# CRACK GROWTH RESISTANCE CURVES FOR POLYMERS - DEVELOPMENT OF A MULTIPLE SPECIMEN TESTING PROTOCOL

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This paper describes work undertaken by the EGF Task Group on Polymers and Composites to develop a standardised testing procedure for evaluating the J-crack growth resistance behaviour of polymers. After reviewing the protocol, the main areas which still need resolution are identified. These are crack length measurement, notch sharpness and initiation toughness parameters. Finally, a comparison of data generated for high density polyethylene is presented which indicates that the achievement of an agreed procedure is progressing successfully.

## INTRODUCTION

The use of linear elastic fracture mechanics (LEFM) for characterising the toughness of polymers is well established within the plastics field and the development of standardised test procedures has been undertaken by the European Group on Fracture (EGF) Task Group on Polymers and Composites (1) as well as a corresponding ASTM group in the U.S.A.

However, many of the tougher engineering polymers, e.g. high density polyethylene (HDPE), do not exhibit linear elastic fracture behaviour at room temperature at the thicknesses generally employed as plane strain conditions at the crack tip cannot be satisfied.

Alternatively, one can employ the concept of elastic-plastic fracture mechanics (EPFM) to these tougher materials. Several investigators (2-4) have identified some of the important features which should be considered when measuring the

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J-fracture toughness of polymers. Within Europe, 20 organisations are participating in the development of a standardised testing protocol.

The objective of the remainder of this paper is to review the position reached so far, to highlight those areas where there is agreement, and to indicate issues on which further study is still needed.

## REVIEW OF PROTOCOL

The current protocol (5) is loosely based on the 'EGF recommendations for determining the fracture resistance of ductile materials' (6) with inputs from the two corresponding ASTM standards, E813-87 and E1152-87 (7,8). The protocol is designed to provide a framework within which tests can be undertaken systematically so that a J-crack growth resistance curve (Fig.1) is produced.

Conventional compact tension (CT) or single edge notch bend (SENB) fracture mechanics specimens are employed. As with metals, attention has centred on deeply cracked testpieces with a crack depth to width ($a_o/W$) ratio of between 0.55 and 0.65.

Each testpiece is loaded at a constant rate to a certain displacement or clip gauge opening, prior to unloading. To minimise the effect of viscoelasticity in polymers, tests are carried out at a fixed loading rate of 1mm/min. Corrections for indentation and extraneous displacements are made in a separate test, after which a load versus load-line displacement diagram can be plotted.

The fracture toughness, $J_o$, is a measure of the energy required to grow a stable crack and it may be evaluated from the area (u) under the load versus load-line displacement plot via the expression:

$$J_o = \frac{\eta u}{B(W-a_o)} \qquad (1)$$

where $\eta = 2$ for SENB specimens and $\eta = 2 + 0.522\ (1-a_o/W)$ for CT testpieces.

After testing, the sample is broken open to reveal the fracture face and the amount of crack growth occurring in the test is measured by a nine-point averaging technique.

This procedure is repeated to obtain a range of crack extensions. Certain spacing requirements are imposed on the data as shown in Fig.2.

A best fit curve is fitted to the data which can usually be described by an offset power law of the form:

$$J = A(\Delta a + C)^D \tag{2}$$

where $C \geq 0$ and A, C, and D are constants

Data points which fall below a 0.1mm exclusion line are not used since the errors at this amount of crack growth may be significant. Similarly, data which falls outside the $\Delta a_{max}$ line are not included in the analysis.

The next step is to assess validity criteria which are based on the metals standard to establish: (a) if plane strain conditions are present at the crack tip; (b) what portion of the data is considered to be size-independent and (c) the limits for J-controlled crack growth. It is important to determine which criteria are most appropriate for use with polymeric materials.

From the best fit crack growth resistance curve, certain parameters which provide an estimate of the initiation toughness can be evaluated (Fig.1). Those currently employed are the value of J at 0.2mm of total crack growth and the parameter $J_{0.2/BL}$ which measures the fracture resistance at 0.2mm of crack growth beyond crack initiation.

## AREAS WHICH REQUIRE RESOLUTION

In this section, a number of topics on which work is still progressing are reviewed:

1. Crack length measurement after testing.
2. Influence of notch sharpness.
3. Initiation toughness parameters.

### Crack Length Measurement After Testing

A number of alternative methods are being investigated:

1. cooling in liquid nitrogen or solid carbon dioxide and fracturing at either normal loading rates or at high rate impact velocities
2. high rate impact at ambient temperature (i.e. no cooling)
3. fatigue cycling after the test at either ambient or lower temperatures
4. injection of ink into the crack to mark the front.
5. measurement of crack length from polished sections viewed under an optical miscroscope while the specimen is under load.

