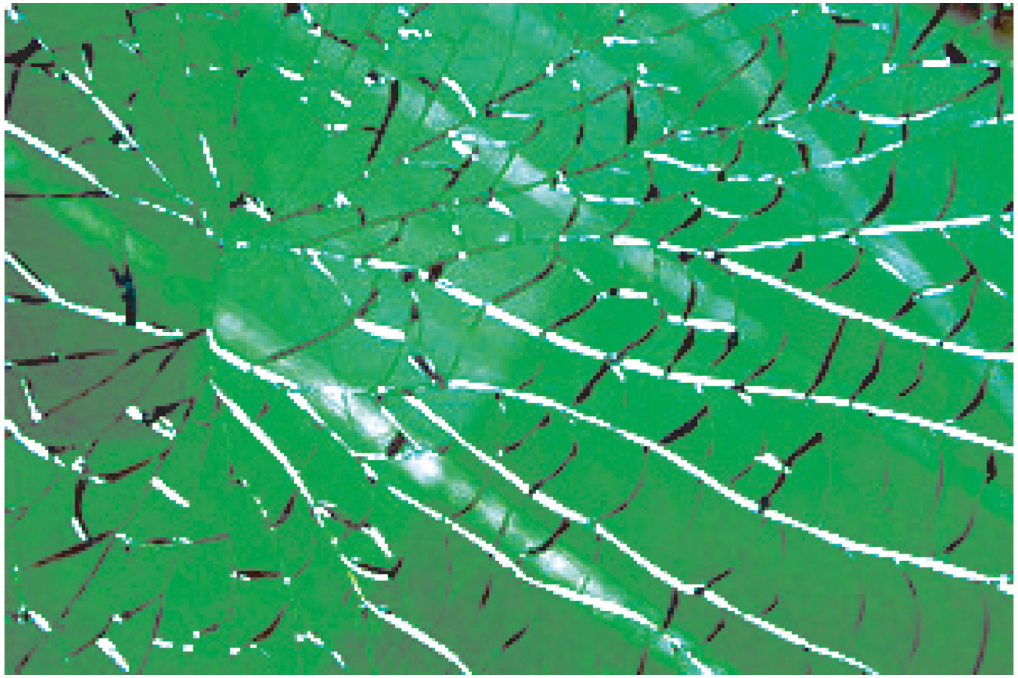
Chapter 8
Fracture and fracture toughness



A fractured Liberty Ship

8.1 Introduction and synopsis

- Distinguishing strength from toughness.
- Understanding fracture toughness.

8.2 Strength and toughness

Strength and toughness? Why bother? What's the difference?

- *Strength* – resistance to plastic flow; onset at yield strength, max at tensile strength (work hardening); area under stress-strain curve to fracture – *work of fracture*.
- *Toughness* – resistance to propagation of a crack. A tough material yields, work hardens, and absorbs energy – the crack is insignificant. A brittle (not tough) material fractures at stress far below yield by crack propagation.

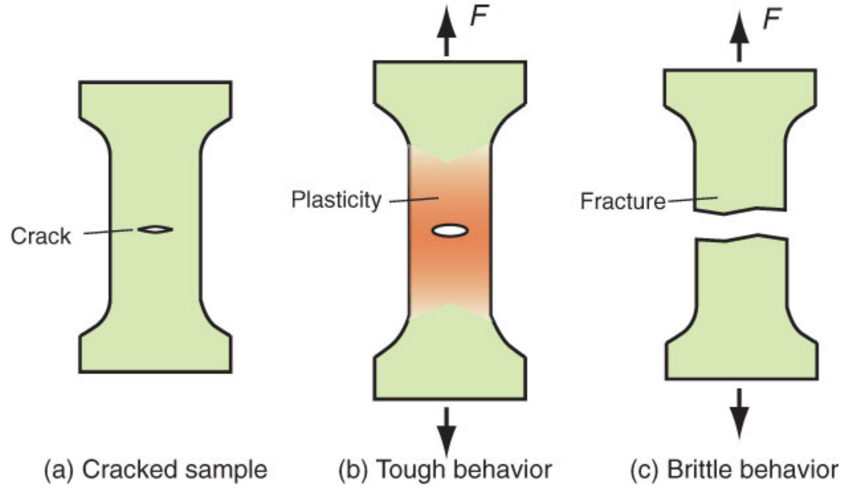


Figure 8.1 Tough vs brittle behavior. The crack in the tough material, shown in (b), does not propagate when the sample is loaded; a similar crack in the brittle material propagates without general plasticity, and thus at a stress less than the yield strength.

- Every material has a certain strength and a certain toughness. It is and/and (not either/or).

Tests for toughness

- Energy methods are good for acceptance and quality control – however they do not measure a material property we can use in design (i.e. independent of size and shape).

