JOURNAL OF MATERIALS SCIENCE 23 (1988) 459–466

Fracture mechanics of polymers. Critical evaluation for linear elastic behaviour at high speed testing

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Over the last few years considerable effort has been made to obtain reliable stress intensity factor and strain energy release rate (K_{IC} and G_{IC}) data on polymeric materials. Experience has shown that a valuable method to minimize viscoelastic losses and plastic deformation is to work at high speed. However, some problems remain, for this kind of experimental method, which have to be solved before standard methods can be defined. On the basis of measurements done with 3-point bending geometry on poly(vinylchloride) (PVC) and poly-(propylene) (PP) at room temperature and over a large range of notch depths, the present work demonstrates that the linearity of experimental data both in the load (F) and in the energy (U) against ($2BW^2/3LY\sqrt{a}$) and ($BW\phi$) plot is not a critical test for linear elastic behaviour, so that K_{IC} and G_{IC} values can be affected by large errors. Only the knowledge of the experimental curves, which can be obtained by means of instrumented pendula in optimized test conditions, allows a critical test to be applied for linear elastic behaviour, based on the comparison between experimental and predicted data for load, displacement and energy. These tests show that the linear elastic fracture mechanics, LEFM, criterion is satisfied for PVC, but not for PP. This conclusion is further supported by the morphologies of the fracture surfaces.

1. Introduction

In recent years attention has been given to the measurement of fracture mechanics properties of polymers by impact testing. The most popular test geometry used was 3-point bending (3PB) [1–8].

In general, the approach is based on measurements taken from plots of the energy against $BW\phi$ (B, W and ϕ are the thickness, the width and the shape factor for the specimen used). If these plots fit a straight line it is agreed that the conditions of linear elastic fracture mechanics (LEFM) principles are fulfilled. In other words G_{IC} is described by the equation:

$$G_{IC} = \frac{U_c}{BW\phi} = \frac{U_{tot} - U_k}{BW\phi} = \frac{U_{tot}}{BW\phi} - \text{constant} \quad (1)$$

where U_{tot} is the total energy spent to break the specimen, U_c is the elastic energy and U_k is the kinetic energy of the specimen [4].

In the fracture mechanics experiments to be described here we observed that such a condition is not sufficient. We found that Equation 1 is valid only if the experimental curves of load–displacement obtained on specimens with different crack lengths are straight, so that the failure compliances are equal to the elastic compliances obtained at approximately the same test speed. The elastic compliances can be obtained by rebound experiments [9].

2. Fracture mechanics parameter from impact testing

Stress intensity factor, K_{IC}, and strain energy release rate, G_{IC}, values may be calculated for the 3PB condition through the well known equations:

$$K_{IC} = Y\sigma_c\sqrt{a} = Y\frac{3F_cL}{2BW^2}\sqrt{a} \quad (2)$$

and

$$G_{IC} = U_c/BW\phi \quad (3)$$

where Y and ϕ are geometric factors dependent on the length of the crack.

Values of the load at failure (F_c) are directly derived from the experimental curves, while the failure energy (U_c) and displacement (δ_c) are derived by integration of the experimental curves through the following equations [10]:

$$U_c = \int_0^{t_c} F\,dt\left(V_0 - \frac{\int_0^{t_c} F\,dt}{2M}\right) \quad (4)$$

$$\delta_c = V_0 t_c - \frac{1}{M}\int_0^{t_c}\left(\int_0^{t_c} F\,dt\right)dt \quad (5)$$

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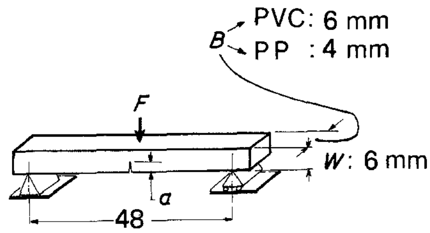

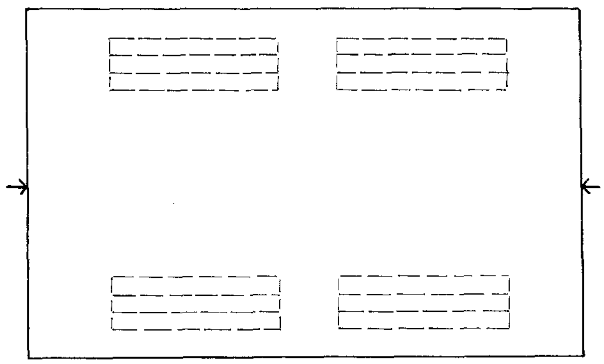

Figure 1 Specimen and test conditions.

where V_0 and M are the initial velocity and the effective mass of the hammer, respectively, and t_c is the time to fracture. The integrations in Equations 4 and 5 can be easily done with an on-line computer.