The problem is to unambiguously distinguish the actual crack growth from other features on the fracture face. Each method tends to have both advantages and disadvantages.

An indication of the problem can be seen in Fig.3 which is a comparison of $J_0$-$\Delta a$ plots for polypropylene specimens broken open by (a) cooling in solid carbon dioxide and (b) fatigue. There is no degree of correspondence between the two sets of data. Polypropylene is a material which crazes and the damage zone can be up to 10mm compared to say 1-2mm of crack growth. Hence, interpretation of the fracture face is difficult.

Further work is continuing in this area of crack length measurement as it is seen as the key step in the development of a reproducible standardised test procedure.

Influence of Notch Sharpness

Since crack tip blunting was thought to occur shortly after these tougher polymers were loaded beyond their elastic limit, it was felt unnecessary to stipulate a natural crack as defined in the LEFM protocol for plastics (1). However, recent results indicate a tendency for lower initiation toughness to be associated with sharper notch tips. Therefore, in future, the same criteria as used for LEFM tests will be applied, i.e. to generate if possible a natural crack by tapping a razor blade into the tip of an existing sharp machined notch. In very tough materials, where a natural crack cannot be generated, then the crack tip must be sharpened by sliding a new razor blade across the notch. The extension of the machined notch must be several times greater than the initial notch tip radius.

Initiation Toughness Parameters

At present, a blunting line construction based on the expression $J = 2\sigma_Y \Delta a$ has been employed as a basis for evaluating the parameter, $J_{0.2/BL}$, (Fig.1). However, evidence is emerging to suggest that the constant in the above equation need not necessarily be two. Adem (9) has measured values ranging from 2.6 to 6.0. Therefore, the best estimate of initiation may be to evaluate J at a specific value of $\Delta a$. Since the metals community use J at a total crack growth of 0.2mm, this was felt to be a good starting point for work on polymers.

## CURRENT SITUATION

Nevertheless, there is clear evidence that when the actual crack growth can be distinguished clearly then a degree of consistency in the crack growth resistance curves and the $J_{0.2}$ fracture toughness parameters can be achieved. This is well illustrated in Fig.4 which is a compilation of data measured for HDPE in the latest EGF round-robin programme.

## SUMMARY

A draft multiple specimen testing protocol to evaluate the J-crack growth resistance curves of polymers has been developed. While certain problems still need to be resolved, notably crack length measurement, there is a growing body of data which indicates that an agreed standardised procedure which can form the basis of national and international standards will be finalised in the near future.



## ACKNOWLEDGEMENTS

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## ADDITIONAL NOMENCLATURE

| | |
|---|---|
| $\Delta a_{max}$ | validity limit for J-controlled crack growth |
| $J_o$ | fracture resistance not allowing for crack growth |
| $J_{0.2/BL}$ | fracture resistance at 0.2mm crack growth beyond initiation |
| $J_{0.2}$ | fracture resistance at 0.2mm of total crack growth |
| $\eta$ | geometric factor |

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(9) Adem, D. Private communication, May 1990.

