The Effect of Various Precracking Techniques on the Fracture Toughness of Plastics

M. S. CAYARD and W. L. BRADLEY
Department of Mechanical Engineering, Texas A & M University, College Station, Texas, 77843, USA

ABSTRACT

The method of introduction of the crack in fracture toughness testing of plastics has been shown to have a significant effect on the measured value of fracture toughness. In this study, three techniques were used to initiate a precrack in standard 1/2–T compact tension specimens made of polycarbonate: (1) fatigue precracking, (2) razor-notch-guillotine, in which a razor blade is pressed into the specimen in a controlled manner perpendicular to the thickness dimension, and (3) razor-sawing, in which the crack is actually cut by cycling the blade in a controlled manner in a direction parallel to the thickness dimension. A photoelastic birefringence technique was used to assess the extent of residual stresses introduced into the specimens by various precracking procedures. Comparisons between the three methods on polycarbonate indicate that if performed under careful administration, all three techniques result in precracks with adequate crack tip acuity and minimal residual stresses ahead of the crack tip, leading to similar values of K_{Ic}.

KEYWORDS

Polymers; plastics; fracture toughness; notching; precracking.

INTRODUCTION

The effect of notch root radius on the value of fracture toughness in metals has been studied in some detail. It has been shown that fracture toughness values can be significantly lower for a fatigue precracked specimen than for a finite root radius specimen (Malkin and Tetelman, 1971; Heald *et al.*, 1972; Rack, 1976; Ritchie *et al.*, 1976; Ritchie and Horn, 1978). This phenomenon is explained by the existence of a lower limit of the notch root radius, below which no effect of the root radius on the initiation stress intensity factor can be observed. This is a result of the fact that the crack tip undergoes some blunting prior to initiation, regardless of material being tested. As long as the initial root radius is much smaller than half the value of critical crack tip opening displacement ($CTOD$), the measured value of $CTOD$, K_{Ic}, or J_{Ic} will not be effected by the crack tip acuity.

In the current standards for the determination of fracture toughness of metals, ASTM E399-81 and ASTM E813-87, a fatigue precrack is required to guarantee a sufficiently sharp root radius at the crack tip to give a minimum value of fracture toughness. However, in polymeric materials, crack tip root radii as sharp as fatigue precracks can sometimes be achieved using methods requiring less time and specialized equipment. Such methods include pressing a new razor blade into the notch, or natural cracks obtained via pop-in on materials exhibiting brittle behavior.

Mandell *et al.* (1983) compared the use of razor sharpened notches with those obtained with the use of a sharpened blade on a milling machine on polyethylene pipe materials and suggested that pressing a razor blade into the pre-existing notch provides adequate sharpness. In another comparison between fatigue precracking and razor notching of polyethylene pipe material, Jones and Bradley (1988) determined that razor notching gave a value of J_{Ic} which was 33% higher than that measured in fatigue precracked specimens.

Darwish *et al.* (1981) and Mandell *et al.* (1982) found on poly(vinylchloride) that specimens containing a notch that was sharpened with a razor blade to a controlled depth gave adequate crack sharpness when compared with other methods such as fatigue precracks and natural cracks grown at low temperatures.

Williams (1984) found on polymethylmethacrylate (PMMA) that cracks can be extended from fine saw cuts in the specimen by pressing a razor into the end of the slot which causes a crack to run slightly ahead of the blade. However, it is noted that this procedure must be exercised with care since any blunting can lead to either a blunt crack tip or a multiple crazed crack tip.

Marshall *et al.* (1973) used three methods to precrack polystyrene (PS) which included slow razor notching, impact razor notching, and fatigue precracking. It was determined both razor notching techniques produced craze bundles at the tip of the crack causing higher initiation values of toughness where fatigue precracking led to a single craze at the crack tip and hence a lower limit on fracture toughness (Williams, 1984).

The objective in this study has been to determine which techniques used to produce a precrack on polycarbonate would give sufficiently low residual stresses and an adequately sharp crack tip radii necessary to give a true minimum in K_{Ic}. Polycarbonate was chosen for use in this study because of its biofringent character which gives a convenient way to examine the extent of residual stresses introduced by the various crack starter methods.

EXPERIMENTAL PROCEDURES

Machining of Specimens

Standard 1/2-T compact tension specimens were machined with the same orientation from a single plaque of Lexan polycarbonate. The plaque was free of an indication of residual stresses using a photoelastic birefringence technique. This technique is accomplished by viewing a photoelastic material between two polarized filters backed by fluorescent lighting. Specimens were machined with either a chevron notch or with a straight across notch parallel to the thickness direction.

