1. Introduction to Fatigue and Fracture Analysis

An oil tanker that fractured in a brittle manner by crack propagation around its girth [1].

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Fracture

- Simple fracture is the separation of a body into two or more pieces
    - In response to applied stress (tensile, compressive, shear, or torsional)
    - At temperatures that are low relative to the melting temperature of the material
- Stages of Fracture or Failure
    - Crack initiation
    - Crack propagation
    - Final fracture

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Fracture

- Based on ability of a material to experience plastic deformation, there are two fracture modes
    - Ductile
    - Brittle
- Ductile fracture
    - The highly ductile materials neck down to a point fracture, showing virtually 100% reduction in area

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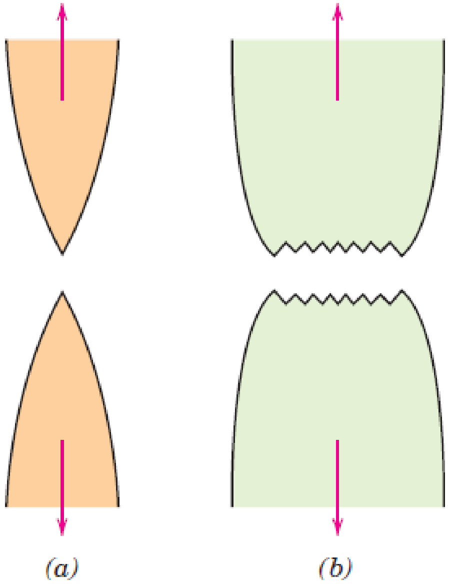
Ductile fracture

- Example
    - Extremely soft metals, such as pure gold and lead at room temperature
    - Other metals, polymers, and inorganic glasses at elevated temperatures



(a) Highly ductile fracture in which the specimen necks down to a point. (b) Moderately ductile fracture after some necking [1].

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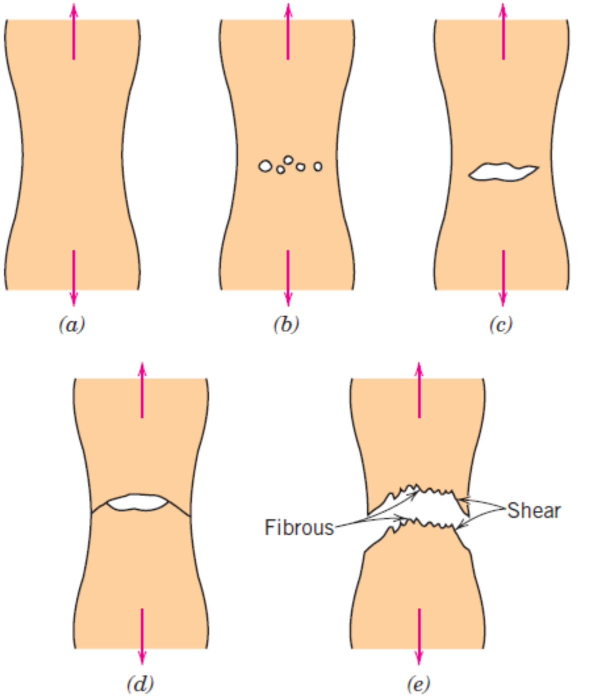
Ductile Fracture

Stages in the cup-and-cone fracture

- (a) Initial necking
- (b) Small cavity formation
- (c) Coalescence of cavities to form a crack.
- (d) Crack propagation
- (e) Final shear fracture at a 45° angle relative to the tensile direction



Stages in cup and cone fracture [1]

Cup-and-cone fracture in aluminum [1]

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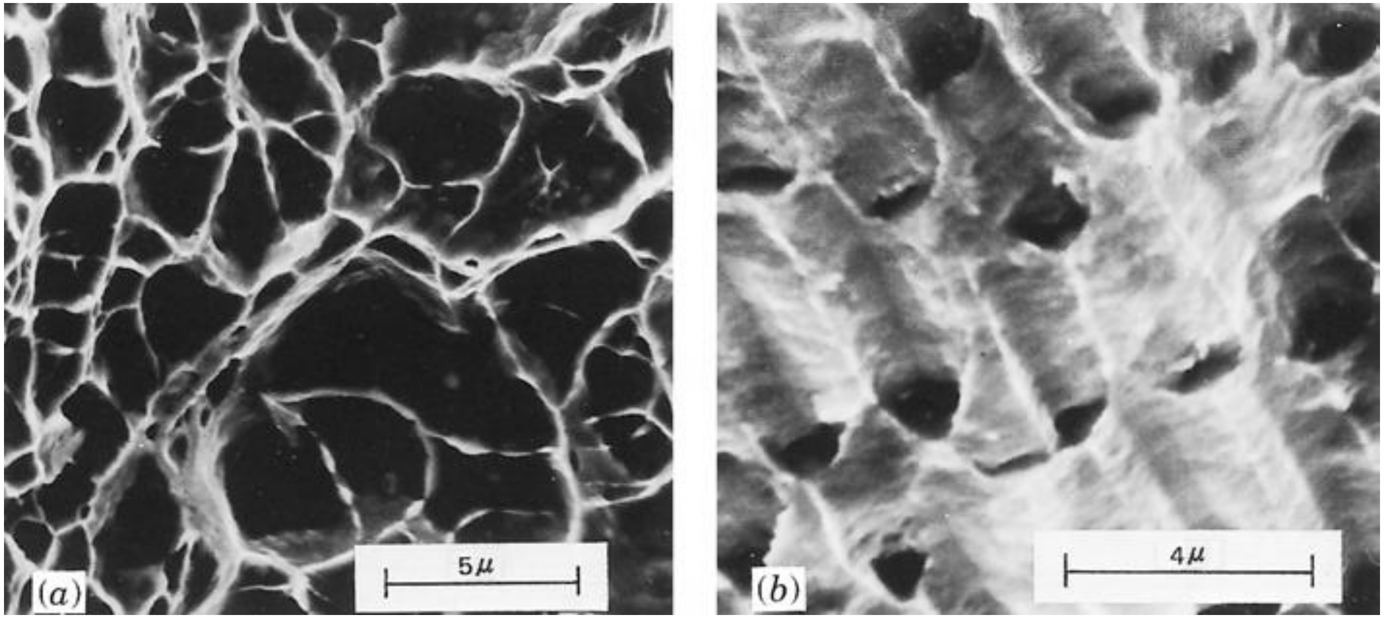

