Letters

Crack propagation and arrest in epoxy resins

There is at present a lack of understanding of the conditions that affect stable or controlled crack growth and unstable (fast) cracking or crack jumping in epoxy resins. Most investigators have been concerned with investigating the effect of chemical composition [1–3] and curing cycle [1] upon the fracture behaviour of these materials. The results indicate that epoxy resins are prone to crack jumping when a high proportion of a cross-linking agent is used in the formulation of the epoxy resin. It is possible, however, to observe both stable and unstable crack growth in an epoxy resin of a particular composition and structure [1]. Lilley [4], for example, found using a double cantilever beam specimen that continuous stable crack propagation replaced crack jumping in an epoxy resin at high displacement rates. We wish to report in this note some observations of the effect of displacement rate and environment upon the fracture behaviour of an epoxy resin of one composition.

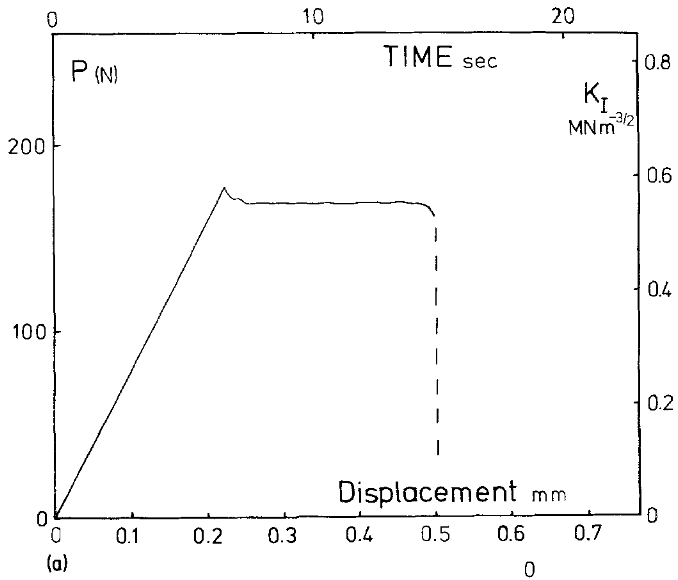
The material studied was supplied by CIBA-GEIGY (UK) Ltd in the form of 6.3 mm thick plates. It was made of CT200 epoxy resin and HT901 hardener in the ratio 100:30 pbw and had been cured for 16 h at 135° C. Specimens were tested using the double torsion (DT) technique which has been described in previously [1, 5–7]. The DT test is carried out on specimens in the form of rectangular plates containing a notch at one end and a centre groove to guide the crack. They are loaded in four-point bending at the notched end and a crack is forced to extend along the length of the specimen. The stress intensity factor, K_I, associated with the crack is proportional to the applied load P, but it is independent of crack length. The crack velocity can be estimated in one of several ways [1, 5–7]. Our results presented in this paper for stable continuous crack propagation were obtained from constant displacement rate tests; a modification of this method described by Scott and Phillips [1] was used to describe crack jumping and crack deceleration. When a crack is propagating continuously in a controlled manner the crack velocity, V, is proportional to the displacement rate, $\dot{y}$;

$$\dot{y} = BPV \qquad (1)$$

where B is the slope of a compliance calibration curve of the specimen [5–7]. For a smoothly decelerating crack, its velocity can be calculated from the displacement rate and the rate of load relaxation [1].

