6. Fracture Mechanics & Impact (from ME330)

7.1 Objective

Fracture mechanics deals with the most severe notch, a crack. This laboratory will also illustrate the temperature sensitivity of steels to high rate impact loading, and illustrate temperature and rate effects for polymeric materials. Stress concentrators or high loading rate can change the failure mode from that observed in previous tensile, compressive, bending and torsion tests. An appreciation of two new material properties, fracture toughness and impact energy should be gained.

7.2 Background

7.2.1 Theoretical considerations

Comments made in our discussion of notches in laboratory 4 are applicable here as well. Griffith[1] conducted experiments on the strength of glass and the effects of defects. Two energy terms, the linear elastic strain energy, V_E, and the energy required to create new surfaces, V_S, are utilized in his formulation.

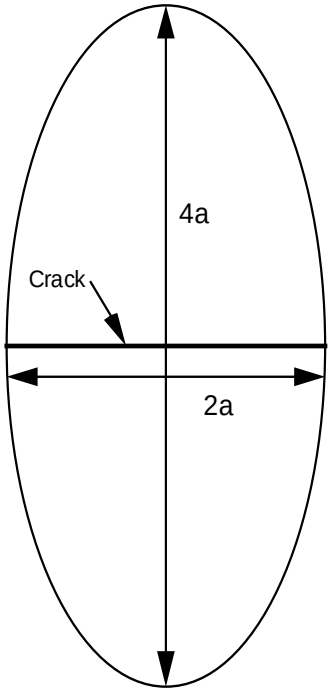

Figure 1 Griffith's crack model

[1] Griffith, A.A., Transactions of the Royal Society of London, Vol. 221, 1920.

At a free surface, most atoms are not optimally bonded; therefore they are at a higher energy state than their counterparts on the interior of the material. From physics we obtain the constant, γ_s , which is the energy per unit area required to create new surfaces. If a center crack of length 2a in a plate with thickness, t, is considered (Fig. 1), then an energy value can be assigned to the creation of the two new surfaces:

$$V_s = 2\gamma_s(2at) \qquad (1)$$

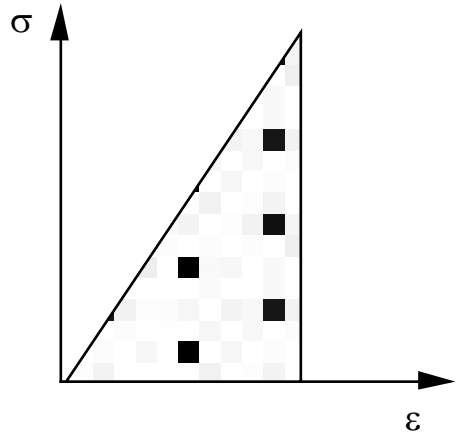

Figure 2 Linear elastic strain energy

As shown in Fig. 2, the linear elastic strain energy is equal to the area under the stress-strain curve. In terms of per unit volume, this can be expressed as follows:

$$\frac{V_E}{Unit\ Volume} = -\frac{1}{2}\sigma\varepsilon = -\left(\frac{\sigma^2}{2E}\right) \qquad (2)$$

If an elliptical region of elastic strain energy shown in Figure 1 is assumed, then the elastic strain energy due to the presence of the crack can be represented in the following format:

$$V_E = -\left(\frac{\sigma^2}{2E}\right)2\pi a^2 t \qquad (3)$$

The minus sign in Equation 3 indicates that the body loses energy due to the release of elastic energy, while the surface energy is positive, since the body needs an input of energy to create new surfaces.

It is now possible to formulate a total energy relation:

$$V_T = V_E + V_s = -\left(\frac{\sigma^2}{E}\right)\pi a^2 t + 2\gamma_s(2at) \quad (4)$$

These terms are plotted in Fig. 3. The partial derivative with respect to crack length will allow examination of the energy changes due to an increment of crack growth:

$$\frac{\partial V_T}{\partial a} = -\left(\frac{2\pi a\ t\sigma^2}{2E}\right) + 4\gamma_s t \quad (5)$$

When the partial derivative is zero, a critical crack length, a_{crit}, has been achieved. All mathematics aside, the basic premise here is that if more energy is required to create new surfaces than will be released in the form of elastic strain energy, the crack will not grow!

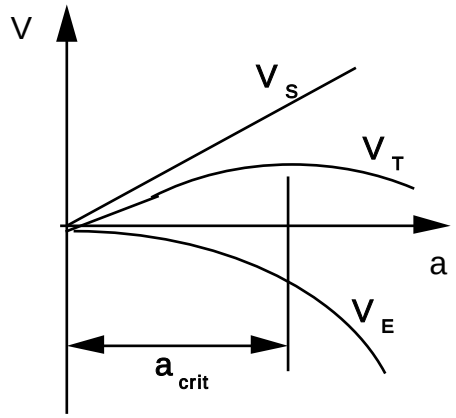

Figure 3 Griffith energy terms

As the load on a specimen increases, the elastic energy increases, but the energy to create new surfaces is assumed to be constant. Solving Equation. 5 to formulate a critical stress in terms of crack size, the following results are obtained for plane stress,

$$\sigma_{crit} = \sqrt{\frac{2E\gamma_S}{\pi a}} \quad (6)$$

and for plane strain:

$$\sigma_{crit} = \sqrt{\frac{2E\gamma_S}{\pi a(1-\nu^2)}} \quad (7)$$

These equations may also be solved for a critical crack size at a given stress level. It is important to note the following relation between stress and crack size:

$$\sigma_{crit} \propto \frac{1}{\sqrt{\pi a}} \quad (9)$$

Twenty years after Griffith reported his experiments, Westergard[2] obtained the linear elastic stress-strain field ahead of the crack. An infinite plate with a center crack of dimension 2a was considered. Plane strain ($\varepsilon_z = 0$) is assumed to derive the following solution using the coordinate system shown in Fig. 4, with z being the through thickness direction.

