K = K_c \quad \equiv \quad Y\sigma\sqrt{\pi a} = \sqrt{EG_c}$$



K: stress intensity factor K = f(Y, σ, a).

- **Y:** geometric factor (dimensionless).
- **σ:** stress applied to the component (MPa).
- **a:** size defect (m).

K_C: critical stress intensity factor or fracture toughness (it is a property of the material).

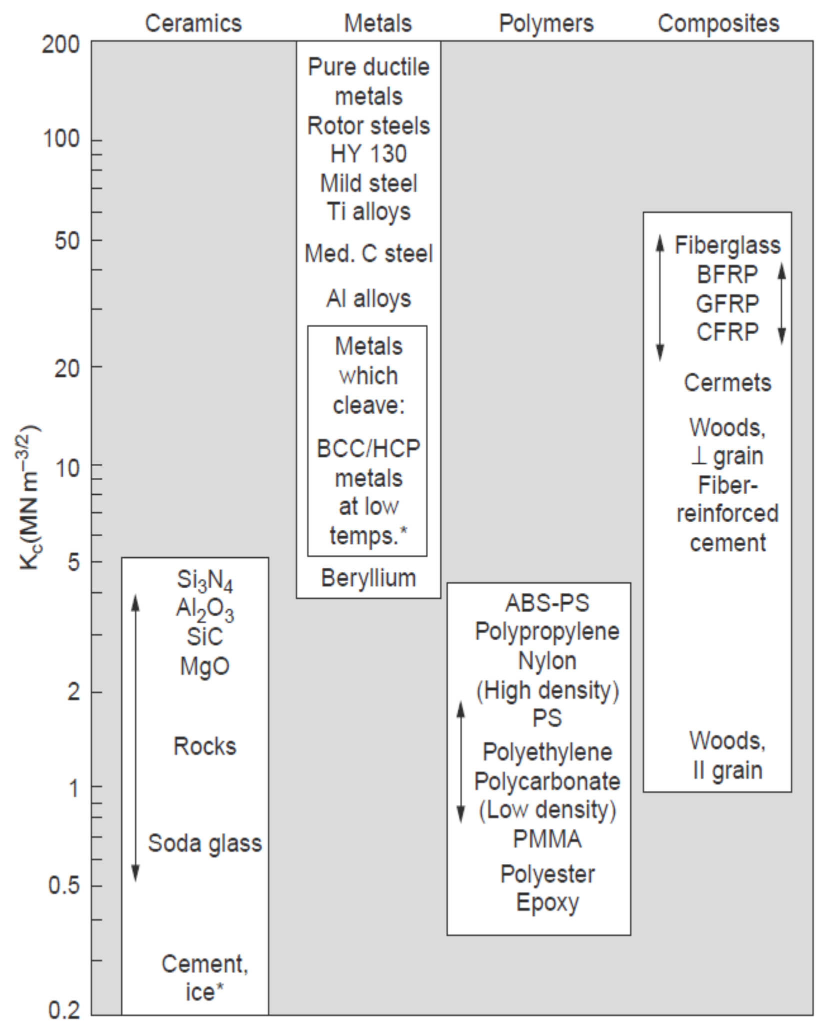
- **E:** young´s modulus (MPa).
- **G_c:** toughness, energy required to generate unit area of crack (kJ/m^2).

