CRACK PROPAGATION IN FIBROUS AND PARTICULATE COMPOSITES

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ABSTRACT

Crack propagation in fibrous and particulate composites was studied by direct observation of advancing cracks in the scanning electron microscope, coupled with mechanical measurements on Double Torsion specimens. The results give insight into the strain field at the crack tip, the mechanism of crack advance, and the origins of the toughness of composites.

INTRODUCTION

The way in which crack propagation through composite materials depends on the mechanical properties of the constituents, the bonding between matrix and reinforcement and the stress-state. A detailed understanding of the fracture behaviour and the development of models for the failure of composite materials is important.

Examination of the fracture surface by scanning electron microscopy[1,2] yields limited information about the initiation, slow growth and fast propagation of the crack. Recent in-situ SEM[3,4] has given further insight into the mechanism of crack propagation in fibrous composites. This work used Double Torsion samples, loaded in the microscope, the dynamic growth of the crack was recorded on video tape. Crack opening displacement (COD) was measured through the deformation of the lattice which was loaded on the specimen surface. The stress intensity factor calculated by critical COD agreed well with the one obtained by mechanical testing.

EXPERIMENTAL METHOD

The epoxy resin used in this study was Ciba-Geigy XD 927 with hardener in the ratio of 100:36 by weight. The glass spheres used were "Ballotini" (supplied by Plasticham Ltd., Esher, Surry) with 80% of their diameters lying in the range 53–105 μm. Specimens were fabricated of epoxy containing volume fractions V_f of 0.1, 0.2 and 0.3 of glass spheres. The carbon and glass fibres used to fabricate the one layer fibrous composites were in the form of unidirectional cloth. The fibre diameter for carbon fibre Type II cloth and glass fibre Type E cloth were 8 μm and 13 μm respectively and the numbers of fibres per tow for the two materials were 5000 and 1600 respectively. The fibres were situated in the middle of the specimen and there were two resin rich layer on the top and bottom surface.

The Double Torsion (DT) test was used to investigate the fracture behavior of composites using an Instron 1195 to apply load. Rectangular specimens, 70×35×3 mm, were notched at the middle of one short edge and the notch was sharpened by a razor blade. In order to observe the crack propagation, a loading rig was mounted in the SEM and it could be adjusted to apply load up to 200 N. A photo resist layer was spread on the specimen surface and then a lattice of dots was loaded on the specimen around the crack tip by photographic method, therefore COD and the displacement field at and near the crack tip could be studied.

The materials used included epoxy resin, particulate composites containing glass spheres, and glass or carbon fibre in epoxy. The fibre composites included specimens with fibres parallel with the initial crack and fibres at an angle of 5° and 10° to the initial crack direction.

EXPERIMENTAL RESULTS

In the Double Torsion specimen, the crack tip stress intensity factor is independent of crack length and is given by[5]

$$K = Pw_m \left[\frac{3(1+\nu)}{Wt^4}\right]^{\frac{1}{2}} \tag{1}$$

here P is the applied load and t, w and w_m are the specimen thickness, width and the moment arm as indicated in Fig. 1. ν is Poisson's ratio and taken to be 0.3 in our calculation.

Pure epoxy resin specimen, glass fibre and carbon fibre reinforced epoxy specimen containing fibres at 5° to the notch direction were tested on an Instron 1195 testing machine at crosshead speed of 0.5 mm/min. At least 5 specimens were tested for each material. Under conditions of constant crosshead displacement rate, the crack propagated in a series of discrete jumps (so-called "stick-slip" propagation), producing a sawtooth load-displacement trace. The load at which the crack jumped forward and arrested are denoted by P_i and P_a. Substituting values of P_i and P_a into equation (1) gave critical stress intensity factors for the initiation (K_{IC}) and arrest (K_{Ia}) of cracks in each material.

The average values of the K_{IC} and K_{Ia} for each material and the normalised results of K_{IC} and K_{Ia} with respect to K_{IC} and K_{Ia} of epoxy resin are shown in Table 1. The results indicate that for the fibre reinforced composite studied here, the crack advance behavior is dominated by epoxy resin itself.

The grid on the specimen allows the crack opening displacement to be measured with considerable precision. Micrographs of the crack tip (Fig. 2) were taken in the SEM as successively higher loads were applied to the sample. Before loading, the grid lies in a net of Parallel lines. Under load, this net is deformed, as illustrated,near the crack tip. Well ahead of the crack (right hand edge of the micrograph), the spacing of lines which lie parallel to the crack, does not change on loading. Behind the crack (left hand edge) the changes are large. We measured the change in spacing of lines on either side of the crack, at points above and below its tip (i.e. in the vertical line). The result, for a given load, is remarkably reproducible (to within 0.2 μm). It increases slightly with the seperation of the lines because of the elastic strain in the epoxy resin itself.

