Topics in Ship Structures

05 Introduction of Fracture Mechanics

Reference : Lecture Note of Eindhoven University of Technology

Fracture Mechanics by T.L. Anderson

2017. 10

by Jang, Beom Seon

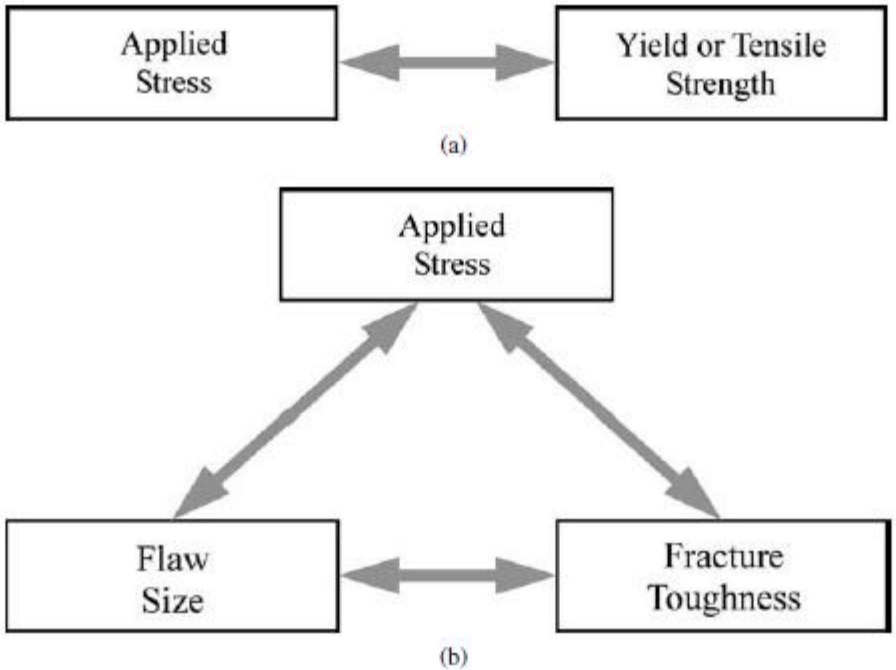
Fracture

- When material damage like micro-cracks and voids grow become localized, discontinuities must be taken into account. This localization results in macroscopic crack, resulting in global failure.

❖Main Interests

  - Will crack grow under the given load?
  - When a crack grows, What is its speed and direction?
  - Will crack growth stop?
  - What is residual strength of a construction part as a function of the (initial) crack length and the load?
  - What is proper inspection frequency?

Fracture



Comparison of the fracture mechanics approach to design with the traditional strength of materials approach: (a) the strength of materials approach and (b) the fracture mechanics approach.

Fracture

❖THE ENERGY CRITERION

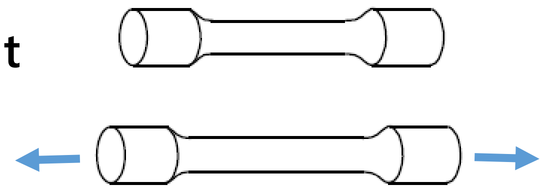
- The energy approach states that crack extension (i.e., fracture) occurs when the energy available for crack growth is sufficient to overcome the resistance of the material.

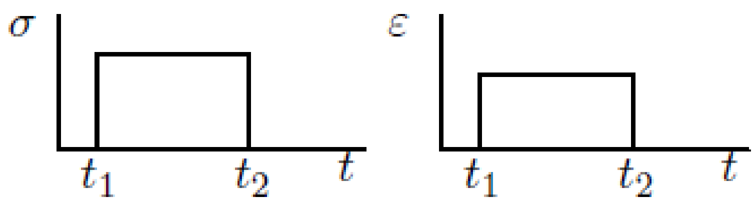
- The material resistance may include the surface energy, plastic work, or other types of energy dissipation associated with a propagating crack.

Types of material behavior

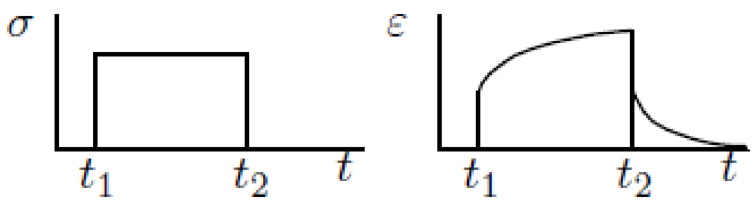
❖Strain-time and stress-time curves

- Elastic : reversible, time-independent
- Visco-elastic : reversible, time-dependent
- Elasto-plastic : irreversible, time-independent
- Visco-plastic : irreversible, time-dependent

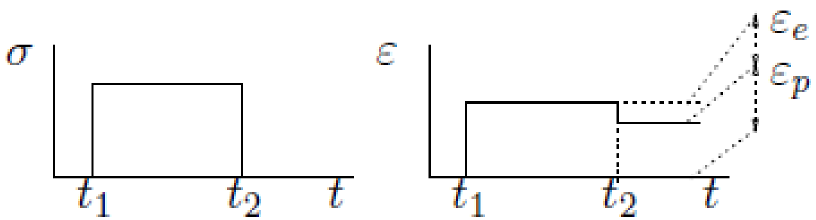




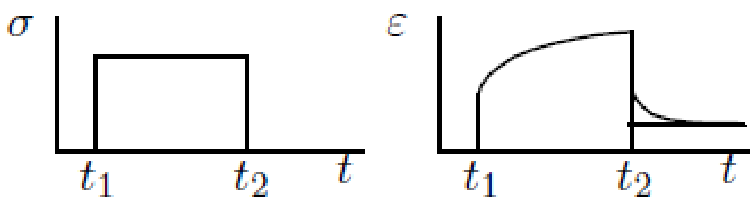
Elastic



Visco-elastic



Elasto-plastic



Visco-plastic

Fracture mechanisms

❖ What is Fracture?

- Fracture : separation of a body into pieces due to stress, at temperatures below the melting point.