Units (International, or Metric, System of measurements): **$MPa \cdot m^{1/2}$** or **$MN \cdot m^{-3/2}$**

- **The fast fracture of a structural element occurs when the stress intensity factor (K) reaches a critical value, which is precisely the fracture toughness of the material (K_C).**

6.4. DATA FOR toughness, G_C AND Fracture toughness, K_C

Material	G_c (kJ m^{-2})	K_c (MN m$^{-3/2}$)
Pure ductile metals (e.g. Cu, Ni, Ag, Al)	100–1000	100–350
Rotor steels (A533; Discalloy)	220–240	204–214
Pressure-vessel steels (HY130)	150	170
High-strength steels (HSS)	15–118	50–154
Mild steel	100	140
Titanium alloys (Ti6Al4V)	26–114	55–115
GFRPs	10–100	20–60
Fiberglass (glassfiber epoxy)	40–100	42–60
Aluminum alloys (high strength–low strength)	8–30	23–45
CFRPs	5–30	32–45
Common woods, crack ⊥ to grain	8–20	11–13
Boron-fiber epoxy	17	46
Medium-carbon steel	13	51
Polypropylene	8	3
Polyethylene (low density)	6–7	1
Polyethylene (high density)	6–7	2
ABS Polystyrene	5	4
Nylon	2–4	3
Steel-reinforced cement	0.2–4	10–15
Cast iron	0.2–3	6–20
Polystyrene	2	2
Common woods, crack || to grain	0.5–2	0.5–1
Polycarbonate	0.4–1	1.0–2.6
Cobalt/tungsten carbide cermets	0.3–0.5	14–16
PMMA	0.3–0.4	0.9–1.4
Epoxy	0.1–0.3	0.3–0.5
Granite (Westerly Granite)	0.1	3
Polyester	0.1	0.5
Silicon nitride, Si_3N_4	0.1	4–5
Beryllium	0.08	4
Silicon carbide SiC	0.05	3
Magnesia, MgO	0.04	3
Cement/concrete, unreinforced	0.03	0.2
Calcite (marble, limestone)	0.02	0.9
Alumina, Al_2O_3	0.02	3–5
Shale (oilshale)	0.02	0.6
Soda glass	0.01	0.7–0.8
Electrical porcelain	0.01	1
Ice	0.003	0.2*



6.5. DESIGN BASED ON FRACTURE MECHANICS

Variables to be taken into consideration:

- Fracture toughness (K_c)
- Applied stress (σ)
- Defect size (a)

- Example: K_c and a fixed by a specific application:

Admissible stress: $\sigma_c = \frac{K_c}{Y\sqrt{\pi a}}$ ⇒ $\sigma_{diseño} = \frac{\sigma_c}{S}$

S: security factor.

- If on the contrary σ and K_c are prefixed:

$$a_c = \frac{1}{\pi}\left(\frac{K_c}{\sigma \cdot Y}\right)^2$$

6.6. PHYSICAL ASPECTS OF DUCTILE FRACTURE

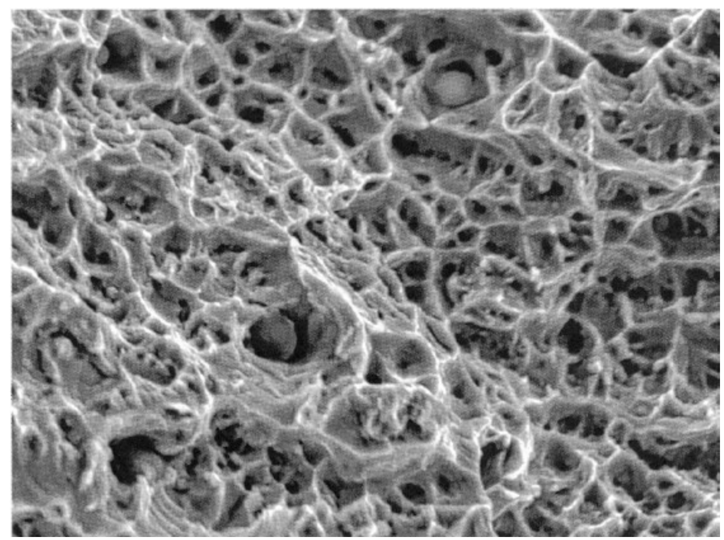
Macroscopics

Mechanism of crack propagation by tear.
Typical of ductile materials (**metals and alloys**).
Large amount of plastic deformation.
Very rough and matt fracture surface.

