SIZE CRITERIA IN THE TESTING OF POLYMERS

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A review of procedures for the fracture testing of polymers is given. It is demonstrated that the LEFM criteria for both thickness and width as prescribed by ASTM are adequate for polymers. Some discussion is also given of notch tip sharpness effects and on the use of J methods of testing.

INTRODUCTION

Polymers are now widely used in serious load bearing applications where the consequences of a fracture can be serious. Probably the largest of such areas, at least in material volume, is the use of plastics in gas and water pipes. In both cases installation costs are high and failures can have very dangerous results. Slow crack growth in gas pipes, for example, can lead to leakage and the consequent risk of explosions while in both gas and water pipe accidental impact could trigger high speed axial cracking with disastrous effect. With all this in mind, therefore, it is desirable to have an accurate method for assessing the toughness of polymers under appropriate conditions and fracture mechanics, via $G_C$, $K_C$ and $J_C$, provides such methods.

In some cases polymers are used when they are somewhat prone to brittle cracking, a typical case is when they are used in glazing applications where the transparency is the overriding factor and frequently the test methods of LEFM (Linear Elastic Fracture Mechanics) are sufficient; for example when testing PMMA (Perspex or Plexiglas). The use of tougher materials, however, results in increased $K_C$ and $G_C$ values and lower yield stresses so that the size of plastic zones increases and the need for larger specimens to sustain LEFM conditions becomes increasingly difficult to meet. If any practical use is to be made of Fracture Mechanics in polymers then these problems must be overcome and to this end a good deal of testing has been performed to determine testing conditions in which valid toughness values can be found. This review will outline what has been done so far and indicate what is reasonably well established and where development is needed.

2. TEST METHODS AND TECHNIQUES

Polymers are usually tested using the single edge notch test configurations in either tension or three point bending. Compression or injection molded sheets can be cut using wood working machinery to give satisfactory rectangular specimens. These are problems concerned with processing and it is difficult to manufacture any sheet of thickness greater than about 25 mm because of cooling problems (polymers have a very low thermal conductivity). Polymers are also rather susceptible to processing conditions

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and so data measured on compression molded samples may not represent
the behaviour of, say, an extruded article. Such difficulties are
real but may often be overcome if a sensible compromise, such
as extruded sheet or injection molded plaques, can give satisfactory
results. Tension testing requires further machining of the test
specimen to fit end clamps or to provide pin loading holes and the
definition of the specimen, which does not, is preferable on this basis. It is
also easier to achieve high constraint in bending and thus, in principle
able to build larger specimens can be used. The author has not found
at least, smaller specimens can be used. The author has not found
that the special problems of crack growth
in series of identical specimens are loaded to deflections
less than that of total failure and then broken open in order to measure
the crack growth. Extrapolation to zero growth gives initiation
to stable crack growth. It is also possible with good lighting and careful observation of the crack
tip to detect initiation directly but this is always a rather subjective
exercise and, although useful when a high level of skill is achieved,
rather difficult to justify on an objective basis.

With all these factors in mind we shall now examine some testing
parameters as they affect the toughness measurements on a number of
commercially important materials.

3. EFFECT OF SPECIMEN THICKNESS B

In order to achieve plane strain conditions in the plastic zone at the crack
tip the specimen thickness must be considerably greater than the zone. On
the specimen surfaces there is no lateral constraint so that plane stress
pertains and a criteria based on a plane stress Ks value is probably the
most sensible. One such is given in [1] and suggests that the critical
thickness is when it is equal to twice the plane stress zone size and if
this is expressed in terms of the plane strain value we have;

\[ B = \frac{1}{1 - 2\nu} \left( \frac{K_{II}}{\sigma_y} \right)^2 \]  

(1)

For \( \nu = 1/3 \) then the factor is ~ 3 which is similar to the empirical ASTM
criterion.

\[ B = 2.5 \left( \frac{K_{II}}{\sigma_y} \right)^2 \]  

(2)

which was established on metals in bend testing. To test its applicability
to polymers tests have been performed on many polymers and Fig. 1 shows data
taken from Hashemi and Williams [2] for four materials of \( K_s \) versus \( B \) with
\( B \) indicated. In all cases it is satisfactory, though perhaps somewhat
conservative for polypropylene. It should be noted that this criterion
does not work for tension [2] and that an extrapolation to \( B = 0 \) must
be used to define a plane strain condition. This is the example mentioned
earlier, of the higher constraint of the bend case and arises from the
neutral axis being present in bending.