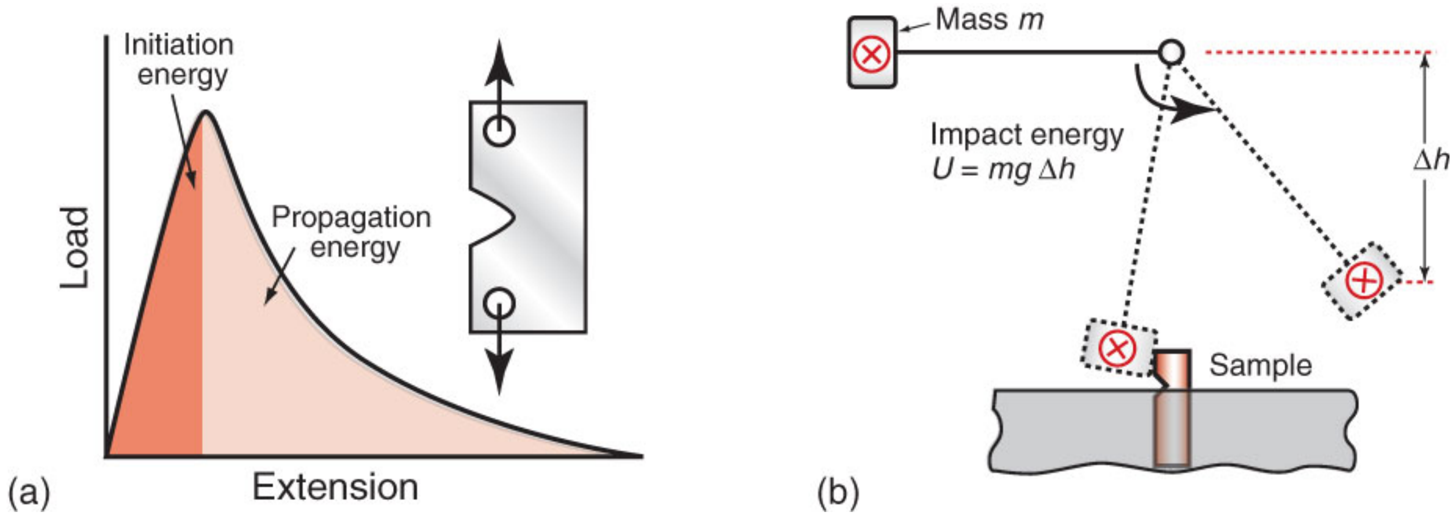


Figure 8.2 (a) The tear test. (b) The impact test. Both are used as acceptance tests and for quality control, but neither measures a true material property.

8.3 The mechanics of fracture

Stress intensity K_1 and fracture toughness K_{1c}

- Cracks concentrate stress - local stress rises steeply as tip is approached. The stress concentration factor (Ch. 7) applies to holes and notches but here we have very sharp features.
- $\sigma_{local} = \sigma[1 + Y(\pi c/2\pi r)^{1/2}]$.
  Y is a constant near 1.
- Near the tip where r << c:
  $\sigma_{local} = \sigma Y(\pi c/2\pi r)^{1/2}$ (Eq. 8.2)
- For a given value of r the local stress varies as $\sigma(\pi c)^{1/2}$, a measure of local stress intensity. Called the *mode 1* (tensile) *stress intensity factor*:
  $K_1 = Y\sigma(\pi c)^{1/2}$ (SI unit: MPa $m^{1/2}$)

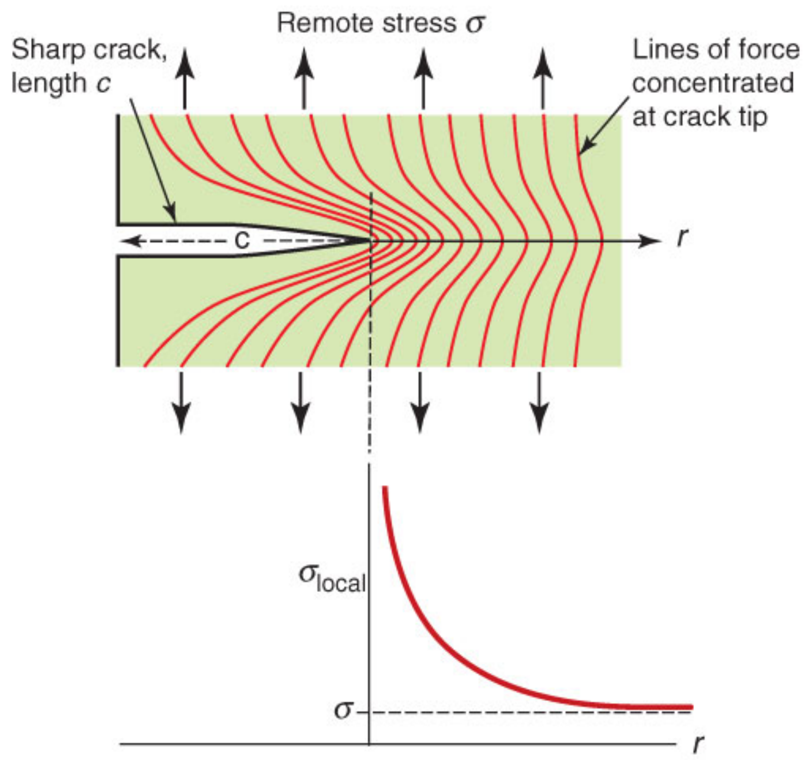


Figure 8.3 Lines of force in a cracked body under load; the local stress is proportional to the number of lines per unit length, increasing steeply as the crack tip is approached.
This geometry is called *mode 1* loading.

- We will see later: Cracks propagate when the stress intensity factor K_1 exceeds a critical value, the *fracture toughness* K_{1c}

- In standard tests the tensile stress (σ^*) for sudden propagation of the crack is measured and $K_{1c} = Y\sigma^*(\pi c)^{1/2} \approx \sigma^*(\pi c)^{1/2}$

- Fracture toughness is a material property (independent of test geometry and usable in design).