(a) Scanning electron fractograph showing spherical dimples characteristic of ductile fracture resulting from uniaxial tensile loads (b) Scanning electron fractograph showing parabolic-shaped dimples characteristic of ductile fracture resulting from shear loading [1]

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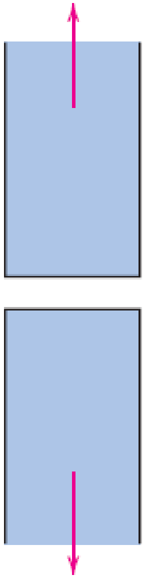
Brittle Fracture

- Brittle fracture takes place without any appreciable deformation, and by rapid crack propagation



Brittle fracture without any plastic deformation [1]

Figure 8: Brittle fracture in a mild steel [1]

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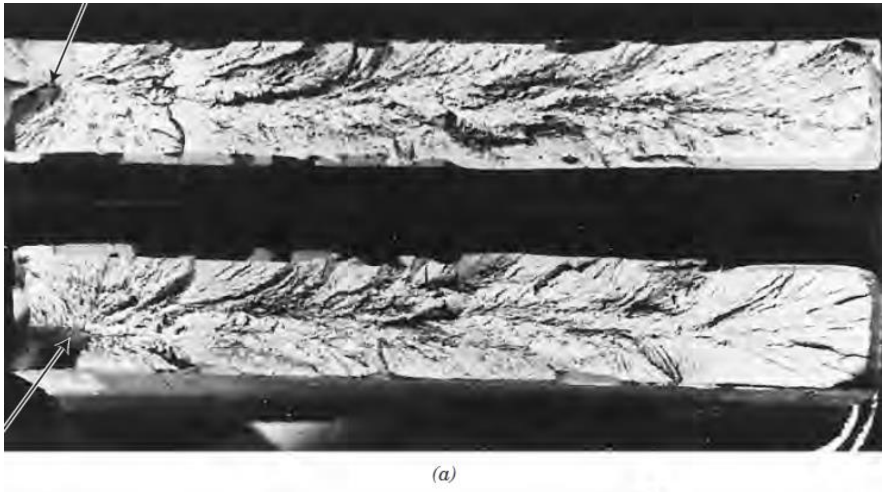
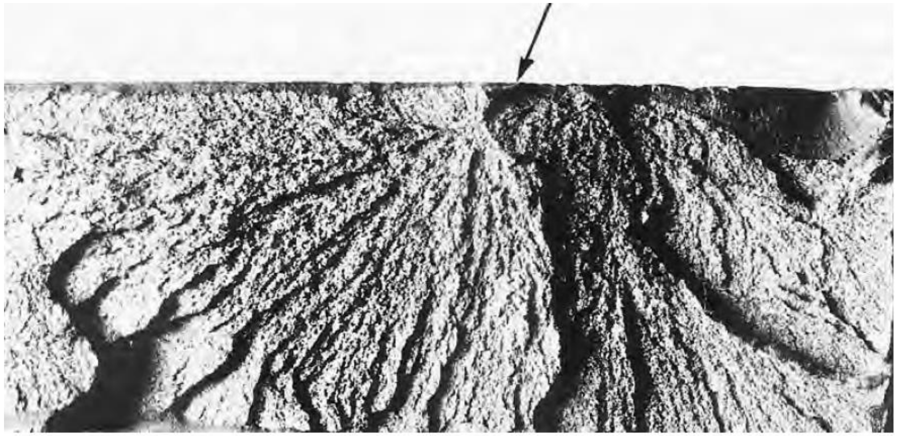

(a)


(b)

(a) Photograph showing V-shaped "chevron" markings characteristic of brittle fracture. Arrows indicate origin of crack. Approximately actual size.
(b) Photograph of a brittle fracture surface showing radial fan-shaped ridges. Arrow indicates origin of crack [1]

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Cleavage fracture

- Crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes

- **Transgranular (or transcrystalline):** The fracture cracks pass through the grains

