ASE 324L

Lab #10: Fracture Energy and Charpy Impact Test

Energy Concepts for Fracture

Energy concepts provide very powerful analytical tools in a number of areas of mechanics, and fracture mechanics is no exception to that. In fact, the original development of fracture mechanics by Griffith in the 1920's was based on an energy approach. Griffith's original postulate was that cracks grow in materials when the energy stored in a cracked structural component equals or exceeds the energy required to create new surfaces. This turned out to be true for very brittle materials (his experiments dealt with glass) but required some modification for tougher structural materials which deform plastically around the crack tip prior to and during crack propagation. As a crack starts to grow, material behind the crack tip unloads and the plastically deformed regions dissipate energy. This means that the resistance to crack growth is essentially increased over and above the energy required to create new surfaces. These observations led to the use of another fracture parameter known as the energy release rate, G. It is defined as the energy that would be released in a cracked component during an incremental crack extension, da. The potential energy, Π, of an elastically deforming component is given by

$$\Pi = U - W\,, \tag{1}$$

where U is the strain energy stored and W is the work done by the external forces. The energy release rate is defined as the change of the potential energy per unit area of crack growth. For a component of unit thickness,

$$G = -\frac{d\Pi}{da} = \frac{d}{da}\left(W - U\right). \tag{2}$$

For any given cracked component, the energy release rate is a function of the loading and geometry in much the same way (but in different functional form) as the stress intensity factor is in the previous Lab. It can be determined by a stress analysis of the component or from handbooks.

Alternatively, the energy release rate can be determined from the inverse slope of the load-displacement response, which is known as the compliance, $C = \Delta / P$. It can be shown that the energy release rate is given by

$$G = \frac{P^2}{2b}\frac{\partial C}{\partial a} \tag{3}$$

The advantage of Eq. (3) is that energy release rates can be determined experimentally, without further recourse to analysis.

No matter how the energy release rate is determined, the criterion for fast fracture based on energy release rates is:

$$G(\sigma, a) = G_c, \tag{4}$$

where G_c is the crack resistance or toughness (lb/in, N/m or J/m^2), a material property. For very brittle materials, $G_c = 2\gamma$, where γ is the energy per unit area of a new surface. The factor 2 reflects the fact that two new surfaces are created during fracture. For tougher materials

$$G_c = 2\gamma + \gamma_p \tag{5}$$

where γ_p is the plastic energy dissipated during the crack growth. In practice, G_c is not partitioned as Eq. (5) suggests, but is determined *in toto* by fracture toughness tests in the same way as K_c was in the previous lab.

The development of the stress intensity factor and energy release rate approaches is predicated on an elastic response from the structural component. The plastic zone has to be small. It may not be surprising then to find that the two fracture parameters are related to one another. In general

$$G = \frac{K^2}{\bar{E}} \tag{6}$$

where $\bar{E} = E/\left(1 - \nu^2\right)$ for plane strain and $\bar{E} = E$ for plane stress. The two parameters G and K can therefore be used interchangeably.

Charpy Impact Test

The energy approach described above is useful for thinking about the test for this week's lab, ***the Charpy Impact Test***. The test was introduced before more quantitative fracture mechanics concepts became generally accepted. It provides a conservative estimate for the potential for fast fracture by suppressing the ability of a material to deform plastically. This is achieved by conducting the test at low temperatures, high strain rates and locally multiaxial stress states, all of which make it harder for a material to deform plastically and thereby dissipate additional energy. The test essentially determines the (Charpy) energy required to break a notched specimen as a function of temperature. It is usually found that the Charpy energy increases with increasing temperature, rising sharply (Fig. 1) at the transition between the lower (brittle) and the upper (ductile or tough) shelves. The transition temperature is used as a design parameter in the sense that a material should not be used below it, because the material is brittle below the transition temperature.

The Charpy Impact Test consists of a notched, three-point bend specimen (Fig. 2) that is loaded at high strain rates and various temperatures by a falling pendulum (Fig. 3). The energy absorbed during the fracture process is determined by measuring the maximum height to which the pendulum rises after breaking the sample. The energy is plotted as a function of temperature

as depicted in Figure 1, in order to determine the transition temperature. The deformed shape of the cross-section can also be measured as a function of temperature. The increase in specimen width increases in a transitional manner with temperature. The appearance of the fracture surfaces also change from pure cleavage at very low temperatures to ductile shearing at higher temperatures. The test is simple to conduct and can be used for quality control purposes or to compare one material against another. It is not a very quantitative test and results should be interpreted carefully with experience.

