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 satisifactory 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 over emphasised and a sensible compromise, such as extruded sheet or injection molded plaques, can give satisfactory results. Tension testing requires further machining of the samples in order to fit end clamps or to provide pin loading holes and the bend configuration, which does not, is preferable on this basis. It is also easier to achieve high constraint in bending and thus, in principle at least, smaller specimens can be used. The author has not found compact tension of particular value since it is a somewhat complicated specimen to make and, because of its hybrid, tension-bending nature, requires a heavy dependence on computed calibration factors and accurate dimensions. If needed for special purposes it can be made to work satisfactorily. For crack growth studies the double torsion test is preferred although the double cantilever beam or its contoured version can be used. No discussion of the special problems of crack growth testing will be given here, (the reader is referred to, Williams [1] for coverage of this topic).

Notch preparation is the most important aspect of specimen manufacture since, in many materials, the measured values are strongly dependent on original tip sharpness. If a natural crack can be propagated stably at the base of the prepared notch this is the best method. This can be sometimes be done by pressing razor blades into the notch root but frequently plastic deformation or microvoiding occurs giving a local residual compressive stress field. Fatigue notching is not very useful in polymers because of the need to keep the test frequency below 10 Hz to limit visco-elastic heating. The use of very sharp single point rotating cutters has been found to be most useful and it is possible to achieve a tip radius of about 15 μm by this method. This is frequently sharp enough, but not always, and some discussion of the effect will be given here. All other data given here is for such machined notches.

We shall be particularly concerned with fracture initiation studies and for this purpose a normal screw-driven Instron testing machine has been found to be the most useful. This allows a modest range of rates to be covered without recourse to special recording facilities and a temperature cabinet allows temperatures down to about - 160°C to be investigated. This latter facility is of particular importance in polymers since there is considerable evidence [1] that the plane strain toughness, K_{c1}, is largely independent of temperature while the yield stress, σ_y, increases significantly as temperature decreases. Low temperature testing does, therefore, tend to LEFM conditions at moderate sizes for which K_{c1} can be found and then at least indicated for the higher temperatures where it is difficult to measure.

The detection of fracture iniation is also a difficult problem in polymers, as in metals. For transparent materials it is much easier of course and for brittle failures initiation often coincides with instability so that the load drops rapidly and there is no problem in identifying the load at initiation. Even in brittle failure, however, caution must be exercised since stable, visco-elastically controlled crack growth can preceed instability and the maximum load does not correspond to the original crack length. An examination of the fracture surface will detect this and other slow growth since it is usually discernable on the fracture surface. The occurence of instability greatly assists the maximum load detection but if it does not occur then it is necessary to use some form of multiple specimen method (as discussed under J testing

later) in which a series of identical specimens are loaded to deflections less than that of total failure and then broken open in order to measure to stable crack growth. Extrapolation to zero growth gives initiation. 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 K_c 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;

$$B = \frac{1}{\pi(1 - 2\nu)^2} \cdot \left(\frac{K_{c1}}{\sigma_y}\right)^2 \qquad (1)$$

For $\nu \sim 1/3$ then the factor is ~ 3 which is similar to the empirical ASTM criterion.

$$\hat{B} = 2.5 \left(\frac{K_{c1}}{\sigma_y}\right)^2 \qquad (2)$$

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_c versus B with $\hat{B}$ indicated. In all cases it is satisfactory, though perhaps somewhat conservative for polypropylene. It should be noted that this criterion does <u>not</u> work for tension [2] and that an extrapolation to $B^{-1} = 0$ 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:

$$W = 5 \left(\frac{K_{c1}}{\sigma_y}\right)^2 = 2\hat{B} \qquad (3)$$

Although this is again an empirical factor it can be justified here in terms of nominal stress level in the ligament of $0.8\ \sigma_y$ 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;

$$\sigma_c = \frac{2}{\pi} \cdot \sigma_{pc} \cdot \cos^{-1} \left[\exp \left(-\frac{\pi^2}{8} \cdot \frac{K_{c1}{}^2}{Y^2 \sigma_{pc}{}^2} \cdot \frac{1}{a} \right) \right] \tag{4}$$