- **Intergranular**: crack propagation is along grain boundaries

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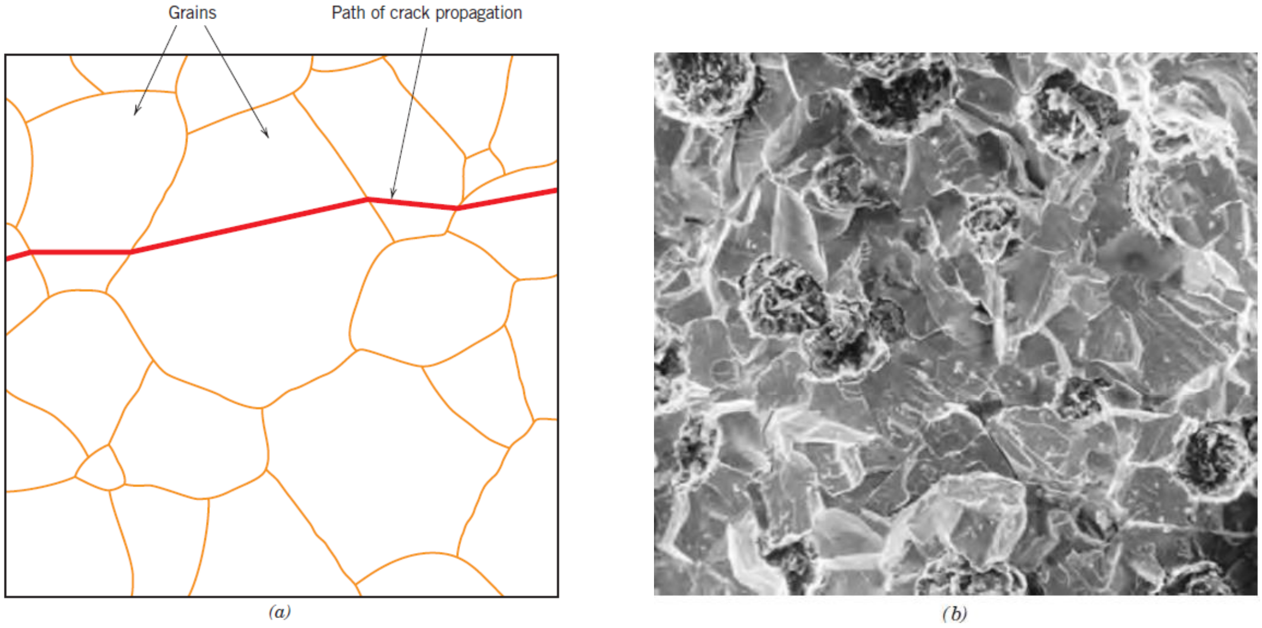

(a) Schematic cross-section profile showing crack propagation through the interior of grains for transgranular fracture. (b) Scanning electron fractograph of ductile cast iron showing a transgranular fracture surface [1].

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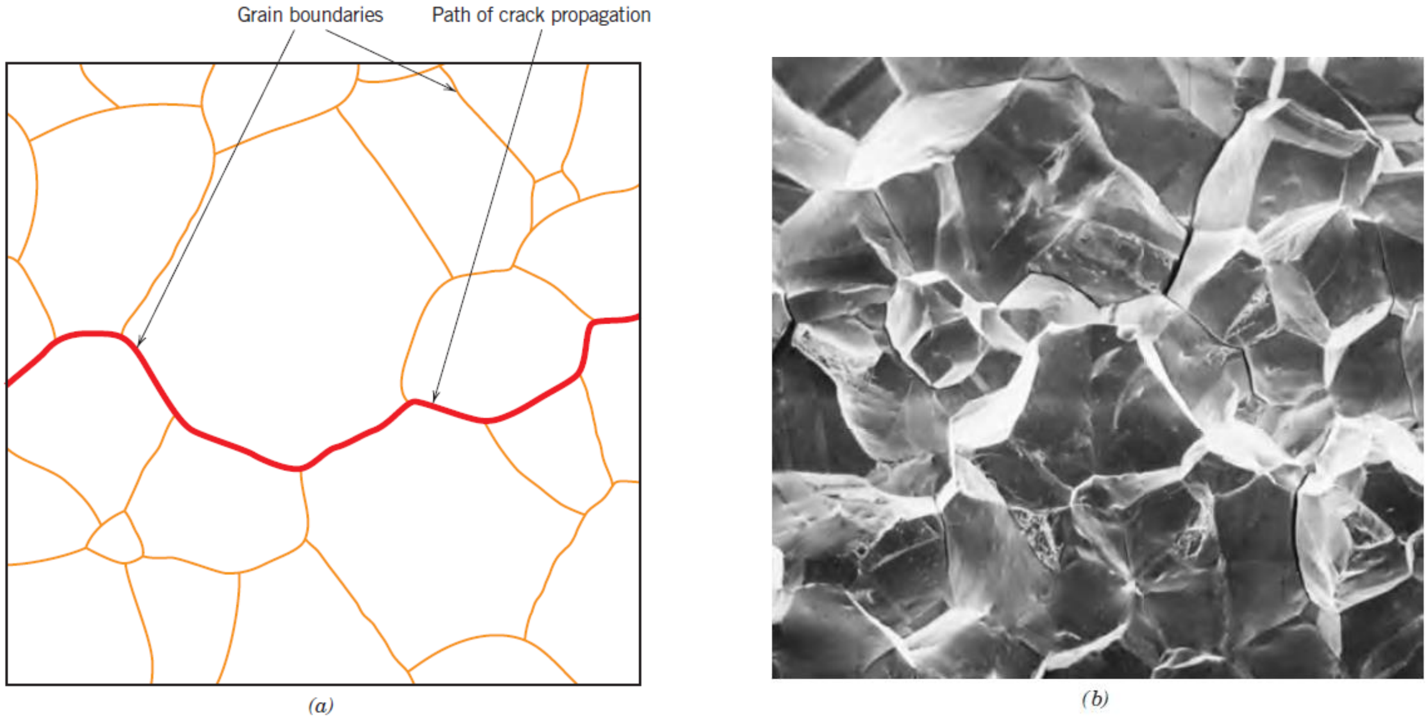

(a) Schematic cross-section profile showing crack propagation along grain boundaries for intergranular fracture. (b) Scanning electron fractograph showing an intergranular fracture surface [1].

