The stability of fracture in epoxy resins

The possibility that the unstable crack growth in air of epoxy resins may be due to the attack of the environment on the material has recently been discussed by Hakeem and Phillips [1] who noted similarities between the fracture of PMMA in methanol and of epoxy resins in air. Yamini and Young [2] suggested that environmental attack does not explain the instability of cracking in epoxy resins and have concluded that instability was an inherent property of the material and not dependent upon environmental water vapour. We would like to add some comments on this inherent instability based on our own results.

Although a number of authors [3, 4] have found that epoxy resins tend to crack unstably when tested at low cross-head speed and stably at fast cross-head speed, this is not necessarily the case. We have tested double cantilever beam specimens of an epoxy resin prepared from Epikote 828 cured with 10 phr TEPA (tetraethylenepentamine) and have observed the same instability at low cross-head speeds and stability at high cross-head speeds that have been reported by Yamini and Young. However, we have also tested double cantilever beam specimens of Araldite D cured with 10 phr HY951 (triethylenetetramine, Ciba Geigy) and this material has been found to fracture stably at cross-head speeds of 5×10^{-2} cm min^{-1} and below, but to fracture unstably at higher cross-head speeds. Conventionally, unstable crack growth has been explained in terms of a blunting of the crack tip, and some controversy has arisen concerning the role which environmental effects may play in determining the amount of blunting. However, in view of our observations of stable crack growth at low cross-head speed, crack blunting cannot be taken *per se* as the cause of instability.

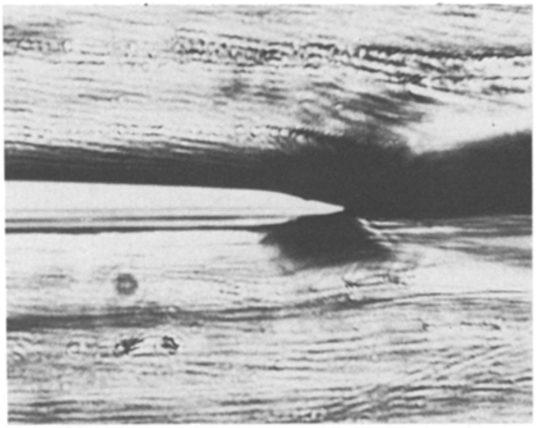

Figure 1 A sharp crack in epoxy resin initiated from a blunted crack.

Photographs of the crack tip show the crack opening out prior to initiation of a sharper crack (Fig. 1) which then accelerates along the specimen until a velocity which is in equilibrium with the cross-head speed is attained. Examination of the load–displacement record shows that K increases as the crack accelerates. Unfortunately, determination of the C.O.D. and the crack tip's position by photography is restricted to the behaviour of the specimens free surface and may not be representative of conditions in the centre of the crack front where initiation occurs.

Slow stable crack growth is accompanied by the production of a very rough surface so that a large plastic zone may have been formed ahead of the crack tip. At slightly higher cross-head speeds the crack becomes unstable soon after initiation,

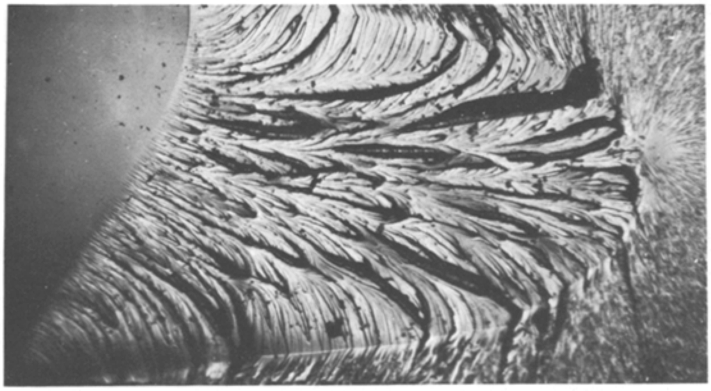

Figure 2 Fracture surface photographed by transmitted light showing stable growth region.

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leaving a crescent-shaped area of rough fracture surface (Fig. 2). With a further increase in cross-head speed, the stable crack growth region disappears leaving a smooth fracture surface with no evidence of extensive plastic deformation. Similar effects have been observed with other materials [6] and explanations offered for the effect have included isothermal/adiabatic and plane strain/plane stress transitions.

In general, for crack propagation through a viscoelastic material, the fracture surface energy R is a unique function of the crack velocity. If a stationary crack is stressed, it will start to move as soon as the crack tip stress reaches a value which is sufficiently high to break intermolecular bonds. Whether or not the subsequent crack propagation is unstable depends upon whether or not the strain energy release rate, G, appropriate to the bond rupture condition, exceeds the fracture surface energy, R_{eq}, for a crack which is propagating at a velocty which is in equilibrium with the cross-head speed. If $G < R_{eq}$, then during the initial bond scission, the crack opening displacement increases and the crack accelerates until the equilibrium condition $G = R_{eq}$ is established. If crack blunting occurs, the crack tip stress is reduced and when it is finally sufficient to cause bond rupture, G is greater than the fracture surface energy of a crack propagating in equilibrium with the cross-head and instability ensues.

While the crack-blunting hypothesis cannot explain the stable to unstable transition discussed above, it may explain a decrease in initiation toughness with increasing cross-head speed and the unstable to stable transition observed in other epoxies. Using a Dugdale model and assuming the crack tip material to act as a Maxwell solid, we hope to show in a later publication that the critical crack tip stress is reached at a G_i which decreases with increasing cross-head speed. This decrease may be even more rapid when the time to failure is close to the relaxation time of the material.

The stable to unstable transition may be explained by the observation of the sharper crack from which propagation occurs. It is well known that the stress required to cause bond rupture in epoxies (and all other polymers) decreases with duration of application. Consequently, if a new crack initiates from a blunted crack at a low crack tip stress then the strain energy release rate may be low enough to support stable crack propagation in equilibrium with a slowly moving cross-head. At higher cross-head speeds and shorter failure times the crack tip stress may be increased so that G is now too great to permit stable propagation.

If we now examine the effect of water on the stability of fracture we find that with Araldite D/HY951 water promotes stable cracking whereas under otherwise identical conditions the specimens fractured unstably in air [6]; The specimens were pre-cracked by loading in air until a crack jumped unstably about half way down the specimen, which was then reloaded while entirely immersed in water. Stable crack growth proceeded at a lower G than was required to initiate unstable fracture at comparable cross-head speeds in air.

The explanation for these results is not entirely clear, but they are not consistent with a simple plasticization hypothesis in which only crack blunting is affected. We have proposed that a stress hydrolysis mechanism which may reduce the stress necessary to cause rupture may be responsible for allowing stable crack growth in the presence of water [9].

In conclusion, we would strongly agree with the other authors who have suggested that the stability of fracture in epoxy resins must be regarded as a complex phenomenon, dependent on the mechanism of fracture and on the deformation properties of material at the crack tip and in the surrounding plastic zone.

References

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