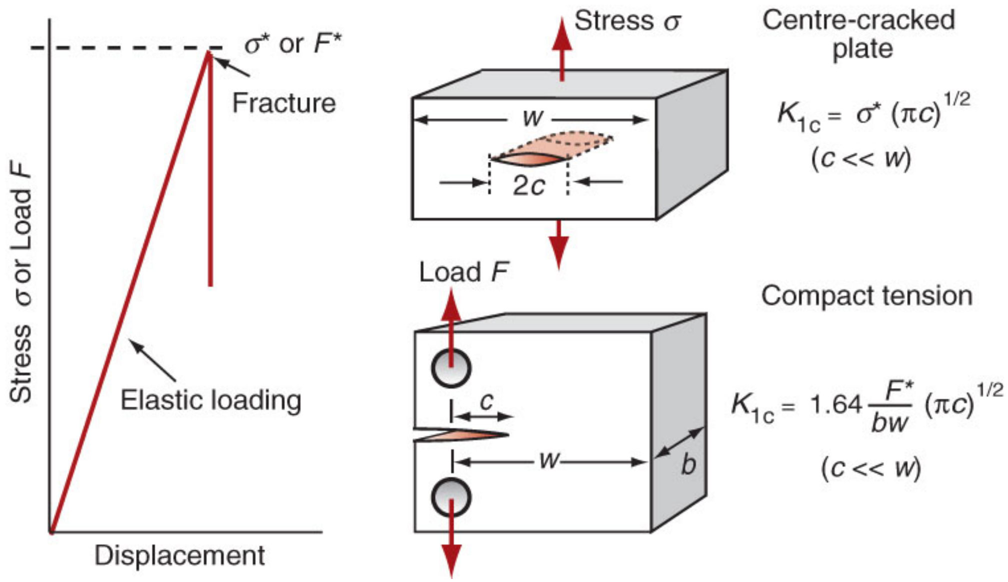
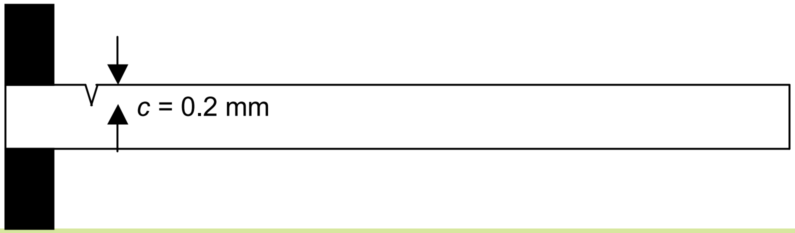


Figure 8.4 Measuring fracture toughness, K_{1c}. Two test configurations are shown.

Example



Example 8.1

The stainless steel and polystyrene rulers in Example 5.2 are loaded as cantilevers of length 250 mm. Both have transverse scratches of depth 0.2 mm, near the base of the cantilever, on the tensile side. For this surface crack geometry, assume the factor Y in equation (8.4) is 1.1. The fracture toughnesses K_{Ic} of steel and polystyrene are 80 and 1 $MPa.m^{1/2}$, respectively. Calculate the stress needed to cause fast fracture in each case. Will the cantilevers fail by yielding or by fast fracture?

Energy release rate G and toughness G_c

- Forget about G mentioned in the book.

- Fracture creates new surfaces with surface energy γ (typically about 1 J/m^2). A sample of cross section A when fractured has 2A new surface area, representing an extra energy of $2A\gamma$.

- Actually growing a crack costs energy G_c (unit: J/m^2) for the two surfaces – it can be seen as an *effective* surface energy; in many materials $G_c > 2A\gamma$, or even $G_c >> 2A\gamma$, because of plastic deformation near the crack tip G_c is called *toughness* or *critical strain energy release rate*.

Relating toughness G_c to fracture toughness K_{1c}

- A slab of unit thickness carrying stress σ stores elastic energy

  $U_v = \sigma^2/2E$ per unit volume (Ch. 4)
- Place a crack of length c which relaxes the stress in a half-cylinder of radius ~ c, releasing energy: $U(c) = \sigma^2/2E(\pi c^2/2)$ per unit length.
- Extend crack by δc: cost is $G_c\delta c$.
- Differentiate U(c):

  $\delta U = \sigma^2/2E(\pi c)\delta c = G_c\delta c$.
- But $\sigma^2\pi c = K_{1c}^2$, let Y = 1;

  $K_{1c}^2/2E = G_c$, or $K_{1c} = (2EG_c)^{1/2}$
- A more exact treatment gives

  $K_{1c} = (EG_c)^{1/2}$

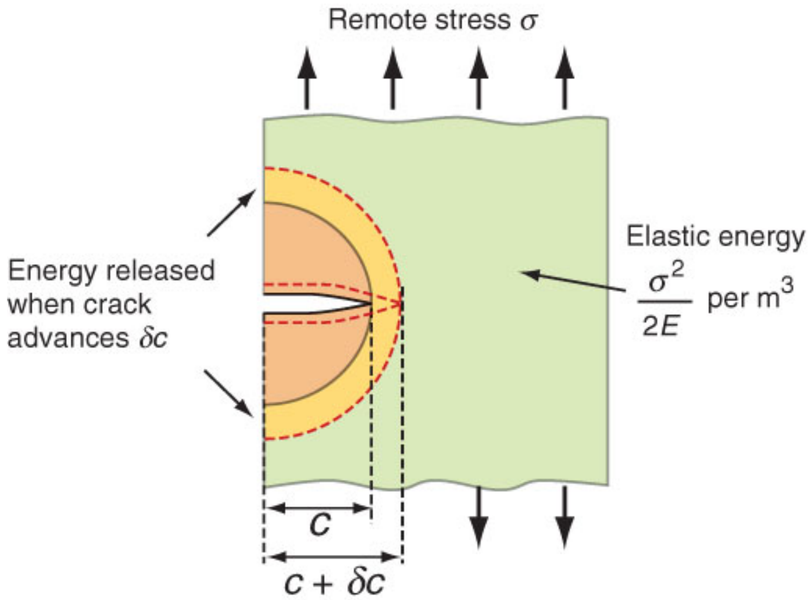


Figure 8.5 The release of elastic energy when a crack extends.