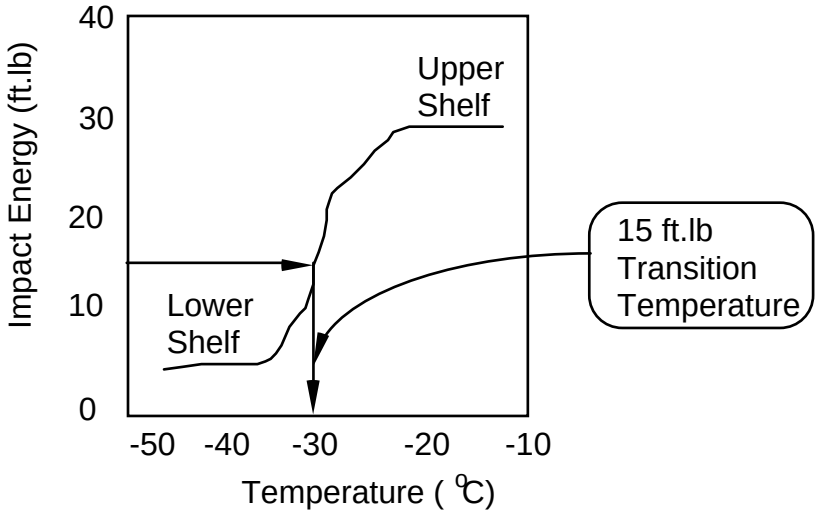


Fig. 1: Schematic of the Variation of Charpy Energy with Temperature.

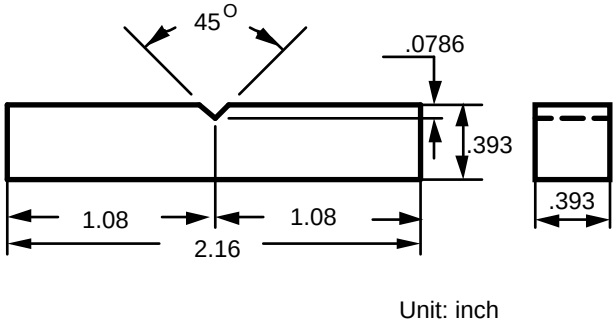


Fig. 2 Charpy Impact Specimen

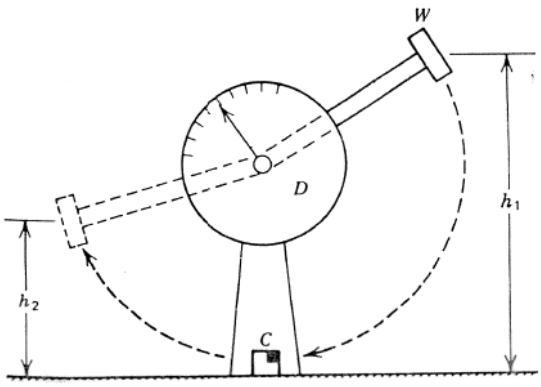


Fig. 3 Charpy Impact Tester

Environmentally assisted crack growth

Environmental conditions can be another source of embrittlement. Slow, time dependent crack growth may arise even under static loads when solvents are being absorbed into the crack tip region. This type of crack growth is known as environmentally assisted crack growth or stress corrosion cracking. Cracks grow more slowly than the fast crack you observed last week. They do so at stress intensity levels that are lower than K_c or K_{Ic}. Resistance to environmentally assisted cracking is displayed schematically in Figure 4, which is a correlation between crack growth rates and the stress intensity factor. The initial rising portion of the curve is a power law. Diffusion effects are dominant in this regime. When crack growth rates outrun diffusion, the crack speeds become independent of the stress intensity factor in what is known as the plateau region. Thereafter, fast crack growth mechanisms begin to dominate and the crack speeds rise sharply with stress intensity factor.

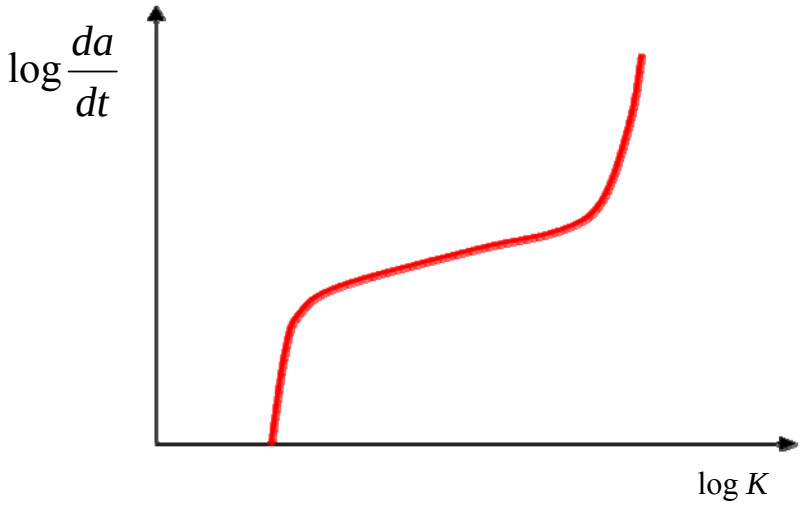


Figure 4. Crack growth rate correlation with stress intensity for environmentally assisted crack growth.

