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Problems in fracture mechanics characterization of rubber-modified glassy polymers, using double torsion

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The double torsion fracture test was tentatively applied to some rubber-modified glassy polymers. By varying the specimen thickness, a substantial variation of the fracture toughness values was obtained, which cannot be attributed to variations of material's properties. Two sorts of problems were encountered, due to the large deformations attained during the test. Firstly, large deformations imply variations in the load moment arm since radii of load points are finite; secondly, system and/or material non-linearities, that are outside the scope of the classic theory of double torsion, may become significant. The application of a purely geometrical correction factor, to account for the large deformations, somewhat reduces, but does not eliminate, the observed thickness dependence of fracture toughness.

1. Introduction

The double torsion (DT) test appears to be an attractive experiment to investigate the fracture toughness, G_c, of rate-sensitive materials such as polymers. Originally developed for ceramics this test has been recently applied to brittle polymeric materials too. Works on the development of the DT test have been reviewed in [1].

In spite of the experimental simplicity of the test, analysis of its results presents some difficulty mainly because of the curved crack profile. One of the basic characteristics of this test configuration is the linear dependence of the specimen compliance, C, on crack length, a, as expected on the basis of linear elastic analysis [2]:

$$C = \frac{l^2}{\mu W B^3 k_1} a + C_0 \quad (1)$$

where l is the distance between the two points of load application, μ is the shear modulus, k_1 is a geometrical correction factor, B and W are the specimen thickness and width respectively (Fig. 1).

If the fracture test is carried out in a displacement-controlled machine and G_c is a monotonically increasing function of the crack speed $\dot{a}$, the crack will grow steadily under a constant load, P_c, and at a constant speed, $\dot{a}$, both of which can be varied by changing the applied displacement rate, $\dot{x}$. The fracture toughness G_c and the nominal crack speed $\dot{a}$ can then be calculated through their dependence on the critical load, P_c, and the compliance derivative, dC/da (which can be obtained from Equation 1 or determined experimentally) as follows:

$$G_c = \frac{P_c^2}{2B_c}\frac{dC}{da} \quad (2)$$

and

$$\dot{a} = \frac{\dot{x}}{P\, dC/da} \quad (3)$$

where B_c is the specimen thickness above the groove (grooving is usually employed in this test to drive the crack, so that $B_c \neq B$). Thus, it is only necessary to measure the steady critical load P_c to be able to determine both G_c and $\dot{a}$. Moreover, by correcting G_c to account for the crack front curvature [3], it is possible to obtain the crack resistance function, $R(\dot{a})$, a postulated material property.

Based on fracture mechanics considerations, it is expected that each fracture test has its own specimen size limits that need to be satisfied in order to obtain valid fracture toughness values, irrespective of specimen size. The size requirements of the DT test have not been established yet.

With the more brittle polymeric materials, the range of specimen dimensions required for valid G_c measurements normally seems to be met, once stationary crack growth conditions (dC/da = const., $\dot{a}$ = const., P_c = const.) are fulfilled [1].

In this work we applied the DT test to different toughened polymers that show more or less ductile fracture behaviour in other more conventional fracture mechanics tests. The validity of fracture toughness determination by DT on these materials was

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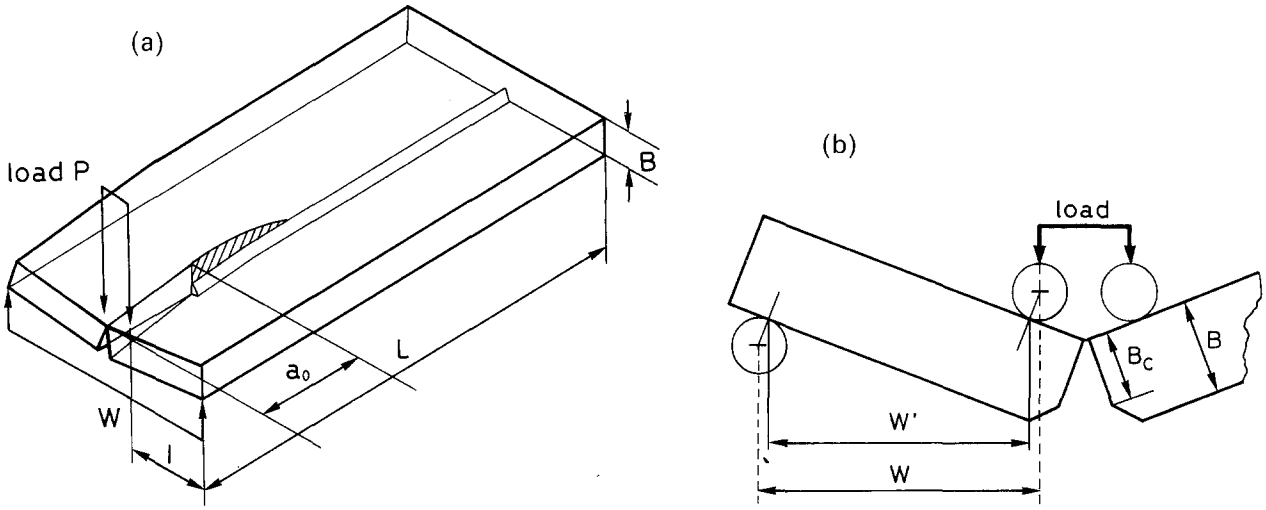