The crack tip plastic zone

- The intense stress field at the tip creates a process zone: plastic in ductile metals, micro-cracking in ceramics, and delamination, debonding, pull-out in composites.
- Stress rises as $1/\sqrt{r}$; at the point it reaches σ_y we have yielding; except for work hardening the stress cannot rise any more.
- We can calculate at what r the local stress reaches yield and find (taking Y = 1):

  $r_y = 2(\sigma^2 \pi c / 2\pi\sigma_y^2) = K_1^2/\pi\sigma_y^2$.
- The zone shrinks rapidly as σ_y increases. Small in ceramics, big in soft metals

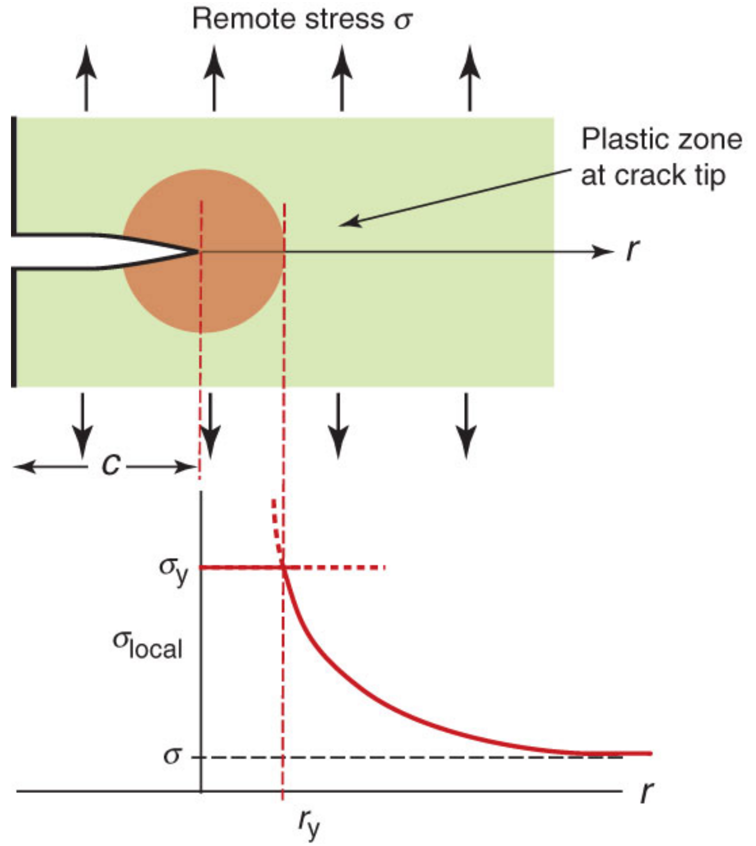


Figure 8.6 A plastic zone forms at the crack tip where the stress would otherwise exceed the yield strength σ_y.

Extra factor 2 with respect to Eq. 8.2, because the stress is redistributed by the truncation

- K_{1c} is well-defined for brittle materials and for those where the plastic zone is small compared to the test sample; in very ductile materials the plastic zone exceeds the sample width and the crack does not propagate: we see only yielding.
- Dependence on crack size: When c is small it is σ_y (failure by yield), when c is large $\sigma_f = K_{1c} /(\pi c)^{1/2}$ (failure by fracture)
- Transition at intersection of $\sigma_f = \sigma_y$ giving a transition crack length of $c_{crit} = K_{1c}^2 / \pi \sigma_y^2$; the same as the plastic zone size at fracture when $K_1 = K_{1c}$

Material	c_{crit} (mm)
Metals	1-1000
Polymers	0.1 – 10
Ceramics	0.01 – 0.1
Composites	0.1 - 10

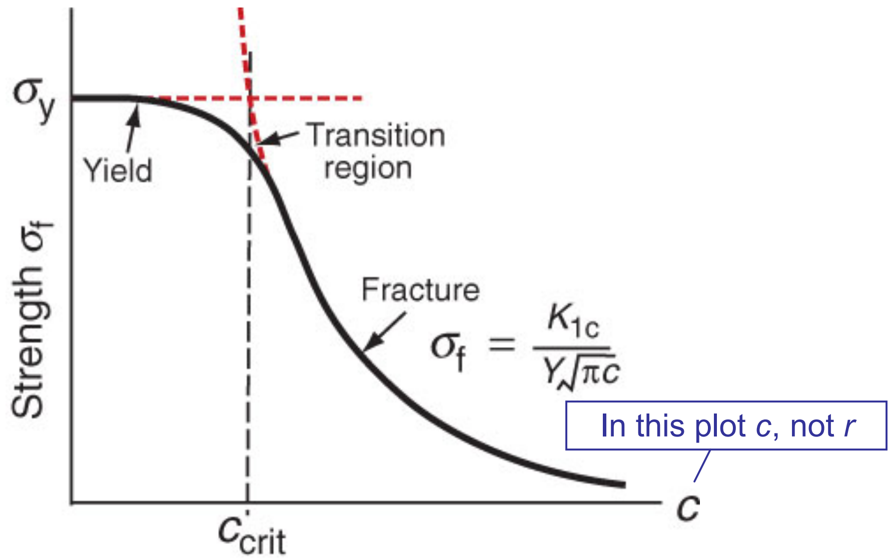


Figure 8.7 The transition from yield to fracture at the critical crack length c_{crit}.

Example

Example 8.2

Estimate the plastic zone sizes for the cracks in the stainless steel and polystyrene rulers in Example 8.1.

8.4 Material property charts for toughness

The fracture toughness-modulus chart

- The range of K_{1c} is large; for brittle materials the values are well-defined, for tough materials they are approximate.
- Metals are almost all > 15 MPa $m^{1/2}$
- Log scales allow plotting of toughness: $G_c \sim K_{1c}^2/E$ (range 0.001-100 kJ/m^2) Ceramics have low toughness values