Fig. 1 shows a set of load–displacement curves for similar samples of epoxy resin loaded at various displacement rates. At the highest displacement rate used (2 mm min^{-1}) the specimen failed by continuous stable cracking. In an intermediate displacement rate test (0.2 mm min^{-1}) the epoxy resin exhibited microcrack jumping. Finally, at the slowest displacement rate (0.02 mm min^{-1}) the material experienced massive crack jumping. This behaviour was reproducible and is a clear indication of how one particular epoxy resin can behave under different test conditions. The maximum load, P_max, recorded (corresponding to $K_\mathrm{I\,max}$) increased as the displacement rate was reduced; in contrast, the crack arrest load, P_arr (corresponding to $K_\mathrm{I\,arr}$) decreased only slightly. From these observations it is possible to rationalize the results of Scott and Phillips [1] and Selby and Miller [2] which at first sight seem to contradict each other. Both pairs of workers carried out similar tests on epoxy resin specimens. Selby and Miller measured $K_\mathrm{I\,max}$ which is the value of K_I required for crack acceleration; however, Scott and Phillips measured velocities of a smoothly decelerating crack and worked close to $K_\mathrm{I\,arr}$.

Fig. 2 is a $V(K)$ curve for the CT200 epoxy resin at 20 ± 2° C in air (R.H. 60 ± 10%). The data above the dotted line were obtained using equation 1 and refer to continuous stable crack growth; data below the line were calculated using the analysis described by Scott and Phillips for a smoothly decelerating crack [1]. A transition between the two types of behaviour occurred at a crack velocity of the order of $6 \times 10^{-4}\,\mathrm{m\,sec^{-1}}$. The implication is clear; controlled crack growth is not possible in this resin in air at velocities below $6 \times 10^{-4}\,\mathrm{m\,sec^{-1}}$. But why is there a transition between the two types of behaviour in this material?



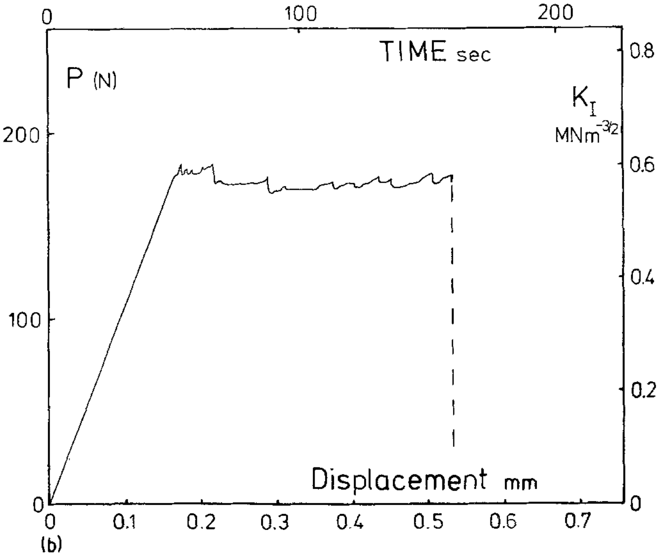
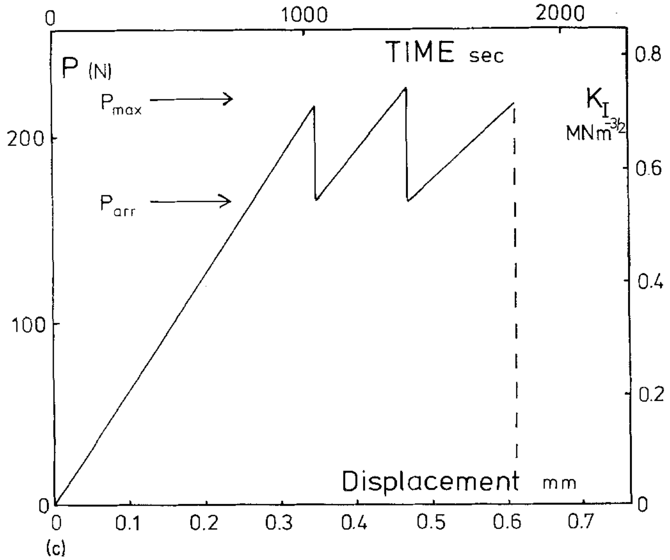


Figure 1 Load–displacement curves for the epoxy resin in air at different cross-head speeds: (a) $2\,\mathrm{mm\,min^{-1}}$; (b) $0.2\,\mathrm{mm\,min^{-1}}$; (c) $0.02\,\mathrm{mm\,min^{-1}}$.