Fatigue Precracking

Chevron notched specimens were fatigue precracked on a closed loop servo-hydraulic materials testing system at various levels of the critical stress intensity, K_{Ic}, of the material. The fatigue precracking loads were calculated using ASTM E399-81.

Razor – Notch Guillotine

In this method, the starter crack is attained by pressing a new razor blade directly into the specimen perpendicular to the thickness dimension. This technique which utilized specimens containing both chevron and standard machined notches. In the case of the chevron notch, a new razor blade was pushed to a depth just past the trailing edge of the chevron into a region of constant thickness. The specimens containing a straight machined notch were first slotted parallel to the machined notch on an Accutom cut-off wheel using a 0.254mm thick, 88.9mm outer diameter jeweler's slotting saw. The saw blade thickness is equivalent to that of a standard razor blade. The angular velocity of the saw blade was set at 500 rpm with a table displacement rate setting of approximately 0.2 mm/min.

Razor – sawing

The idea behind this technique is that the notching would be accomplished by actually cutting the material in a sawing motion parallel to the thickness dimension of the specimen in an attempt to minimize the amount of compressive residual stresses induced into the crack tip region. Prior to razor sawing, these specimens which also contained a standard (non-chevroned) machined notch, were slotted with the jeweler's slotting saw, as previously described.

RESULTS AND DISCUSSION

Extent of Residual Stresses Introduced During Precracking

A photoelastic birefringence technique was again used to give a qualitative assessment of the extent of residual stresses being induced ahead of the crack tip by the various notching techniques. Figure 1 shows a comparison of the damage zones introduced by the initial specimen machining alone. Note that the specimen containing the chevron is free of damage ahead of the notch, while that of the specimen which was notched straight across exhibits a large region of compressive residual stress ahead of the notch. Therefore, the machining of specimens alone may induce varying degrees of residual stresses adjacent to the notch prior to the final notch sharpening.

Fatigue precracking can create varying degrees of damage prior to testing depending on the level of loading. Figure 2 shows the results of fatigue precracking at 40%, 30%, and 10% of the load necessary to fracture the specimen, as determined in subsequent testing. However, it should be noted that the crack tip is located at the end of the butterfly zones shown in Fig. 2, and hence, the material ahead of the crack tip is free of residual stresses.

The razor-notching using a guillotine was utilized in two methods. The first involved pressing the razor blade directly into a chevron notched specimen with the use of the

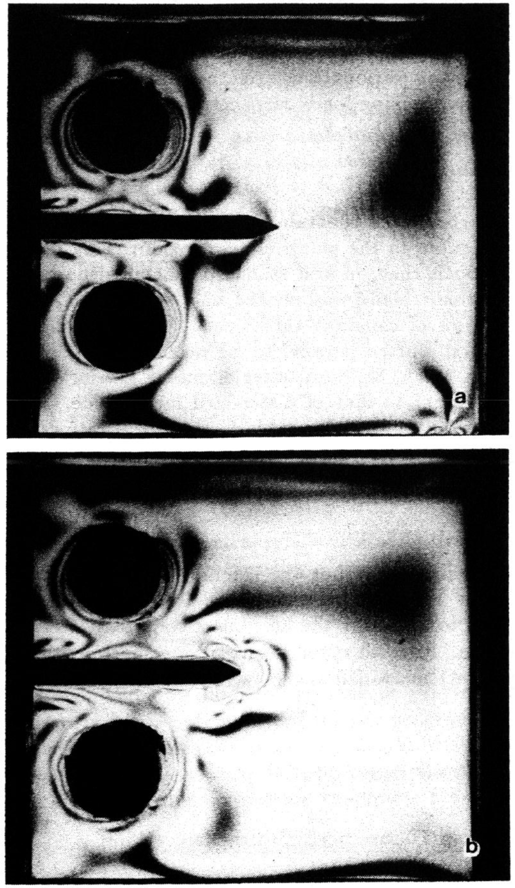

Fig. 1. Photoelastic birefringence patterns resulting from the initial machining of the specimens which contain a chevron and straight across notch respectively.