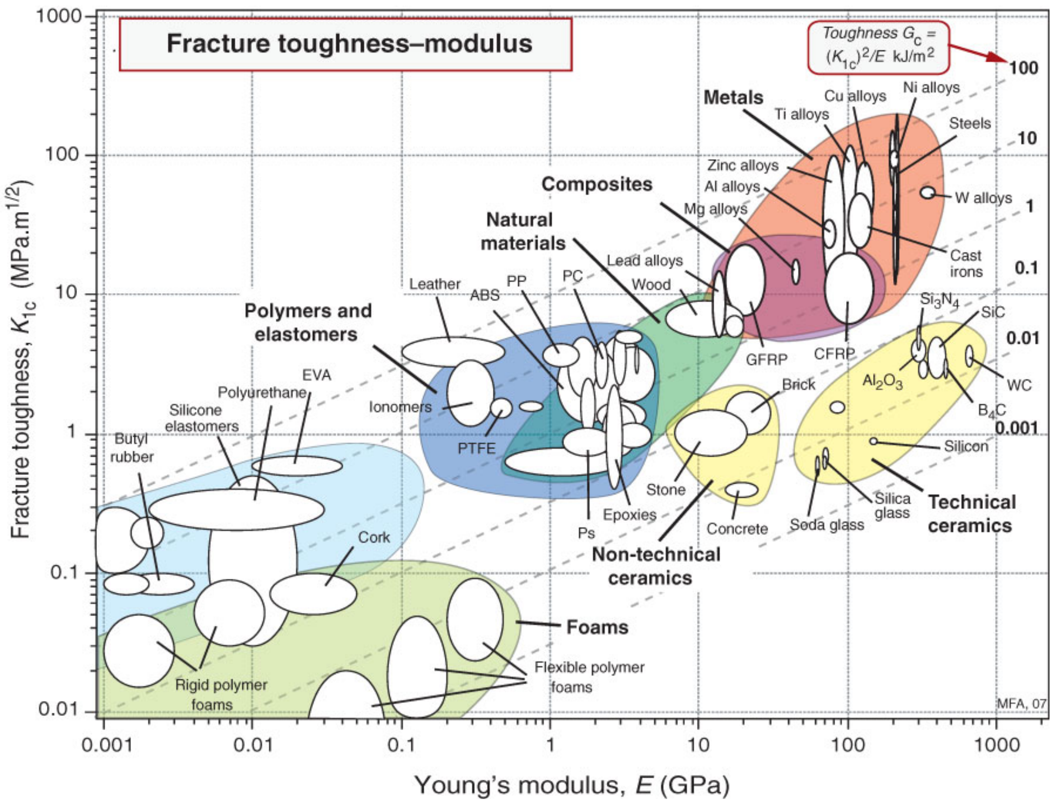


Figure 8.8 A chart of fracture toughness K_{Ic} and modulus E. The contours show the toughness, G_c.

The fracture toughness-strength chart

- Metals are strong and tough.
- The transition crack length, at which ductile behavior is replaced by brittle behavior, can also be plotted.
- Bottom right: high strength, low toughness (fracture before yield)
- Top left: low strength, high toughness (yield before fracture)

$c_{crit} = K_{1c}^2 / \pi \sigma_y^2$

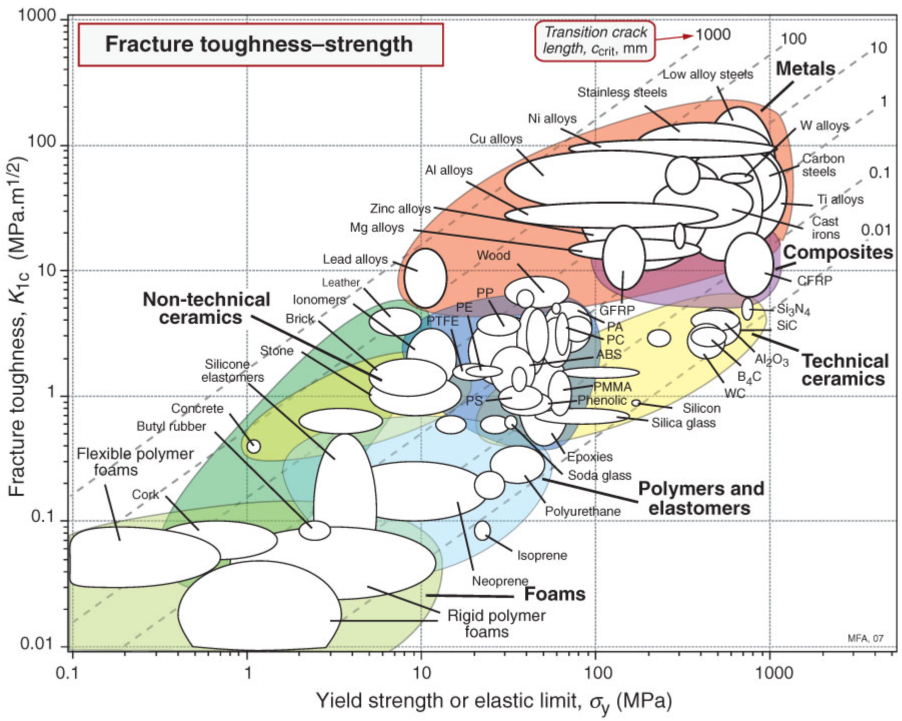


Figure 8.9 A chart of fracture toughness K_{1c} and yield strength σ_y. The contours show the transition crack size, c_{crit}.

8.5 Drilling down: the origins of toughness

Surface energy

- Cutting through a simple cubic crystal we break 1/6 of the bonds of a surface atom, requiring 1/6 the cohesive energy per volume H_c for a slice $4r_0$ thick
- So the surface energy for unit cut area $2\gamma \approx (H_c/6)(4r_0)$ or $\gamma \approx H_c r_0/3$
- $H_c \approx 3 \times 10^{10}$ J/m^3, $r_0 \approx 10^{-10}$ m $\rightarrow \gamma \approx 1$ J/m^2

