ASE 324L
Lab #9: Fractography and Fracture Toughness Testing

For the remainder of the semester, we are going to discuss the failure of materials and structures due to crack growth and fatigue. It is possible for materials to fail even though the stresses are well below the yield point of the material. This can happen if, for example, there are cracks or preexisting flaws in the material. The cracks produce very high stresses locally near the crack tip, so that even though the stresses far away from the crack tip are low in the elastic regime, the local stresses around the crack exceed the strength of the material and the crack may grow. The crack growth may be stable or unstable, depending on the geometry of the cracked component and the nature of the loading (load vs. displacement controlled, fatigue or cyclic loading). Fracture mechanics is the branch of mechanics that is used to analyze the severity of cracks and predict their growth. It provides a method for designing damage or crack tolerant structures, i.e., structures that can be designed to contain flaws. This permits lighter structures to be built and nondestructive inspection schedules to be specified for tracking the growth of cracks in structural components.

Figure 1: An oil tanker that fractured in a brittle manner by crack propagation around its girth. (Photography by Neal Boenzi. Reprinted with permission from *The New York Times*.)

Our introduction to fracture mechanics this week will start with *fractography*, the information on fracture mechanisms that is provided by examining the *appearance of the fracture surfaces*. This is an extremely useful component of fracture analysis because it can often be used to determine the cause and progression of failure in a structural component (Fig.1). This is possible because many fracture mechanisms occur under quite specific conditions and leave behind very characteristic features on the fracture surface.

Macroscopic Fracture Features

These are features that are observable with the naked eye and give the first clues as to the possible causes of failure. They are related to the roughness of the fracture surfaces and the orientation of the fracture surfaces to the loading direction. There are three possibilities:

(a) Smooth, glassy or shiny fracture surface perpendicular to loading direction. This is a very *brittle* form of fracture where failure is due to direct cleavage of atomic bonds with very little plastic deformation. In glasses and polymers the fracture surfaces may be optically smooth. In metals, they are rougher but still exhibit a bright, shiny texture and have a rock candy-like appearance. The increased roughness is related to the polycrystalline nature of metals.

(b) Rough fracture surfaces perpendicular to the loading direction. This type of fracture occurs in tougher materials. The surface is much rougher and duller than those in (a) due to void formation in the more ductile materials. It occurs in relatively thick sections (Fig. 2, left) under *plane strain* conditions and is often known as *flat* fracture.

(c) Rough fracture surfaces at 45˚ to the loading direction. This also occurs in relatively tough materials and the degree of roughness is the same as in (b). It occurs in relatively thin sections (Fig.2, right) under *plane stress* conditions and is often known as *slant* fracture.

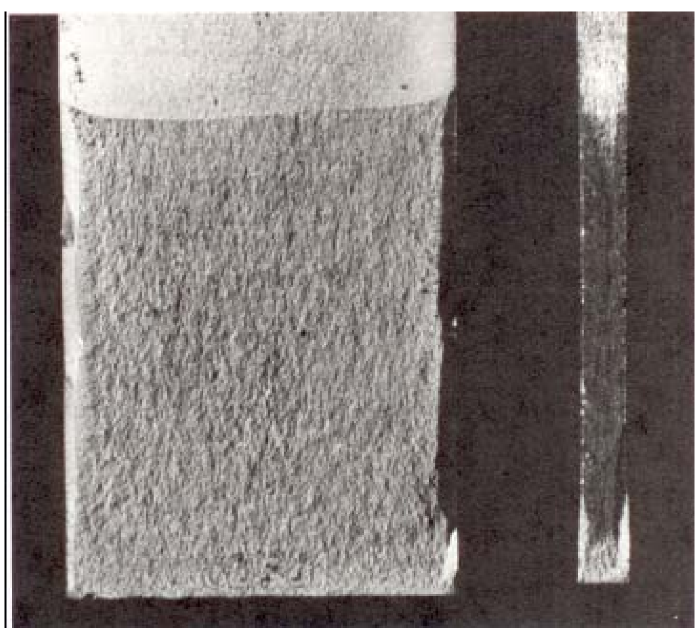

Fig. 2: Flat (left) and slant (right) fracture surfaces.