It is now possible to calculate the value of the experimental compliance at failure (C_c) by:

$$C_c = \delta_c/F_c \tag{6}$$

If the specimen behaviour was linear elastic up to the rupture, the failure compliance must agree with the elastic compliance (C_0) determined through rebound tests upon specimens with various crack lengths i.e. :

$$C_0 = \frac{t_0^2}{\pi^2}\frac{1}{M} = \frac{1}{\omega^2 M} = C_c \tag{7}$$

where t_0 is the rebound time (see Fig. 3) and ω is the angular velocity ($\omega = \pi/t_0$).

The values of the loads, displacements and energies at break can be theoretically calculated, on the basis of the rebound experiments, by means of the following equations (These equations are a simplification of those reported in [9].):

$$F_{c,\mathrm{LEFM}} = MV_0\omega \sin \omega t_c \tag{8}$$

$$\delta_{c,\mathrm{LEFM}} = \frac{V_0}{\omega} \sin \omega t_c \tag{9}$$

$$U_{c,\mathrm{LEFM}} = \frac{F_c\delta_c}{2} = \frac{F_c V_0 \sin \omega t_c}{2\omega} \tag{10}$$

3. Experimental methods

3.1. Materials and specimens

Fracture mechanics experiments were carried out on poly(vinylchloride) (PVC) and polypropylene (PP) specimens. PVC and PP specimens were machined out of injection moulded plates. In both cases the major axis direction of the specimens was parallel to the direction of injection, as shown in Fig. 1.

The specimen dimensions were thickness × 6 mm × 60 mm. The notch was made in two stages; first by a flying cutter fitted with a U-tool; then it was sharpened by inserting a razor blade at the tip of the U-notch. The sharp notch was not deeper than 0.2 mm. The total notch depth was varied to give a/w ratios between 0.1 and 0.8.

3.2. Experimental testing procedure

Previous work showed that very reliable data can be obtained from instrumented pendula under the following experimental conditions.

1. The transient, caused by the inertia effect and the pulse at the moment of first contact between the nose of the hammer and the specimen [11] can be minimized

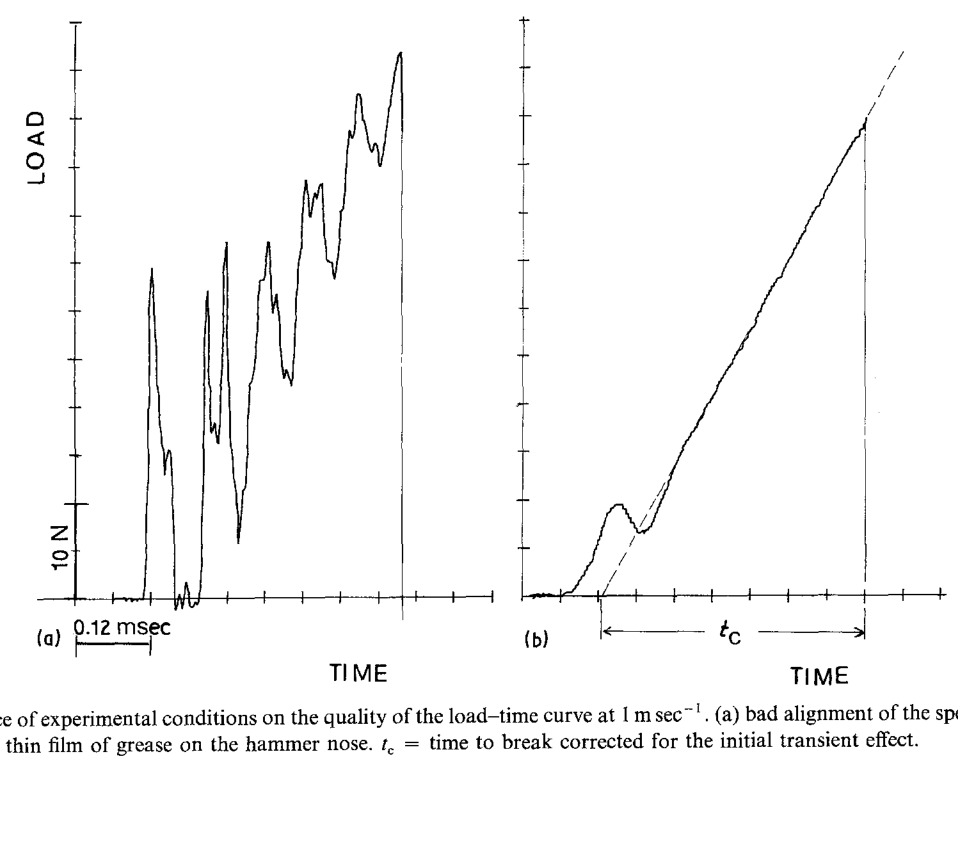

Figure 2 Influence of experimental conditions on the quality of the load–time curve at 1 m sec^{-1}. (a) bad alignment of the specimen. (b) good alignment and a thin film of grease on the hammer nose. t_c = time to break corrected for the initial transient effect.