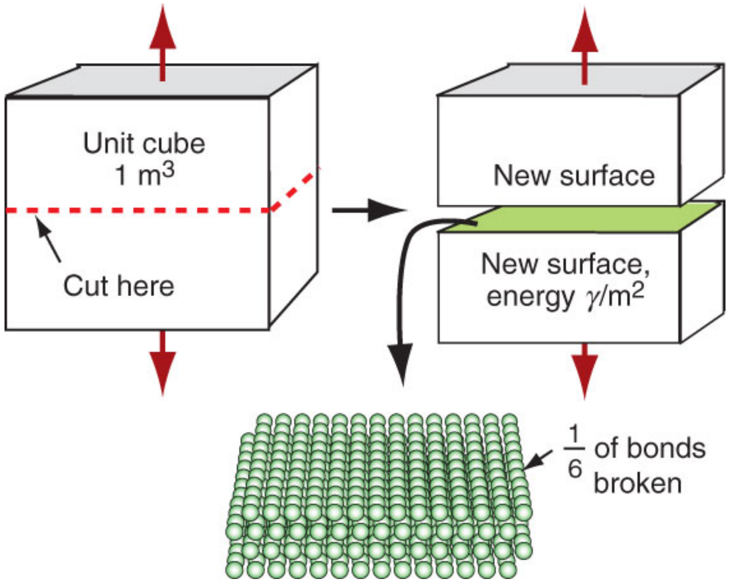


Figure 8.10 When new surface is created as here, atomic bonds are broken, requiring some fraction of the cohesive energy, H_c.

Brittle cleavage fracture

- Ceramics and glasses – no yielding, so stress reaches ideal strength (atomic bonds break), crack grows and since

$$K_1 = Y\sigma(\pi c)^{1/2}$$

K_1 grows. The crack accelerates as it lengthens to the speed of sound.

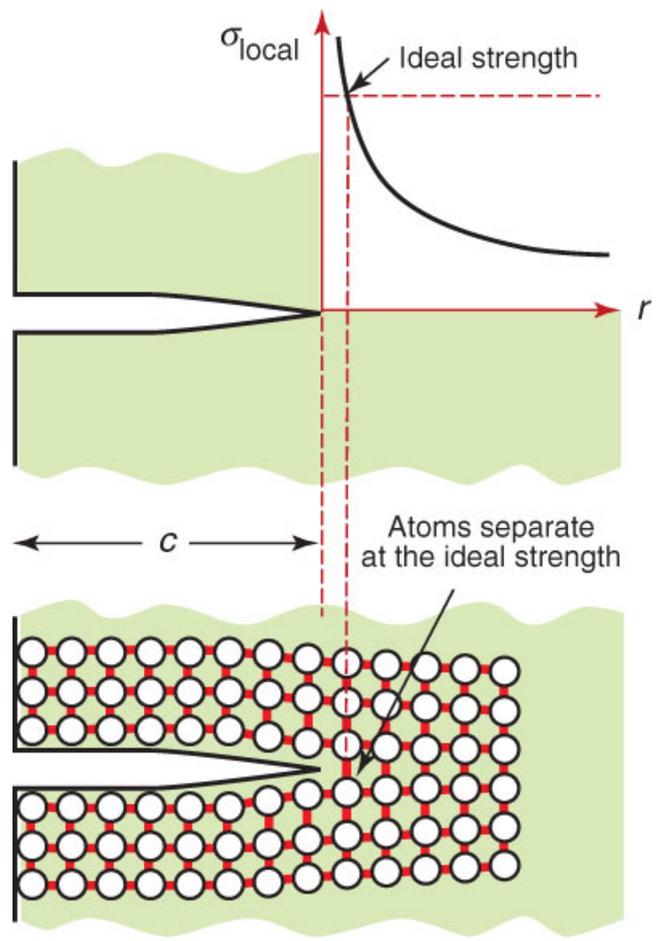


Figure 8.11 Cleavage fracture. The local stress rises as $1/\sqrt{r}$ towards the crack tip. If it exceeds that required to break inter-atomic bonds (the 'ideal strength') they separate, giving a cleavage fracture. Very little energy is absorbed.

Tough ductile fracture

- First consider no crack. Get plastic deformation, work hardening up to tensile strength, then weaken and fail. In engineering alloys the weakening begins at inclusions which concentrate stress and nucleate tiny holes. The holes grow, coalesce, and lead to ductile fracture.
- Many ductile polymers behave similarly with crazing replacing holes.

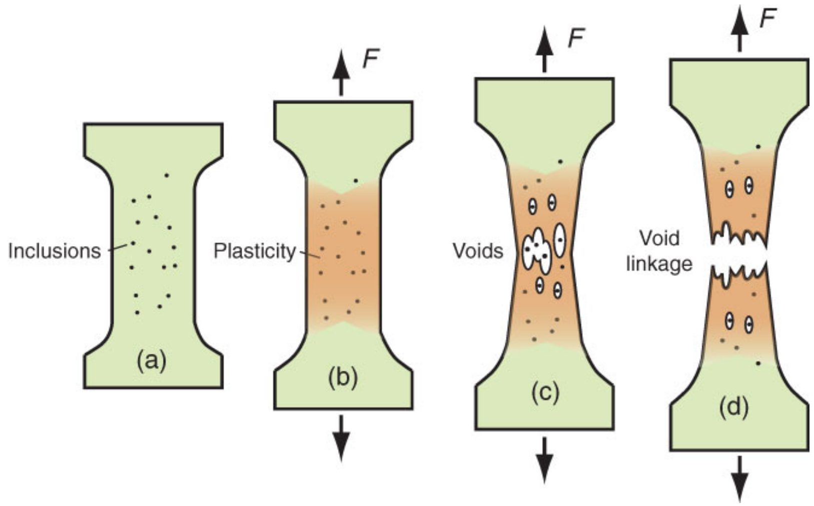


Figure 8.12 Ductile fracture. Plasticity, shown in red, concentrates stress on inclusions that fracture or separate from the matrix, nucleating voids that grow and link, ultimately causing fracture.

- Now consider a cracked sample.
- Plastic zone develops in front of crack tip and void process begins locally.
- Plasticity blunts tip and absorbs energy.
- At blunt tip stress is just sufficient to keep plastically deforming the material
- Crack can advance by repeating process.