In both (b) and (c) above you can obtain chevron markings that point back to the origin of the fracture (Fig. 3).

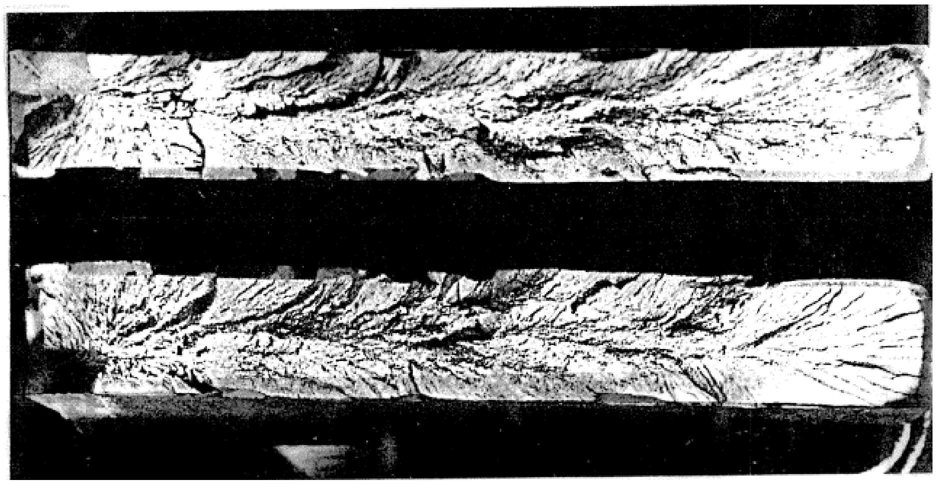

Fig. 3. Chevron Markings: crack growth direction is from left to right.

Microscopy

Further information can be gained by microscopic observation using optical or electron microscopes. The advantages and disadvantages of each technique are tabulated below. The resolution of optical microscopes is limited by the wavelength of light and the depth of view is quite small. This makes it hard to resolve the peaks and the valleys of a fracture surface at the same time unless you section a fractured component, polish it and view the fracture surface in profile. Electron microscopes use electrons to probe the surface and so their resolution is much higher. Transmission electron microscopy (TEM) involves the fabrication of replicas of the fracture surface which are so thin that electrons can pass through the replica onto a sensor on the other side. Surface roughness features deflect the electron beams and produce regions of brightness (concentration of electrons) and darkness (scarcity of electrons) that produce an image of the fracture surface. Because TEM has the highest resolution, fractographs obtained from it have very sharp, well defined features. Valleys become peaks and vice versa on account of the replicas which are relatively time consuming to fabricate. This led to the development of the scanning electron microscope (SEM) which does not require replication of the fracture surface. Instead, a single electron beam is scanned or rastered back and forth over the fracture surface. Secondary electrons are backscattered off the surface and strike a sensor which is being rastered at the same frequency as the input beam. This has the effect of "freezing" a picture in much the same way as a strobe light can be used to produce a still picture of a vibrating object. The only preparation required is to coat any nonconducting fracture surfaces with a very thin (2 nm) layer of gold or paladium. Some resolution and depth of view are lost compared to TEM but stereo pairs of pictures can be obtained by rotating the stage by 6˚. When these are viewed with special glasses, you can obtain a feeling for the three-dimensionality of the fracture surface.

TABLE 1. Comparison of Microscopic Techniques

Microscopy	Resolution	Depth of Field	Direct Observation
Optical	500 nm	1 µm	yes/no
TEM	0.15 nm	200 µm	no
SEM	5 nm	100 µm	yes

Microscopic Features

The magnification provided by the electron microscopes allows a number of features to be observed which are characteristic of different fracture mechanisms. These features and their formation will now be described in detail.