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

$$\sigma_{pc} \sim 1.5\ \sigma_y\ (1 - a/W)^2$$

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;

$$\frac{K_{c1}}{K_c} = \left(\frac{2}{\pi}\ \frac{\sigma_{pc}}{\sigma_c}\right) \left(\ln . \sec^2 \frac{\pi}{2}\ \frac{\sigma_c}{\sigma_{pc}}\right)^{\frac{1}{2}} \tag{5}$$

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_o plus that induced by the crack opening displacement $\delta/2$. 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 r_c criteria and enables the sharp notch ($R = 0$) toughness to be derived. The equation has the form [1];

$$\frac{K_b}{K_c} = \frac{(1 + R/2r_c)^{3/2}}{(1 + R/r_c)} \tag{6}$$

where K_b is that value of K measured for the blunt notch. The K_c values and r_c values are given in Table 1. together with the minimum value it is possible to obtain with an $R_o = 0$ test. This is not K_c since self blunting can occur. Also given is the value obtained for the sharp cutter tests ($R_o = 12.5\ \mu m$) 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 presume 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.

TABLE 1. EFFECT OF NOTCH TIP RADIUS ON TOUGHNESS.

MATERIAL	K at $R_o = 12.5\ \mu m$ $MPa\sqrt{m}$	K_c $MPa\sqrt{m}$	K_{min} $MPa\sqrt{m}$
PMMA	1.80	1.95	1.87
PVC	2.50	2.84	2.61
Polyacetal	4.25	3.66	3.92
Nylon	5.00	3.66	4.21
Polypropylene	5.80	3.02	4.04

6. J TESTING, Chan and Williams [5]

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;

$$W - a\ ,\ B\ > 25\ (J_c/\sigma_y) \tag{7}$$

is about a factor of three smaller than that for K_c ($25\ (J_c/\sigma_y) \sim 25\ e_y\ (K_c/\sigma_y)^2$ and since $e_y \sim 0.03$ 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). These specimens are then broken open and the slow crack growth Δa measured, equation 6. For this configuration J can be found from the energy under the load-deflection curve U using (c);

$$J = \frac{2U}{B(W - a)} \qquad (8)$$

so that finally J may be plotted as a function of $\Delta a(d)$. A line is drawn to correct for crack tip blunting and the intercept of this with the J-Δa line gives the iniation 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_{c1} derived from;