1. Introduction to Fatigue and Fracture Analysis

- Fracture Mechanics: It is a relationship
  - Material properties
  - Stress level
  - presence of crack-producing flaws, and crack propagation mechanisms

- Two sub-branches of fracture mechanics
  - Linear elastic fracture mechanics (LEFM)
    - It considers the fundamentals of linear elasticity theory
  - Elastic plastic fracture mechanics (EPFM)
    - It characterizes elastic and plastic behaviours of solids

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- **Stress concentration**
  - Very small, microscopic flaws or cracks always exist under normal conditions at the surface and within the interior of a body of material
  - These flaws are a detriment to the fracture strength because an applied stress may be amplified or concentrated at the tip, the magnitude of this amplification depending on crack orientation and geometry
  - The magnitude of this localized stress diminishes with distance away from the crack tip
  - At positions far removed, the stress is just the nominal stress or the applied load divided by the specimen cross-sectional area
  - Due to their ability to amplify an applied stress in their locale, these flaws are sometimes called stress raisers

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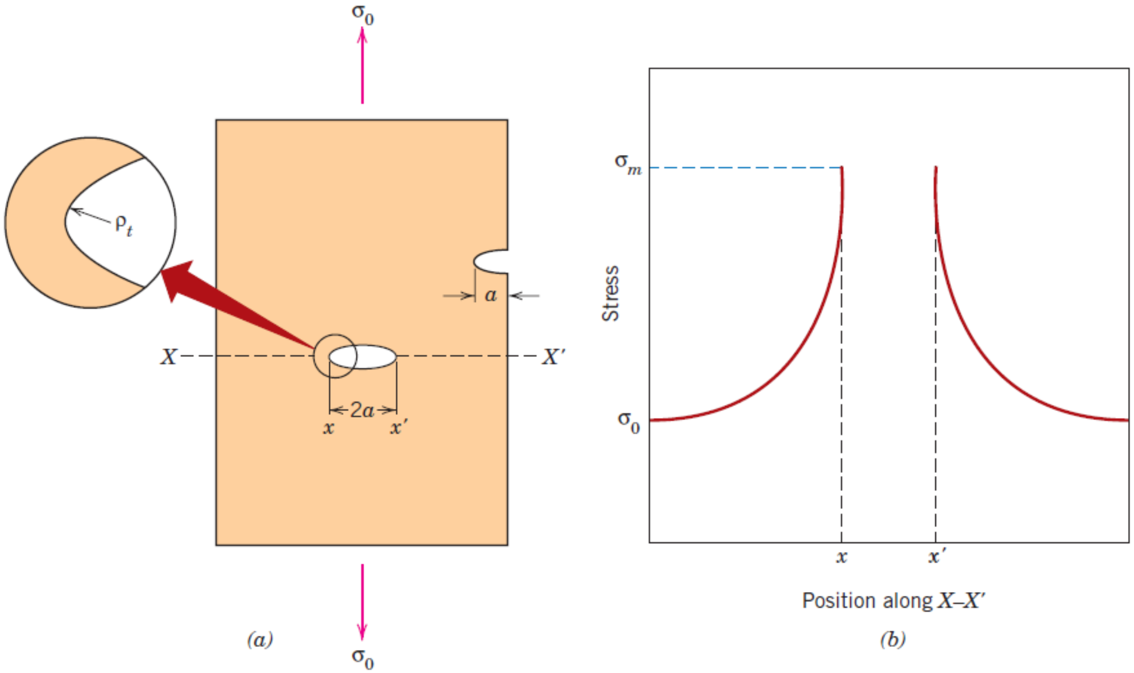

(a) The geometry of surface and internal cracks. (b) Schematic stress profile along the line X–X' in (a), demonstrating stress amplification at crack tip positions [1].

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$$\sigma_m = \sigma \left[1 + 2\left(\frac{a}{\rho_t} \right)^{1/2} \right]$$

$$K_t = \frac{\sigma_m}{\sigma} = \left[1 + 2\left(\frac{a}{\rho_t} \right)^{1/2} \right]$$

$$K_t = \frac{\sigma_m}{\sigma} = 2\left(\frac{a}{\rho_t} \right)^{1/2}$$

where

K_t = stress concentration factor
ρ_t = Radius of curvature
σ = Applied stress
σ_m = Stress at crack tip
a = Length of a surface crack, or half of the length of an internal crack

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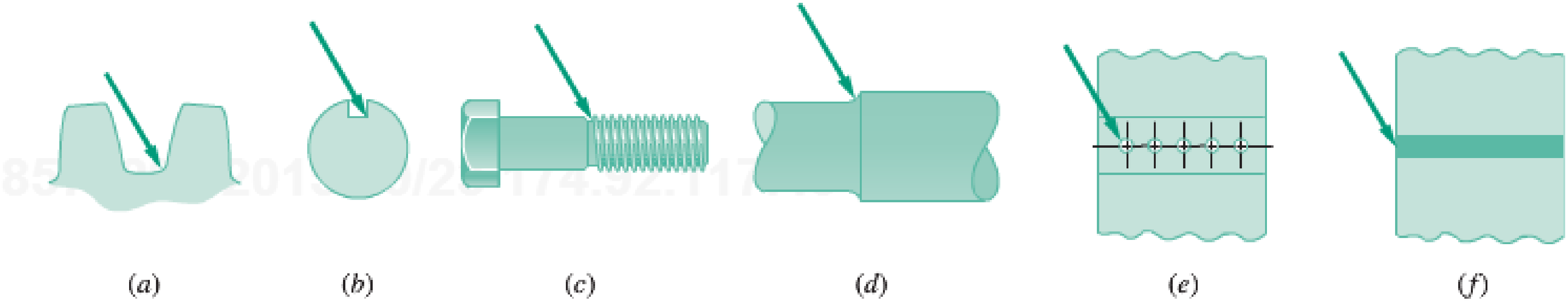
(a) (b) (c) (d) (e) (f)