<u>Transgranular (Cleavage) Fracture</u>

This is a brittle form of fracture that occurs due to direct breakage of atomic bonds. In metals, it occurs across the weakest crystal planes and is therefore very flat (Fig. 4) within each crystal (grain) and because each grain is oriented differently produces the multifaceted, shiny macroscopic feature. Within each crystal, the fracture may occur on several parallel cleavage planes which are offset from one another. The planes are joined by atomic sized “cliffs” which appear as lines on the fractographs. These lines produce a pattern known as *river lines* (see Fig. 4c) where tributaries appear to flow into a main river. The direction of the river flow is also the direction of crack growth, which is very useful for tracking back to the origin of the crack growth. This brittle type of crack growth occurs at low temperatures, high strain rates, or because of improper heat treatment, all of which inhibit plastic deformation.

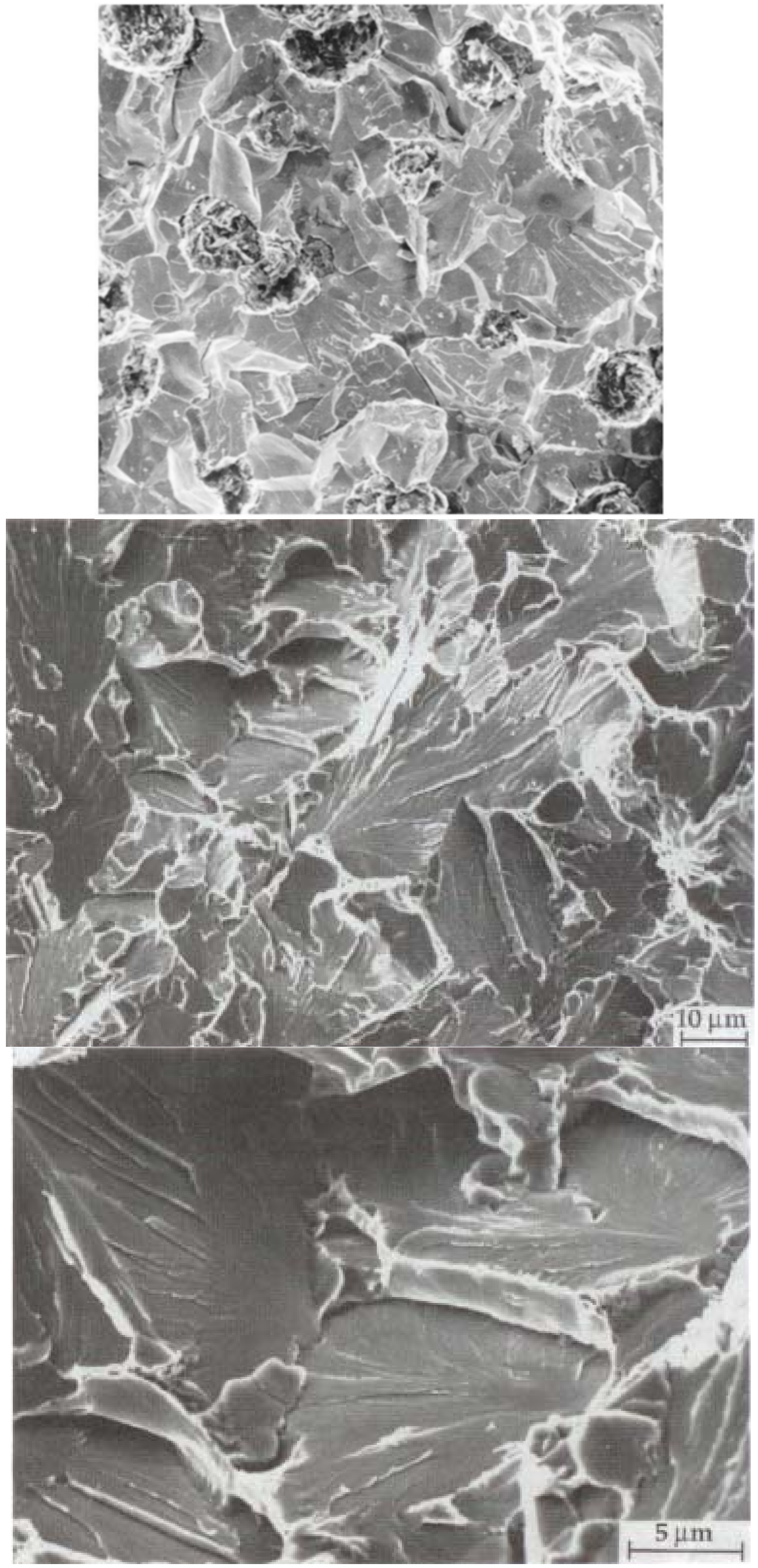

Fig. 4 Cleavage Fracture and River Lines.

Intergranular Fracture

This is another brittle form of fracture. However, in this case, cracks grow along the grain boundaries (Fig.5) rather than straight across the grain, leaving the fracture surfaces with three-dimensional grain structures. This is because the grain boundary has been weakened by improper heat treatments, diffusing fluids or gases or neutron radiation. Hydrogen embrittlement is an excellent example of this process.