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} Cos\frac{\theta}{2}\left[1 - Sin\frac{\theta}{2} Sin\frac{3\theta}{2}\right] \quad (10)$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} Cos\frac{\theta}{2}\left[1 + Sin\frac{\theta}{2} Sin\frac{3\theta}{2}\right] \quad (11)$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} Sin\frac{\theta}{2} Cos\frac{\theta}{2} Cos\frac{3\theta}{2} \quad (12)$$

$$\sigma_z = \nu\left(\sigma_x + \sigma_y\right) \quad (13)$$

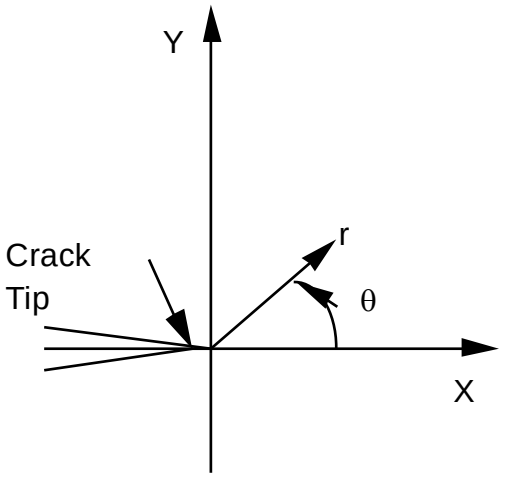

Figure 4 Westergard's coordinate system

All stress, displacements and strains surrounding the crack tip are dependent on a single constant, the stress intensity factor, K_I. The quantity K_I was determined to have the following form:

$$K_I = \sigma_{nom}\sqrt{\pi a} \quad (14)$$

where σ_n is the nominal (remote) stress in the y direction. This relationship between crack size and stress is similar to that obtained by Griffith.

[2] Westergard, H.M., Journal of Applied Mechanics, Trans ASME, Vol. 61, p. 49, 1939.

7.2.2 ASTM K_I testing methods

The solution for the infinite plate renders considerable insight into the nature of cracks. A common ASTM E-399[3] fracture mechanics test specimen is shown in Fig. 5. Of interest here is the determination of a material property, K_{IC}, which is essentially based on Equation. 17. For a finite width specimen, geometric corrections have to be made. The stress intensity factor for the compact tension specimen has the following format:

$$K_I = \frac{P}{t\sqrt{W}} f\left(\frac{a}{W}\right) \qquad (15)$$

where f(a/W) is a geometric correction factor. The ASTM approved empirical correction factor for this geometry is,

$$f\left(\frac{a}{W}\right) = \left(\frac{2+\left(\frac{a}{W}\right)}{\sqrt{\left(1-\left(\frac{a}{W}\right)\right)^3}}\right) \left(0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.6\left(\frac{a}{W}\right)^4\right) \qquad (16)$$

There are many other K_I solutions available for a wide variety of geometries.[4,5,6]. Only K_I solutions have been discussed. It is important to consider that, for some applications, K_{II} and K_{III} solutions will be essential. These are also contained in the previously noted references.

In order to insure that machining differences do not affect the results (i.e. that the notch is sharp), all specimens are fatigue pre-cracked prior to testing. Pre-cracking should result in a crack dimension within the range $0.45 < (a/W) < 0.55$. The zero to maximum cycling will be conducted at a maximum load of $P_{pre\text{-}crack}$.