Figure 1 (a) Double torsion geometry and loading arrangement, and (b) load-plane section showing variation in the load moment arm ($W \rightarrow W'$) due to finite load point radii.

investigated by varying specimen thickness. Comparison with results obtained from more conventional three-point-bending ($SE(B)$) fracture tests will also be presented.

2. Experimental procedures

Two different grades of rubber-modified polymethylmetacrylate (PMMA), containing 9 and 18 wt % of acrylic rubber, were compression moulded at 200° C into plates of different thicknesses. Extruded sheets of different thicknesses of an unmodified PMMA were also examined. All PMMA samples were kindly supplied by Vedril S.p.A. (Italy).

A rubber-modified epoxy resin containing about 18 wt % of carboxyl-terminated-butadiene-nitrile (CTBN) rubber (commercially available from 3M Co.) was shaped into plates of different thicknesses, cured at 120° C for 1 h and post-cured at 160° C for 24 h. The tensile properties (Young's modulus, E, and yield stress, σ_y) as a function of the rubber content of the materials are shown in Table I.

The DT specimens, with in-plane dimensions L = 127 mm and W = 25 mm, and thickness B ranging from 3 to 12 mm, were side-grooved to a depth of 15 to 20% of the thickness and notched at one end. The $SE(B)$ specimens, with span-to-width ratio $L/W = 4$, L = 12.7 mm and thickness B ranging from 3 to 12 mm, were sharply notched to a notch-to-width ratio $a_0/W = 0.6$.

All tests were carried out at room temperature. Cross-head speed in $SE(B)$ was 5 mm min^{-1}, whereas in the DT tests it was chosen in such a way as to obtain crack speeds ranging from 1.5 to 2 mm s^{-1}.

TABLE I Tensile properties of the materials studied

	PMMA			Epoxy
Rubber content	0	9	18	18
E (GPa)	3.3	2.6	1.8	2.0
σ_y (MPa)	–	67	51	49

3. Results

The G_c values obtained from DT tests via Equation 2 for the PMMA samples with different rubber contents are shown in Fig. 2a, as a function of specimen thickness, B_c. While unmodified PMMA shows substantially constant values of the fracture toughness, both rubber-modified PMMAs exhibit a marked increase in G_c with thickness. A quite similar thickness effect is shown by the G_c values obtained for the rubber-modified epoxy resin (Fig. 2b). Correction of all G_c values to account for the crack front curvature does not alter the results obtained significantly. However, since large deflections are involved in tests performed on the rubber modified samples, the data in Fig. 2 should also be corrected according to Leevers [4], to take into account the finite load point radii when large deflections are attained (LD correction).

Figure 3 shows the LD correction factor calculated as a function of the load point displacement, u, – normalized with respect to specimen width, W – for the different thicknesses; displacement ranges covered during the crack propagation in our fracture tests are also outlined.

It is apparent that: (i) the LD correction varies strongly with specimen thickness and (ii) as the crack propagation extends over a large range of deflections, the LD correction varies considerably during each single test. This last observation implies that the load, too, ought to vary considerably during the test, if G_c is to remain constant as expected*. It is also worth remarking on the non-monotonic dependence of the LD correction factor on deflection in Fig. 3; the maximum (or minimum) value of the correction does not necessarily coincide with the maximum (or minimum) deflection reached by the specimen during the test.