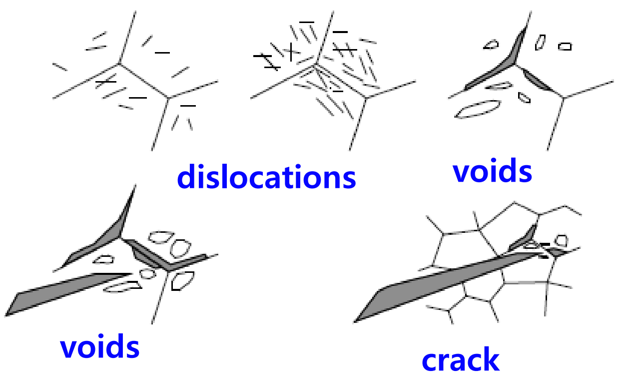
- Steps in fracture
  - ✓ Crack formation
  - ✓ Crack propagation

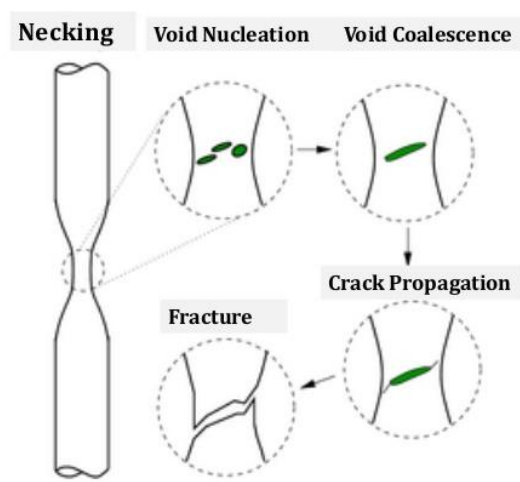
- Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined – ductile or brittle.

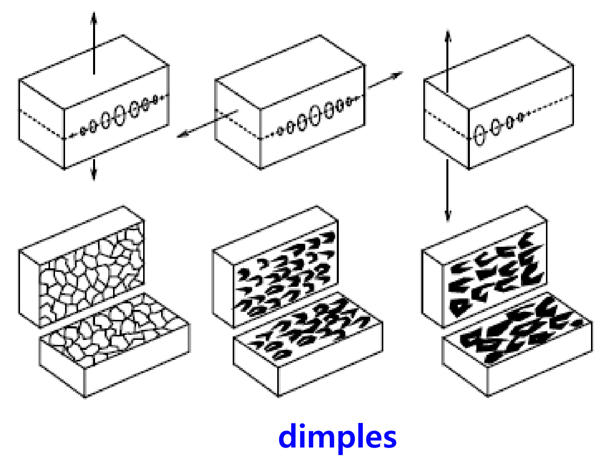
Fracture mechanisms

❖ Shearing (Ductile fracture)

- The origin and growth of cracks is provoked by shear stresses.
- When a crystalline material is loaded, dislocations start to move through the lattice due to local shear stresses and the number of dislocations increases.
- The dislocations coalesce at grain boundaries and accumulate to make a void.
- The fracture surface has a 'dough-like' structure with dimples, the shape of which indicate the loading of the crack.
- Extensive plastic deformation takes place before fracture.



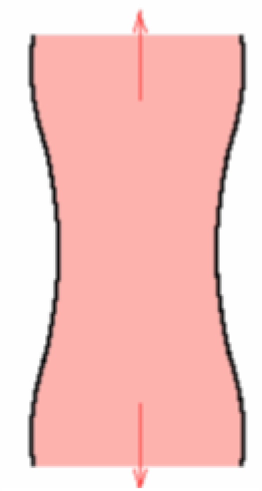




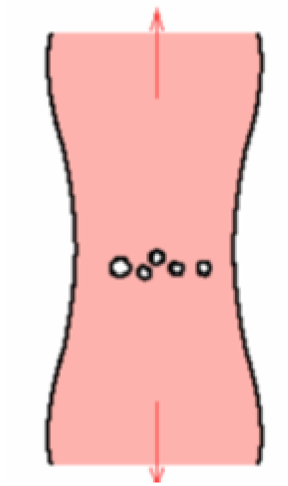
Dislocation movement and coalescence into grain boundary voids, resulting in dimples in the crack surface