Fig. 5 Intergranular Fracture

Void Formation or Dimple Fracture

This mechanism is characteristic of tougher materials where some degree of plastic deformation accompanies the growth of the crack. As we have seen, plastic deformation involves the movement of dislocations, which, in cracked components, emanate from the crack tip. The dislocations are often blocked by hard second phase particles and pile up around them. Eventually, enough stress is produced to cause debonding of the surrounding matrix material from the second phase particles and voids appear. The voids grow and coalesce as more dislocations empty out into them. The voids appear as craters on the fracture surface and give rise to the rougher surfaces (b) and (c) of the macroscopic features. The shapes of the voids or dimples (Fig. 6) give us information regarding the stress state and, in one case, the direction of crack growth.

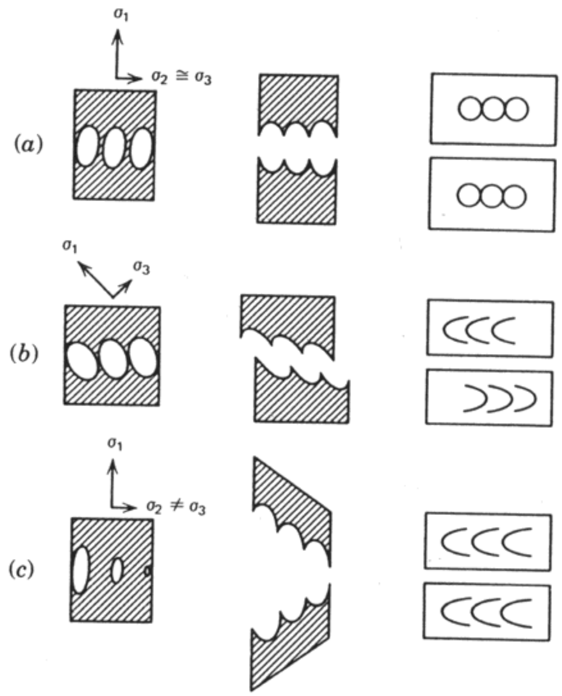

Fig. 6 Schematic of Different Types of Dimples.

(a) Equiaxed dimples – circular features due to a predominance of normal stresses.

(b) Shear dimples – parabolic features due to a predominance of shear stress. The parabolic features on each fracture surface point in opposite directions.

(c) Tear dimples – parabolic features due to tearing stresses. The parabolic features on each fracture surface point back to the origin of crack growth.

Example fractographs of equiaxed and shear dimples are shown in Figure 7.