$$K_{c1}^{\ 2} = E\ J_c$$

and this matches K_{c1} 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

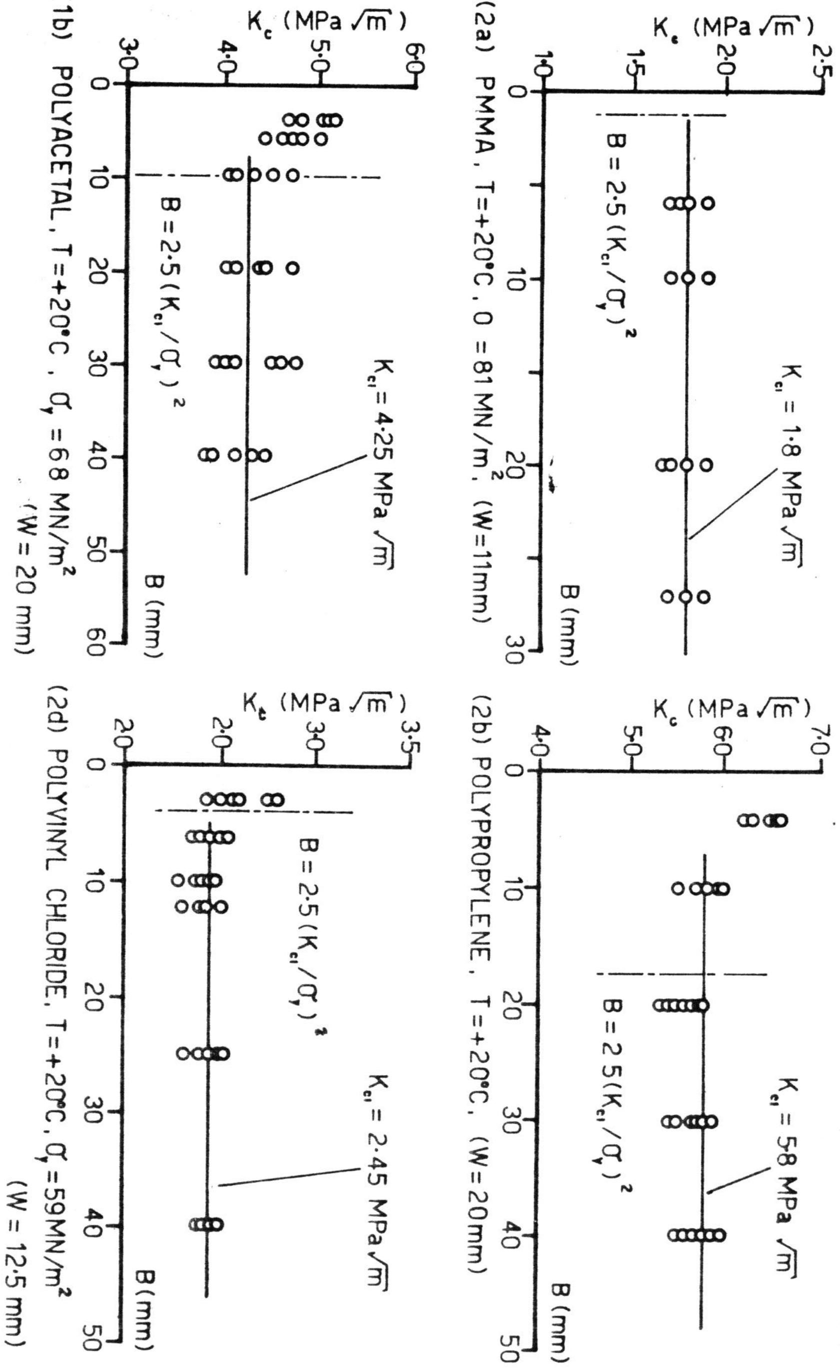
1.Williams, J.G. "Fracture Mechanics of Polymers", Ellis Horwood-Wiley, 1984.

2.Hashemi, S., and Williams, J.G., J. Mat. Sci., in press.

3.Chan, M.K.V., and Williams, J.G., Polym. Engng. Sci., 21, (1981) 1019-1026.

4.Hashemi, S., and Williams, J.G., J. Mat. Sci., in press.

5.Chan, M.K.V., and Williams, J.G., Int. J. Fract., (1983) 145-159.



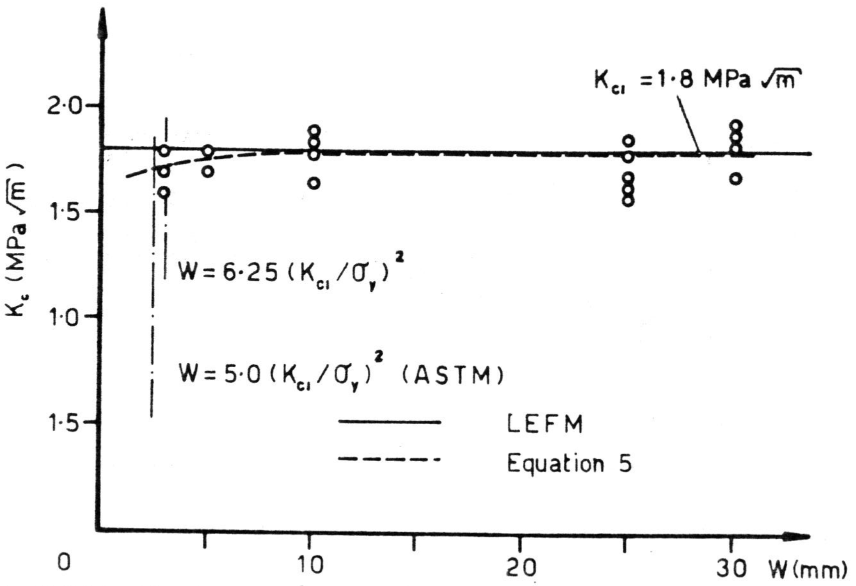
(2a) PMMA, T = +20°C, σ = 81 MN/m², (W = 11 mm)