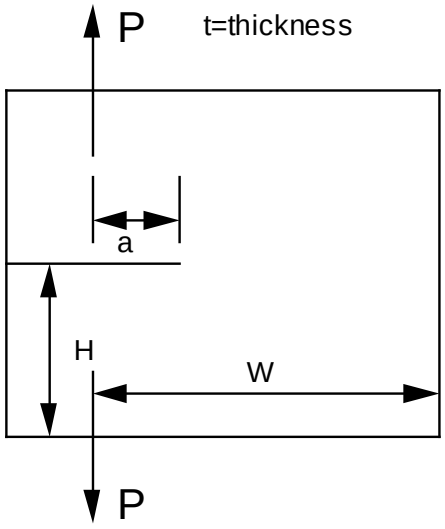

Figure 5 ASTM compact tension specimen

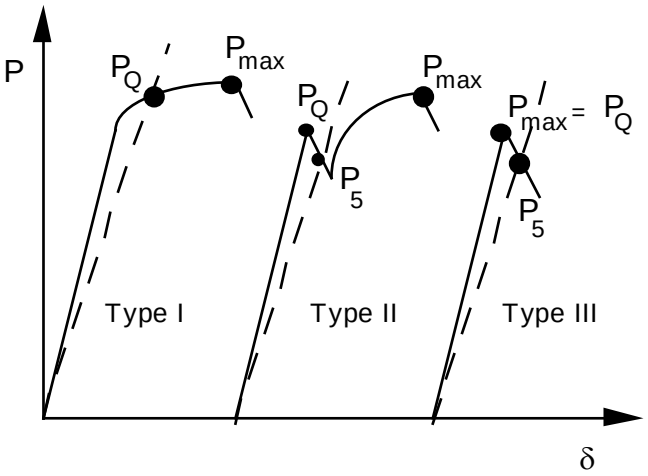

Figure 6 Typical load-displacement curves

When a test is conducted on a compact tension specimen, it is customary to measure the load and the displacement of the crack at the edge of the specimen. The three types of load displacement curves that result are shown in Fig. 6. Also shown are dashed lines that have a slope of 95% of the initial load deflection curve. To some degree this technique is analogous to the 0.2% offset yield strength methodology in that it eliminates the ambiguity with the intersection of the load-displacement curve. Ideally, a critical stress would be achieved and failure would occur (Type III). This is not always the case. Often a bend over in the curve that indicates plastic

[3] ASTM Annual Book of Standards, American Society for Testing and Materials, Philadelphia, PA.

[4] Rooke, D.P., and Cartwright, D.J., A Compendium of Stress Intensity Factors, Hillington Press, UK, 1982.

[5] Tada, H., Paris, P., and Irwin, G., The Stress Analysis of Cracks, Del Research Corporation, Hallerton, PA, 1985.

[6] Peterson, R.E., Stress Concentration Factors, John Willey and Sons, NY, 1977.

deformation is noted experimentally. Type I behavior indicates that there was plastic deformation at the crack tip, but the size remained essentially constant. The drop off and reloading evidenced for Type II indicates that the crack increased in size, self arrested, then failed after further loading. It is for these tests that the 95% slopes are required. Two quantities, P_5 and P_{max}, are defined. P_5 corresponds to the intersection of the load-deflection curve and the 95% slope. P_{max} is the maximum load achieved during the test. These two quantities will later form part of a criterion to ascertain the validity of the test.

Bend over in the load displacement curve indicates plastic deformation. A simple estimate of the plastic zone size ahead of the crack is obtained by setting Equation. 11 equal to the yield strength at $\theta = 0$ and solving for $r=r_y$, resulting in the following estimate for plane stress:

$$r_p = \frac{1}{2\pi}\left(\frac{K}{\sigma_{ys}}\right)^2 \qquad (17)$$

and for plane strain:

$$r_p = \frac{1}{6\pi}\left(\frac{K}{\sigma_{ys}}\right)^2 \qquad (18)$$

The notation σ_{ys} for the yield strength is employed in Equations. 17 and 18 to avoid confusion with the y direction stress.

The solution used in ASTM E-399 is a linear elastic formulation. If no plastic deformation were allowed, many metals could not be assigned a fracture toughness, K_{IC}. Therefore, when an experimental K_Q is assigned by,

$$K_Q = \frac{P}{t\sqrt{W}}\, f\left(\frac{a}{W}\right) \qquad (19)$$

the following four criteria must be satisfied:

i) $$P_{precrack} < 0.6\, P_Q \qquad (20)$$

ii) $$P_{max} < 1.1\, P_Q \qquad (21)$$

iii) $$a_o, W-a, t > 2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2 \approx 50\, r_p \qquad (22)$$

iv) $$0.45 \le \left(\frac{a_o}{W}\right) \le 0.55 \qquad (23)$$

If these conditions are satisfied, then:

$$K_{IC} = K_Q \qquad (24)$$

Condition i) insures that the fatigue plastic zone, which differs from the static zone, does not influence the results. Excessive strain hardening at the crack tip is not expected if condition ii) is satisfied. Equation 22 resembles the plastic zone size estimate and assures that specimen dimensions are large in comparison to this approximation. Finally, condition iv) makes sure the geometric correction factor is valid. Additionally, the crack front must not be closer than 1.3 mm to the machined notch, and the curvature of the crack must not cause more than a 15% variation in initial crack measurements which are averaged to estimate an initial crack length. If these conditions cannot be met, a nonlinear approach such as the J-integral (ASTM E-813) may be employed. Discussion of this topic is beyond the scope of this laboratory. But as a practical aside, it seems those materials that don't qualify in K_I testing probably have a fracture toughness that does not limit their use in the design of a component or structure.

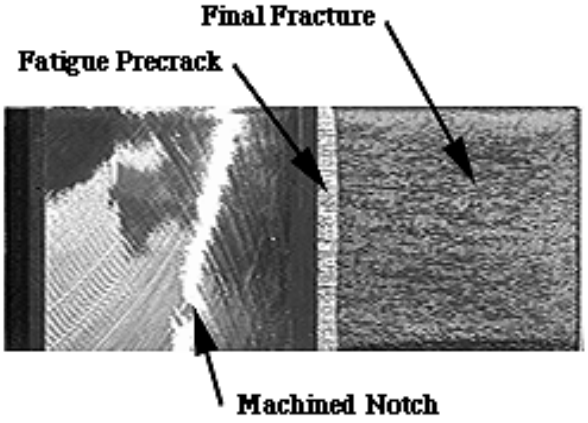

Figure 7a, Fracture surface of a 7075-T6 Aluminum displaying flat fracture surface

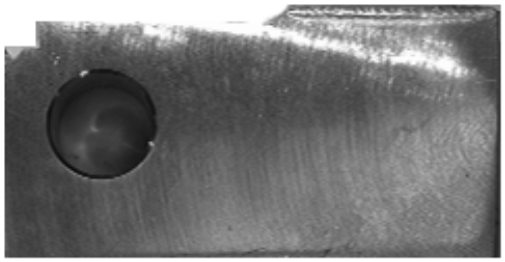

Figure 7b, Side view of specimen in Fig. 7a

Examination of the fracture surface can also render insight into the validity of the test. A flat fracture surface (Figs. 7a, b, c) where the fatigue pre-crack is a distinct region is probably a valid

test. Alternately, extensive shear lips (Figs. 8a,b, c)are evidence of shear or plasticity dominated failure. It should be noted that K_{IC} is formatted as a principal stress type failure criterion, therefore the failure observed in a valid test should be a decohesion or tensile type for a valid test.