✓ Nucleation : 핵형성, Coalescence : 합체 융합, dough : 밀가루, dimple: 보조개

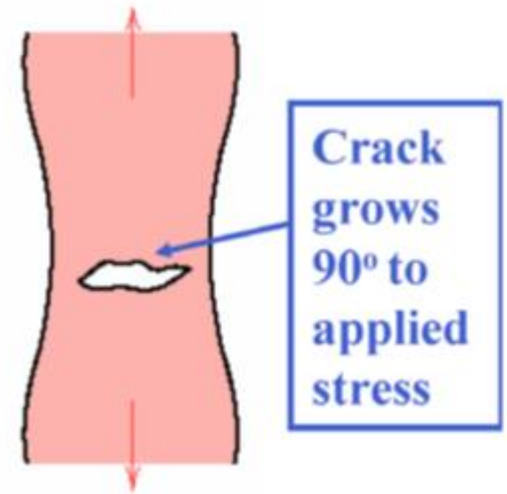
Ductile Fracture



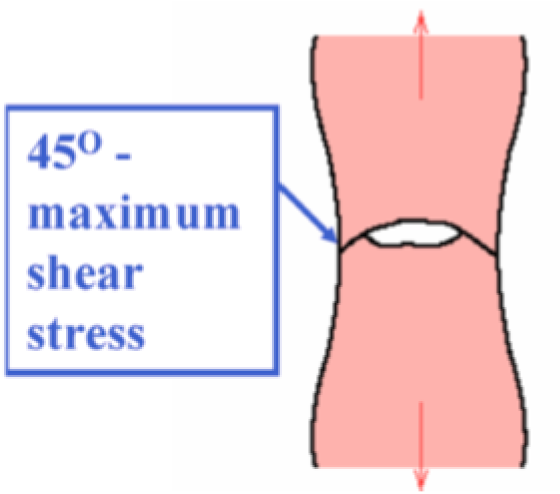
(a) Necking



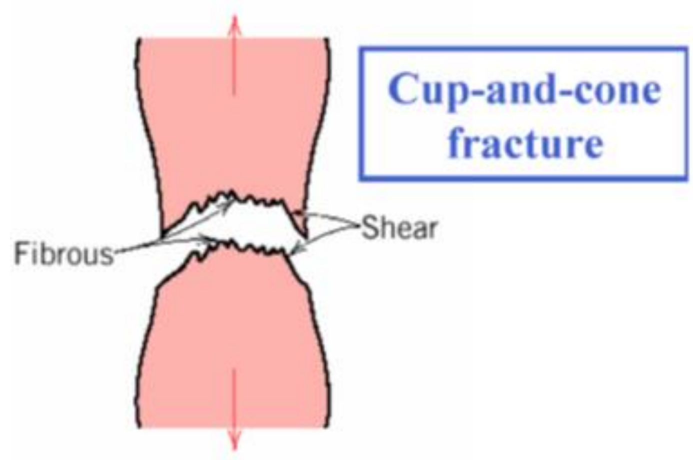
(b) Formation of micro-voids



(c) Coalescence of micro-voids to form a crack

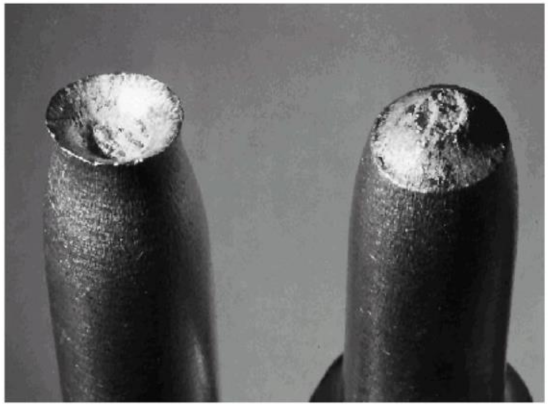


(d) Crack Propagation by shear deformation



(e) Fracture

Ductile Fracture



(Cup-and-cone fracture in Al)

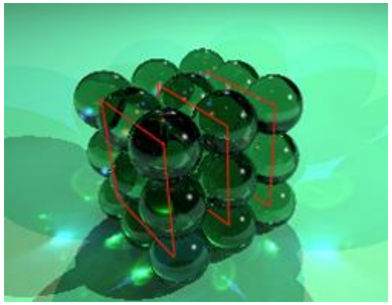
What is dislocation?

- Dislocation : a crystallographic(결정학상의) defect, or irregularity, within a crystal structure.

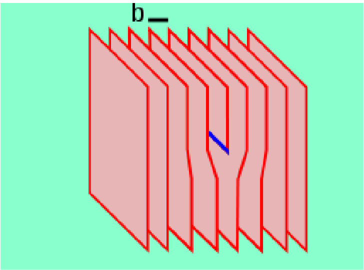
- A crystalline material : consists of a regular array of atoms, arranged into lattice planes.

- An edge dislocation : a defect where an extra half-plane of atoms is introduced mid way through the crystal, distorting nearby planes of atoms.

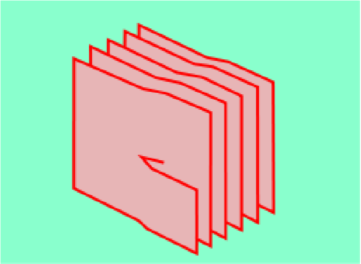
- A screw dislocation : Imagine cutting a crystal along a plane and slipping one half across the other.



Crystal lattice showing atoms and lattice planes



Edge dislocation

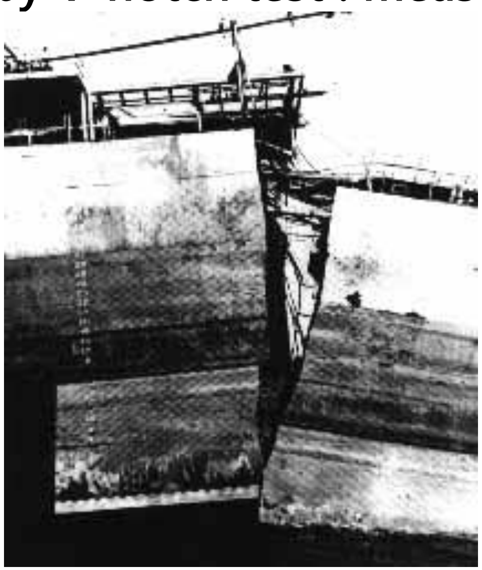


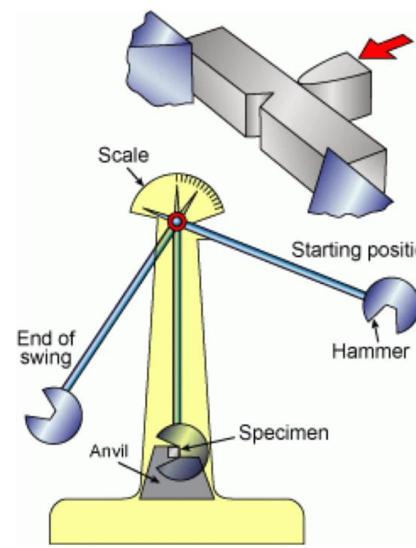
Screw dislocation

Brittle Fracture

❖Brittle failure of the Liberty Ships.

- Low temperatures in winter can severely embrittle steels. The Liberty Ships, produced in great numbers during the WWII were the first all-wleded ships.
- Crack was arrested at rivet hole in the previous vessels
- A significant number of ships failed by catastrophic fracture.
- Fatigue cracks nucleated at the corners of square hatches and propagated rapidly by brittle fracture.
- Fracture toughness : the resistance to brittle fracture
- Chrapy V-notch test : measure fracture toughness



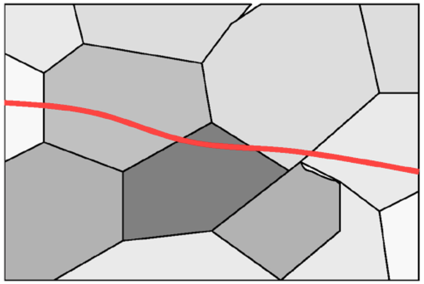


Charpy v-notch test

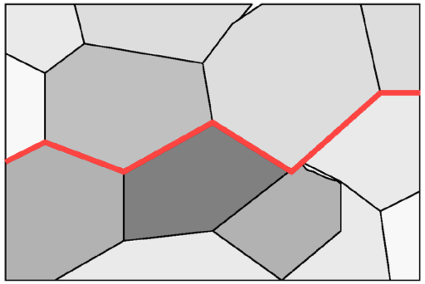
Brittle Fracture

❖Cleavage fracture (Brittle fracture)

- When plastic deformation at the crack tip is prohibited due to low temperature or high strain rate.
- The crack can travel through grains by splitting atom bonds in lattice planes.
- Trans-granular cleavage : cracks pass through grains. Fracture surface have faceted (깎은 면이 있는) textures because of different orientation of cleavage planes in grains. The crack surface has a 'shiny' appearance.
- Inter-granular cleavage : crack propagation is along weak or damaged grain boundaries
- No apparent plastic deformation takes place before fracture.