1 mm

Microscopics

Large plastic area at the crack tip.
Generation and growth of microvoids.
Enromamiento del fondo de fisura.
High energy consumption (high G_c).



50 μm

6.7. PHYSICAL ASPECTS OF BRITTLE FRACTURE

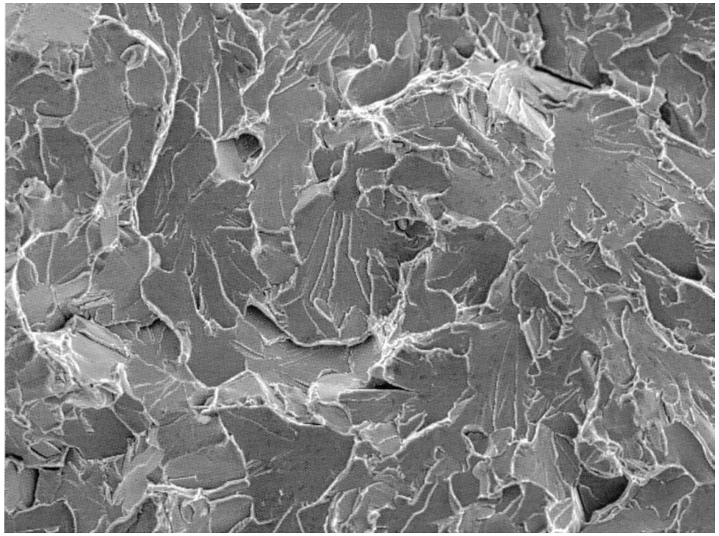
Macroscopics

Cracks propagation mechanism by cleavages.
Typical of brittle materials (**ceramics and glasses**).
Very little or no plastic deformation.
Smooth and shiny fracture surface.

5 mm

Microscopics

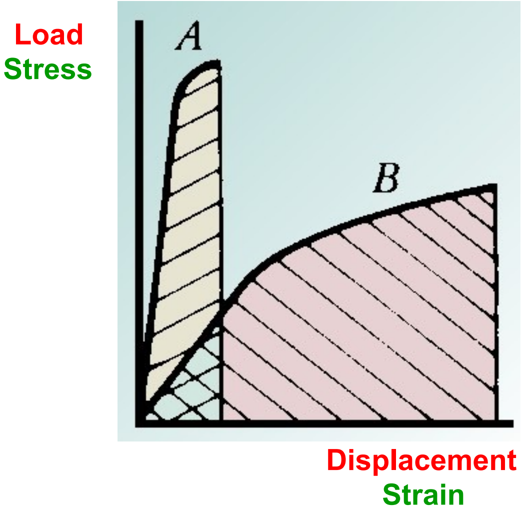
Small plastic area at the crack tip.
Detachment of crystallographic planes (cleavages).
No blunting (or little) at the crack tip.
Small energy consumption (low Gc).



50 μm

6.8. IMPACT TOUGHNESS

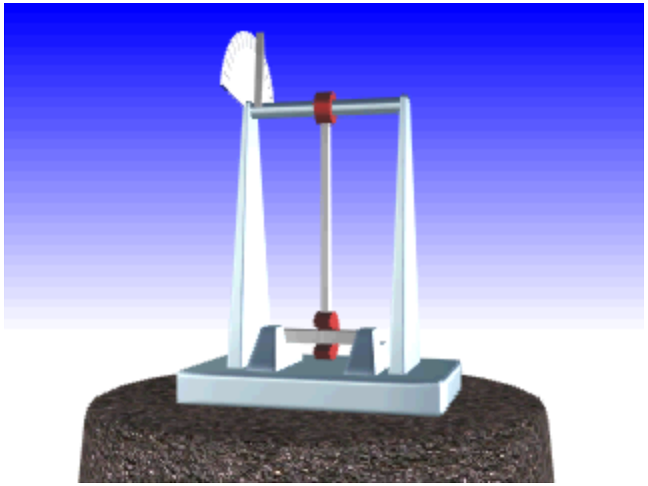
- It is defined as the ability of a material to withstand dynamic impact loads.
- Toughness combines the strength and deformability of a material, and it is defined as the work developed when it is deformed and broken by the effect of a sudden external force.
- Tough materials easily absorb the kinetic energy of a mass that crashes against them.
- Impact toughness: energy consumed in the fracture produced by the impact of another body. The main method to determine this property is the Charpy test.
- The impact energy corresponds to the area under the Load - Displacement curve.
- The impact energy per volumen corresponds to the área under the Stress - Strain curve.