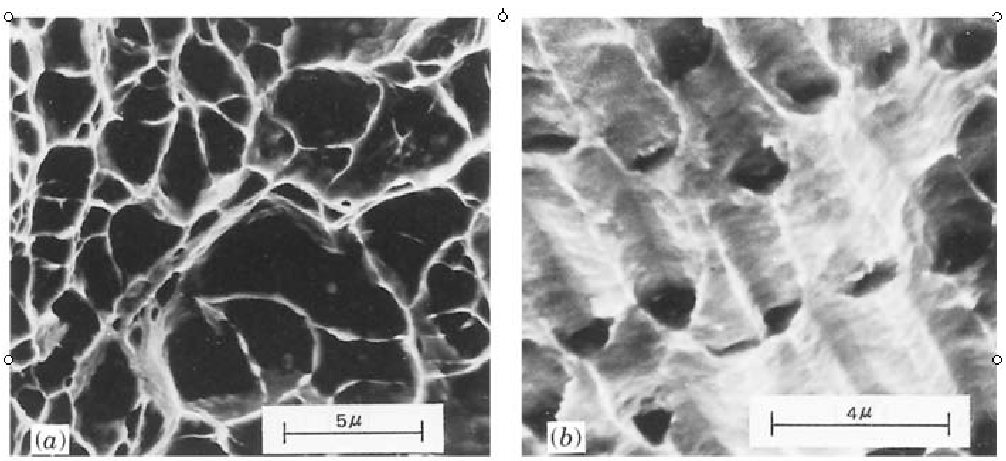

Fig. 7 (a) Equiaxed and (b) Shear Dimples

Striations

Striations are a series of regularly-spaced ridges on the fracture surfaces. They mark the location of the crack front at successive cycles in fatigue or cyclic loading (Fig. 8). The ridges are caused by plastic deformation around the crack front (see Fig. 9). The striations are convex in the direction of crack growth and can therefore be used to track the origin of the failure. Groups of striations whose spacings differ from one another form beach marks (Fig. 10). Each beach marking reflects different load amplitudes or environmental conditions that arose during the time that the crack was growing.

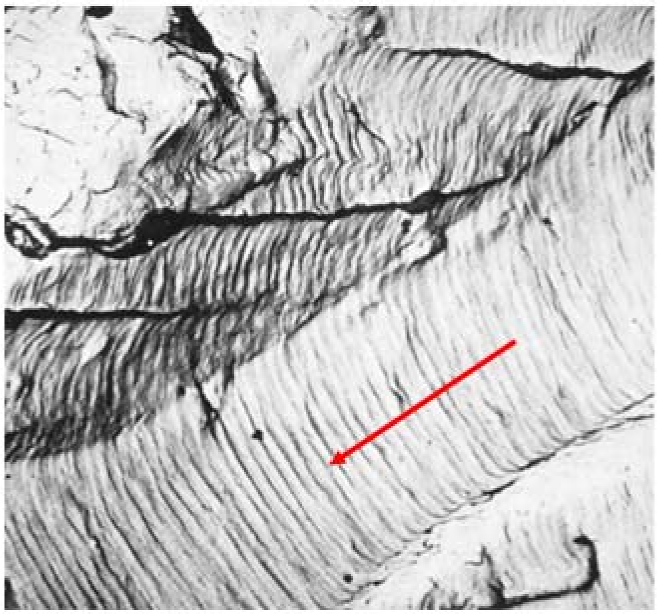

Fig. 8: Transmission electron fractograph showing fatigue striations in an aluminum component.