trans-granular

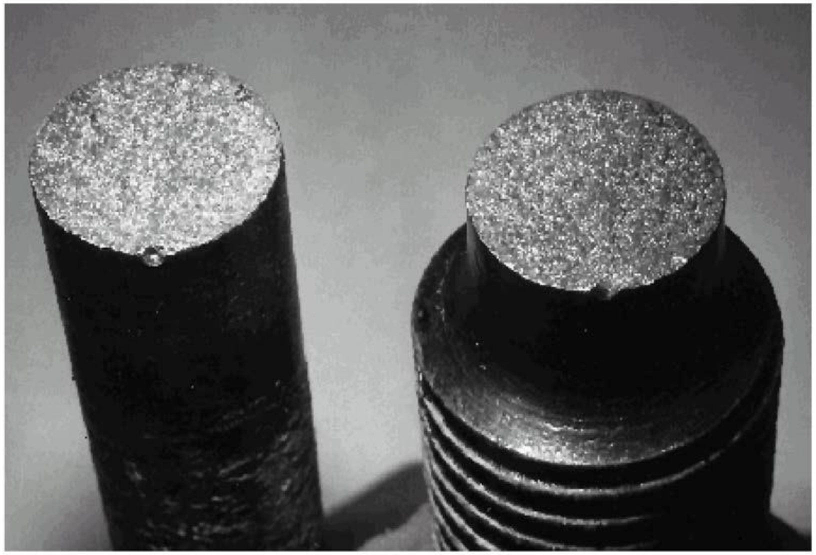


Inter-granular

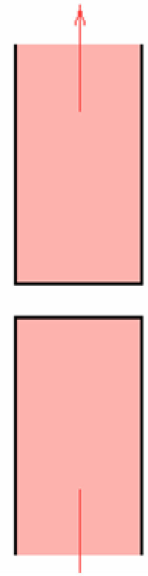
Brittle Fracture

❖ Brittle Fracture (Limited Dislocation Mobility)

- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage – breaking of atomic bonds along specific crystallographic places cleavage planes)



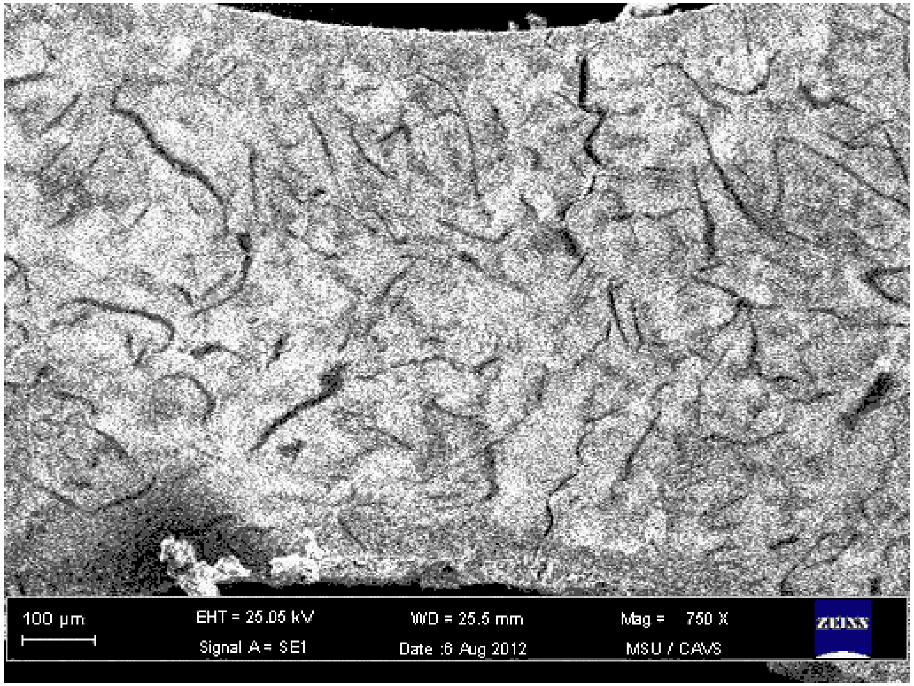
Brittle fracture in a mild steel



Brittle Fracture vs. Ductile Fracture

❖Fracture phenomena

Brittle Fracture (Grey cast iron)



Ductile fracture(A7 steel)

	Brittle	Ductile
Macroscopic observation	Sudden	Slow
Energy dissipation	Little	substantial
Microscopic observation	Breaking of atomic bonds	Slip on slip planes and void coalescence

Brittle Fracture vs. Ductile Fracture

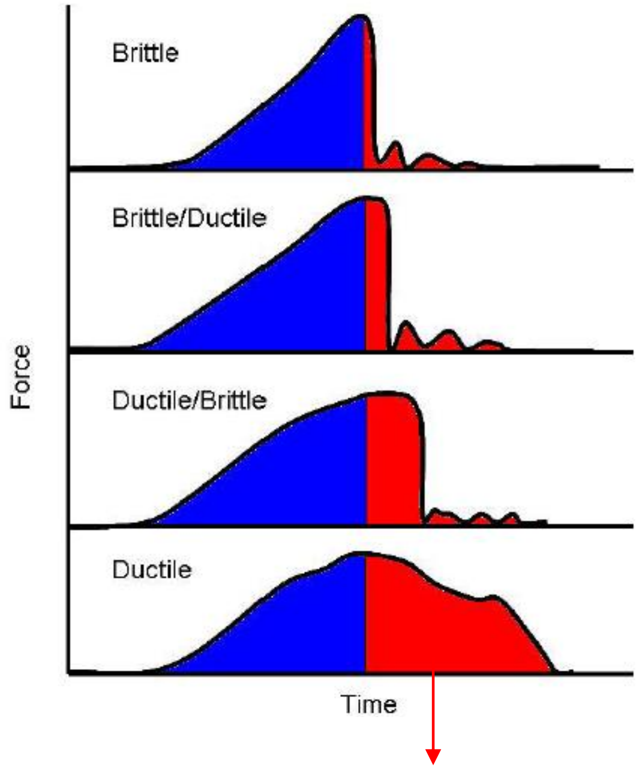
❖ Ductile fracture – most metals (not too cold)

- Extensive plastic deformation ahead of crack
- Crack is "stable" : resists further extension unless applied stress is increased

❖ Brittle fracture – ceramics, ice, cold metals

- Relatively little plastic deformation
- Crack is "unstable" : propagates rapidly without increase in applied stress