(1b) POLYACETAL, T = +20°C, σ_y = 68 MN/m² (W = 20 mm)

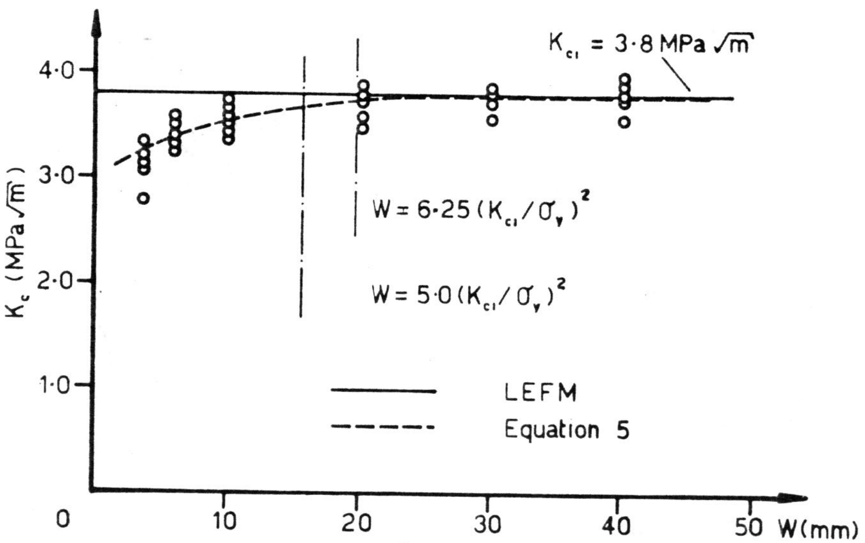
(2b) POLYPROPYLENE, T = +20°C, (W = 20 mm)

(2d) POLYVINYL CHLORIDE, T = +20°C, σ_y = 59 MN/m² (W = 12·5 mm)

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

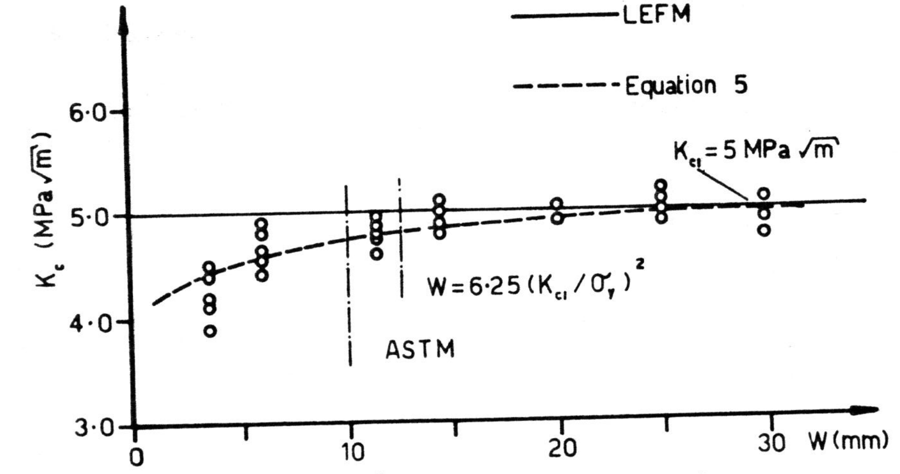


(2a) PMMA. σ_y = 81 MN/m², T = +20°C (B = 6 mm)