guillotine device. A large, compressive residual stress field completely surrounding the crack tip resulted, as seen in Fig. 3, due to the significant amount of razor blade wedging. The second method involved an intermediate cut with a jeweler's slotting saw before pressing in a razor blade to sharpen the crack tip. Using an intermediate cut with a jeweler's slotting saw minimized the amount of razor blade penetration, which significantly reduced the extent of residual stresses introduced. Specimens which were initially machined with a straight across notch were used for this approach. Figure 4 shows the photoelastic birefringence photographs of the specimen after both slotting on the Accutom cut-off wheel and pressing in the razor blade with the guillotine device. The introduction of the fine slot cut through the compressive damage zone, which was present after machining the straight across notch, leaving the end of the slot in a damage

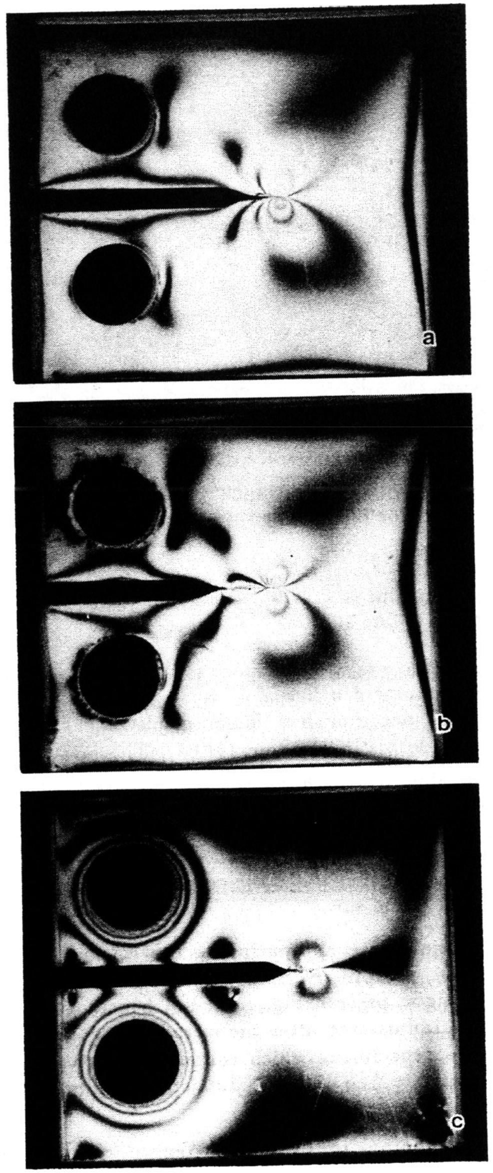

Fig. 2. Photoelastic birefringence patterns resulting from fatigue precracking at 40%, 30%, and 10% of the load necessary for fracture respectively.

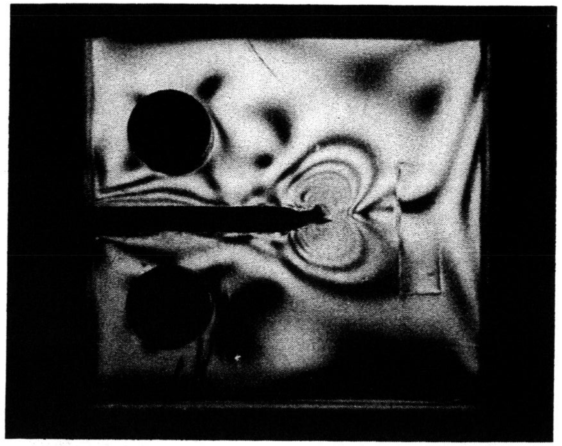

Fig. 3. Photoelastic birefringence pattern resulting from pressing a razor blade directly into a chevron notched specimen.

free region. For the specimens used in this method, the razor was pressed approximately 1.3mm past the end of the fine slot.

The razor-sawing technique was used on specimens which were machined straight across, followed by the introduction of a fine slot on an Accutom cut-off wheel. The actual cutting, or sawing, was accomplished under displacement control on a closed loop servo- hydraulic materials testing system (MTS). This approach, when compared to the guillotine approach, should generate more actual cutting of material, and hence, introduce less deformation in the crack tip region. Figure 5 shows the resulting photoelastic photograph of the specimen after razor-sawing. The region of material ahead of the crack tip is clear of any indication of residual stresses and is very similar to the resulting specimen prepared with the razor-notch guillotine device used in conjunction with the introduction of a fine slot.