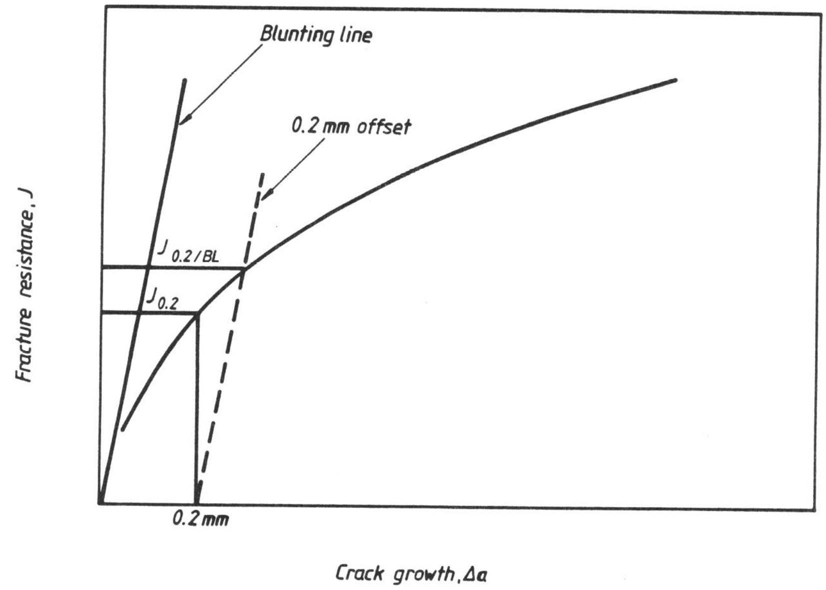


Figure 1 Schematic J-crack growth resistance curve

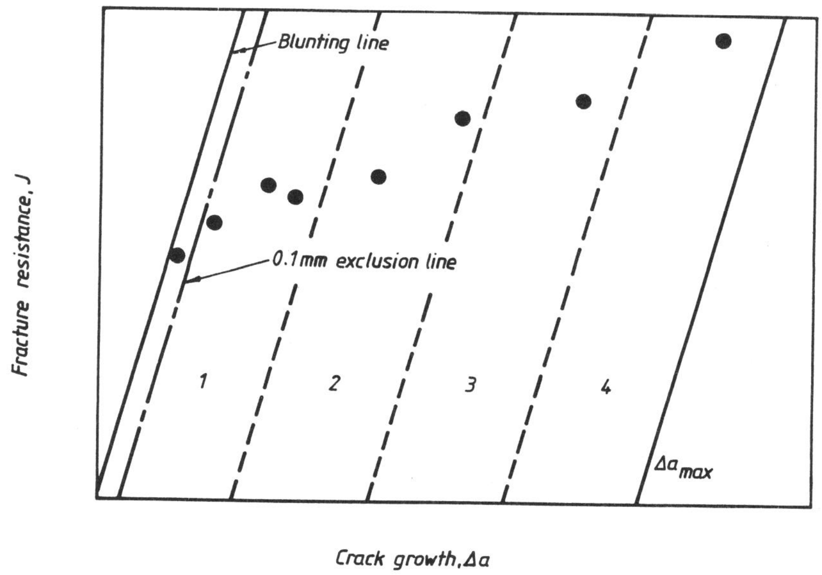


Figure 2 Data spacing requirements

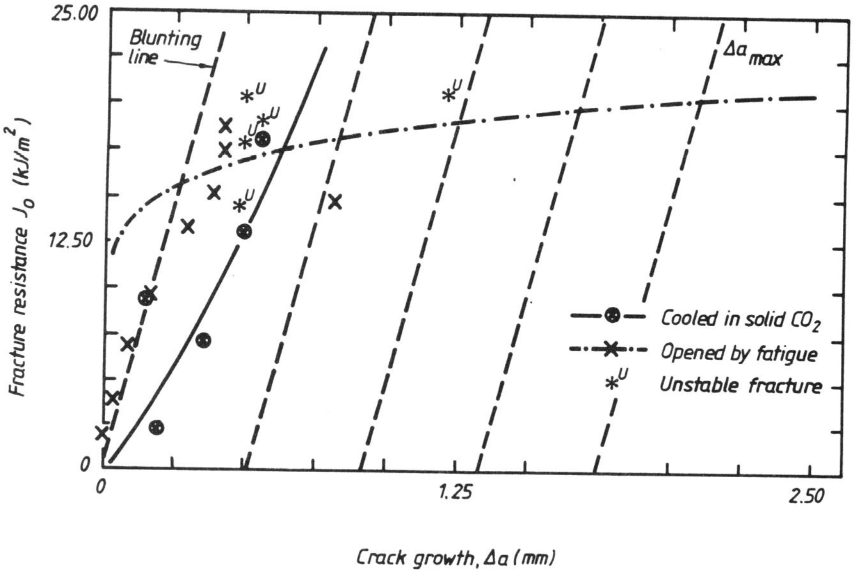


Figure 3 Effect of breaking-open technique on the R-curves measured for polypropylene

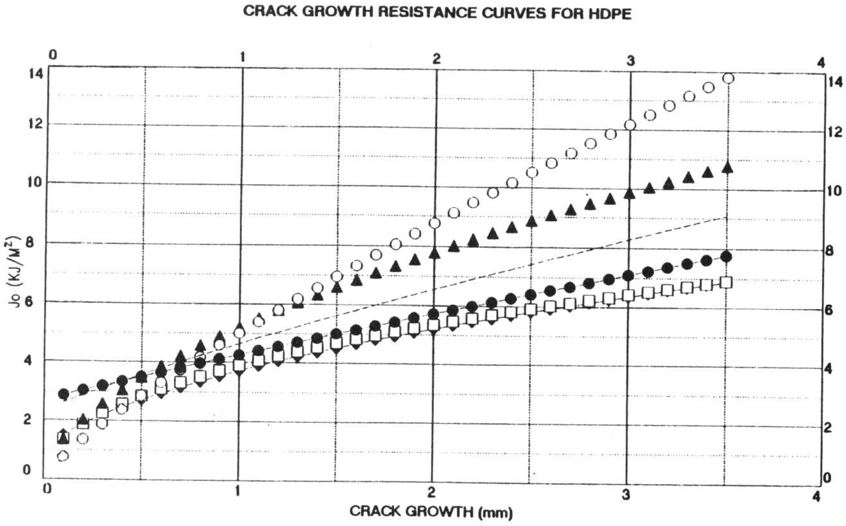


Figure 4 Comparison of J R-curves for HDPE measured by six laboratories