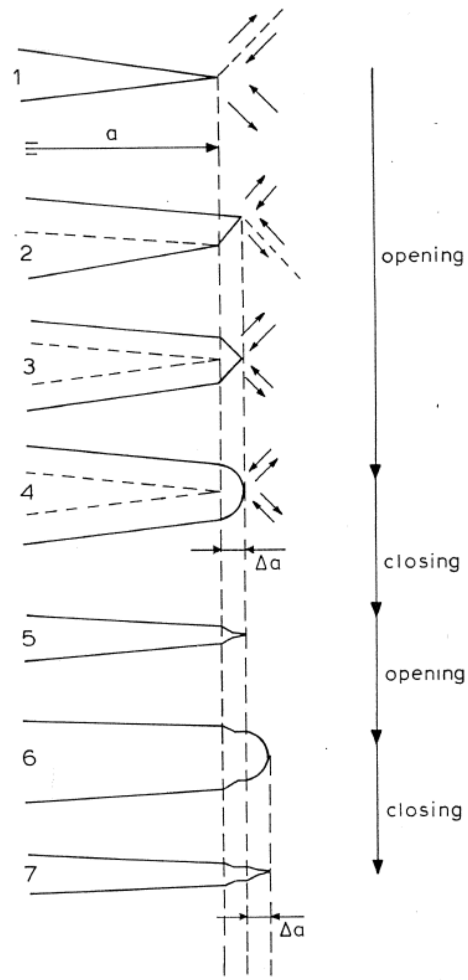

Fig. 9 Formation of Striations.

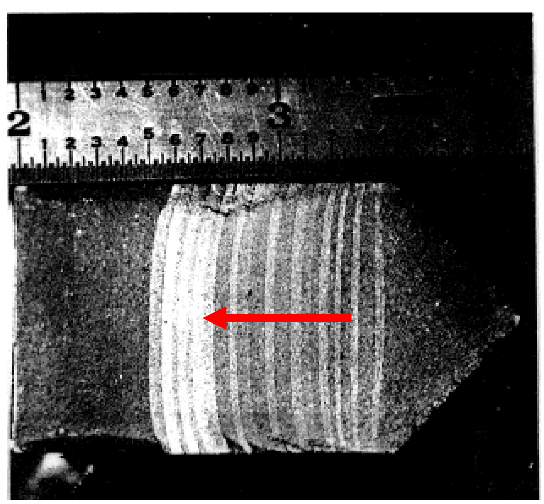

Fig. 10 Beach Marks Due to Blocks of Constant Amplitude Fatigue Loading of Various Magnitudes. Crack Propagating from Right to Left.

Fracture Toughness Testing

Fracture toughness tests are used to determine a material's resistance to fast fracture. For any cracked component, the stress normal to the plane of the crack is

$$\sigma_y = \frac{K}{\sqrt{2\pi r}} \cos\theta/2\,[1 + \sin\ \theta/2\ \cos\ 3\theta/2] \tag{1}$$

where K is the stress intensity factor and (r, θ) are polar coordinates centered on the crack tip (Fig. 11).