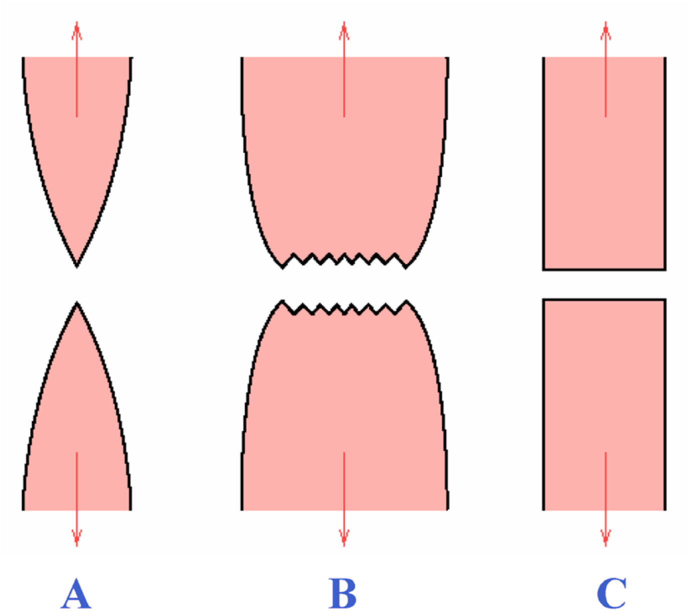
✓ Ductile fracture is preferred in most applications

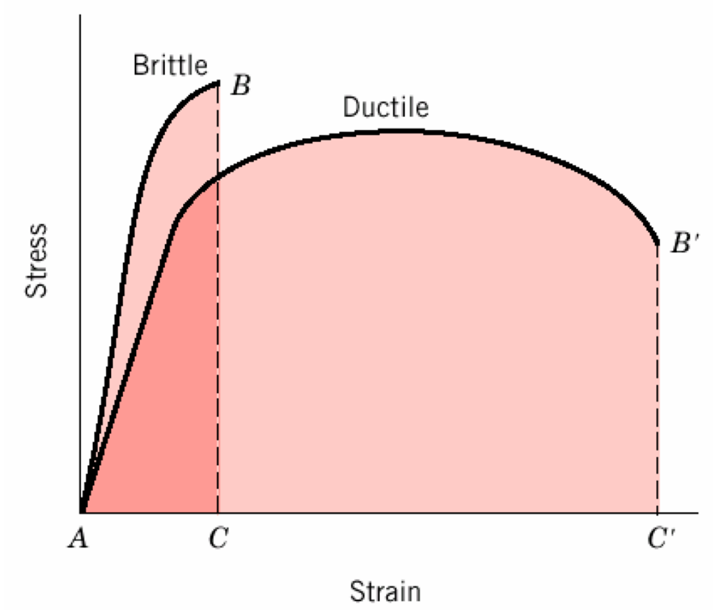


After crack commencement

Lecture source: Prof. Leonid Zhigilei, http://people.virginia.edu/~lz2n/mse209/index.html
MSE 2090: Introduction to Materials Science Chapter 8, Failure

Brittle Fracture vs. Ductile Fracture





A. Very ductile : soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature
B. Moderately ductile fractures : typical for ductile metals
C. Brittle fracture : cold metals, ceramics

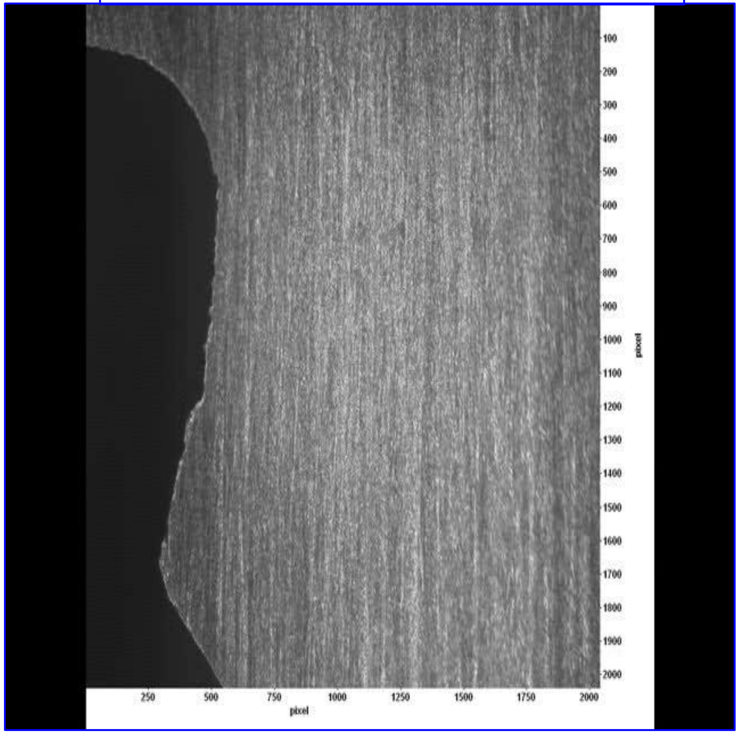
A. Ductile materials : extensive plastic deformation and energy absorption ("toughness") before fracture
B. Brittle fracture : little plastic deformation and low energy absorption before fracture

Fatigue

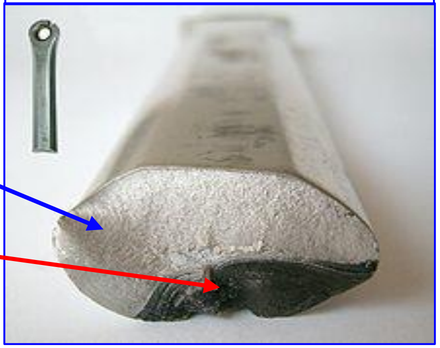
❖Fatigue

- When crack is subjected to cyclic loading
- Crack tip travels very short distance in each loading cycle
- Clam shell patterns in the crack surface