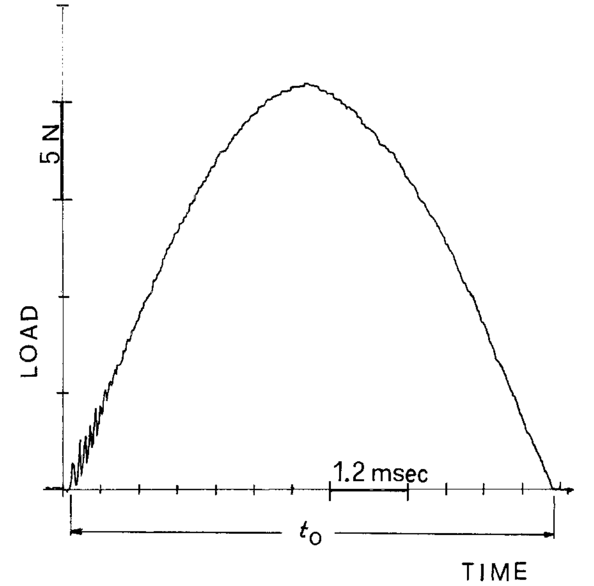

Figure 3 Determination of compliance from a rebound test. Example of an experimental curve obtained for 3PB geometry on a U-notched specimen. Pulse time (t_0) is used to calculate the elastic compliance C_0 through Equation 7. Experiment carried out without the thin film of grease.

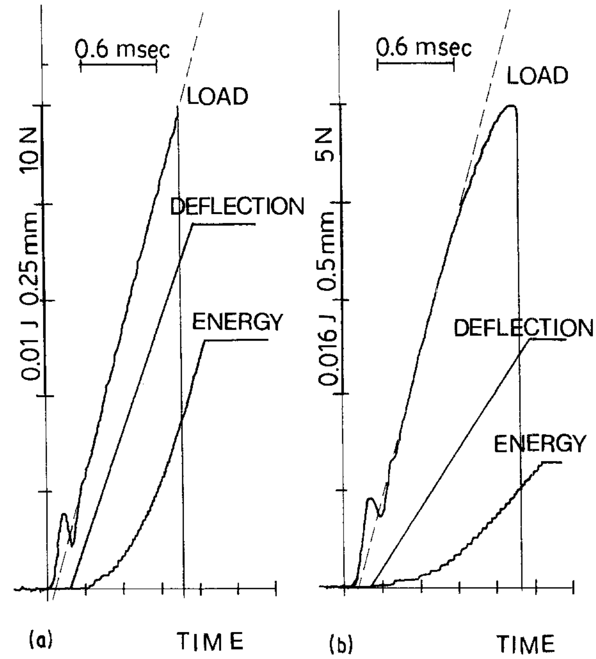

Figure 4 Fracture mechanics, 3PB. Example of experimental curves of load, displacement and energy. Displacement and energy are calculated from the load signal by means of a microcomputer using Equations 4 and 5. (---) theoretical curves calculated using rebound data and the equation: $F_{\text{LEFM}} = MV_0\omega \sin \omega t$.

if the impact speed is not higher than $2\,\text{m sec}^{-1}$ and a very thin film of grease is put on the nose of the hammer.

2. The alignment of the specimen with respect to the support plane and the hammer nose must be optimized to avoid small rotations of the specimen and spurious vibrations at the beginning of the experiment which can adversely affect the quality of the recorded curves. An example is given in Fig. 2.

3. The compliance of the pendulum must be taken into account. Sometimes it is comparable, or at least not negligible, to that of the specimen. Ignoring the compliance correction can bring about large errors for displacement and energy.

Consequently great care was used in carrying out experiments. The instrumented pendulum [12] had an effective mass for the hammer of 2.35 kg and the measured machine stiffness was $10\,\text{MNm}^{-1}$ [13].

The span of the 3PB geometry used was 48 mm.