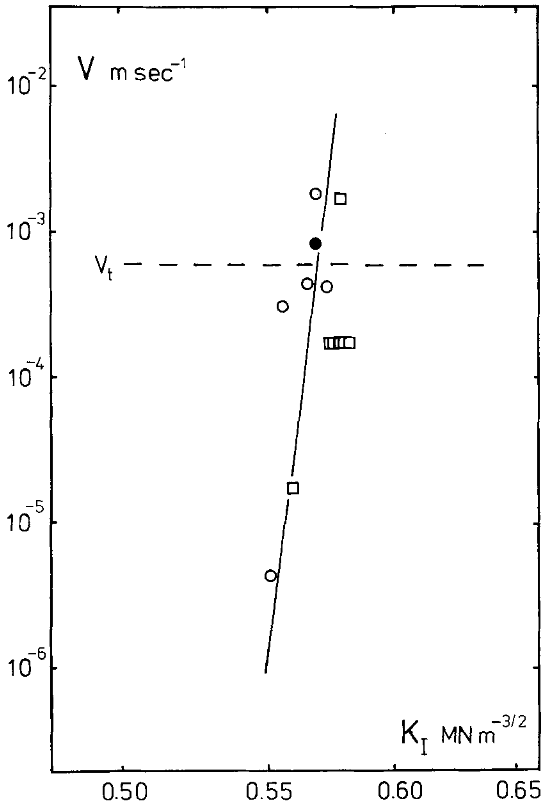


Figure 2 $V(K)$ curve for the epoxy resin in air. The various symbols are for sets of runs on the same and different specimens. The cracks grew continuously at velocities above V_t but below this velocity the data were obtained only from decelerating cracks.

Fig. 3a is a photomicrograph of a fracture surface of a DT specimen that underwent massive crack jumping (at $\dot{y} = 0.02\,\text{mm min}^{-1}$). The fracture surface is at first quite smooth and corresponds to unstable (fast) crack propagation; as the crack decelerates the fracture surface becomes less smooth. Eventually the crack arrests and the fracture surface is rough indicating a high degree of plastic deformation in the vicinity of where the crack was arrested. This feature was absent in specimens that exhibited controlled crack propagation such as the one shown in Fig. 3b. In this case ($\dot{y} = 2\,\text{mm min}^{-1}$) the entire surface was similar to the less smooth area where the crack was slowing down before arrest. We conclude that when a crack is loaded slowly some localized plastic deformation occurs at the tip of the crack and the crack becomes blunted. Such plastic deformation, which could result from craze branching [8] or shear yielding [9–11], may have occurred