Fig. 3 shows a plot of the crack opening displacement as a function of load P for two different samples. It increases as P^2, as expected from simple theory of fracture mechanics[6]. By extropolating to the fracture load P_{crit}, a value of the critical crack opening displacement is obtained. For the two samples tested, the results are:

$$\delta_{crit} = 5.9 \pm 1 \ \mu m$$

and

$$\delta_{crit} = 4.8 \pm 1 \ \mu m$$

We may now use this information for our independent calculation of K_{IC} for the material. We have that[6]:

$$K_{IC}^2 = \delta_{crit} E \sigma_y$$

where E and σ_y are Young's modulus and the yield strength of the material. For the material used here, the approximate values are:

$$E = 3 \text{ to } 4 \text{ GN/m}^2$$

and

$$\sigma_y = 55 \text{ MN/m}^2$$

This leads to values of:

$$K_{IC} = 1.05 \pm 0.15 \text{ MN/m}^{3/2}$$

and

$$K_{IC} = 0.95 \pm 0.15 \text{ MN/m}^{3/2}$$

for the two materials. The agreement with the measurements listed in Table 1 is remarkable.

Table 1. K_{IC}, K_{Ia} and Normalised $\overline{K}_{IC}$, $\overline{K}_{Ia}$ from DT Test

	K_{IC}(MN $m^{-3/2}$)	K_{Ia}(MN $m^{-3/2}$)	$\overline{K}_{IC}^*$	$\overline{K}_{Ia}^*$
Epoxy Resin	0.78	0.58		
Glass Fibre (5°)	1.09	0.89	1.4	1.5
Carbon Fibre (5°)	1.10	0.99	1.4	1.7

* $\overline{K}_{IC}$, $\overline{K}_{Ia}$ equal to $K_{IC}/K_{IC(resin)}$ and $K_{Ia}/K_{Ia(resin)}$ respectively.

OBSERVATIONS OF DYNAMIC CRACK PROPAGATION

On loading the specimen in the SEM, attention was focussed on the crack tip and the dynamic growth of the crack was recorded on video tape. The following observations were made:

(a) The photo resist layer deforms with the specimen so that the change of pattern of the dots characterises the strain field at and near the crack tip. On the other hand, surface cracks appear in the brittle layer when the stress reaches a critical load. The surface cracks have a unique shape, especially in front of the crack tip, and they move or disappear as the crack advances. It appears that the surface cracks form in the stretched area near the crack tip and disappear when the stretch is released. The movement of this area with successive positions of crack tip shows the advance of the stress field. Fig. 4a shows the surface crack around the crack tip and they have disappeared as the crack has moved on (Fig. 4b). Fig. 5 shows the shift of the surface-cracked area as the crack grows. The pattern of the surface cracks (Fig. 4a) is quite similar to the pattern of the measured strain field shown in Figs. 7 and 8 of reference [7].

(b) Sometimes, several small cracks (holes) were observed ahead of crack tip (Fig. 6). These small cracks extended and linked with the main crack before it propagated.

In some of the tests on carbon fibre-reinforced epoxy, a small damaged zone of diameter about 100 μm was observed at the crack tip. Within it many microcracks of length from 2 μm to 60 μm could be seen. A series of pictures (Fig. 7) indicate the sequence of crack events and microcracking in this damaged zone.

(c) Slow growth of the crack was observed just before it jumped rapidly. This was possible because our loading rig could be adjusted very slowly, and show propagation occured at essentially constant stress.

In most cases, when loading the specimen slowly and continuously, the crack remained stationary, and its tip blunted as it was forced open.when the load reached certain value, the crack jumped quickly by the distance shown in this micrograph in less than the frame time (1/50 s)

(d) When the starter crack in a fibrous composite lies parallel to the fibres, the crack itself propagates in the fibre direction. In general this caused debonding of the fibres, and some misoriented fibres across the crack faces could be seen. In reinitiating crack propagation, both the matrix in front of the crack and the fibres which lie across the crack have to be broken.

In the case of specimens containing fibres at 5°C and 10°C to the notch direction, the fracture phenomena were complicated. In some instances, the crack propagated along the fibre direction. The fibres crossing the crack surfaces, were broken and pulled out as the crack advanced. In other cases, the crack did not initially propagate along the fibre direction, but at 5° to the notch away from the fibre direction. This mode of failure was only found in the test of composite containing glass at 5°C and 10°C to the notch direction. The results of these tests indicate that the load to reinitiate the crack was higher than previous. The process of crack extension involved propagation across fibres (the fibre remaining intact) for several jumps, and then the crack propagated for a considerable distance along the fibre direction. The pictures taken from a specimen which failured in this model show a stepped fracture surface. The sharp horizontal marks show the edges of the step where the broken fibres had pulled-out (Fig. 8).