Using the razor-notch guillotine approach directly, without the intermediate slotting step, resulted in a large, compressive residual stress field completely surrounding the crack tip. However, fatigue precracking, razor-notch guillotine, and razor-sawing (the latter two approaches administered after the introduction of a fine slot with a jeweler's slotting saw) resulted in specimens which contained regions of material ahead of the crack tip that were relatively free of any indication of residual stresses.

Effect of Precracking Technique on Crack Tip Acuity

The crack tip radii resulting from the three different techniques were measured on a Joel-25 Scanning Electron Microscope. Figures 6–8 show the micrographs of the crack tips on the specimens notched by fatigue precracking, razor-notch guillotine, and razor-sawing respectively. Measurements at higher magnifications than shown in the micrographs were made and the crack tip radii were all found to be approximately 0.125 microns for each technique. The tip of a razor blade was also measured, and found to contain a tip

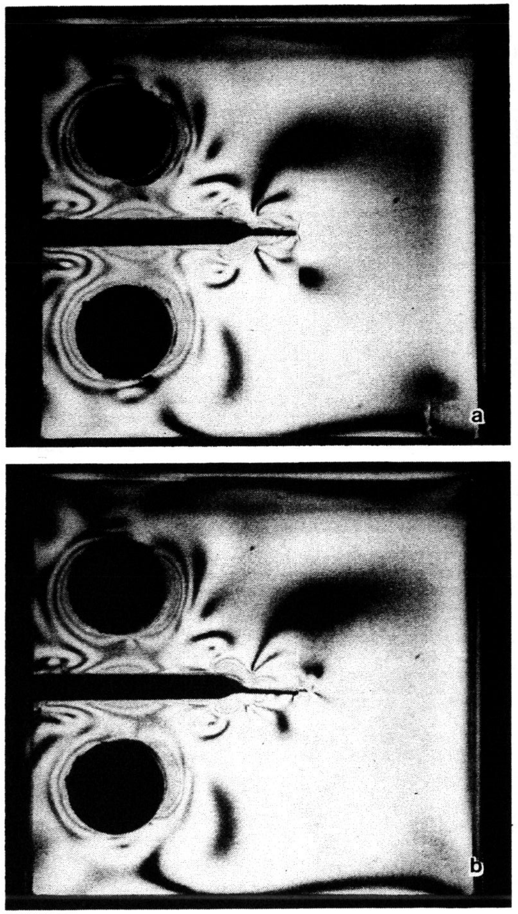

Fig. 4. Photoelastic birefringence patterns of (a) a specimen slotted with a jeweler's slotting saw, and (b) a specimen which was first slotted and then razor-notched with the guillotine device.

radii of 0.25 microns, twice the size of the resulting crack tip radii of the razor-notch guillotine and razor-sawing approaches. This phenomenon could be explained by either of the following two hypotheses. First, when the razor blade was removed, the elastic energy, stored in the material ahead of the crack tip, helped close the crack faces, thereby decreasing the crack tip radii. Secondly, the crack could have popped-in ahead of the razor blade tip, providing a natural crack similar to the fatigue precracked sample, which is a plausible explanation for the behavior seen in Fig. 8(b).

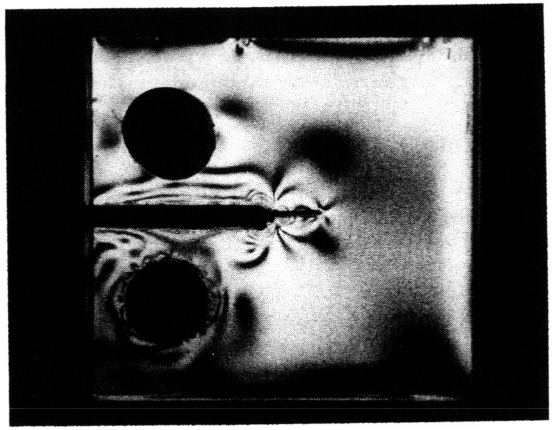

Fig. 5. Photoelastic birefringence pattern resulting from slotting on an Accutom cut-off wheel followed by sharpening with the razor-sawing device.