4. EFFECT OF SPECIMEN WIDTH W

Here we are concerned with the onset of plastic collapse in the uncracked
ligament and the ASTM criterion:

\[ W = 5 \left( \frac{K_{II}}{\sigma_y} \right)^2 = 2 \dot{B} \]  

(3)
Although this is again an empirical factor it can be justified here in terms of nominal stress level in the ligament of 0.8 \( \sigma_d \) as a limit or in terms of the line zone or BCS model [2], Chan and Williams [3]. Both of these give factors of 6.25 instead of 5. The line zone result is:

\[
\sigma_c = \frac{2}{\pi} \sigma_{pc} \cos^{-1} \left( \exp \left( -\frac{2}{8} \frac{K_C^2}{V^2 \sigma_{pc}^2} \frac{1}{a} \right) \right)
\]

(4)

where \( \sigma_c \) = gross failure stress, \( \sigma_{pc} \) = gross stress at plastic collapse of the notched specimen and \( V \) is the usual finite width correction factor. The use of \( V \) in this equation is somewhat empirical but a good fit to the data is obtained by using [2].

\[
\sigma_{pc} \sim 1.5 \sigma_c (1 - a/W)^2
\]

Fig. 2 shows data taken from [2] of \( K_c \) versus \( W \) for the same materials as in Fig. 1. The ASTM criteria is shown to be quite satisfactory if somewhat conservative and it should be noted that specimens which are too small give a low value of \( K_c \) which is independent of \( a \) (the points cover the range \( 1 < a/W < .5 \)). This is because the presence of plasticity does not allow the stress to rise high enough to meet the elastic condition.

An approximate correction to \( K_c \) may be computed from equation 4;

\[
\frac{K_c}{K_c} = \left( \frac{\pi}{2} \frac{\sigma_{pc}}{\sigma_c} \right)^{\frac{1}{2}} \left( 1 + \frac{a}{2W} \right)^{\frac{1}{2}}
\]

(5)

and this line is shown in Fig. 2 for \( a/W = 0.3 \). It should be noted that the correction is 36% for \( \sigma_c/\sigma_{pc} = 0.9 \) and falls to 6% at 0.5.

For tension tests the same criteria apply here, unlike the thickness case, because it is basically a yield limited situation.

5. EFFECT OF NOTCH TIP RADIUS \( R \)

Data on a number of polymers where the original notch tip radius was varied is shown in Fig. 3, Hashemi and Williams [4]. The radius shown is the original \( R_0 \) plus that induced by the crack opening displacement \( 6a/2 \). This is the concept of cracks self blunting which is discussed in [4] and is given only in outline here. The lines fitted to the data come from a blunt crack elastic analysis which uses a critical stress at a critical distance \( \tau_c \) criteria and enables the sharp notch (\( R = 0 \)) toughness to be derived. The equation has the form [1]:

\[
\frac{K_0}{K_c} = \left( 1 + \frac{R}{2 \tau_c} \right)^{3/2}
\]

(6)

where \( K_0 \) is that value of \( K \) measured for the blunt notch. The \( K_c \) values and \( \tau_c \) values are given in Table 1. Together with the minimum value it is possible to obtain with an \( R = 0 \) test. This is not \( K_c \) since self blunting can occur. Also given is the value obtained for the sharp cutter tests (\( R = 12.5 \mu m \)) which in some cases are actually slightly lower than the minimum. This apparent anomaly stems from the suppression of \( K \) which can arise from the plasticity effects discussed earlier. For those materials showing rather brittle failures (PMMA and PVC) there is only a slight effect and the machined notch gives a satisfactory result. For the rather tougher materials there is a significant difference and it is reasonable to assume that very sharp existing cracks, from whatever cause, would give \( K_{min} \) values. Whether \( K_c \) can ever be achieved is a question unresolved at the time of writing.

\[\text{TABLE 1. EFFECT OF NOTCH TIP RADIUS ON TOUGHNESS}\]