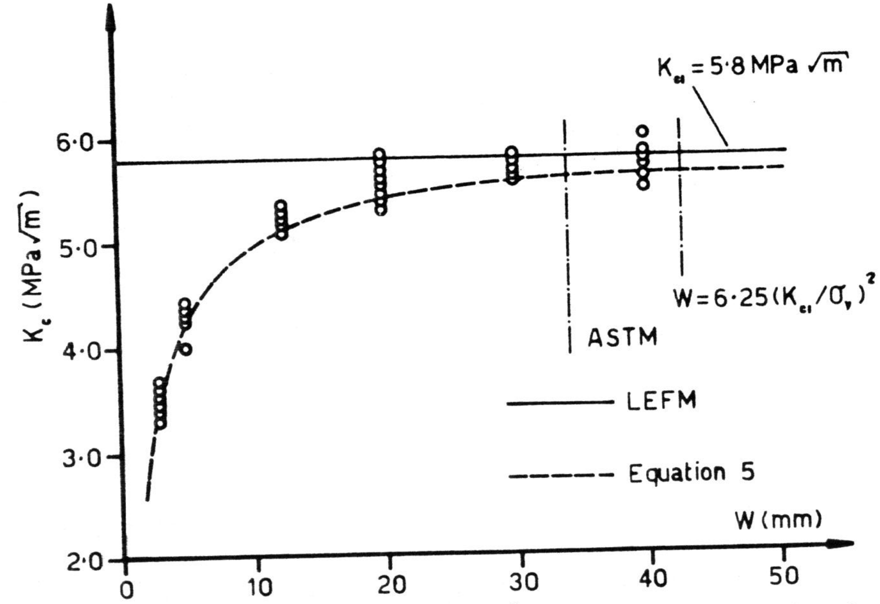


(2b) POLYACETAL. σ_y = 68 MN/m², T = 20°C (B = 20 mm)

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



(2c) NYLON. σ_y = 111 MN/m^2, T = −40°C, (B = 11mm)



(2d) POLYPROPYLENE. σ_y = 70 MN/m^2, T = −60°C, (B = 20mm)

Figure 2.