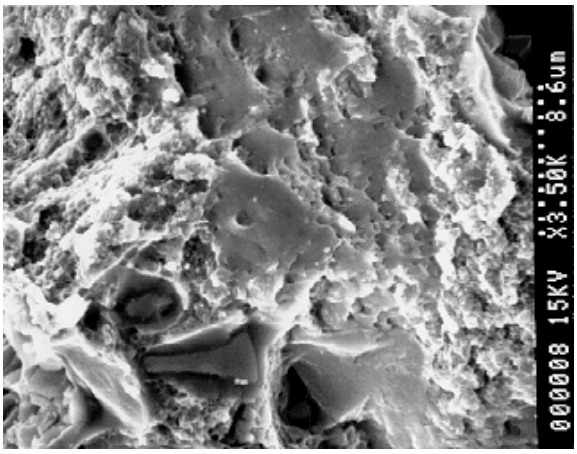

Figure 7c, SEM of 7075-T6 fracture surface.

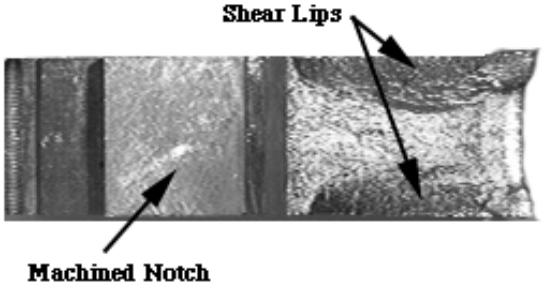

Figure 8a, Fracture surface of a 6061 Aluminum displaying extensive shear lips

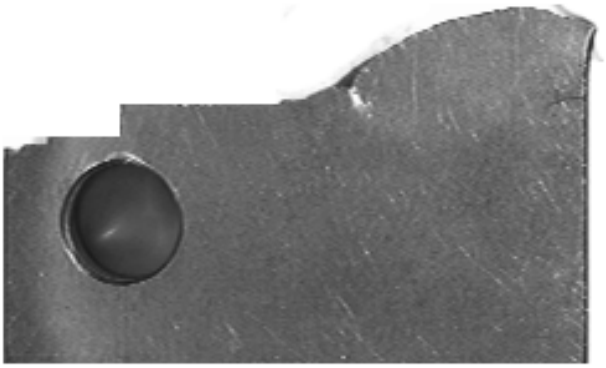

Figure 8b, Side view of specimen in Fig. 8a

The compact tension specimen testing is conducted at slower loading rates. Another approach to ascertaining the susceptibility of a material to cracks and flaws is Charpy impact testing. Two common methods are the pedulum and drop tests. In both tests, a mass is either attached to a swinging pendulum or dropped vertically to strike a notched specimen. For the pendulum test, the height that the pendulum achieves after striking the specimen is compared to the starting height. This difference in potential energy is interpreted as energy absorbed by the specimen. In the vertical drop apparatus utilized in this laboratory an instrumented load cell and the basic equations of motion will be used to analyze the energy absorbed by the specimen.

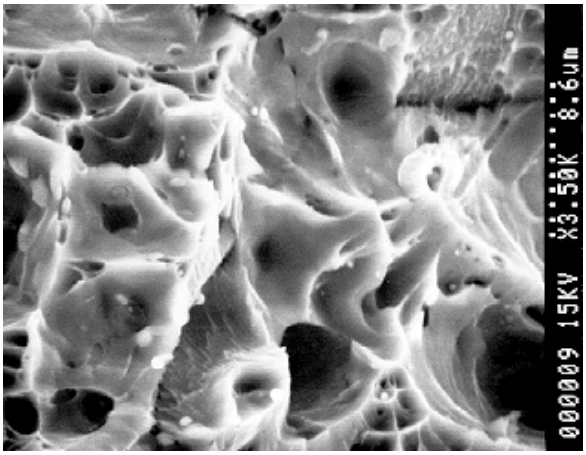

Figure 8c, SEM of 6061 shear lip fracture surface.

7.2.3 Impact and transition temperature testing

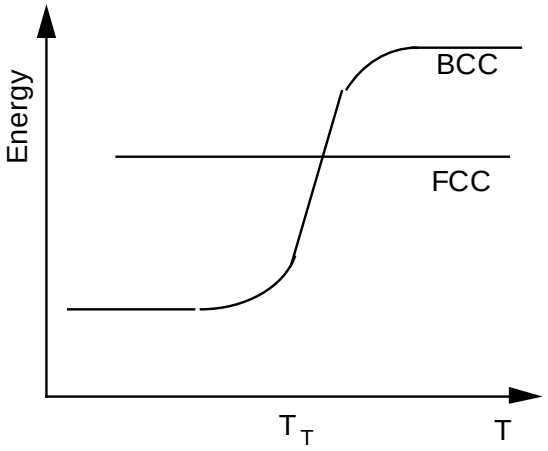

Figure 9, Charpy transition temperature

One significant feature noted for many steels (Body Centered Cubic crystallographic structure) is a transition temperature, T_T (Fig. 9). A significant difference in the energy absorbed, or toughness, is associated with this temperature. This phenomenon was responsible for the failure of Liberty ships in the North Atlantic produced during World War II; fracture tests conducted at room temperature did not reflect the metal's material properties in the colder environments.