Some common examples of stress concentration (a) Gear teeth (b) Shaft keyway (c) Bolt threads (d) Shaft shoulder (e) riveted or bolted joint (f) Welded joint [3]

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Criterion for crack propagation

Crack propagates if crack-tip stress (σ_m) exceeds a critical stress (σ_c)

For brittle materials

i.e., $\sigma_m > \sigma_c$

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

where

E = modulus of elasticity
γ_s = specific surface energy
a = one half length of internal crack

For ductile materials => replace γ_s with $\gamma_s + \gamma_p$

where γ_p is plastic deformation energy

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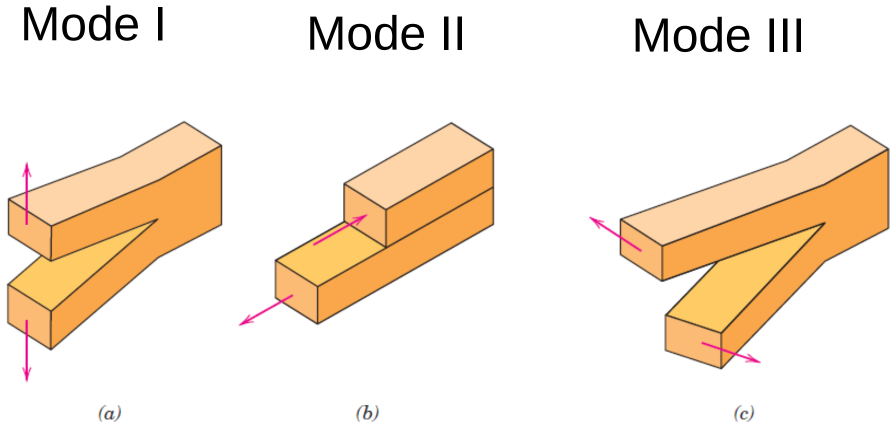
- ❑ Three modes of crack surface displacement
    - Mode I, opening or tensile mode
    - Mode II, sliding mode
    - Mode III, tearing mode.



The three modes of crack surface displacement [1]

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- ❑ Fracture mechanics introduces a parameter, the crack driving force, called stress intensity factor (K)
- ❑ The stress intensity factor depends linearly on the applied load and is a function of the crack length and the geometrical configuration of the cracked body and can be defined as a general function

K_i = f (Stress, crack geometry, specimen configuration)

Where i = I, II, III which stand for mode 1, mode 2 and mode 3, respectively

Or

$$K_I = Y\sigma\sqrt{\pi a}$$

Where

K_I = Stress intensity factor in mode I

Y = A dimensionless parameter or function that depends on both crack and specimen sizes and geometries, as well as the manner of load application

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- ❑ Fracture toughness (K_c)
  - The critical value of stress intensity factor (a property of the material) determined from laboratory tests known as the fracture toughness

  - A property that is a measure of a material's resistance to brittle fracture when a crack is present

  - It relates
    - Critical stress for crack propagation (σ_c) and crack length (a) as

$$K_c = Y\sigma_c\sqrt{\pi a}$$

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- ❑ Fracture toughness (K_c)
  - For relatively thin specimens, the value of K_c will depend on specimen thickness
  - Plane stain condition: when specimen thickness is much greater than the crack dimensions, K_c becomes independent of thickness
  - The fracture toughness in plain strain condition is known as the plane strain fracture toughness, K_{Ic}