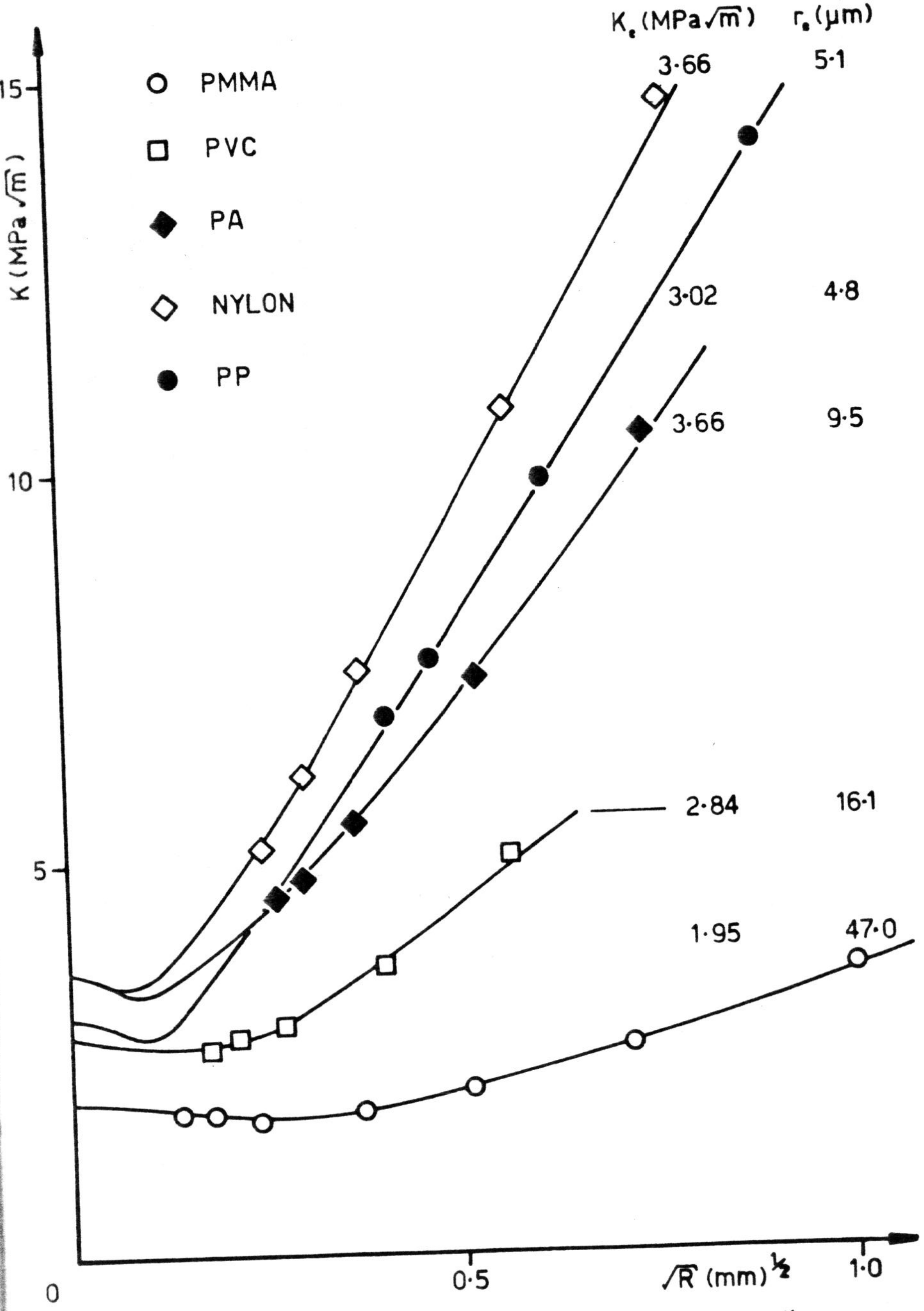


Figure 3. K_b values plotted verses total root tip radius – lines fitted from equation 5 (data from [4])