Application of these correction factors to calculate more accurate values of G_c is presented in Fig. 4: the bars indicate the total variation of the corrected G_c (corresponding to variations of the correction factor between its minimum and maximum values in each test) for all the materials examined. The thickness

*Hine *et al.* [5], in fact, have noticed a rise in the load during fracture when they tested materials that require deflections large enough to call for some correction. No appreciable load variations have so far been noticed in our tests.

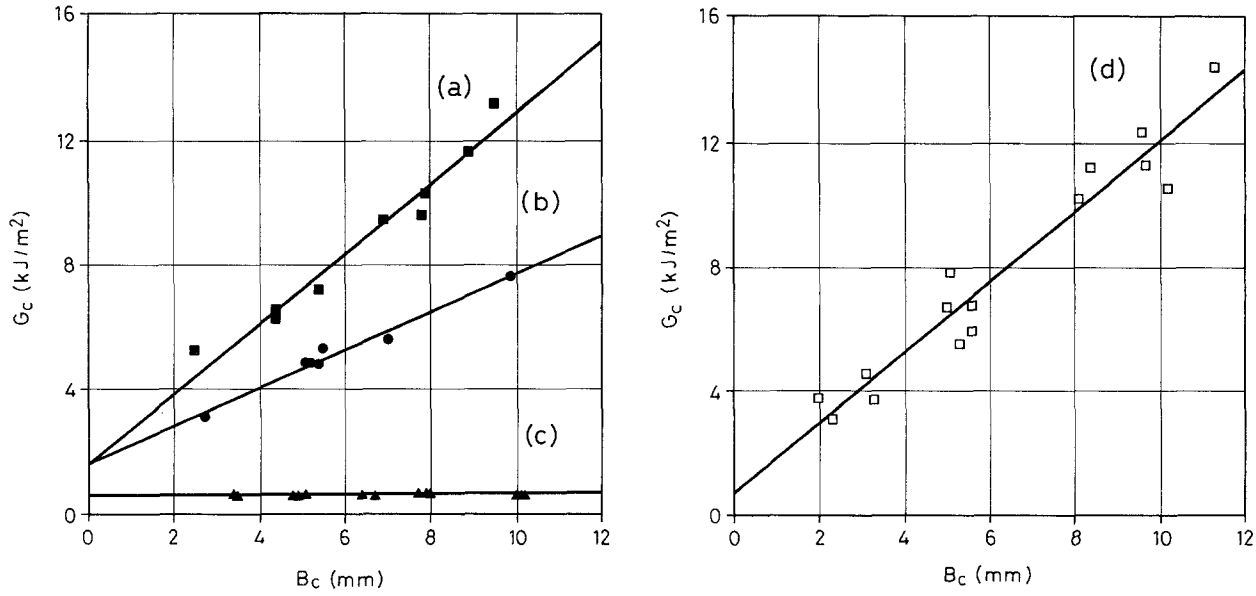

Figure 2 Fracture toughness G_c determined from linear elastic Equation 2 plotted against specimen thickness B_c for neat PMMA (a), two 9% and 18% rubber-modified PMMAs (b and c respectively), and an 18% rubber-modified epoxy (d). Points, experimental; lines, least-squares fit.