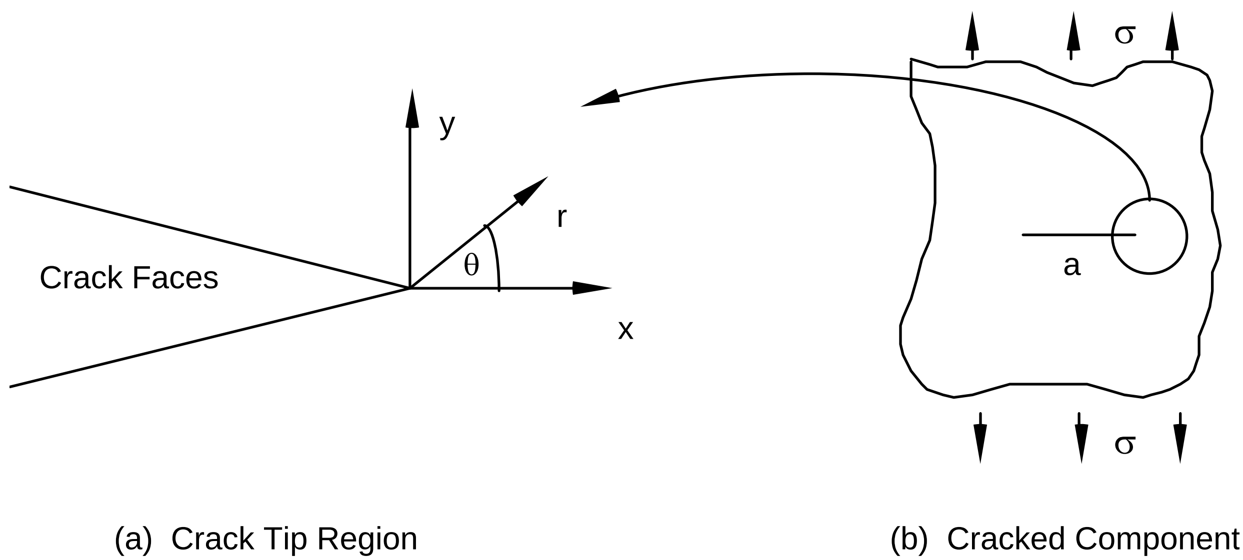

Fig. 11: Crack Geometry

The inverse square root of r and the θ dependence is the same for all cracks. The stress intensity factor K is what characterizes the severity of one cracked configuration against another. It depends on the loading and the geometry, often represented by σ and a, i.e., the applied stress level and crack length, respectively. As stress levels are increased, the stress intensity factor increases until it reaches a critical value, K_C, at which the crack starts to grow. This is known as the ***fracture toughness*** of the material. This material property is then added to the list of material properties (Young's Modulus, Poisson's ratio, yield strength, etc.) that are used to check the suitability of a material for a particular design. The design equation for a cracked component then becomes

$$K(\sigma, a) = K_C \tag{2}$$

where $K(\sigma, a)$ is determined from a stress analysis of the cracked component. There are several handbooks that give $K(\sigma, a)$ for various standard configurations. If a particular case is not in a handbook, then finite element stress analyses can be conducted. Equation (2) is used to set allowable stress levels for a given crack length (such as the smallest resolvable crack by nondestructive evaluation, NDE). Alternatively, if stress levels are fixed, equation (2) can be used to determine how large a crack can grow in a subcritical fashion (by fatigue, stress corrosion cracking, etc.) before it transitions to fast fracture.

Procedure: Fracture toughness tests will be conducted on 2024–T3 Aluminum specimens of various thicknesses (0.5, 0.25 and 0.125 in), each having a different crack length. The compact tension specimens (Fig. 12) are subjected to ramp displacement loading at 10^{-3} in/s. The initial crack in each specimen was produced by cyclic (fatigue) loading to produce a sharp, natural crack. The reactive load, P, is measured along with the applied displacement, Δ. A schematic of the anticipated response is shown in Fig. 13 where crack initiation occurred at $P_{\max}$. The stress intensity factor, K, for the compact tension specimen is given by

$$K = \frac{P}{bW^{1/2}}\left[29.6x^{1/2} - 185.5x^{3/2} + 655.7x^{5/2} - 1017x^{7/2} + 639x^{9/2}\right] \qquad (3)$$

$$\text{for} \quad 0.45 \le x \le 0.55$$

or

$$K = \frac{P}{bW^{1/2}}\, f(x), \quad \text{where } x = \frac{a}{W}.$$

The fracture toughness, K_C, of the material is determined from the maximum load in the load displacement curve and equation (3). That is

$$K_C = \frac{P_{\max}}{bW^{1/2}}\, f(x). \qquad (4)$$

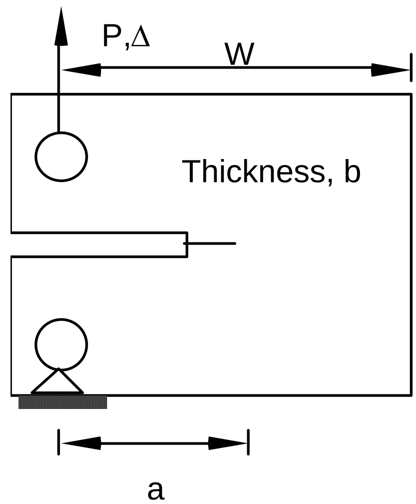

Fig. 12: Compact Tension Specimen (W=2", b=0.5", 0.25", 0.125")