$$K_{Ic} = Y\sigma\sqrt{\pi a}$$

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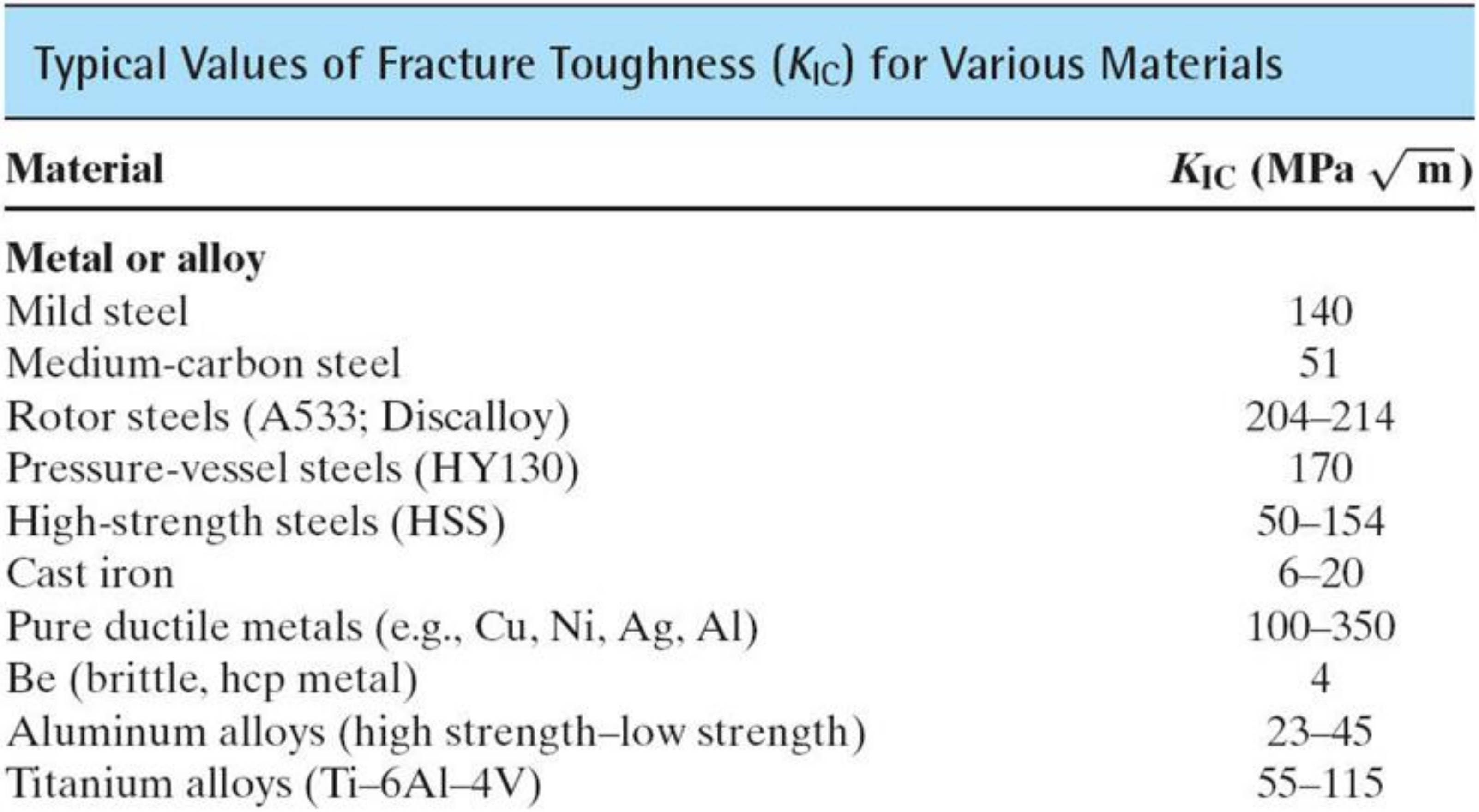
Typical values of fracture toughness (K_{IC}) for various materials [4]



Typical Values of Fracture Toughness (K_{IC}) for Various Materials

Material	K_{IC} (MPa $\sqrt{m}$)
Metal or alloy	
Mild steel	140
Medium-carbon steel	51
Rotor steels (A533; Discalloy)	204–214
Pressure-vessel steels (HY130)	170
High-strength steels (HSS)	50–154
Cast iron	6–20
Pure ductile metals (e.g., Cu, Ni, Ag, Al)	100–350
Be (brittle, hcp metal)	4
Aluminum alloys (high strength–low strength)	23–45
Titanium alloys (Ti–6Al–4V)	55–115

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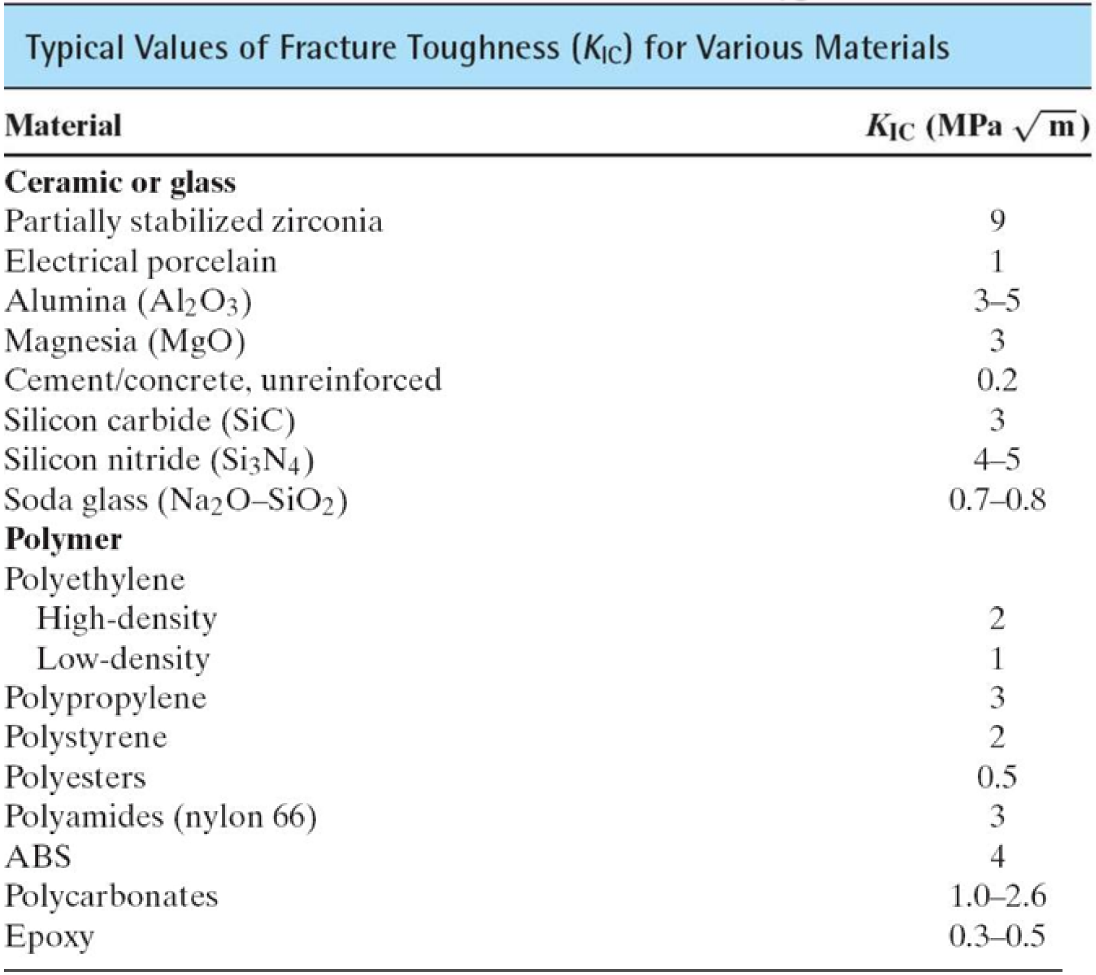
Typical values of fracture toughness (K_{IC}) for various materials [4]