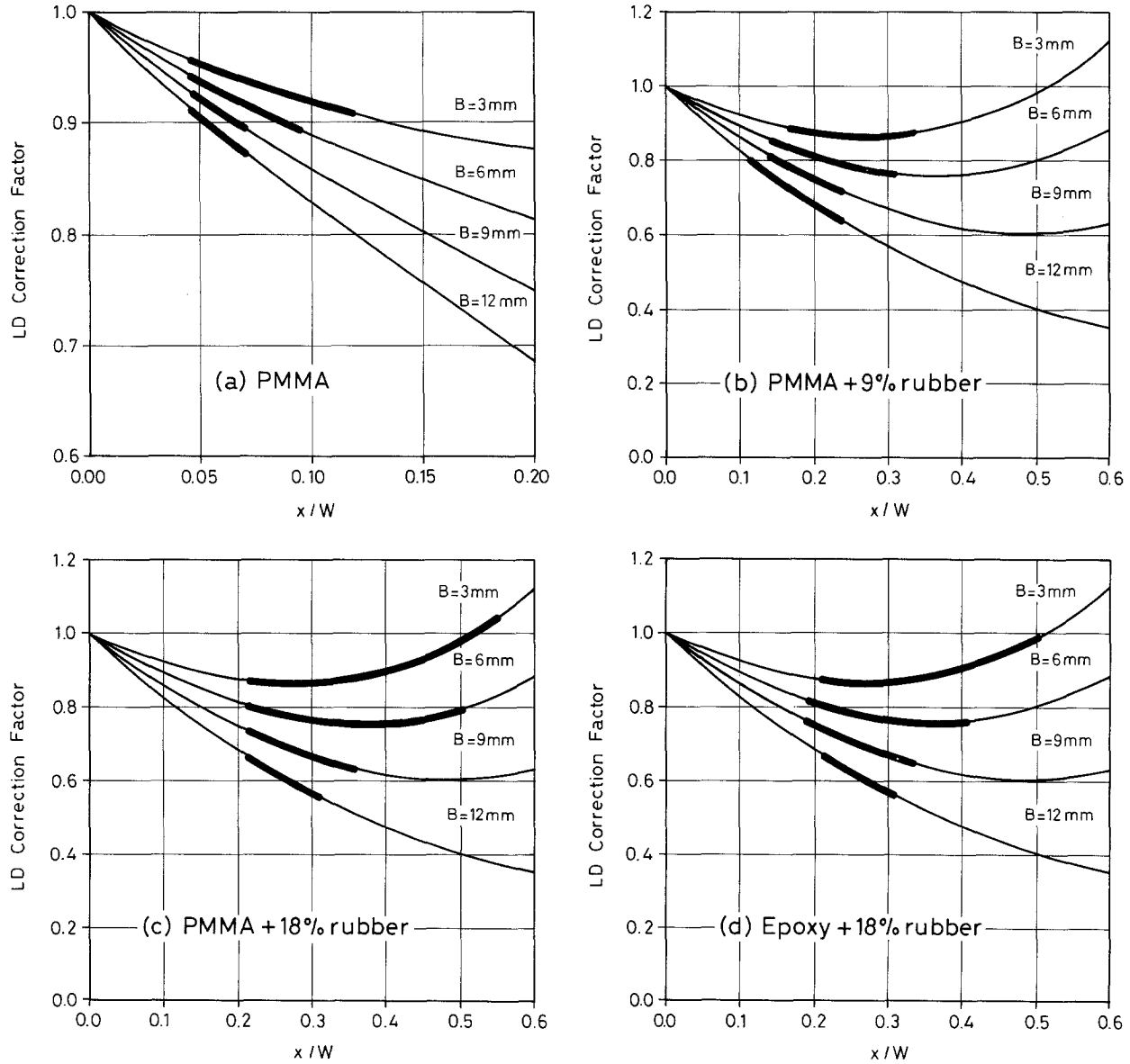

Figure 3 Large displacement (LD) correction factor against normalized load point displacement. Thick sections of the lines refer to the deflection ranges covered experimentally with each material tested: (a)–(d) as per Fig. 2.