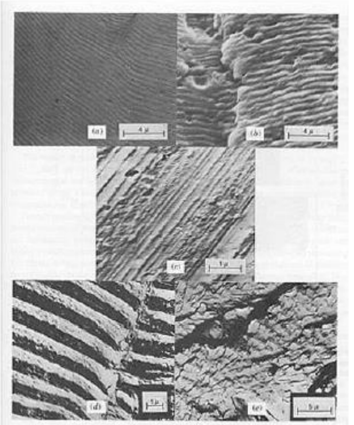
Crack propagation due to fatigue



Brittle + fatigue fracture

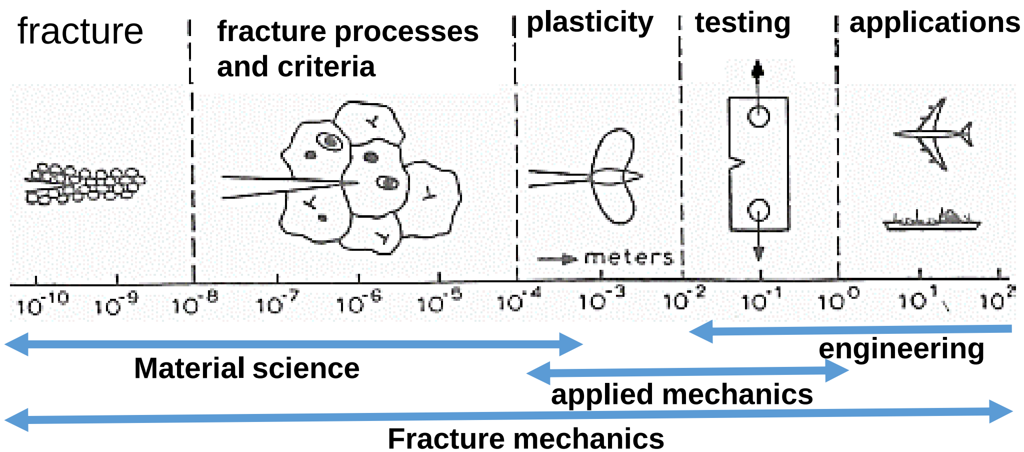


Clam shell

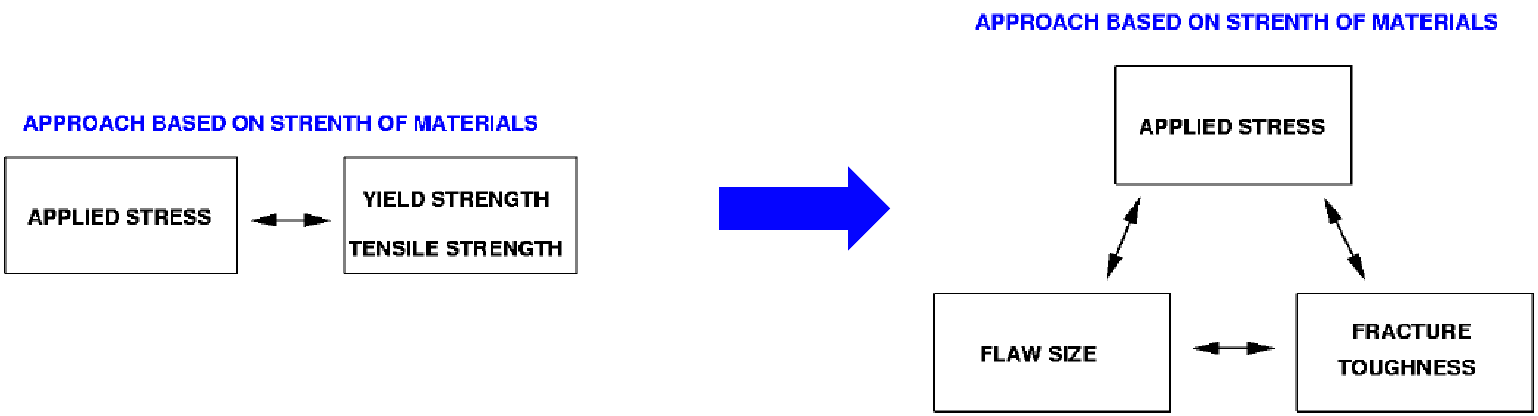


Fracture mechanics approach

❖Fracture mechanics approach



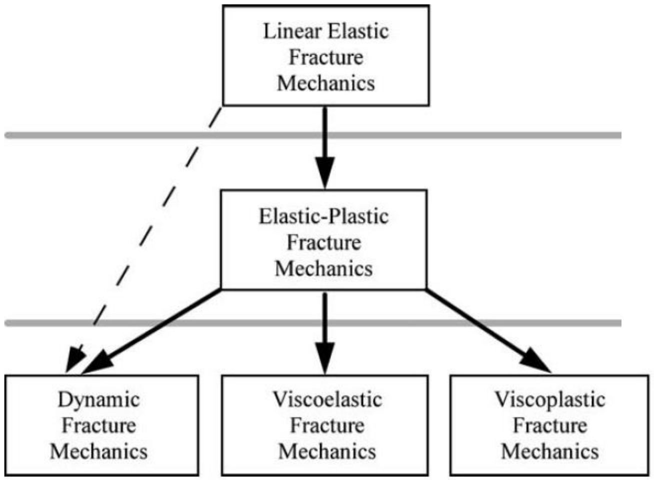
- Determines material failure by energy criteria, possibly in conjunction with strength (or yield criteria)
- Considers failure to be propagating throughout the structure rather than simultaneous throughout the entire failure zone or surface



Theories of fracture mechanics

❖Linear elastic fracture mechanics(LEFM)

- Sharp cracks in elastic bodies
- Small scale yielding
- Brittle or quasi-brittle fracture



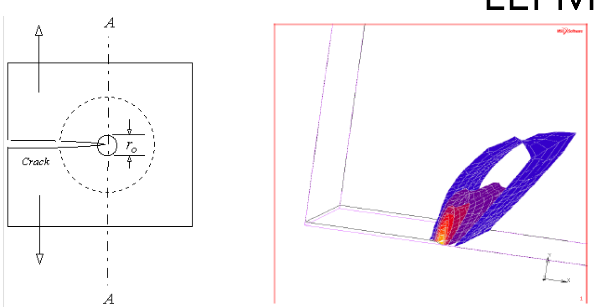
❖Dynamic fracture mechanics(DFM)

- Predict the speed and direction of its growth

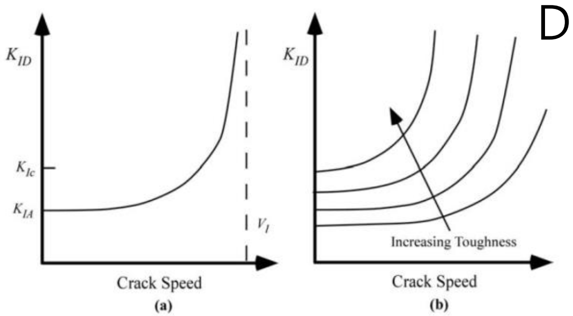
❖Non-linear fracture mechanics

- Large plastic crack tip zone (large plastic zone)
- Ductile fracture
- Crack growth criteria can no longer be formulated with LEFM method