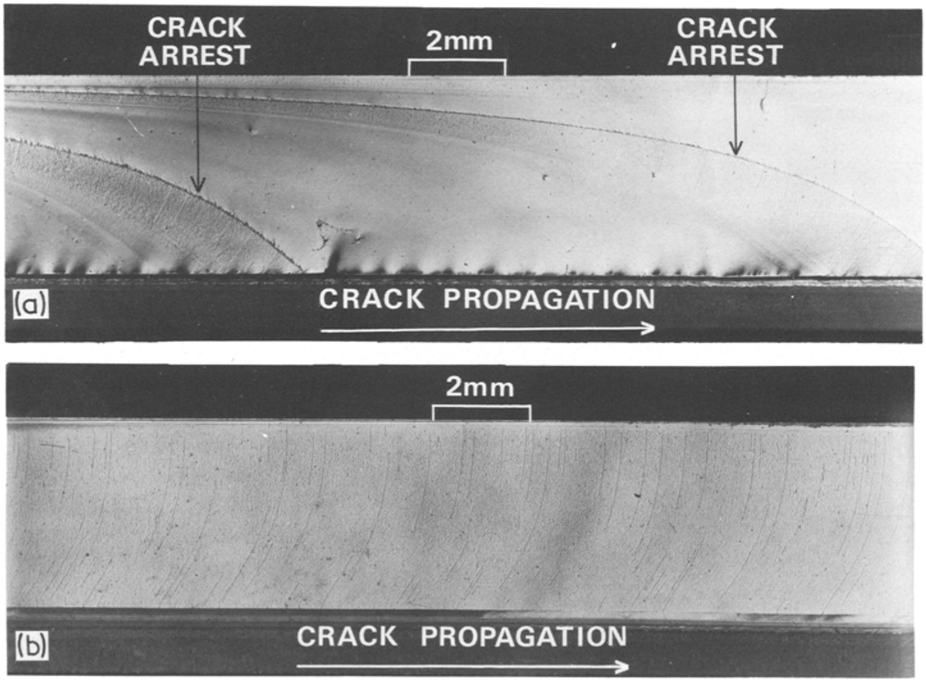


Figure 3 Optical micrographs of fracture surfaces obtained from specimens fractured at different cross-head speeds. (a) 0.02 mm min^{-1}. The crack arrest lines are marked; (b) 2 mm min^{-1}. Crack propagation took place continuously.

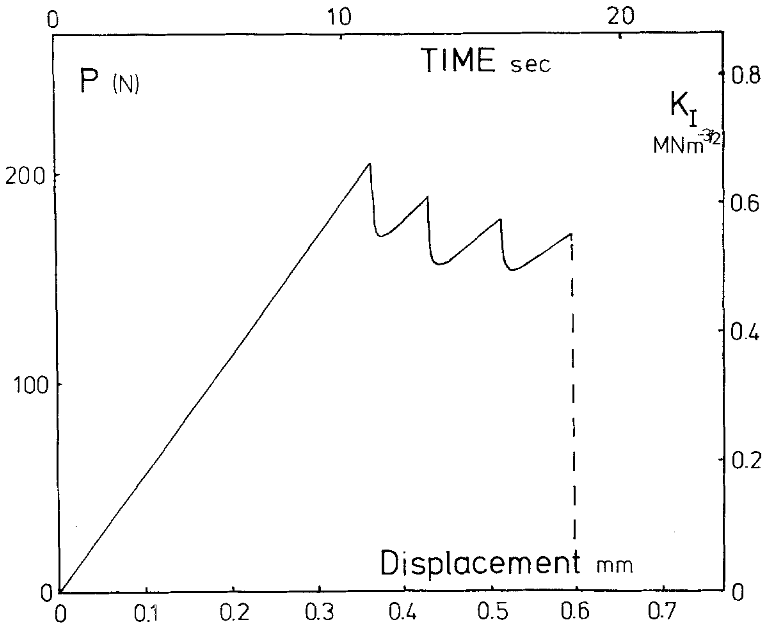


Figure 4 Load–displacement curve for the epoxy resin in distilled water fractured at a cross-head speed of 2 mm min^{-1}.

in the epoxy resin by one of the following two mechanisms: (1) localized plastic yielding at the crack tip which is both stress and time dependent; or (2) the diffusion of reactive species such as water to the crack tip. This could result in plasticization of a small volume of epoxy resin at the crack tip. Such an effect would be limited by the diffusion rate of water molecules to the advancing crack front.

The second of these hypotheses was tested by performing a constant displacement rate test on a double torsion specimen in distilled water at 20 ± 2° C. A DT specimen was precracked in air and water was drawn into the crack under vacuum. It was loaded at a displacement rate of 2 mm min^{-1} and the resulting load–displacement curve is shown in Fig. 4. The epoxy resin exhibited crack jumping which was quite unlike the behaviour of an identical sample loaded in air at the same displacement rate (Fig. 1a). This implies that water plasticized a small volume of epoxy resin adjacent to the crack tip and resulted in the blunting out of the propagating crack. However, the first mechanism proposed cannot be ruled out; neither can the possibility of combined influence of mechanically-induced cracking and environmental-induced crack growth, with or without a synergistic effect.

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