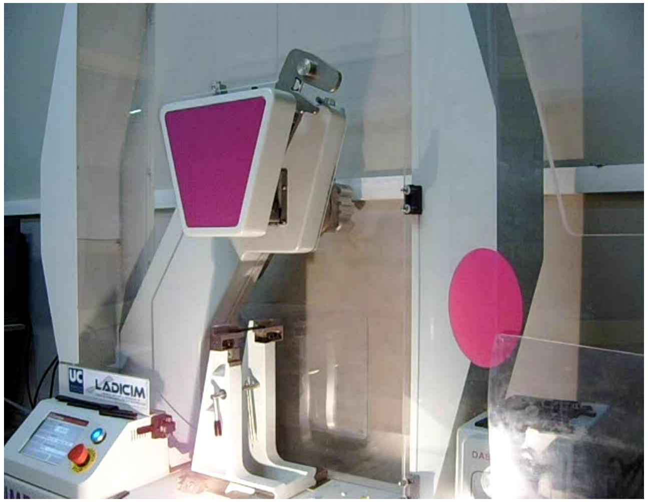


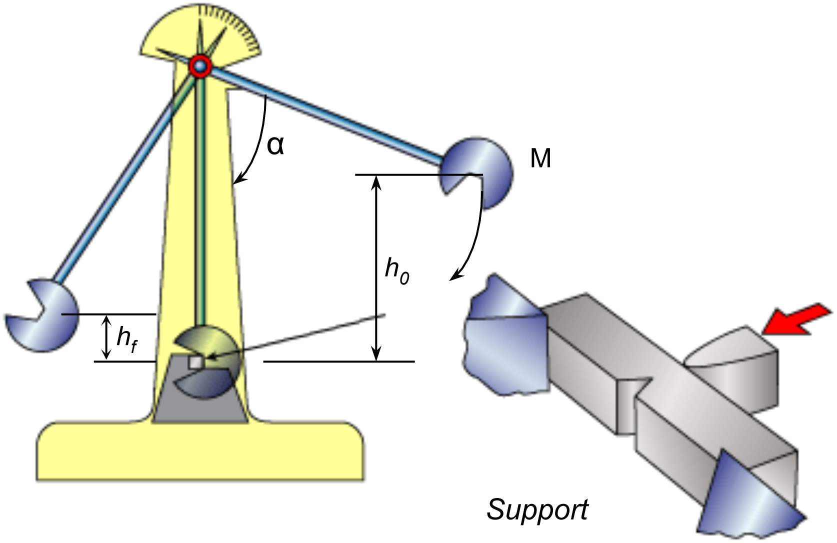
CHARPY TEST

- **A schematic drawing of an impact testing apparatus.**

- **The hammer is released from fixed height h_0 and strikes the specimen; the energy expended in fracture is reflected in the difference between h_0 and the swing height (h_f).**