Other materials, such as aluminum, chrome, copper, and nickel alloys, do not display a transition temperature (Fig. 9). They all have a Face Centered Cubic structure .

Several metallurgical factors affect the temperature and range of temperatures over which the transition occurs. While attempts have been made to integrate the results of impact testing into the methodology of the previous section, they are mostly empirical and very material dependent. Some researchers have concluded that this test is useless. While it doesn't render a reliable material property for design, it is an inexpensive test that can be utilized in a comparative manner to determine rate sensitivity and temperature dependence. This information can then be used when deciding the scope of more expensive K_{IC} testing needed to assure product safety. Further details on impact testing can be found in ASTM E-23[3].

Again, examination of the fracture surface can be useful. While the K_{IC} and Charpy tests have different rates of loading, a 6061-T6 aluminum alloy displays shear lips near the edges of the fracture surface (Fig. 10). In general for a given chemical composition, the greater the percentage of the fracture area that has shear lips, the greater the amount of energy absorbed.

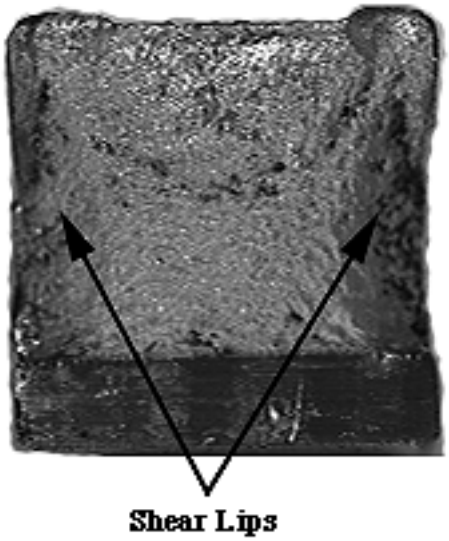

Figure 10, 6061-T6 Charpy Failure

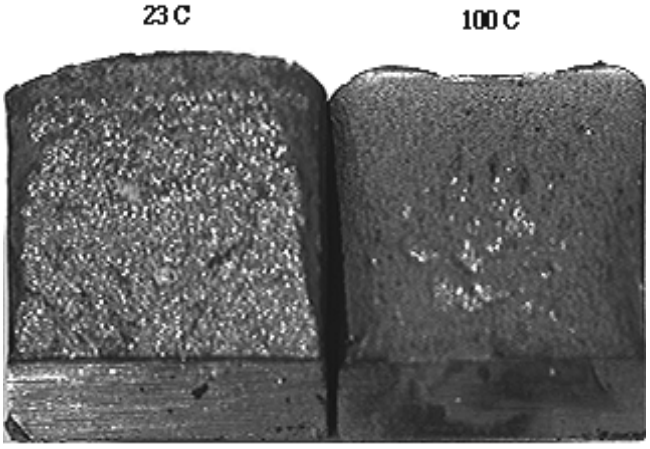

Figure 11, Charpy fracture surfaces, 1045 hot rolled steel at 23ºC and 100ºC

More subtle changes in the fracture surfaces of hot rolled 1045 steel are displayed in Figure 11. The higher temperature test was above the transition temperature and has a more mottled surface in comparison to the room temperature test where more sharply defined facets are indicative of a more "brittle" failure. It is cautioned that since the Charpy test is a high rate test, materials that are rate sensitive (as many steels are) may show different results and fracture behavior for K_{IC} testing and Charpy testing

Polymeric materials are being utilized for a broader range of applications than 20 years ago. Standard Charpy or Izod specimens can be utilized to analyze the notch sensitivity at higher loading rates. Many plastic products are produced in plate form and susceptibility to damage by impact of a projectile is considered to be of engineering importance. A 12.7 mm spherical indenter is specified by ASTM D-3029[3], which is employed with a vertical drop tester. Since the glass transition temperature, T_G , is often within the range of temperatures considered in this laboratory, a transition in energy absorbed will also be noted for these materials. However, the mechanism for the transition temperature observed for plastics is different than that responsible for similar behavior in steels.

7.2.4 ASTM Vertical Drop testing methods

The basic premise of the vertical drop test is to have a mass at a height with a given potential energy (typically referred to as *mgh*). When the mass is released and accelerated by gravity, the potential energy is converted into kinetic energy ($1/2\ mv^2$). At impact, some of the kinetic energy of the mass is absorbed by the specimen, which decelerates the mass. A load cell is attached to the mass to measure the force which the specimen exerts on the mass.