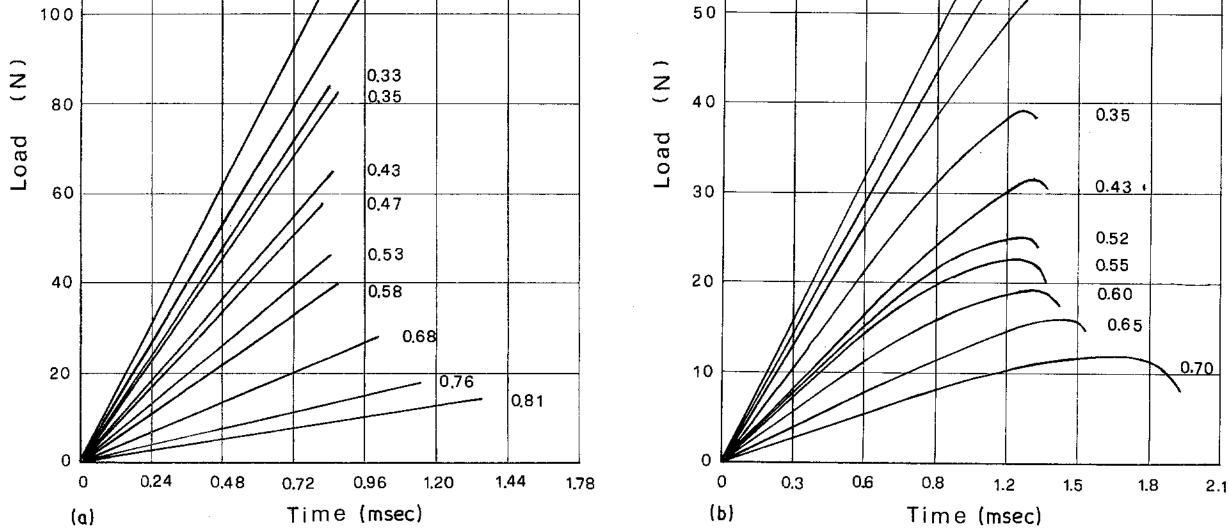

Figure 5 Fracture mechanics, 3PB. Experimental load–time curves of the two materials for specimens with different crack lengths. Test conditions: $V_0 = 1\,\text{m sec}^{-1}$, $T = 23°\,\text{C}$. These data have been corrected for the compliance of the pendulum.

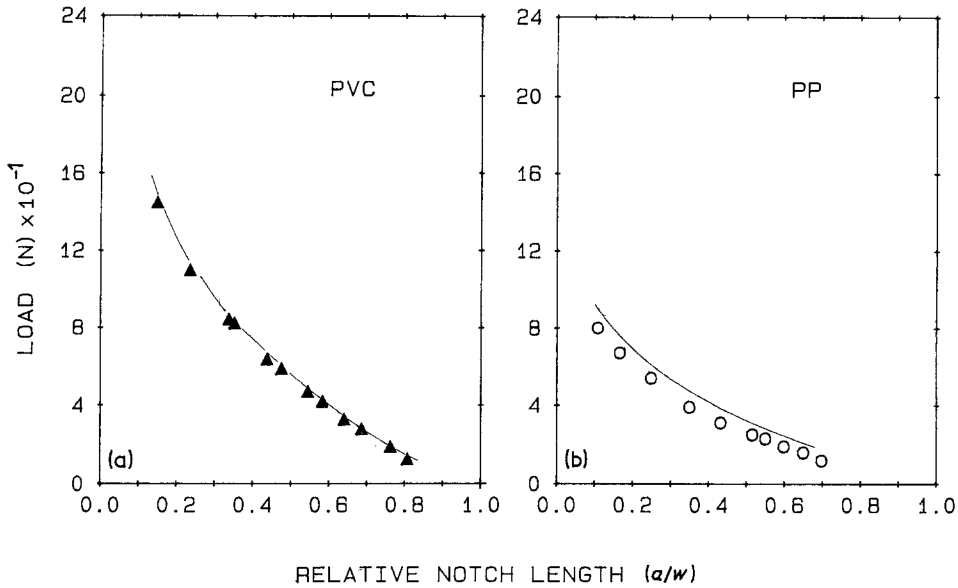

Figure 6 Fracture mechanics, 3PB. Comparison between experimental failure load values (▲) (○), and those calculated by Equation 8 (– – –) against relative notch length (a/w). Test conditions: $V_0 = 1\,\mathrm{m\,sec^{-1}}$, $T = 23°\mathrm{C}$.