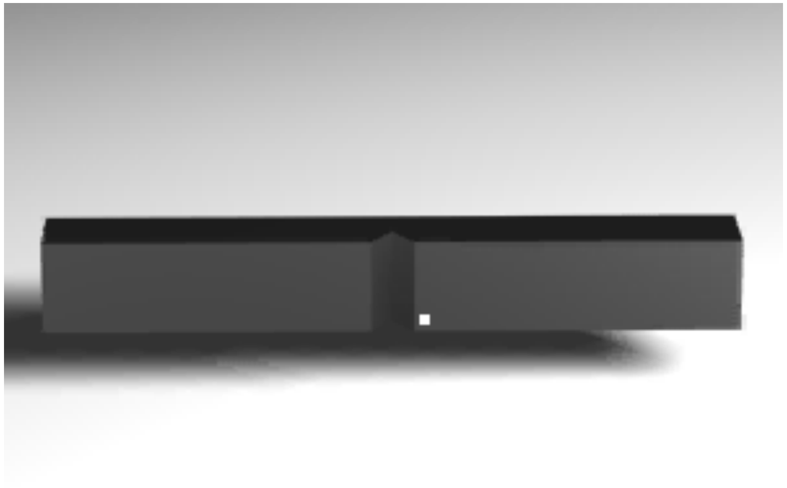


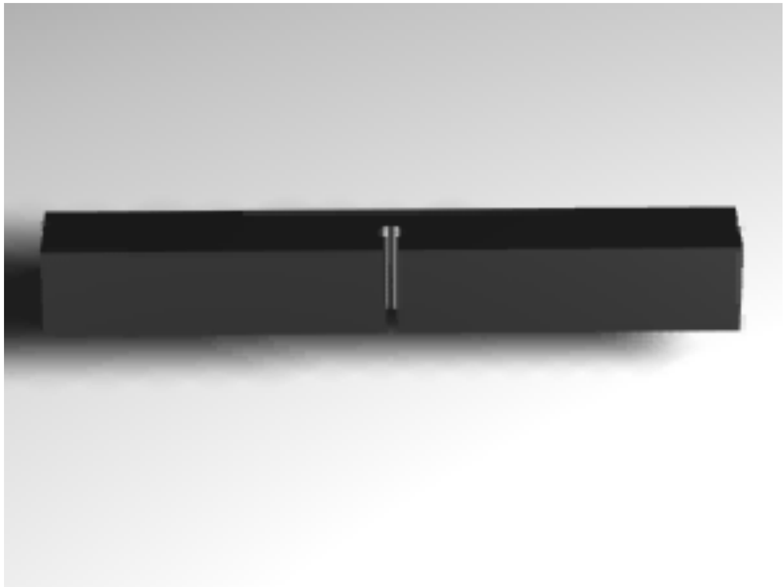


CHARPY SPECIMENS

- **The notches caused by deficient machining, fabrication or design, cause stress concentration, reducing the toughness of the material.**

- **The sensitivity to notches of a material can be evaluated by comparing the energies absorbed by notched and unnotched specimens. The energies absorbed by notched specimens are much lower if the material is sensitive to this type of defects.**