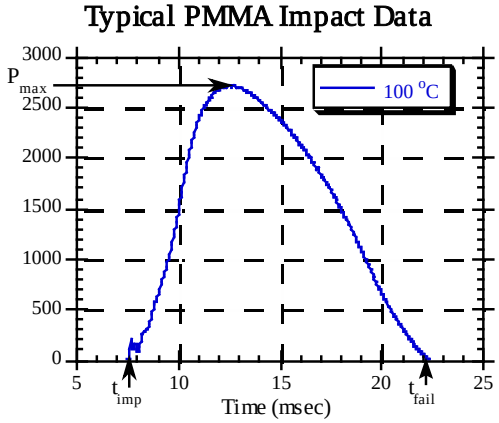

Figure 12, Typical load time impact data

One could measure the height of the mass and calculate a velocity at impact. This test is fast in comparison to others, requiring a short data interval and synchronization of data acquisition Since it is desirable to start data acquisition slightly before impact, a photo sensor is utilized to start data acquisition at the appropriate time. Closer examination of the photo sensor flag that is attached to the falling mass reveals a cut-out of a known dimension. The time that the flag blocks the beam can be measured If the flag velocity were constant, the formula

$$v = \left(\frac{width\ of\ \ flag}{time\ beam\ blocked} \right) \qquad (25)$$

would suffice. But the flag is accelerating as it passes through the beam, so the following formula will give an improved approximation of the flag velocity as it passes through the beam:

$$v_{measured} = \left(\frac{width\ of\ \ flag}{time\ beam\ blocked} \right) + \left(\frac{g[time\ beam\ blocked]}{2} \right) \qquad (26)$$

where g = acceleration of gravity, 9.81 meters/sec^2 and the flag width is 5.84 mm. Elapsed time from this velocity measurement before impact is utilized to calculate the additional acceleration that occurs up to the point of impact, resulting in the following formula.

$$v_{imp} = v_{measured} + g\,t_{imp} \qquad (27)$$

The time of impact is determined by viewing the load-time data (Fig. 12),

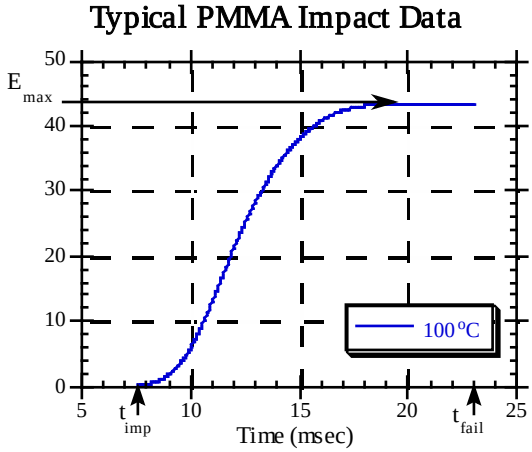

Figure 13, Typical impact test data

A final time corresponding to specimen failure (return to zero load) is also identified. It will be used in subsequent integration of the equations of motion.

The force, F(t), acting on the mass at any time is given by:

$$F(t) = mg - p(t) \qquad (28)$$

where w = weight of the mass dropped and p(t) is the value of load measured by the load cell at time t. In the original formula, w is replaced by mg, where m is the hammer mass, but the result is the same since m=w/g. Therefore, the acceleration or deceleration of the mass can be stated as a function of time by rewriting the familiar equation, F=ma as follows.

$$a(t) = \frac{F(t)}{m} = g - \frac{p(t)}{m} \qquad (29)$$

Velocity can be calculated by integrating over the time of interest.

$$v(t) = \int_{t_{imp}}^{t_{fail}} a(t)\ dt = \int_{t_{imp}}^{t_{fail}} \left(\frac{F(t)}{m} \right) dt = \int_{t_{imp}}^{t_{fail}} \left(g - \frac{p(t)}{m} \right) dt \qquad (30)$$

Another integration renders position of the mass as a function of time.

$$x(t) = \int_{t_{imp}}^{t_{fail}} v(t)\, dt \qquad (31)$$

With this basis and the assumption that the total energy of the mass/specimen system $U_T(t)$ is a constant, and is composed of the following components: (i) kinetic energy (U_k) of the mass at time t, (ii) potential energy (U_p) of the mass at time t, and (iii) the energy absorbed by the mass/specimen U_{spec} at time t.

$$U_{total}(t) = U_{specimen}(t) + U_{kinetic}(t) + U_{potential}(t) \quad (32)$$

The program utilizes the following equation to calculate energy absorbed by the specimen.

$$U_{specimen}(t) = \frac{m}{2}\left(v_{imp}^2 - [v(t)]^2\right) + mg[x(t)] \qquad (33)$$

It should be noted that at impact, the absorbed energy U_{spec} (t) is zero; the potential energy $U_p(t)$ is also zero; total energy $U_T(t)$ is equal to the kinetic energy $U_k(t)$ of the mass at the velocity, v_{imp},. After impact, mass velocity slows down, thus kinetic energy decreases, and absorbed energy rises.