LEFM



DFM

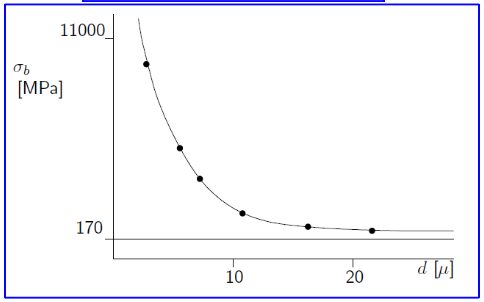


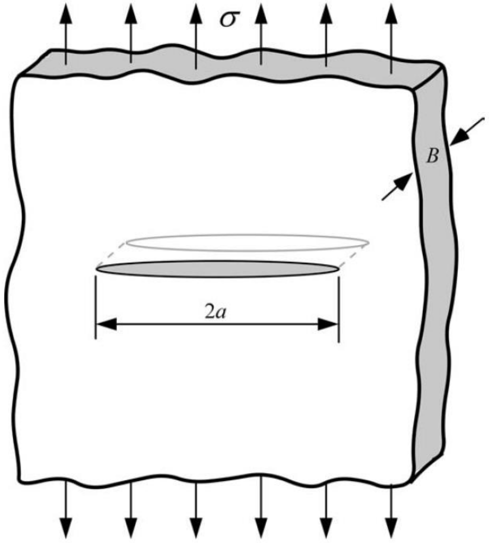
Fracture mechanics approach to design

❖Griffith Energy Criterion

- Crack extension occurs when the energy available for crack growth is sufficient to overcome the resistance of the material.
- Material resistance : Surface energy, plastic work, other types of energy dissipation associated with a propagating crack
- If Energy release rate exceeds critical energy release rate(measure of fracture toughness, crack growth is initiated

Griffith's experiment





$$\Pi = W - U - S$$
$$\delta\Pi = 0$$
$$\therefore \frac{\partial S}{\partial a} = \frac{\partial}{\partial a}(W - U)$$

- π : Potential Energy
- W : External work
- U : Strain Energy
- S : Surface energy used for crack growth

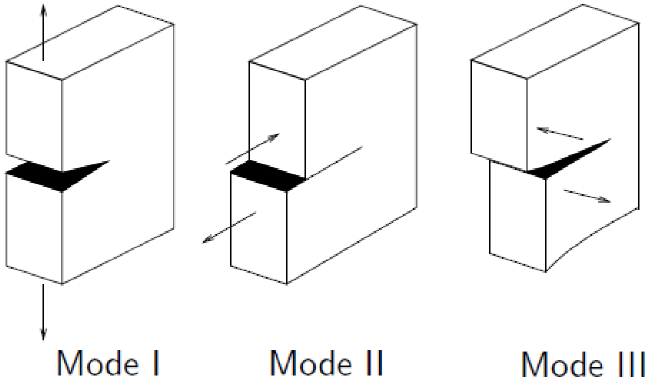
$$G = \frac{\pi\sigma^2 a}{E}$$
$$G_c = \frac{\pi\sigma_f^2 a_c}{E}$$

- G : Energy release rate
- G_c: Critical Energy release rate

Fracture mechanics approach to design

❖Stress intensity approach

- Analyze stress field near crack-tip
- Fracture must occur at critical stress intensity K value (Another fracture toughness measurement)
- Crack is initiated when $K_I \geq K_{IC}$
- Three Crack loading modes are introduced
- Mode 1 : Opening mode
- Mode 2 : Sliding mode
- Mode 3 : Tearing mode



Fracture mechanics approach to design

❖Stress intensity approach

- For the plate subjected to tensile stress

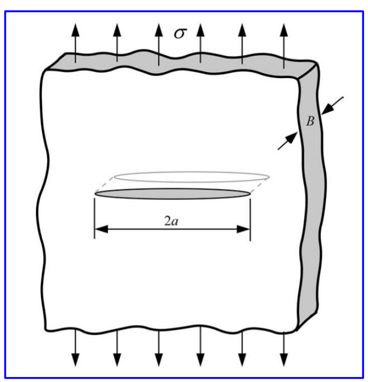
$$K_I = \sigma\sqrt{\pi a}$$

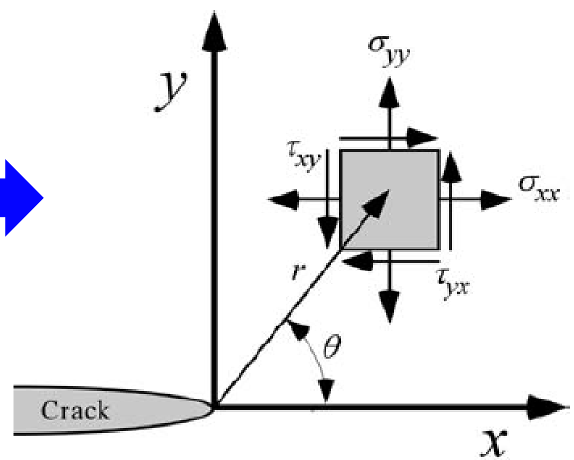
$$G = \frac{K_I^2}{E}$$

General equation

$$\sigma_{ij}(r,\theta) = \frac{1}{\sqrt{2\pi r}}\left[K_I f_{i,j}^{I}(\theta) + K_{II} f_{i,j}^{II}(\theta) + K_{III} f_{i,j}^{III}(\theta)\right]$$

- K_I = mode I stress intensity factor
- K_{II} = mode II stress intensity factor
- K_{III} = mode III stress intensity factor
- $f_{i,j}$ = Shape function





$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1 - \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right]$$

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1 + \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right]$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{3\theta}{2}\right)$$