Typical Values of Fracture Toughness (K_{IC}) for Various Materials

Material	K_{IC} (MPa $\sqrt{m}$)
Ceramic or glass	
Partially stabilized zirconia	9
Electrical porcelain	1
Alumina (Al_2O_3)	3–5
Magnesia (MgO)	3
Cement/concrete, unreinforced	0.2
Silicon carbide (SiC)	3
Silicon nitride (Si_3N_4)	4–5
Soda glass (Na_2O–SiO_2)	0.7–0.8
Polymer	
Polyethylene	
High-density	2
Low-density	1
Polypropylene	3
Polystyrene	2
Polyesters	0.5
Polyamides (nylon 66)	3
ABS	4
Polycarbonates	1.0–2.6
Epoxy	0.3–0.5

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Conditions for using Linear Elastic Fracture Mechanics (LEFM)

1. The deformation at the crack tip must be mostly elastic
2. The material must be isotropic and homogeneous at the crack tip
3. There must only be a single well defined crack
4. Plastic zone must be small compared to in-plane dimensions of specimen/ structure (crack length, grain size, etc.), which mean that there can only be limited plastic deformation at the crack tip at the time of fracture
5. Crack must propagate in mode I (opening mode)
6. Plane-strain conditions must prevail

Elastic Plastic Fracture Mechanics (EPFM)

1. It shall be used if LEFM does not apply
2. Crack Tip Opening Displacement
3. J-Integral

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Impact loading:

- Severe testing case
- Makes material more brittle
- Decreases toughness

Impact Testing

- Impact energy or notch toughness
- Two standardized tests (manner of specimen support): Charpy and Izod
- The hammer is released from fixed height h and strikes the specimen
- The energy expended in fracture is reflected in the difference between h an the swing height h'
- The energy absorption, computed from the difference between h and h' is a measure of the impact energy

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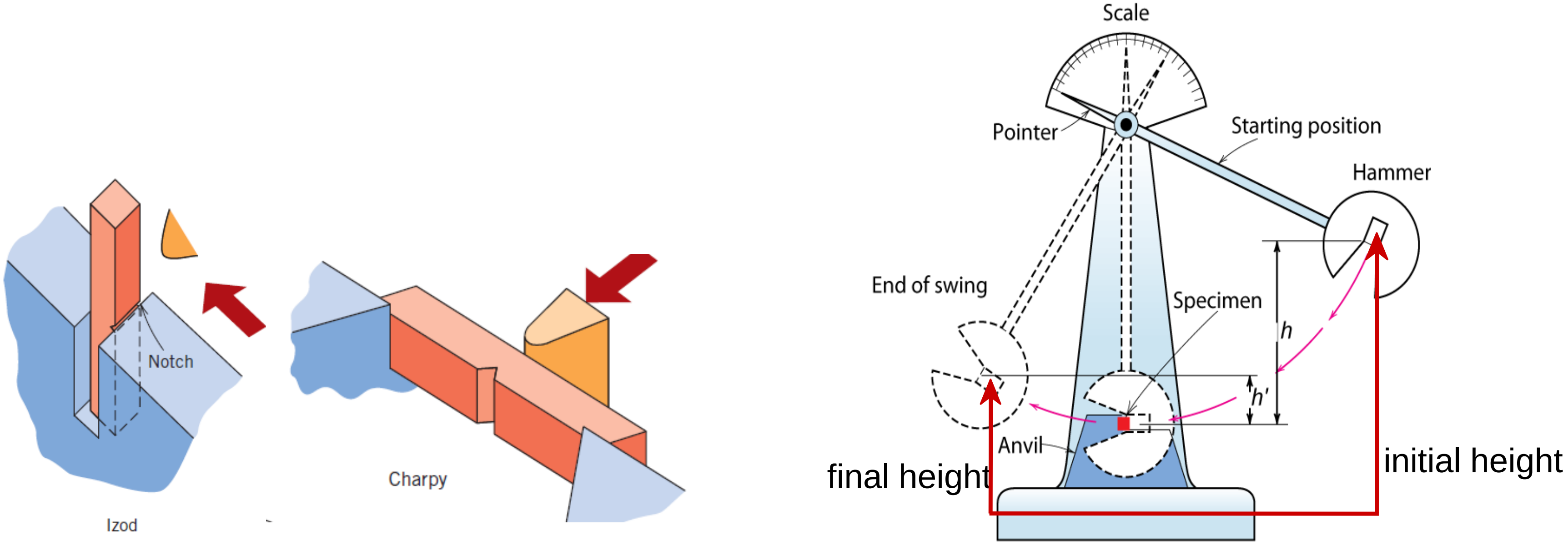

(a)

(b)

(a) Specimen used for Charpy and Izod impact tests. (b) A schematic drawing of an impact testing apparatus [1]