Homework Assignment:

1. Answer the following questions based on the Charpy impact tests conducted in the lab:

   (a) Plot the Charpy impact energy *vs.* temperature for the 1020 CRS specimens.
   (b) Determine the transition temperature on the basis of the plot obtained in question 1.
   (c) Discuss three phenomena that could be used to determine the transition temperature at which the type of fracture changes from brittle to tough.
   (d) Discuss the limitations of the transition temperature philosophy. How does the transition temperature vary with specimen thickness?

2. A center cracked plate made of aluminum (E = 70 GPa) has a toughness of 10 kJ/m^2. Find the stress level at which a 1 cm crack would grow. What if the plate is made of a ceramics (E = 300 GPa) with a toughness 10 J/m^3.

3. Consider a double-cantilever beam of initial crack length c_0 = 10 cm. Subject to increasing opening displacement, Δ, the crack first remains stationary and then grows stably. If the critical energy release is 30 J/m^2, find the critical opening displacement and the corresponding force when the crack starts to grow. The thickness of the beam (2H) is 1 cm and the width (B) is 0.5 cm. The Young's modulus of the material is 100 GPa. Plot the force versus displacement curve up to the point when the crack length reaches 20 cm. Assume that the energy release rate remains a constant as the crack grows.

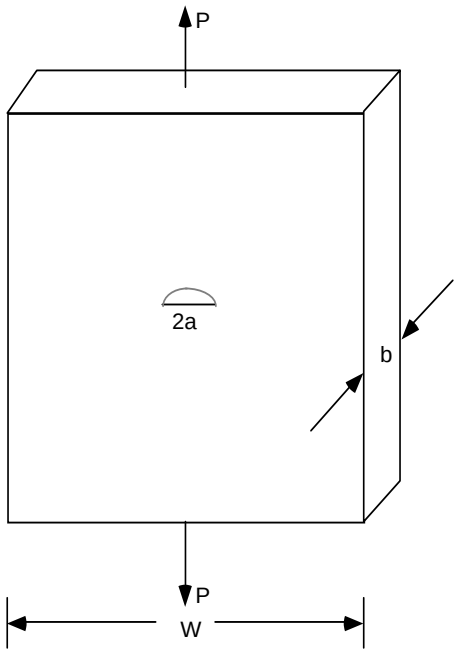
4. A plate with a semi circular flaw is subjected to a constant load P in a hostile environment. The subcritical crack growth law is given by

$$\frac{da}{dt} = 2(K)^{20},$$

   where crack growth rates are in m/s and K is in MPa√m. K_{IC} for the material is 11 MPa√m. The stress intensity factor for this configuration is

$$K = \frac{0.73P}{Wb}(\pi a)^{1/2}$$

   Determine how long it will take for the plate to



fail if the initial flaw size is 10 μm, the load is 100 kN, W = 10 cm and b = 1 cm.

5. The cracked strip shown below is subject to a bending moment M in a corrosive environment. The stress intensity factor for this configuration is $K = \frac{3.975M}{a^{3/2}}$, where M is a bending moment per unit thickness.

   (a) The plane strain toughness of the material is 6 MPa√m. The resistance to environmentally assisted crack growth is given by $\frac{da}{dt} = AK^n$ for $K_{th} \le K \le 2\mathbf{MPa}\sqrt{\mathbf{m}}$. The power law exponent $n = 12$ and $A = 5\text{x}10^{-4}$, where crack growth rates are given in mm/day, K is in MPa√m and $K_{th} = 1\mathbf{MPa}\sqrt{\mathbf{m}}$. When $2\mathbf{MPa}\sqrt{\mathbf{m}} \le K \le K_c$, the crack growth rate is $\dot{a}_p = 2\mathbf{mm/day}$. Describe what experiments you would need to conduct in order to determine all the properties just given and draw a schematic graph that puts them all in perspective. Indicate what fracture mechanisms dominate in each regime of the plot.

   (b) Corrosion has already produced an initial flaw of 1.5 mm when a fixed moment of 200 N/m/m is applied to the strip. Determine how long it would take the crack to arrest completely.