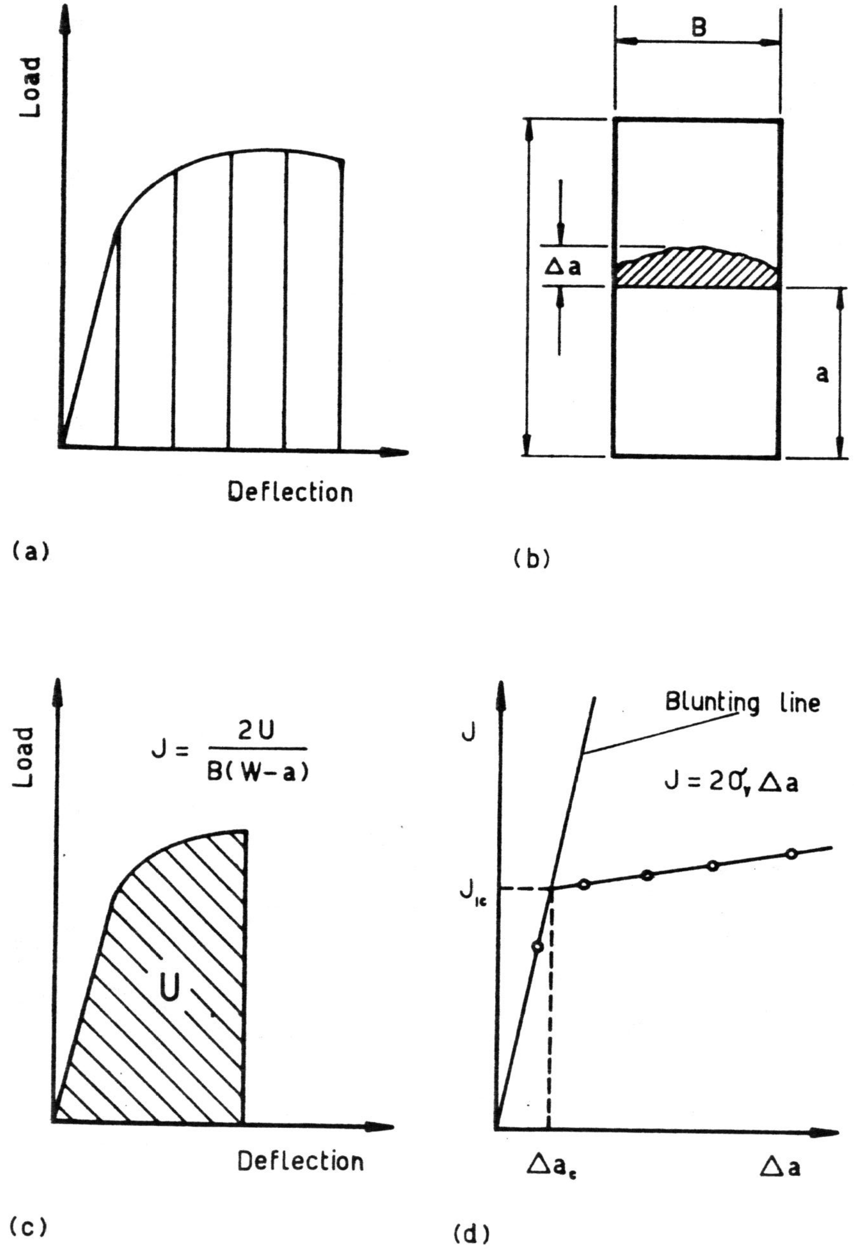


Figure 4. Procedure for measuring J

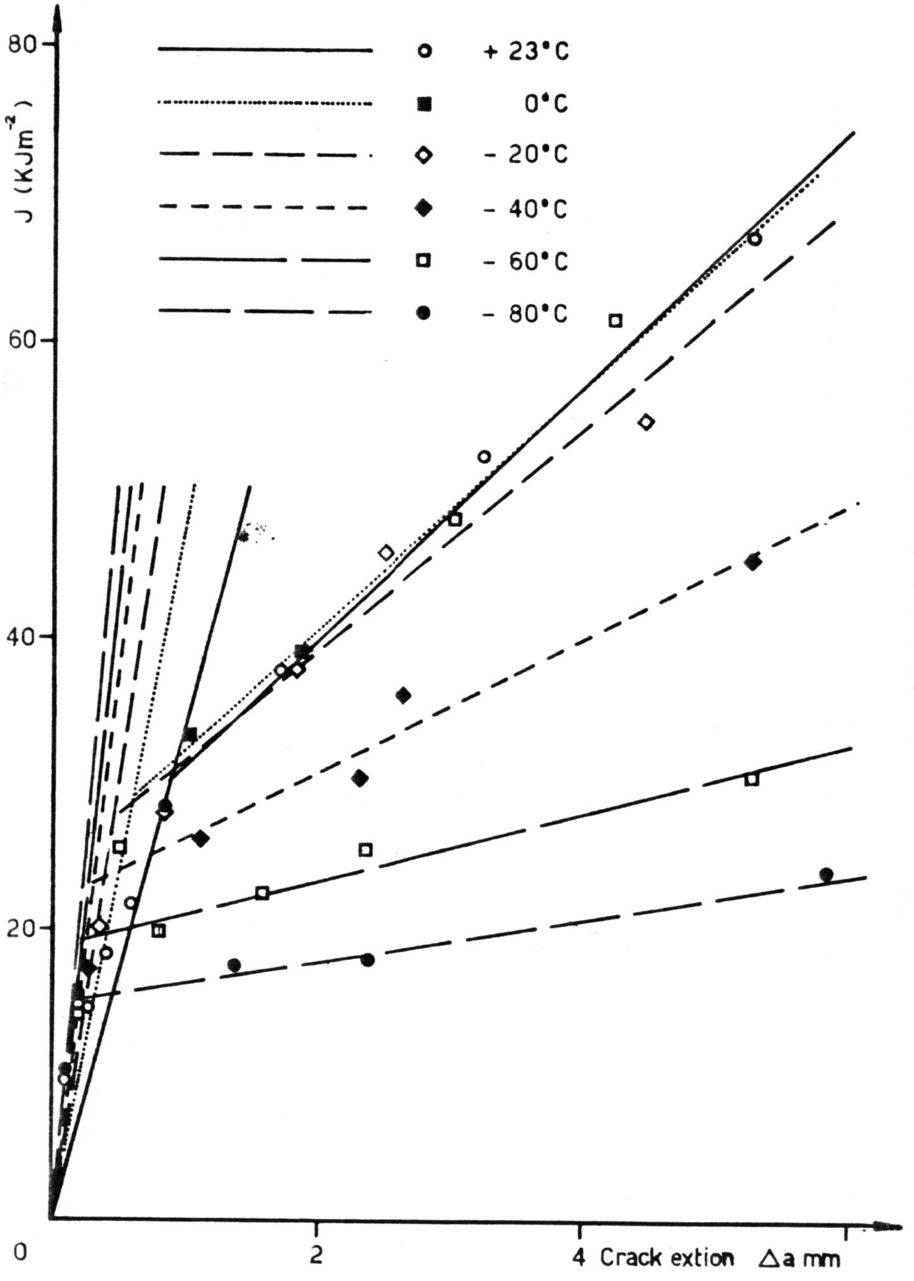


Figure 5. J versus crack extention – medium density P.E. (data from [5])