7.3 Equipment and Materials

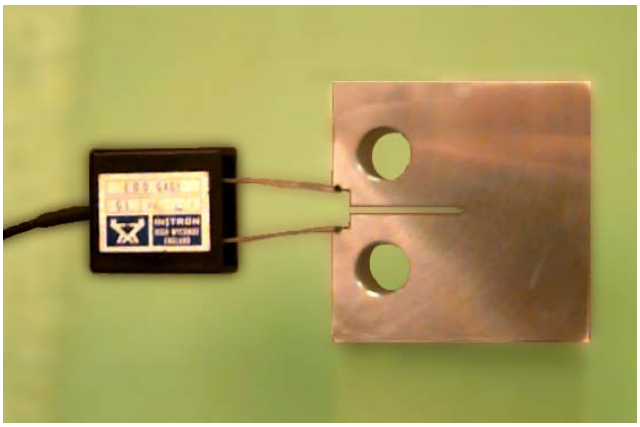

Figure 14, ASTM E399 specimen with COD gage

An aluminum (2024-T4, 6061-T6 or 7075-T6) or a normalized 1045 steel compact tension specimen will be tested to demonstrate K_{IC} testing. The 100 kN capacity servo-hydraulic test frame is used to apply cyclic axial loads to pre-crack the specimen. Swivel pin grips attach the specimen to the testing machine, and a COD (crack opening displacement) gage with l_o= 10 mm is employed to measure deformation (Fig. 14). A digital data acquisition system is used to record load and deformation data. The initial fatigue pre-cracking was performed prior to the laboratory. Approximate dimensions for the compact tension specimen are shown in Fig. 15.

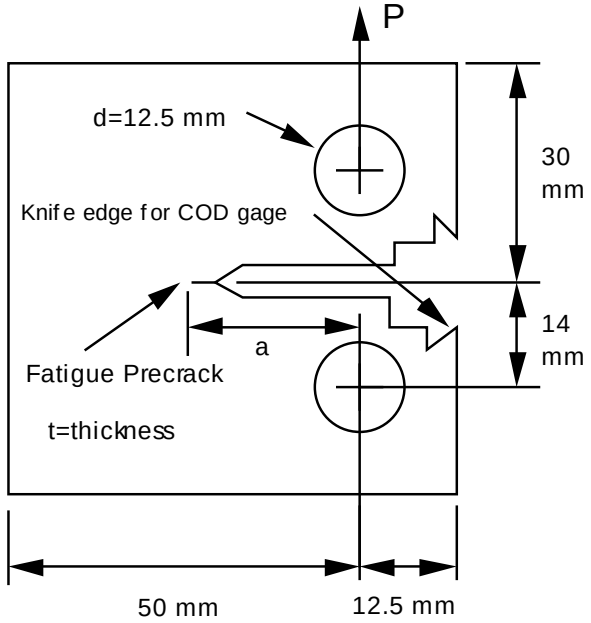

Figure 15 ASTM E-399 compact tension specimen

A standard Charpy specimen and a Dynatup instrumented impact testing machine (Fig. 16) will be used to conduct three impact tests on a steel and one of the aluminum alloys previously tested (either 2024-T4, 6061-T6 or 7075-T6). Temperatures of 0ºC (ice water), room temperature (read lab thermometer), and 100ºC (boiling water) will allow examination of the transition temperature phenomenon for steel. The specimens (Fig. 17) will have approximate dimensions: L = 55 mm, and W = D = 9.5mm. The notch will be about 1.5 mm deep (d_o), have an included angle of 45 degrees, and will have a notch root radius of approximately 0.25 mm. The spacing between specimen supports is 40 mm.

Square plate specimens (100 mm x 100 mm) will be employed for the toughness testing of plastic materials. The plate is clamped in a pneumatically activated fixture (it can pinch you fingers) with a circular diameter of 76 mm. A similar Dynatup vertical drop instrumented test apparatus will be utilized for the plastic tests. Specimen fixture, type of indenter, lack of a notch and lower mass to be dropped will be the only significant differences for these tests in

comparison to the metals impact tests. Again, temperatures of 0 ^{o}C (ice water), room temperature, and 100 ^{o}C (boiling water) will allow examination of the transition temperature.

Figure 16, Vertical drop impact test machine

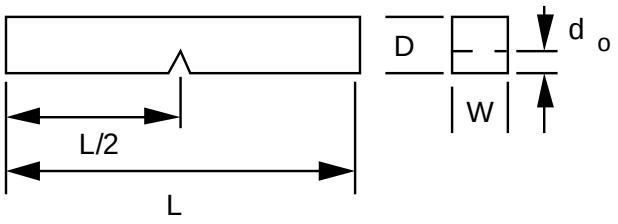

Figure 17, Charpy specimen

7.4 Experimental Procedure

7.4.1 Compact tension testing

1) Observe the fatigue pre-crack employing the traveling microscope and video monitor.

2) Mount specimen in test fixture and attach COD gage. ASTM E-399 suggests a loading rate such that dK_I/dt = 0.55 to 2.75 MPa$\sqrt{m}$ /sec, which corresponds to 20 to 100 kN/ sec for the specimen under consideration.

3) Load the specimen until failure occurs. Using the digital calipers, measure the specimen and crack dimensions. Use Table 1 to record these data. Then Sketch the fracture surface features.

7.4.2 Charpy & Plastic Plate impact testing

1) Using digital calipers measure the Charpy specimen length, height, width, and notch depth. Use the optical microscope to measure the notch radius. Record these and other data in Table 2. For the plastic specimens record the length, width and thickness data in Table 3. **Safety glasses are required.**

2) A LABVIEW operating system, similar to but not identical to the one used for the tensile machines, will be utilized to conduct these tests.

3) The Charpy tester is equipped with an automatic weight retrieval system. For the plastic test, manually raise the impacter / weight. Record the mass and drop height in the appropriate table.

4) Insert the appropriate specimen. It is best to do the room temperature test first to become acquainted with the procedure. Make sure the lower and higher temperature specimens have been held at temperature for at least five minutes.