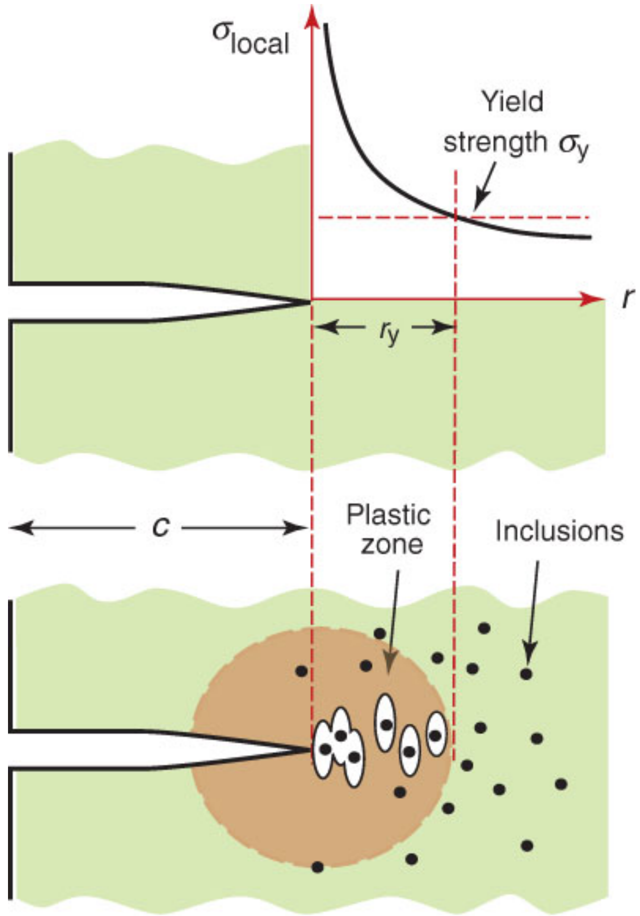


Figure 8.13 If the material is ductile a plastic zone forms at the crack tip. Within it voids nucleate, grow and link, advancing the crack in a ductile mode, absorbing energy in the process.

The ductile-to-brittle transition

- Brittle fractures (cleavage) are more dangerous than ductile: no warning, no prior plastic deformation.
- As T is lowered many materials (non-fcc metals and all polymers) experience the ductile-to-brittle transition. The yield strength increases as T decreases, making the plastic zone shrink to (near-)zero, and causing brittle failure.

Embrittlement of other kinds

- Chemical segregation - grain boundary segregation leading to low toughness network; failure by intergranular fracture.

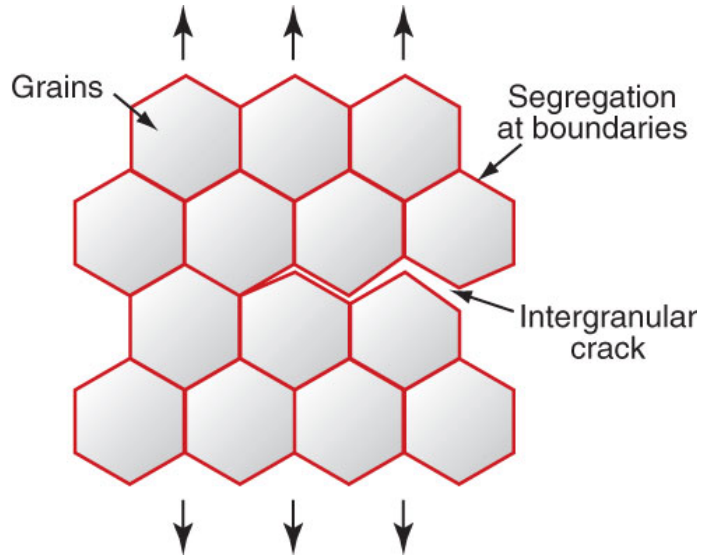


Figure 8.14 Chemical segregation can cause brittle intergranular cracking, since the boundaries may end up as repositorty for the impurities.

Metals

- It is difficult to combine strength and toughness. Increasing yield stress decreases plastic zone, decreasing energy absorption.
- Cleaning alloys to remove inclusions improves toughness.