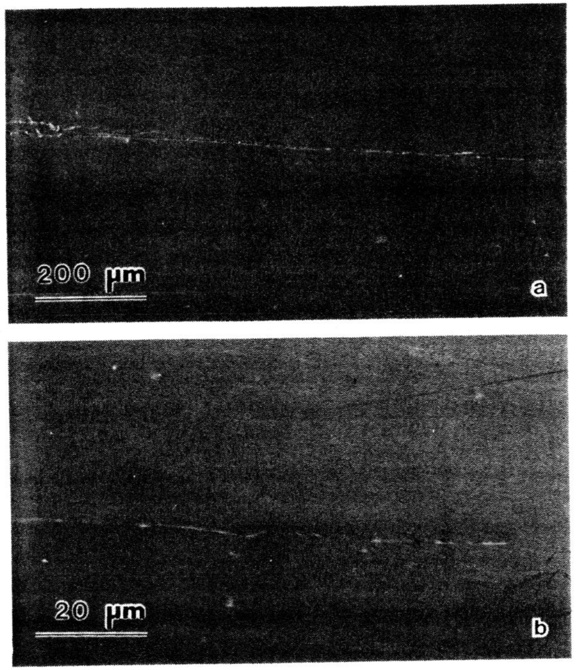

Fig. 6. Scanning electron micrographs of the crack tip in a fatigue precracked specimen.

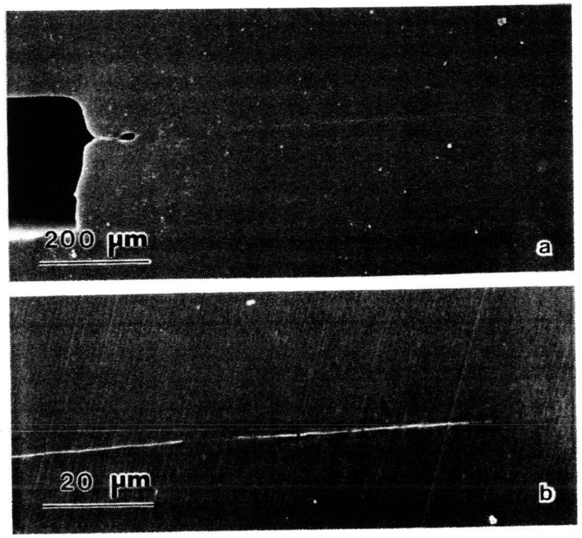

Fig. 7. Scanning electron micrographs of the crack tip in a specimen razor-notched with the guillotine device.

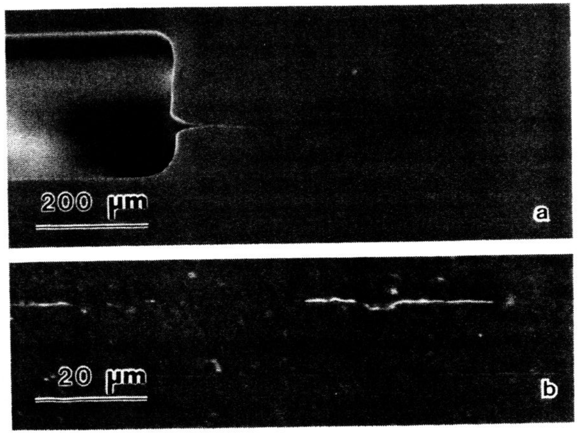

Fig. 8. Scanning electron micrographs of the crack tip in a specimen notched with the razor-sawing decice.

Effect of Precracking Technique on Measured Value of K_{Ic}

After precracking, the specimens were quasistatically tested at room temperature under displacement control at a rate of 1 mm/min on a closed loop servo-hydraulic materials testing system (MTS). Crack lengths were measured on a Nikon Measurescope 20 equipped with table micrometers accurate to within 0.001mm and then calculated using the nine point averaging technique described in ASTM E813-81. The resulting values of the critical stress intensity factor, K_{Ic}, are shown in Fig. 9. The highest value of fracture toughness was measured on the specimens containing chevron notches, razor-notched with the guillotine device directly without the introduction of a fine slot. This is to be expected since these specimens had the largest induced compressive residual stress fields ahead of the crack tip prior to testing. The specimens precracked by the remaining methods all contained regions of stress-free material ahead of the crack tip, which gave lower values of fracture toughness as measured by K_{Ic}.