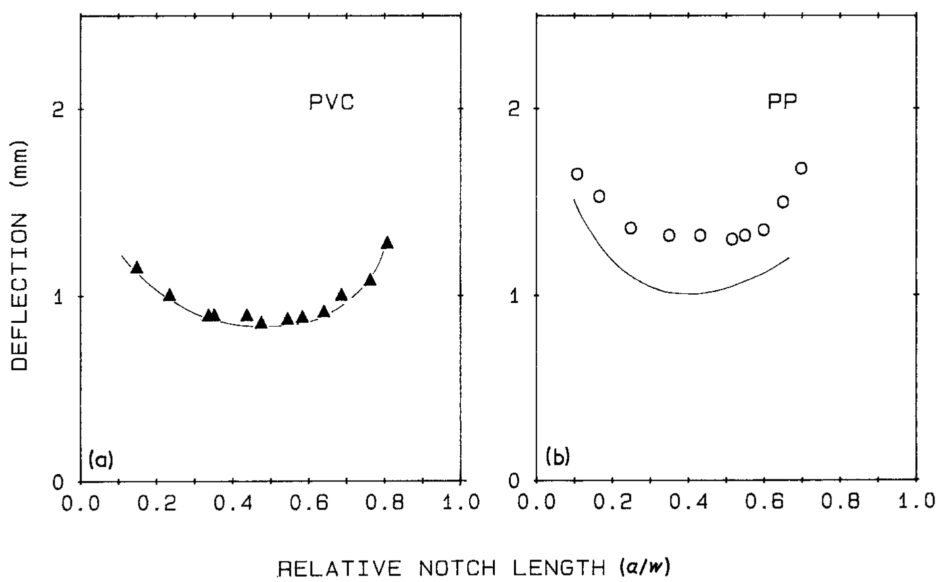

Figure 7 Fracture mechanics, 3PB. Comparison between experimental deflection values at the maximum load (▲) (○), and those calculated by Equation 9 (– – –) against relative notch length. Test conditions: $V_0 = 1\,\mathrm{m\,sec^{-1}}$, $T = 23°\mathrm{C}$.

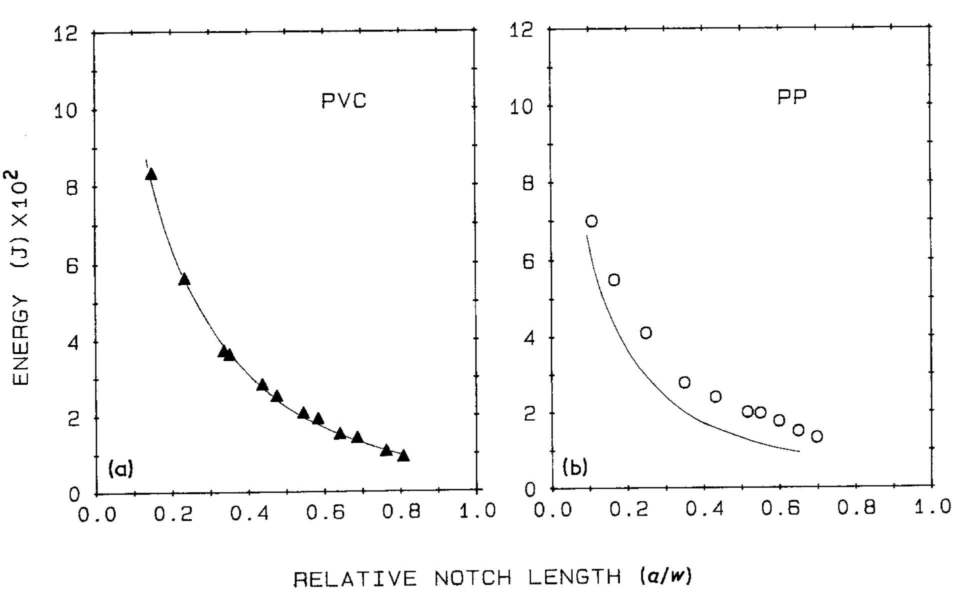

Figure 8 Fracture mechanics, 3PB. Comparison between experimental energy values at the maximum load (▲) (○), and those calculated by Equation 10 (– – –) against relative notch length. Test conditions: $V_0 = 1\,\mathrm{m\,sec^{-1}}$, $T = 23°\mathrm{C}$.