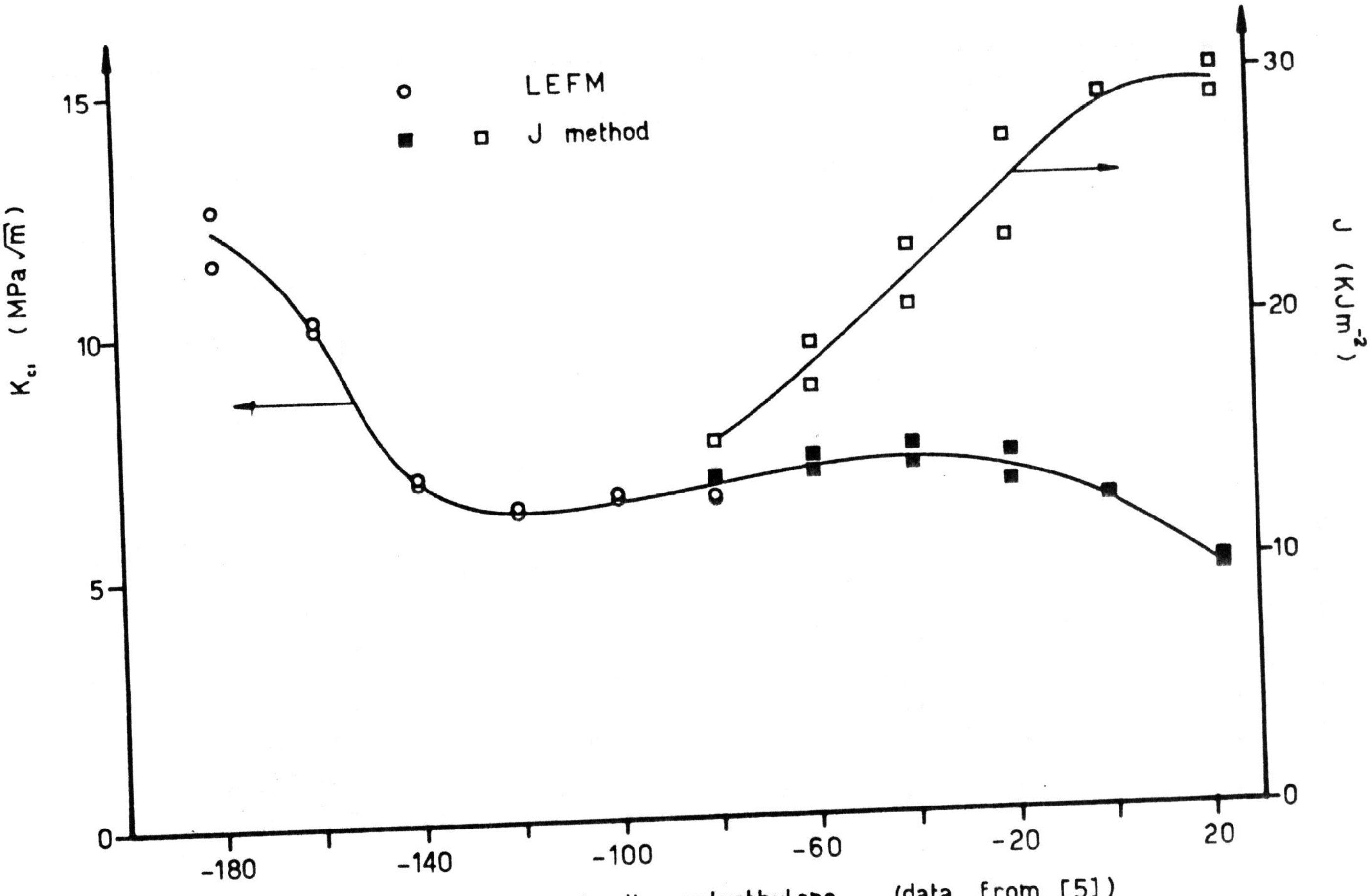


Figure 6. J_c and K_{c1} data for medium density polyethylene (data from [5])