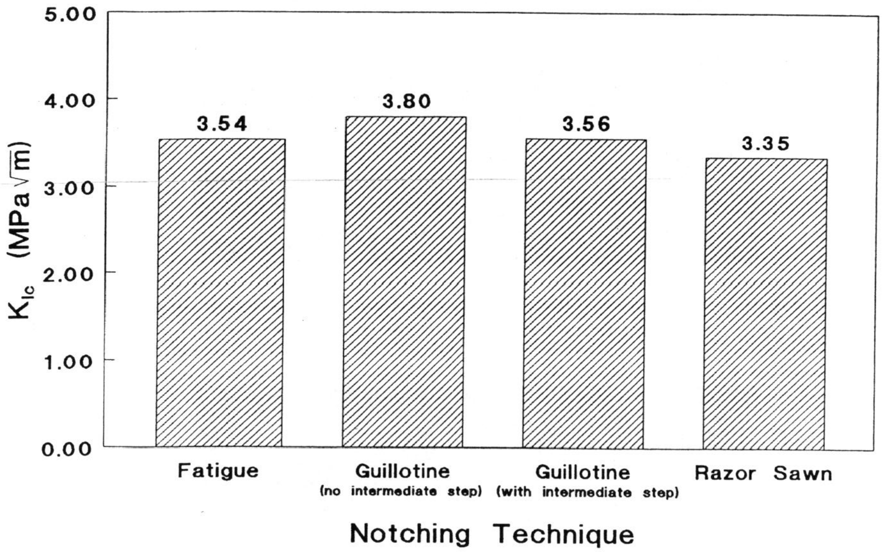

Fig. 9. Average values of the critical stress intensity factor, K_{Ic}, as a function of notching procedure.

CONCLUSIONS & RECOMMENDATIONS

Several conclusions may be drawn from this study.

1. Residual stresses may result from the initial machining of the specimen. This consequence may be minimized by machining the specimen with a chevron.

2. The introduction of a fine slot with a jeweler's slotting saw allows the final sharpening of the crack tip by either the razor-notch guillotine or razor-sawing techniques to be accomplished with a minimal amount of razor blade penetration, minimizing the amount of induced residual compressive stresses ahead of the crack tip.

3. The use of razor notching on certain plastics, if done under careful administration, can yield crack tip radii equivalent to that of fatigue precracking with comparable crack tip residual stress zones which are equivalent or smaller in size.

4. Fatigue precracking, razor-notch guillotine, and razor sawing (the latter two accomplished after the introduction of a fine slot using a jeweler's slotting saw) all provide similar values of fracture toughness under careful administration in polycarbonate.

ACKNOWLEDGMENTS

This work was supported by E.I. Dupont De Nemours & Company located in Wilmington, Delaware. The authors would also like to thank General Electric Company for supplying the Lexan polycarbonate used for this study.

REFERENCES

Darwish, A.Y., J.F. Mandell and F.J. McGarry (1981). Applicability of linear elastic fracture mechanics to rigid PVC pipe Material. *J. Vinyl Technol.*, 3, 246.

Heald, P.T., G.M. Spink and P.J. Worthington (1972). Post yield fracture mechanics. *Mater. Sci. and Eng.*, 10, 129–137.

Jones, R.E. Jr. and W.L. Bradley (1988). Fracture toughness testing of polyethylene pipe materials. In: *3rd International Symposium on Nonlinear Fracture Mechanics* (H. Mahy, Ed.), ASTM STP 995, American Society for Testing and Materials, Philadelphia.

Malkin, J. and A.S. Tetelman (1971). Relation between K_{Ic} and microscopic strength for low alloy steels. *Eng. Fract. Mech.*, 3, 151–167.

Mandell, J.F., A.Y. Darwish and F.J. McGarry (1982). Time and temperature effects on the fracture toughness of rigid poly(vinylchloride) pipe materials. *Polym. Eng. and Sci.*, 22, 826–831.

Mandell, J.F., D.R. Roberts and F.J. McGarry (1983). Plane strain fracture toughness of polyethylene pipe materials. *Polym. Eng. and Sci.*, 23, 404–411.

Marshall, G.P., L.E. Culver and J.G. Williams (1973). Fracture phenomena in polystyrene. *Int. J. of Fract.*, 9, 295–309.

Rack, H.J. (1976). Notch constraint effects on the dynamic fracture toughness of an unaged beta titanium alloy. *Mater. Sci. and Eng.*, 24, 165–170.

Ritchie, R.O., B. Francis and W.L. Server (1976). Evaluation of toughness in AISI 4340 alloy steel austenitized at low and high temperatures. *Met. Trans. A*, 7A, 831–838.

Ritchie, R.O. and R.M. Horn (1978). Further considerations on the inconsistency in toughness evaluation of 4340 steel austenitized at increasing temperatures. *Met. Trans. A*, 9A, 331–341.

Williams, J.G. (1984). *Fracture Mechanics of Polymers.* Ellis Horwood Limited, Chichester, England.