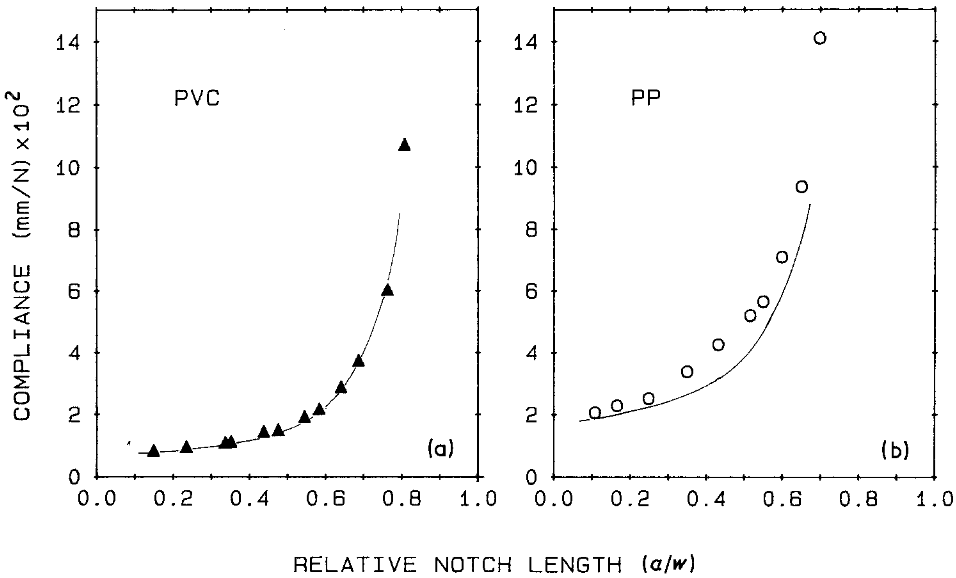

Figure 9 Rebound and fracture mechanics test, 3PB. Comparison between compliance values at the maximum load by fracture mechanics test (▲) (○), and elastic compliance values obtained by rebound test (– – –) against relative notch length.

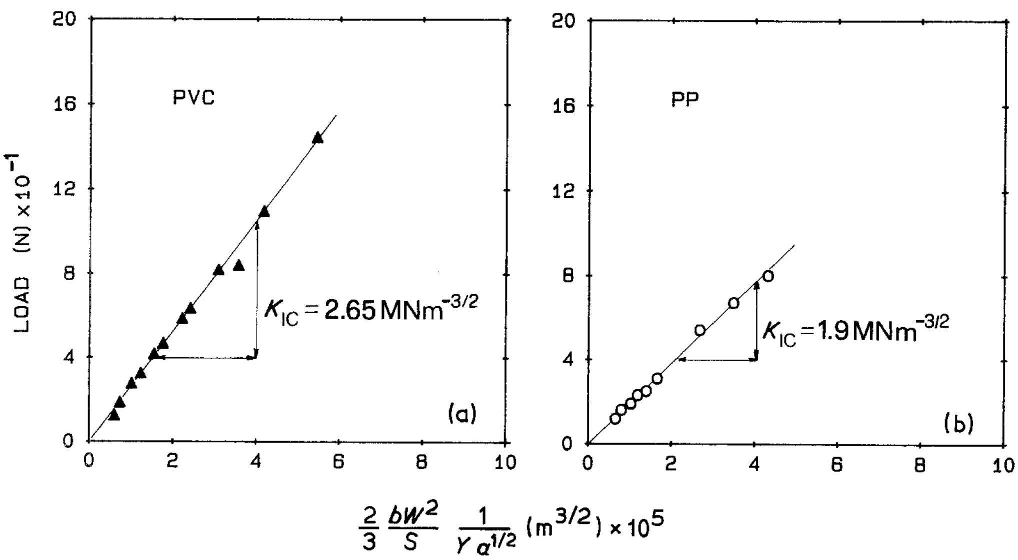

Figure 10 Fracture mechanics, 3PB. Graphical evaluation of K_{IC} by Equation 2.