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- **Ductile-to-Brittle Transition Temperature (DBTT)...**
    - It is related to the temperature dependence of the measured impact energy absorption
    - At higher temperatures the CVN energy is relatively large, in correlation with a ductile mode of fracture
    - As the temperature is lowered, the impact energy drops suddenly over a relatively narrow temperature range, below which the energy has a constant but small value; that is, the mode of fracture is brittle

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- **Ductile-to-Brittle Transition Temperature (DBTT)...**

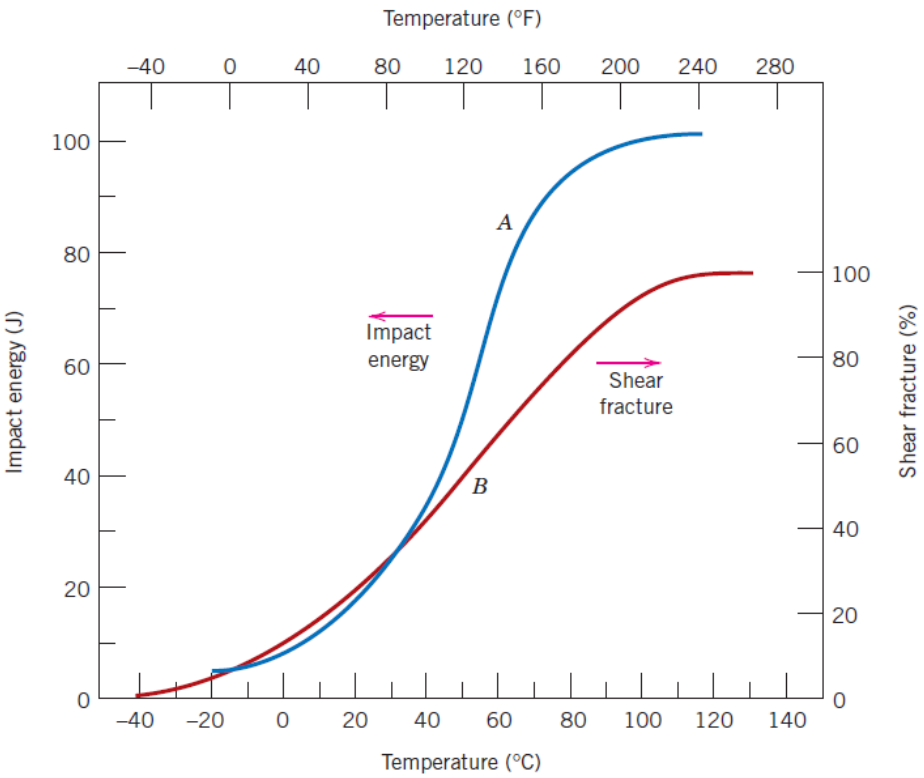

Figure 17: Temperature dependence of the Charpy V-notch impact energy (curve *A*) and percent shear fracture (curve *B*) for an A283 steel [1].

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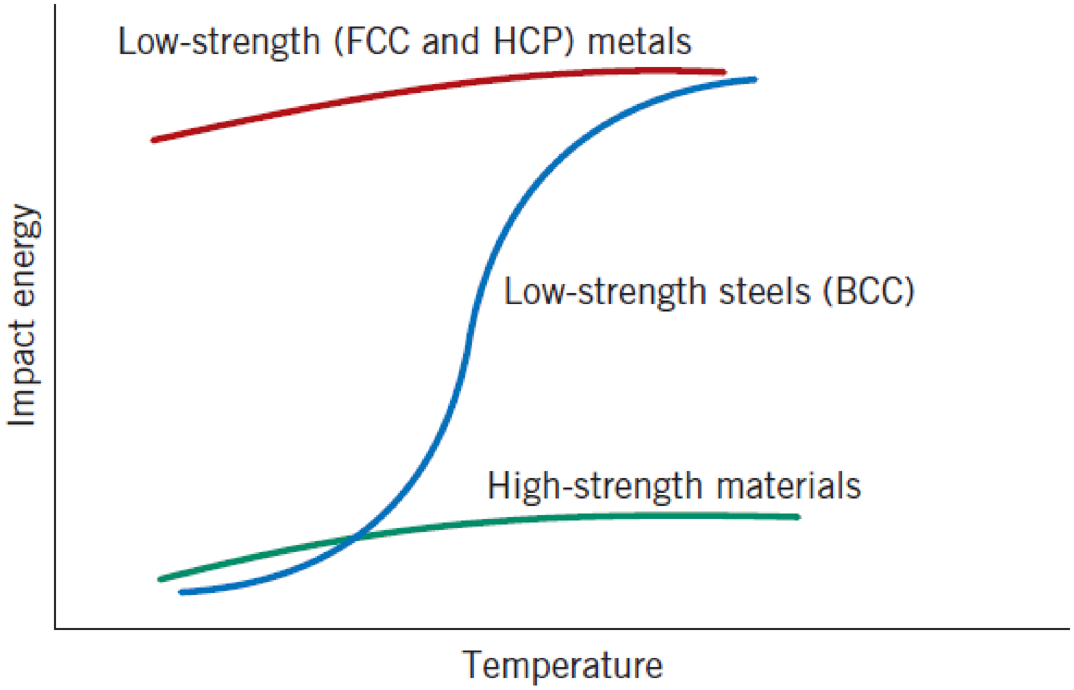
Ductile-to-Brittle Transition Temperature (DBTT)...



Schematic curves for the three general types of impact energy-versus-temperature behavior [1]

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