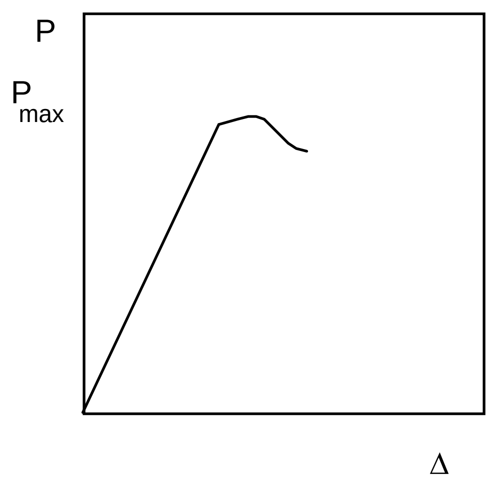

Fig. 13: Schematic of the specimen response in a fracture toughness test.

Although we would like to think of fracture toughness as a material property that is constant and independent of geometry, it turns out that it depends on the thickness, *b*, of the test specimen (Fig. 2).

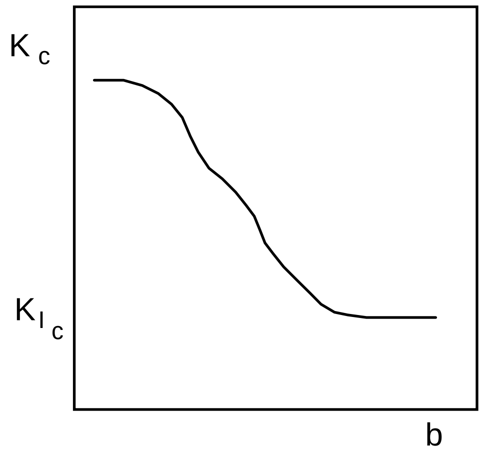

Fig. 14: Schematic illustration of the variation of measured fracture toughness with specimen thickness.

For specimens with large thicknesses, the fracture toughness approaches a constant value known as the plane-strain fracture toughness, K_{IC}. The increase in toughness with decreasing thickness is due to increase of the relative sizes of the plastic zone ahead of the crack. From equation (1), it can be estimated that the plastic zone size is

$$r_p = \frac{1}{2\pi}\left(\frac{K}{\sigma_{ys}}\right)^2 \tag{5}$$

where σ_{ys} is the yield strength of the material. When $r_p << b$ (the specimen thickness is much greater than the plastic zone size), plane strain condition (flat fracture) applies and relatively little plastic energy is dissipated. On the other hand, for $r_p >> b$, plane stress (slant fracture) prevails and the amount of plastic dissipation is greater, giving rise to a larger toughness. There is an ASTM specification that

$$a, b \geq 2.5\left(\frac{K_c}{\sigma_{ys}}\right)^2 \tag{6}$$

for a valid plane strain test, in which case the K_C determined in the test is indeed the plane strain fracture toughness K_{IC}.

Further Reading: Chapter 8 in *Materials: Engineering, Science, Processing and Design*.

Assignment:

For each specimen thickness, fracture toughness tests will be conducted on four specimens, each having different initial crack lengths. Prepare a formal lab report that describes the test procedures and incorporates answers to the following questions.

1. Calculate the values of K_C as a function of crack length, a.
2. Plot the values of K_C as a function of crack length, a.
3. Determine the average toughness for the each specimen thickness using data from other sessions when necessary. Plot toughness as a function of specimen thickness.
4. If the yield strength of the aluminum is 57 ksi, determine whether or not K_C for any of the thicknesses can be used as the plane strain fracture toughness, K_{IC}.
5. From an examination of the fracture surfaces, distinguish between plane strain and plane stress fracture modes. Explain why the fracture plane followed a 45˚ plane near the specimen edges.
6. From each experiment, plot load *vs.* displacement and determine the compliance ($C = \Delta / P$) from the linear portion of the response. Then plot the compliance values obtained for each specimen thickness as a function of the initial crack length (using data from other sessions if necessary). Make some observations about the trend in the data.
7. A set of fractographs will be observed in the lab. In a separate section of your lab report, describe the features in the fractographs and possible fracture mechanisms.