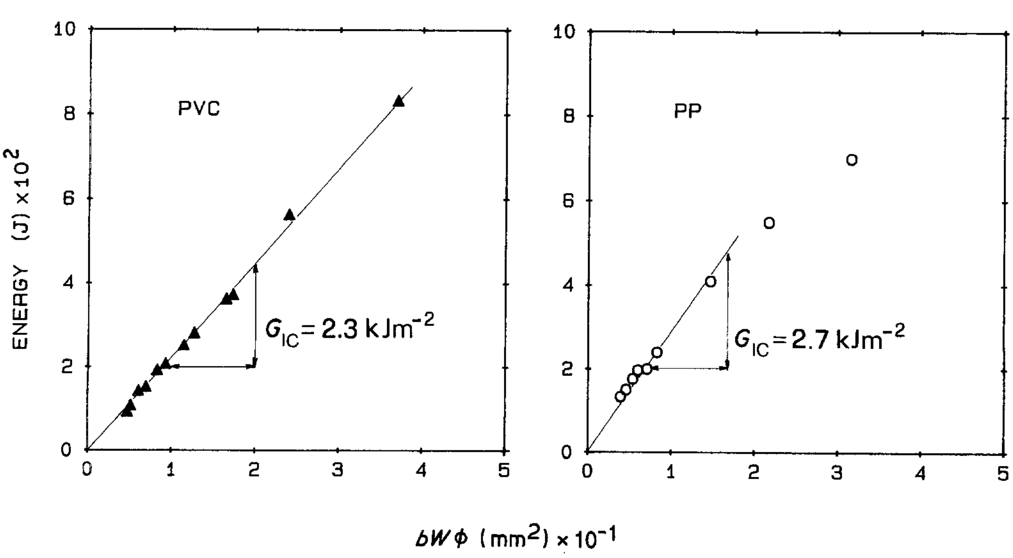

Figure 11 Fracture mechanics, 3PB. Graphical evaluation of G_{IC} by Equation 3.

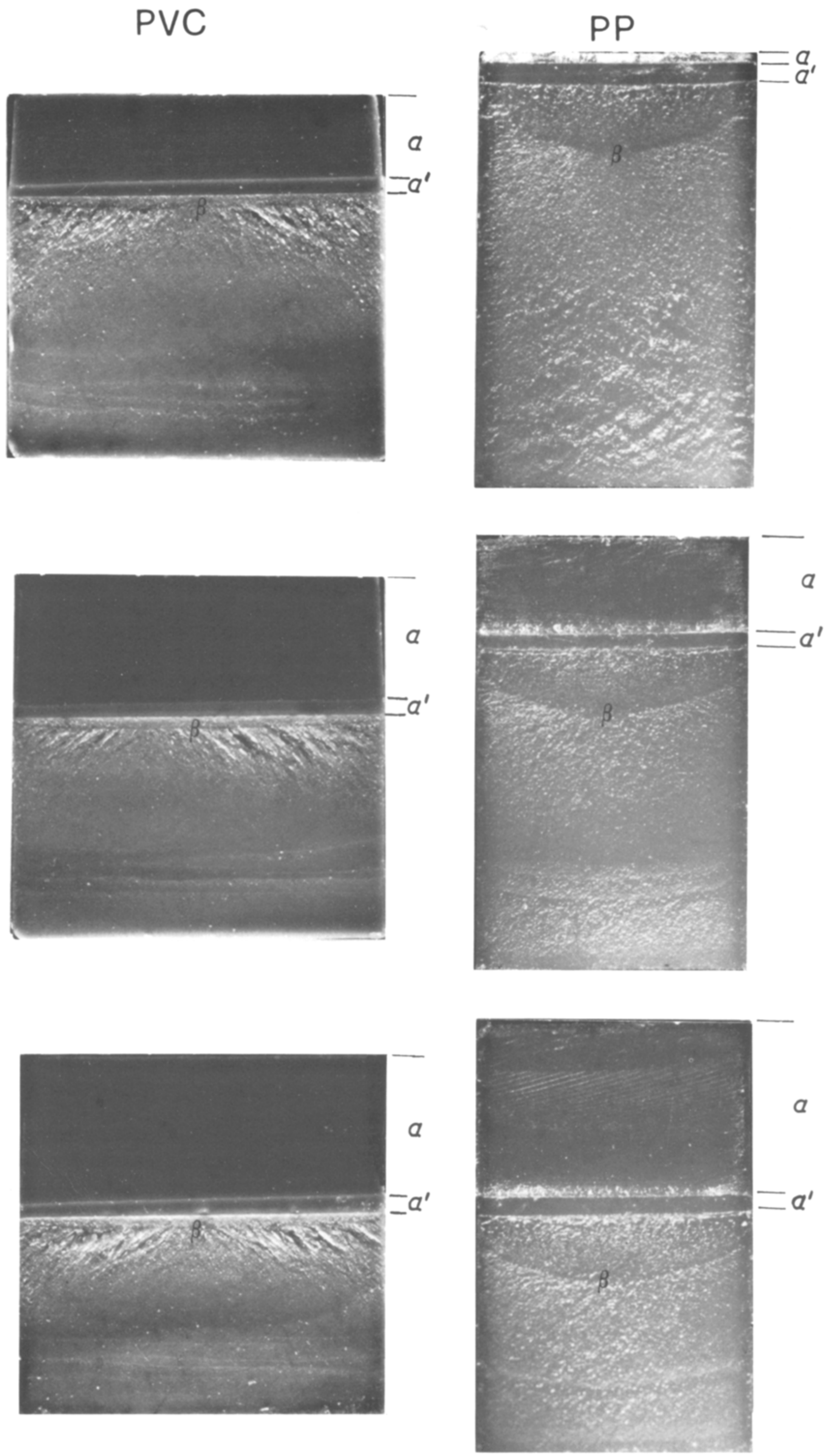

Figure 12 Fracture mechanics, 3PB. Fracture surface morphologies of specimens with different a/w ratios. a: notched by U-tool only. a': sharp notch, β: curved front of crack slow growth area.