5) Use tongs for cold or hot testing to prevent injury. For cold and hot testing, it is important that less than 5 seconds elapse between removal of the specimen from the bath and actual testing. Practice with the tongs at room temperature so you feel comfortable when conducting other temperatures.

5) *Caution: Flying objects are common to this test; stand clear. and close safety doors. The machine has safety interlocks and will not operate unless the doors are closed.* Release the weight with the fire button for either impact test and allow the LABVIEW program to collect the load-time data. Proceed to the next data screen.

6) Record the maximum load and set the integration limits (see Fig. 12) for the energy calculations (Eqs. 30 through 33). These will be used by the program to calculate impact velocity and energy absorbed. Proceed to the next screen.

7) Record the maximum energy absorbed in the appropriate table (Fig. 13). Use a marker to note the temperature tested on the specimen.

8) Examine and sketch the fracture/failure surfaces of all specimens.

9) Place a specimen with the notch "up" (wrong direction) and conduct a test at room temperature.

Table 1

Compact Tension Testing Data

Measurement or Property			**Material**		
Quantity	*Symbol*	*Units*			
Specimen and Fixture Dimensions					
Width	W				
Height	H				
Thickness	t				
Crack front to back edge measurements	Z_1				
	Z_2				
	Z_3				
Initial Crack Size, $(W-Z_i)$	a_i				
Gage Length	l_0				
Loading Rate	$d\delta/dt$				
Experimental Quantities					
Type of Load-deflection Curve	--	--			
Proportional Limit	P_Q				
Maximum Load	P_{max}				
Experimental Fracture Toughness	K_Q				
Material Properties					
Fracture Toughness	K_{IC}				

FILENAME for data					

Notes and sketches

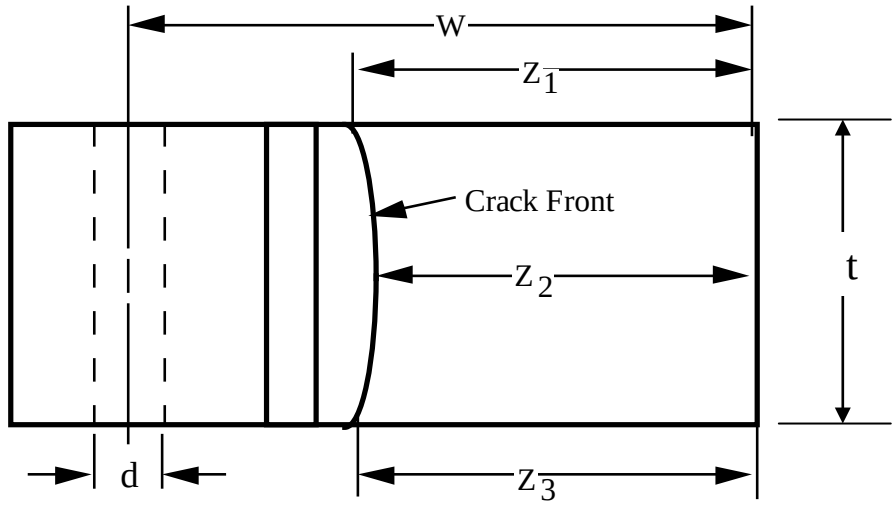

Table 2
Metal Charpy Impact Data

MATERIAL_____

Measurement or Property			**Temperature**		
Quantity	*Symbol*	*Units*	0 °C	°C	100 °C
Specimen and Fixture Dimensions					
Mass, drop weight and tup	m				
Drop Height	h				
Width	W				
Depth	D				
Length	L				
Notch Depth	d_o				
Notch Radius	r_o				
Experimental Quantities					
Maximum Load	P_{max}				
Time at impact	t_{imp}				
Time at Failure	t_{fail}				
Energy Absorbed	E_{max}				

MATERIAL_____

Measurement or Property			**Temperature**		
Quantity	*Symbol*	*Units*	0 °C	°C	100 °C
Specimen and Fixture Dimensions					
Mass, drop weight and tup	m				
Drop Height	h				
Width	W				
Depth	D				
Length	L				
Notch Depth	d_o				
Notch Radius	r_o				
Experimental Quantities					
Maximum Load	P_{max}				
Time at impact	t_{imp}				
Time at Failure	t_{fail}				
Energy Absorbed	E_{max}				

FILENAME for Charpy summary data: _____

FILENAMES for Charpy baseline data: _____

Table 3
Plastic Plate Impact Data

MATERIAL_____

Measurement or Property			**Temperature**		
Quantity	*Symbol*	*Units*	0 °C	°C	100 °C
Specimen and Fixture Dimensions					
Mass, drop weight and tup	m				
Drop Height	h				
Width	W_1				
Width	W_2				
Thickness	t				
Experimental Quantities					
Maximum Load	P_{max}				
Time at impact	t_{imp}				
Time at Failure	t_{fail}				
Max Energy Absorbed	E_{max}				

MATERIAL_____

Measurement or Property			**Temperature**		
Quantity	*Symbol*	*Units*	0 °C	°C	100 °C
Specimen and Fixture Dimensions					
Mass, drop weight and tup	m				
Drop Height	h				
Width	W_1				
Width	W_2				
Thickness	t				
Experimental Quantities					
Maximum Load	P_{max}				
Time at impact	t_{imp}				
Time at Failure	t_{fail}				
Max Energy Absorbed	E_{max}				

FILENAME for polymer summary data: _____

FILENAMES for polymer baseline data: _____