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>( K ) at ( R_0 = 12.5 \mu m )</th>
<th>( K_c ) MPa/m</th>
<th>( K_{min} ) MPa/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>1.80</td>
<td>1.95</td>
<td>1.87</td>
</tr>
<tr>
<td>PVC</td>
<td>2.50</td>
<td>2.84</td>
<td>2.61</td>
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<tr>
<td>Polycarbonate</td>
<td>4.25</td>
<td>3.66</td>
<td>3.92</td>
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<tr>
<td>Nylon</td>
<td>5.00</td>
<td>3.66</td>
<td>4.21</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>5.80</td>
<td>3.02</td>
<td>4.04</td>
</tr>
</tbody>
</table>


Some very tough materials give size criteria which it is not possible to meet since it is impossible to mold sheets of the required thickness. One such is medium density polyethylene used in gas pipes and some effort has been expended in using the ASTM J method to characterise toughness since the J criterion;

\[
W = a, 8 > 25 \left( \frac{J_c}{\sigma_y} \right)
\]

(7)
is about a factor of three smaller than that for $K_a$ ($25 \cfrac{J_c}{\sigma_y} - 25 \sigma_y$) and since $\sigma_y \sim 0.03$ in polymers the factor is 0.75 instead of 2.5. The notion behind the method is that deep notched, fully plastic specimens in three point bend have a stress state close to plane strain and that initiation under such conditions will be at the same state as in the elastically controlled field.

The procedure is shown in Fig. 4, where a series of tests using identical specimens with $a/W = 0.5$ are performed loading to fraction of the final failure value $a_f$. These specimens are then broken open and the slow crack growth $\Delta a$ measured, equation 5. For this configuration $J$ can be found from the energy under the load-deflection curve using (c):

$$J = \frac{\Delta U}{2(W - a)}$$  \hspace{1cm} (8)

so that finally $J$ may be plotted as a function of $\Delta a$ or $a$. A line is drawn to correct for crack tip blunting and the intercept of this with the $J$-$\Delta a$ line gives the initiation of value of $J$. Fig. 5 shows such lines for this material over a range of temperatures and clearly the scheme works quite well. Fig. 6 shows $J$ as a function of temperature and also the value of $K_{CI}$ derived from:

$$K_{CI}^2 = EJ_c$$

and this matches $K_{CI}$ values using the usual LEFM test where the data overlap. Such agreement is encouraging but does not constitute proof of the case. The values obtained are rather high and certainly blunting does occur. It is certainly possible that this is sufficient to cause a loss of constraint at the crack tip and thus give high values. The matter has not been resolved at the time of writing.

7. CONCLUSION

It is clear that the ASTM size for LEFM testing is quite adequate for polymers and enables useful plane strain values to be obtained when specimens of the required size are available. Notch tip sharpness is an important factor, particularly for tougher materials, and its effect can be evaluated using crack blunting theory. The ASTM $J$ method appears to work and thus smaller specimens may be used but the validity of the resulting data is not fully established.

REFERENCES

Figure 1. Effect of specimen thickness on the fracture toughness in three-point bend (data from [2]).

(2a) PMMA, $T = 20°C, \sigma_y = 81 MN/m^2$ (W = 11mm)

(2b) Polyvinyl chloride, $T = 20°C, \sigma_y = 59 MN/m^2$ (W = 12.5mm)

(2c) Polypropylene, $T = 20°C$ (W = 20mm)

(2d) Polycrystal, $T = 11°C$ (W = 3mm)

Figure 2. Effect of specimen width on the fracture toughness in three-point bend. (Data from [2]).
Figure 2.

(2c) NYLON. $\sigma_y = 111$ MN/m$^2$, $T = -40^\circ C$, $(B = 11mm)$

(2d) POLYPROPYLENE. $\sigma_y = 70$ MN/m$^2$, $T = -60^\circ C$, $(B = 20mm)$

Figure 3. $K_a$ values plotted versus total root tip radius--lines fitted from equation 5 (data from [4])
Figure 4. Procedure for measuring J

Figure 5. J versus crack extension - medium density P.E. (data from[5])
Figure 6. \( J \) and \( K_t \) data for medium density polyethylene (data from [5]).