Two tests were carried out on each specimen:

(a) the rebound test on U-notched specimens in order to determine the elastic compliances; the testing speed was $0.2\,\mathrm{m\,sec^{-1}}$;

(b) the impact test was carried out at $1\,\mathrm{m\,sec^{-1}}$ on the same specimens after sharpening the notch with the razor blade.

The maximum load reached in the course of the rebound test was between 1 and 10% of the maximum load measured in the impact test.

4. Results and discussion

An example of a rebound curve is shown in Fig. 3 and examples of traces recorded for load, energy and displacement for PVC and PP are given in Fig. 4.

The set of experimental curves obtained on both samples as a function of the reduced crack depth are shown in Fig. 5. While the PVC behaviour is linear elastic over the a/w range, PP always shows marked deviations from linearity. Such non-linear behaviour, first of all raises the problem of choosing data to be used in the calculation. It was decided to use the data at the maximum load since these are not only available for each a/w value, but also the deviation from linearity is less than for data taken at break. The values of maximum load (at break for PVC), displacement, energy and compliance at the maximum load (at break for PVC) obtained from the experimental curves are compared in Figs 6 to 9 with the corresponding theoretical values calculated using Equations 8 to 10 and Equation 7, respectively, on the basis of rebound data and the time at break (t_c).

These data confirm the non-linear elastic behaviour of PP and the compliance data clearly show that the deviation increases with reduced notch depth.

However, when the data for the maximum load or energy is plotted, in the usual manner against $2BW^2/3LY\sqrt{a}$ or $BW\phi$, respectively, one obtains the unexpected result that both PVC and PP data fit straight lines passing through the origin (Figs 10 and 11). Consequently one can erroneously conclude that both materials behave in a linear elastic manner and that the calculated values for K_{IC} and G_{IC} (reported on the same figures) are soundly based.

However, it has to be noted that the geometric factors Y and ϕ are calculated on the basis of the elastic compliances. In the case of PP the compliances at the maximum load are higher than the elastic ones as a consequence of plastic deformation occurring at the crack tip. Thus it is doubtful whether the geometric factors, calculated on the basis of linear elastic behaviour, still apply. The linearity of the plot can be accidental. Finally another fact must be underlined from the experimental point of view. The U against $BW\phi$ line passes through the origin and correction for the kinetic energy of the specimen is unnecessary since it is very low (for a specimen of $3\,\mathrm{mm} \times 6\,\mathrm{mm} \times 60\,\mathrm{mm}$ and $V_0 = 1\,\mathrm{m\,sec^{-1}}$ it is about 0.0005 J). In the case of non-instrumented pendula, it is possible that the energy at break includes the energy spent in spurious deformation of the hammer, since these generally have very low stiffness. This illustrates the superiority of the instrumented method.

The different mechanical behaviour of the two polymers is further confirmed by the shape and size of the slow crack growth areas (thumbnail areas). These are shown in Fig. 12 for specimens with different a/w ratios. Thumbnail areas for PVC are very small, while those for PP are larger and have a very curved boundary (β in Fig. 12).

All these results reflect the differences in behaviour of the two polymers, which can be explained in terms of a portion of the specimen thickness being subject to yielding because of the plane-stress state. Moreover a contribution from molecular relaxation phenomena [14] cannot be excluded for PP. Indeed for the testing temperature and speed used here, the amorphous phase of PP is in proximity to a strong dissipation peak [15].

5. Conclusion

The results of this work show that the normal criterion used to assess the linear elastic behaviour in fracture mechanics experiments is not always a critical one. It can lead to misleading results especially in the case of impact testing with non-instrumented pendula. The new critical criterion proposed here is based on the following experimental observations:

1. linearity of load–time curves up to rupture or, alternatively, equality between elastic compliances measured by the rebound technique and those measured at break;
2. very small slow crack growth area.

It has also been pointed out that results from instrumented pendula can be reliable only if certain experimental procedures are used and the compliance of the pendulum is taken into account. Very small specimens should be used to avoid the kinetic energy correction for example.

The results reported here are the preliminary part of a larger programme on high speed fracture mechanics. Work now in progress is concerned with the specimen size effect on K_{IC} and G_{IC} limiting values and on the size of the crack slow growth area, and further work seeks a simple experimental fracture mechanics method for rigid–plastic behaviour of polymers.

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Received 24 March 1986
and accepted 15 January 1987