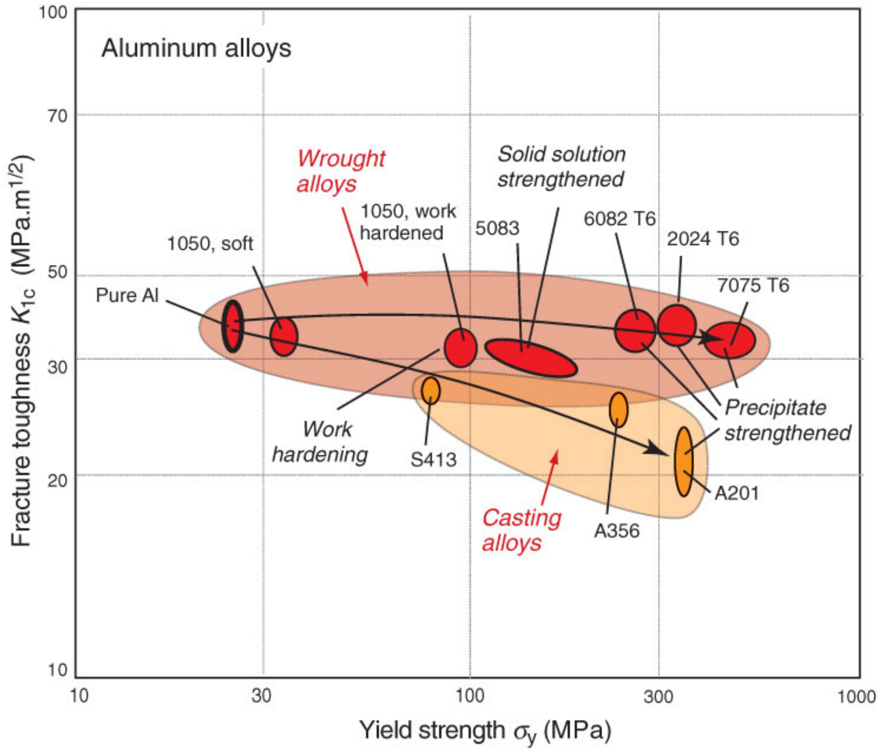
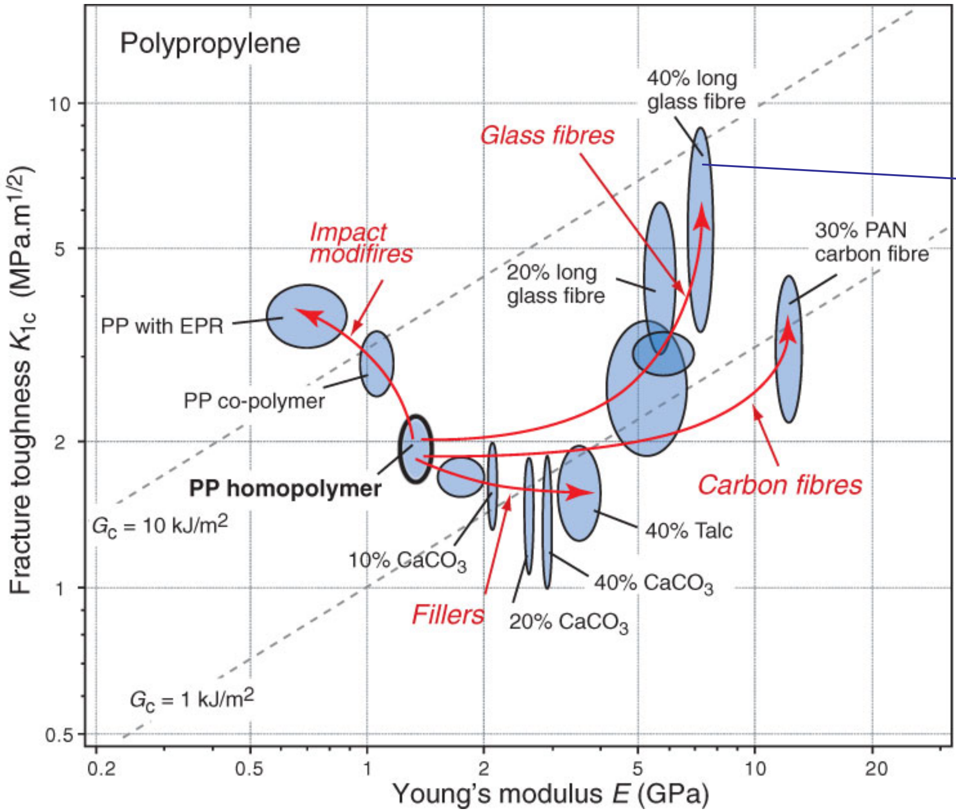


Figure 8.15 The strength and toughness of wrought and cast aluminum alloys. Toughness drop for cast alloys is due to intergranular fracture.

Polymers and composites

- Optimizing by blending, fillers, reinforcement.



How can a relatively brittle polymer like pp, mixed with even more brittle glass fibres, give a tougher material?

(See next slide)

Figure 8.16 The strength, fracture toughness and toughness of polypropylene, showing the effect of blending (impact modifiers), fillers, and fibers.

Toughening by fibers

- The fibers have high strengths and remain intact as a crack approaches. The crack has to begin again on the other side. Therefore multiple cracking. Overall dissipation increases.
- When fibers break and pull-out dissipation continues by friction. Adhesion between fiber and matrix can be engineered.

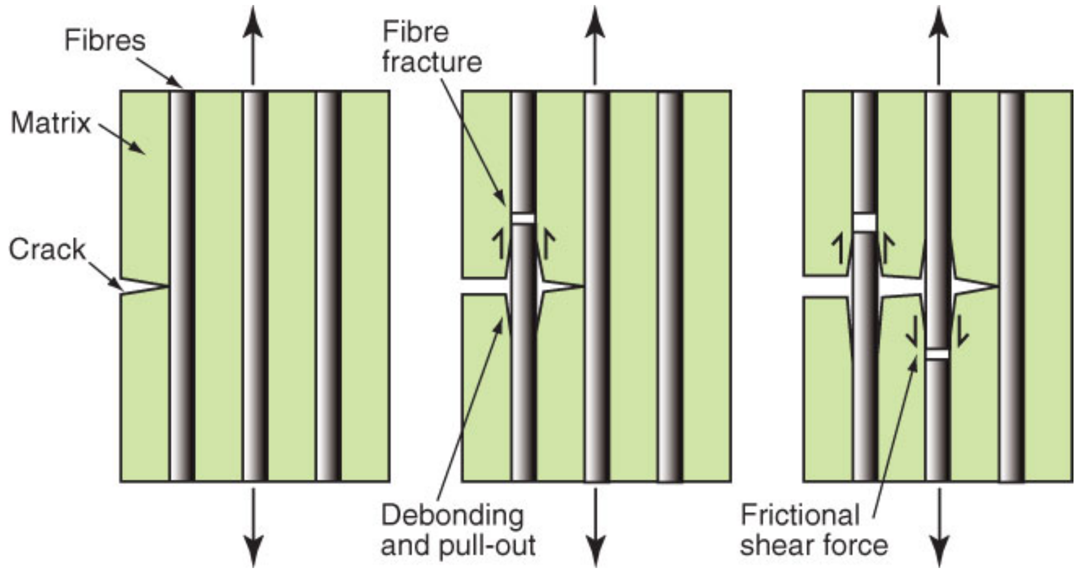


Figure 8.17 Toughening by fibers. The pull-out force opposes the opening of the crack.

Exercise

E 8.4. A tensile sample of width 10 mm contains an internal crack of length 0.3 mm. When loaded in tension the crack suddenly propagates when the stress reaches 450 MPa. What is the fracture toughness K_{1c} of the material of the sample? If the material has a modulus E of 200 GPa, what is its toughness G_c?