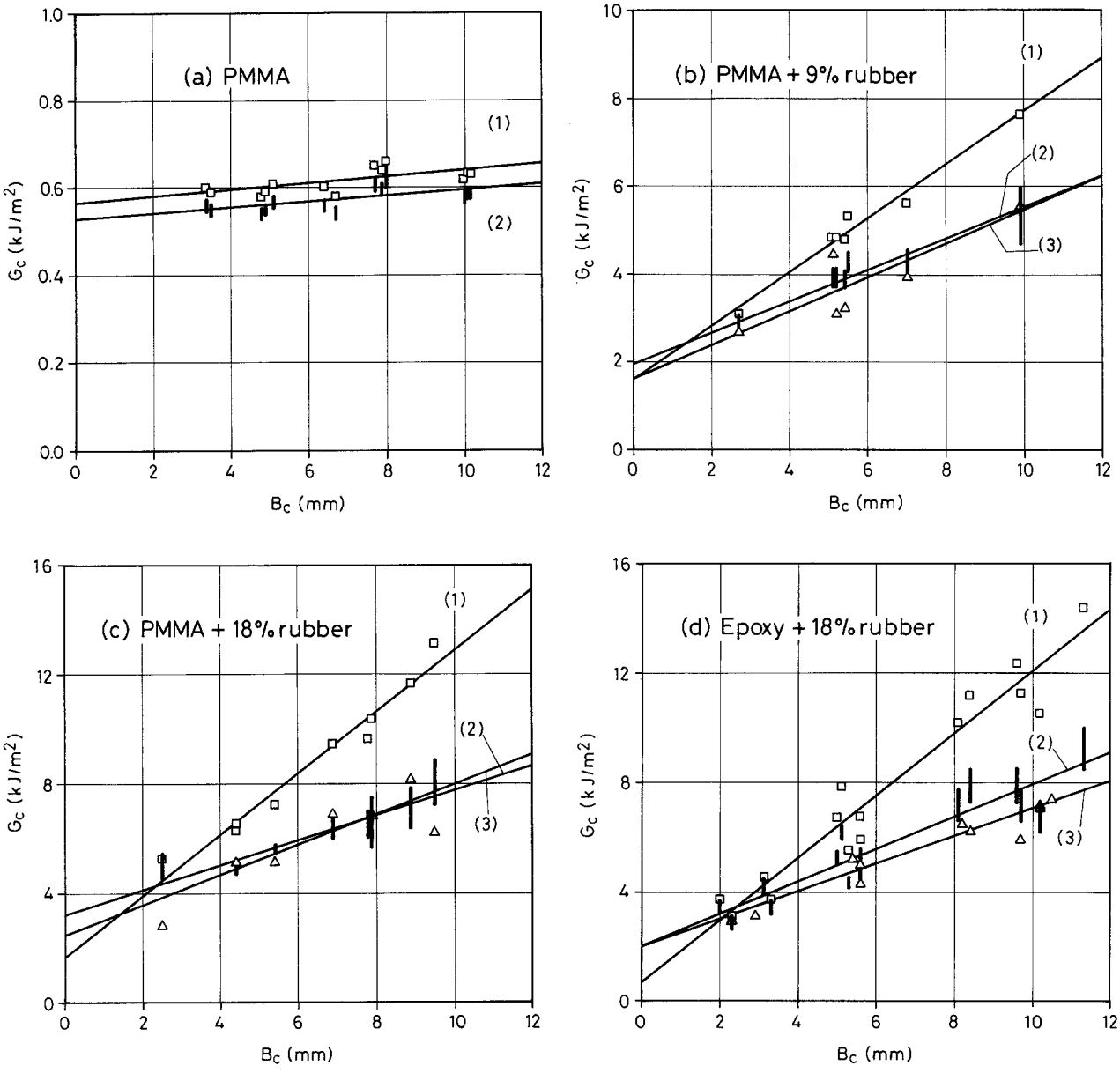

Figure 4 Fracture toughness G_c plotted against specimen thickness B_c for each material tested: (a)–(d) as per Fig. 2. (1) G_c determined from Equation 2: points □, experimental; line, least-squares fit; (2) G_c determined from Equation 2 corrected for LD: bars, total variation of corrected G_c (see text); line, least-squares fit through mid points; (3) G_c measured according to its definition, Equation 4: points △, experimental; line, least-squares fit.

dependence of G_c appears significantly reduced, but still present in all rubber-modified materials, while it remains negligible in neat PMMA.

In order to cross-check this result, we have also estimated G_c directly, according to its definition:

$$G_c = -\mathrm{d}U/\mathrm{d}A \tag{4}$$

where $\mathrm{d}U$ is the amount of strain energy released by the specimen for an increase $\mathrm{d}A$ in the cracked surface area. Since the transition from stable crack growth to final catastrophic break always leaves a clear mark on the fracture surface, it was possible to identify the total area of stationary fracture (as specified in [1]), ΔA, on the specimen surface after the test, Fig. 5b, while the corresponding amount of released fracture energy, ΔU, was obtained from the load-displacement record, as shown in Fig. 5a. The G_c values calculated in this way are also shown in Fig. 4. They appear to be in close agreement with those obtained by evaluating G_c via Equation 2 plus LD correction, showing the same thickness dependence.

In order to verify that no variations of material properties arose from processing the materials into plates of different thicknesses, the three rubber-modified materials were also studied in *SE(B)*, i.e., a better consolidated fracture mechanics test, on specimens cut from the same plates used for DT tests. The fracture toughness was determined by the *J*-resistance curve method, according to the multispecimen technique covered by the ASTM standard E 813-81†. The values of fracture toughness at crack initiation, J_{Ic},

† Although the data handling recommended by this standard is now being questioned, on the grounds that a plot of *J* against crack extension may be non-linear for some materials, we have adopted this conventional method to identify an "engineering" value of *J* at the onset of crack extension.