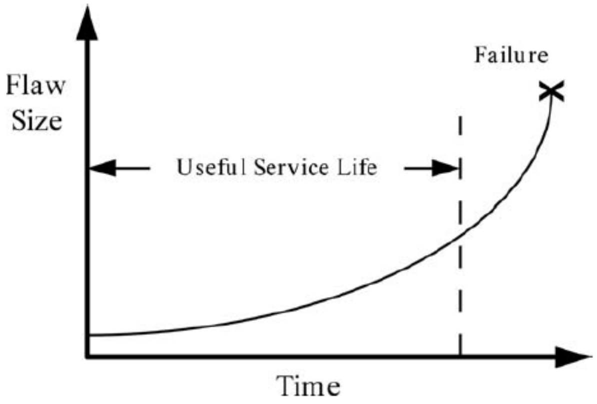
Fracture mechanics approach to design

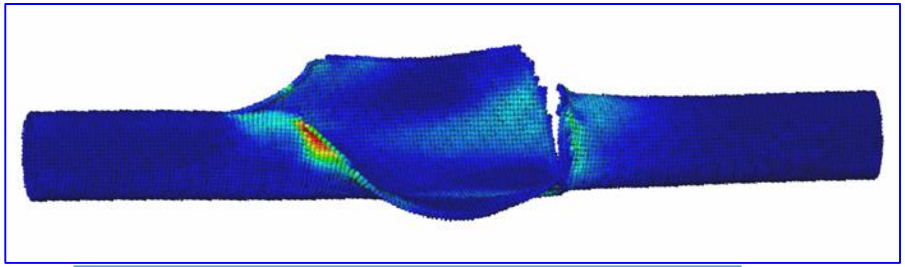
❖Time dependent crack growth and damage tolerance

- Rate of cracking can be correlated with fracture mechanics parameter such as the stress-intensity factor
- Crack size for failure can be computed if the fracture toughness is known.
- Fatigue crack growth rate in metals.

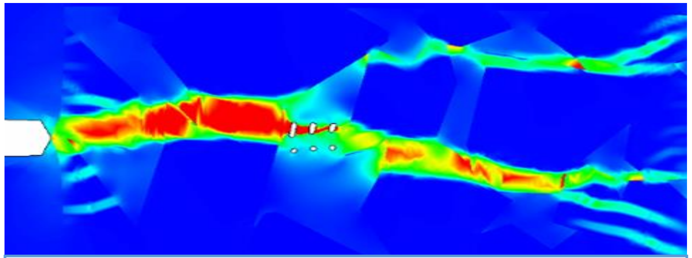
$$\frac{da}{dN} = C(\Delta K)^m$$

- da/dN : Crack growth per cycle
- ΔK : Stress intensity range
- C, m : Material constants





Crack propagation simulation (XFEM)



Crack of heterogeneous materials

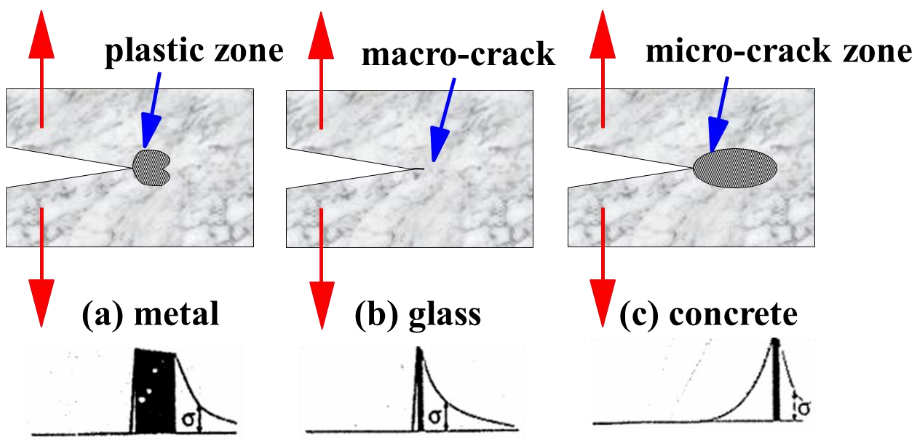
Non-linear fracture mechanics

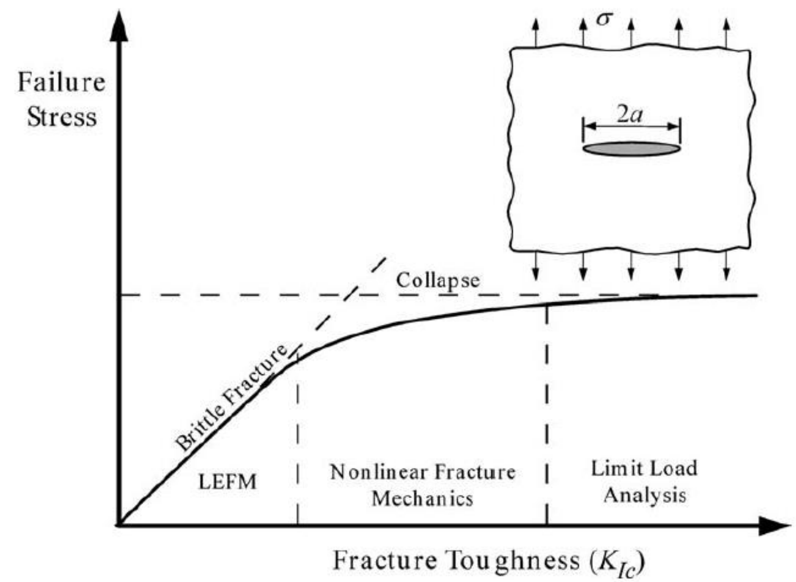
- Energy criterion and stress intensity factor is only valid for brittle fracture.
- At very high fracture toughness, LEFM is no longer valid
- Non-linear fracture mechanics bridges the gap between LEFM and collapse

TABLE 1.1
Typical Fracture Behavior of Selected Materials[a]

Material	Typical Fracture Behavior
High strength steel	Linear elastic
Low- and medium-strength steel	Elastic-plastic/fully plastic
Austenitic stainless steel	Fully plastic
Precipitation-hardened aluminum	Linear elastic
Metals at high temperatures	Viscoplastic
Metals at high strain rates	Dynamic/viscoplastic
Polymers (below T_g)[b]	Linear elastic/viscoelastic
Polymers (above T_g)[b]	Viscoelastic
Monolithic ceramics	Linear elastic
Ceramic composites	Linear elastic
Ceramics at high temperatures	Viscoplastic

[a] Temperature is ambient unless otherwise specified.
[b] T_g —Glass transition temperature.





Reference

1. Dr. P.J.G. Schreurs, Lecture note on fracture mechanics, Eindhoven University of Technology
2. Dr. Alan T. Zehnder, Lecture notes on fracture mechanics, Cornell University
3. T.L. Anderson, Fracture mechanics – fundamentals and applications, Taylor & Francis