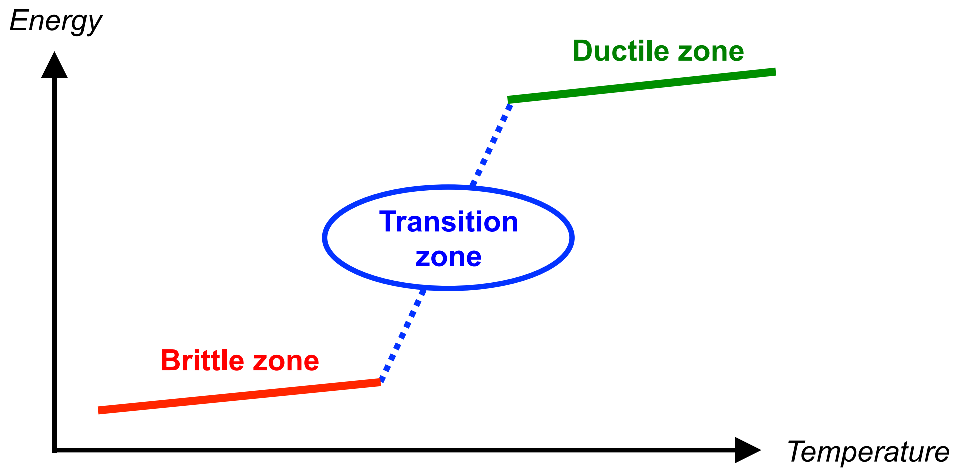


RESULTS

Ductile-to-Brittle Transition

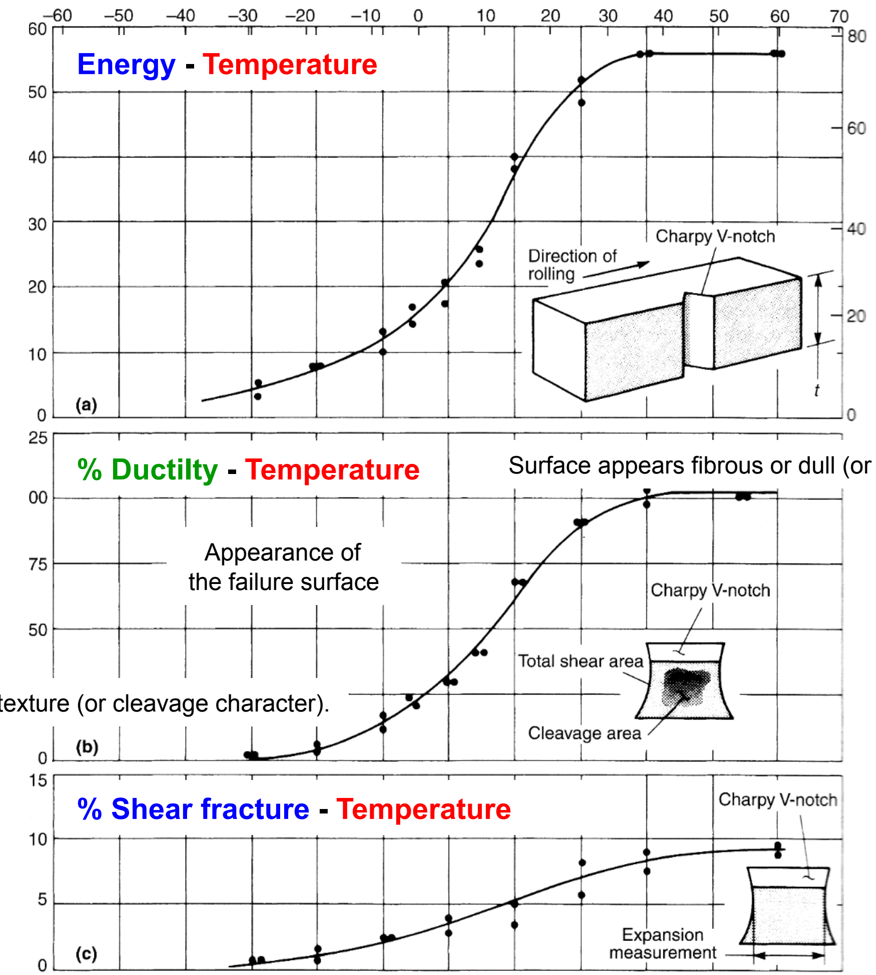
- **The Charpy test is carried out at various temperatures to define the ductile - brittle transition curve.**

- **Its main use is the selection of materials resistant to brittle fracture:**
  - **At low temperatures the material behaves in a brittle way (small absorbed energy).**
  - **At high temperatures the behavior will be ductile (energy absorbed high).**
  - **Intermediate zone: transition zone (abrupt jump).**



Ductile-to-Brittle Transition curve

Surface appears fibrous or dull (or of shear character).



Surfaces have a granular (shiny) texture (or cleavage character).