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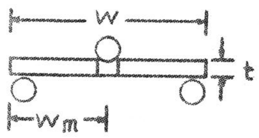

Fig.1 D.T. specimen dimensions

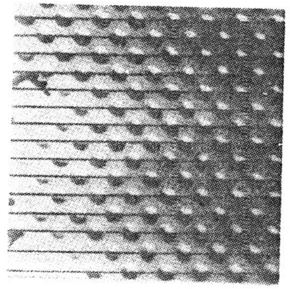

Fig.2(a) Undeformed grid

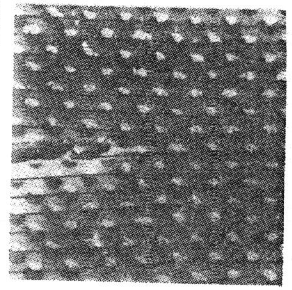

Fig.2(b) Deformed grid

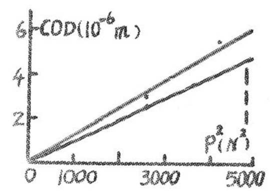

Fig.3 COD plot

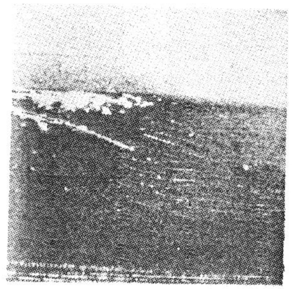

Fig.4(a) Surface crack

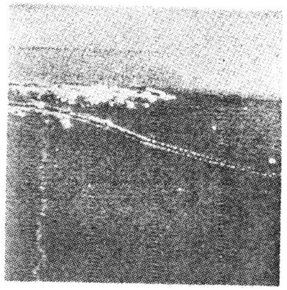

Fig.4(b) Disappearance of surface crack

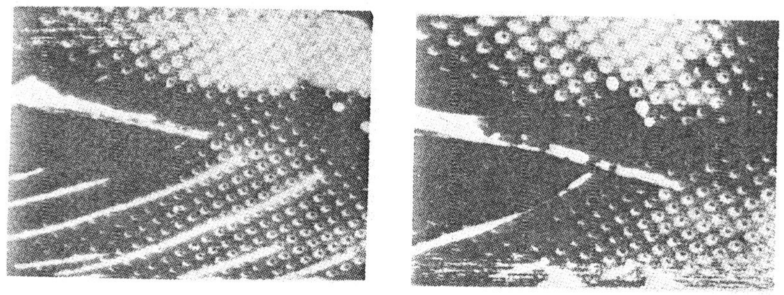

Fig. 5(a),(b) Appearance and disappearance of surface crack

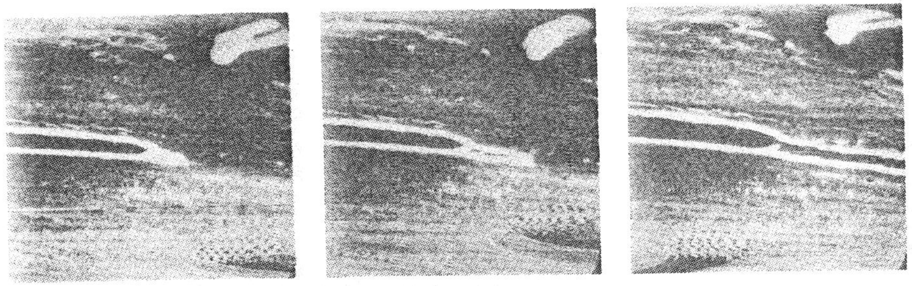

Fig.6(a), (b), (c) Small crack ahead of the main crack

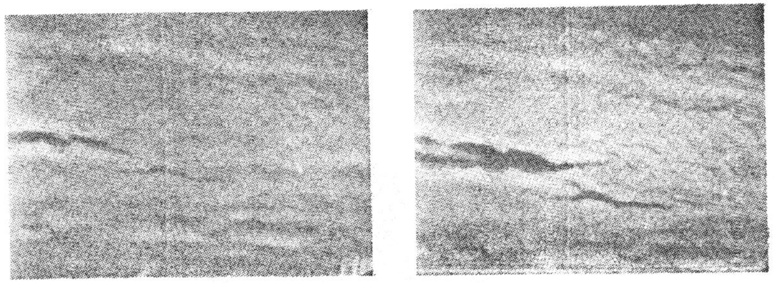

Fig.7(a), (b) Damaged zone in front of the crack tip

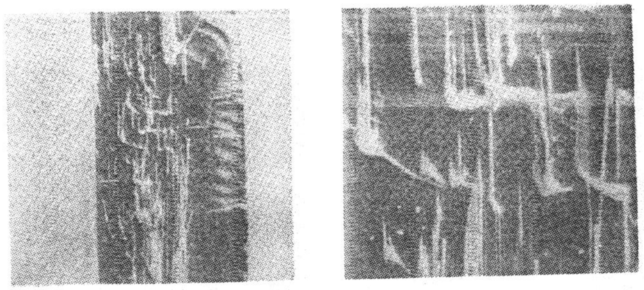

Fig.8 Fracture surface of glass fibre (10) reinforced composite
(a) 10x (b) 50x