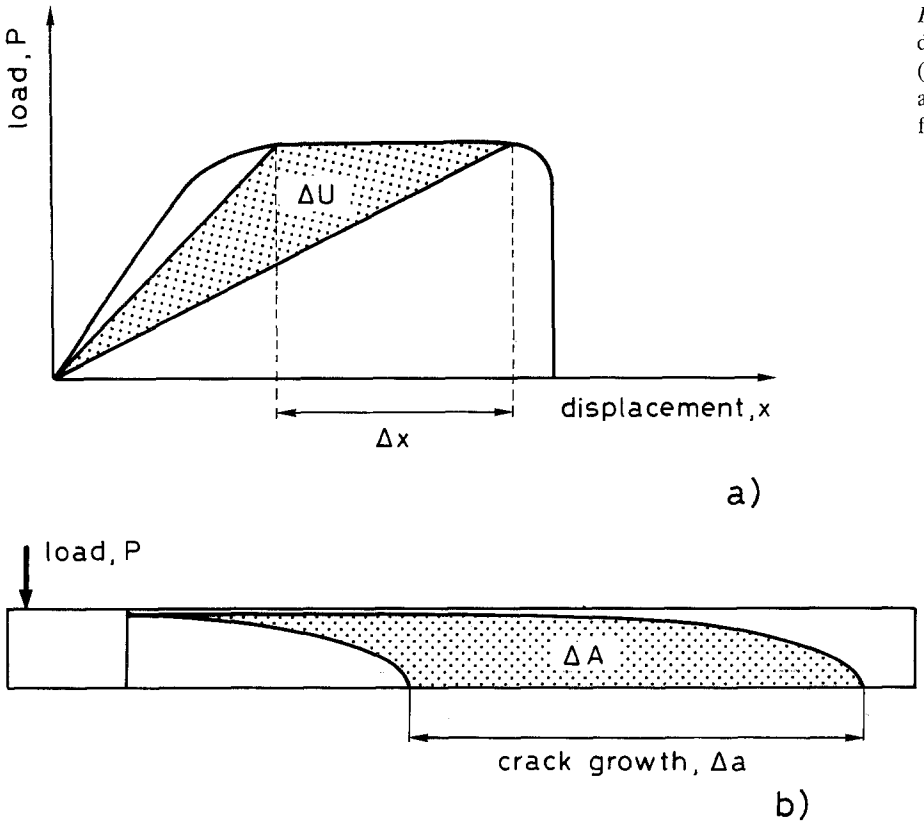

Figure 5 (a) Fracture energy, ΔU, during stationary crack growth, and (b) corresponding fracture surface area, ΔA, considered in calculating G_c from its definition, Equation 4.

were found to be invariant with plate thickness and are given in Table II below.

With these values of J_{Ic} the size requirements set forth by the same standard, i.e.,

$$B, (W - a_o) > 25 J_{Ic}/\sigma_y$$

were found to be met by all specimens. Since no thickness dependence of J_{Ic} was detected, it is demonstrated that no variations of material properties arose from processing the materials into plates of different thicknesses and that the effect observed in DT is specific to that type of test.

4. Conclusions

In the present investigation the double torsion fracture test was tentatively applied to some rubber-modified glassy polymers. Compared with plain glassy polymers these toughened variants need to attain larger deformations to fracture specimens of usual sizes. Because of this, two sorts of problems arise. Firstly, large deformations imply variations in the load moment arm since radii of load points are unavoidably finite. Secondly, when large deformations are attained, system and/or material non-linearity may be encountered, that are outside the scope of the classic theory of double torsion testing.

With these reservations in mind, we have examined the effect of varying specimen thickness. It was found that the measured values of apparent fracture toughness, G_c, increase with specimen thickness in all three rubber-modified glassy polymers (two PMMAs and one epoxy) tested, while the sample of neat PMMA yielded valid G_c values, irrespective of specimen thickness.

Application of Leevers' correction factor for the purely geometrical effects of large deformations, while it somewhat reduces the dependence of the apparent G_c on thickness, does not eliminate it completely. No account was taken of possible non-linearity effects. The peculiar thickness effect observed remains unexplained and open to further investigation.

TABLE II Toughness at crack initiation as determined by using the *SE(B)* test

	Modified PMMA		Modified epoxy
Rubber content	9	18	18
J_{Ic} (kJ m^{-2})	1.9	2.1	2.7
$25J_{Ic}/\sigma_y$ (mm^{-1})	0.7	1	1.4

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