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Unstable crack propagation – a fractographic study using PMMA in liquid environments

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Double-torsion tests have been performed in liquid environments on PMMA samples with and without a grease coating to restrict the access of liquid, and over a range of testing speeds. Stable or "stick-slip" crack propagation could be obtained at will by varying the test conditions. Characteristic fracture markings accompanying unstable crack propagation provide evidence concerning the mechanism of crack arrest.

1. Introduction

There is currently considerable interest in the phenomena of crack initiation and arrest under conditions where cracking proceeds by a "stick-slip" mode. Recent investigations employing test-pieces with linear compliance variation have revealed much concerning the effect of process variables such as strain rate, temperature, and the presence of aggressive environments upon the incidence of unstable crack propagation. However, in those materials where this phenomenon is of the greatest technical importance, such as epoxies [1, 2] and polyesters, the precise conditions governing initiation and arrest of unstable cracks are not yet established. The principal reason is that those materials show inexplicable variations between stable and unstable behaviour under nominally identical conditions.

Some current work upon the fracture of PMMA in liquid environments leads the authors to propose that a polymer/liquid system may be used as a model for studying the relationships between stable and unstable crack propagation, with the advantage that either type of behaviour may be produced at will. In the course of this work, a new definition of the crack arrest condition has recently been proposed [3]. In the present paper, some fractographic evidence is presented in support of the suggested model.

2. Experimental details

The double-torsion technique developed by Kies and Clark [4] was selected to study the fracture behaviour of PMMA in dry and wet environments. Samples were cut from 6.0 mm clear acrylic sheet; dimensions were a width of 80 mm with central grooves 1 mm deep and 0.1 mm wide to contain the crack. To control initiation of the crack, a vee notch was milled at one end of the sample and a blade was pressed into the root using an attachment fitted to a Vickers hardness testing machine. This technique was earlier employed by Marshall [5]. The moment arm employed to bend the sample was 25 mm. Tests were carried out over a range of cross-head speeds in an Instron testing machine, type 1122. Where required, samples were fully immersed in a bath of liquid surrounding the test fixture.

3. Results and discussion

3.1. Circumstances of crack arrest

Fig. 1a shows the now-familiar "saw-tooth" curve of load versus deflection which characterizes stick-slip crack propagation in tests at constant load-point displacement rate upon samples with linear compliance variation. Where the testing machine is hard, and the cross-head speed is constant, this can be presented as a graph of load against time.

A single load drop corresponding to a crack jump is presented on a much extended timescale in Fig. 1b. Such curves can be obtained with the aid of a transient recorder [3]. It can be deduced from the form of Fig. 1b that the fast moving unstable crack decelerates progressively, not immediately to rest, but to a constant velocity v_c corresponding to the value of stress intensity factor K_a (Fig. 1a). K_a is reportedly very close to

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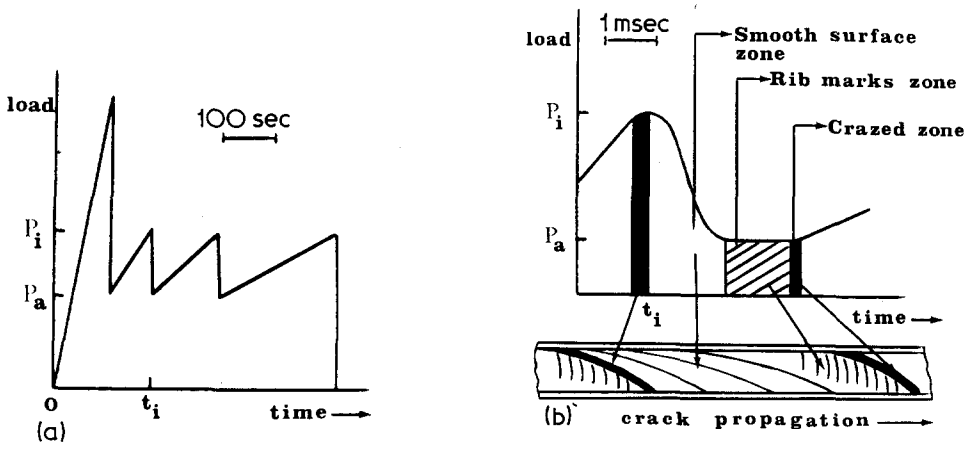

Figure 1 (a) "Saw-tooth" (P, t) curve. (b) Relation of load transient to features of fracture.

K_c for stable propagation where this can be obtained [6, 7].

The implication is that the crack does not simply stop because of the exhaustion of elastic energy. In the type of test described, elastic energy is being continuously supplied by the testing machine. For the crack to arrest, some new phenomenon must intervene, such that K_a ($\equiv K_c$) is no longer adequate to maintain the velocity v_c. The crack, therefore, decelerates and, under these test conditions, an inevitable consequence is that the load rises. The point of true crack arrest, therefore, lies slightly above the minimum point of the load/time curve of Fig. 1a, being defined by the condition [3]:

$$\frac{dP}{dt} = \frac{P}{t}$$

For PMMA in an aggressive liquid environment, one can readily accept that the phenomenon causing crack arrest is the arrival at the crack tip of liquid left behind during the fast unstable propagation phase.

3.2. Characterization of fracture markings on PMMA

The basis of the present experimental programme is the observation that stable crack propagation in dry PMMA in double-torsion tests is accompanied by the formation of very clear and characteristic fracture surface markings, which will be referred to as "rib marks" (Fig. 2). This photograph also shows at the right-hand end the smooth, relatively featureless, surface associated with fast fracture. Finally, the curved boundary between ribbed and smooth zones shows the form of crack front invariably observed in double torsion tests.

The rib marks appear to correspond to those reported by several authors, e.g. Atkins *et al.* [8]. Each "rib" is the locus of a point on the crack front. Whereas the marks are almost straight or slightly divergent on samples of the SEN and DCB

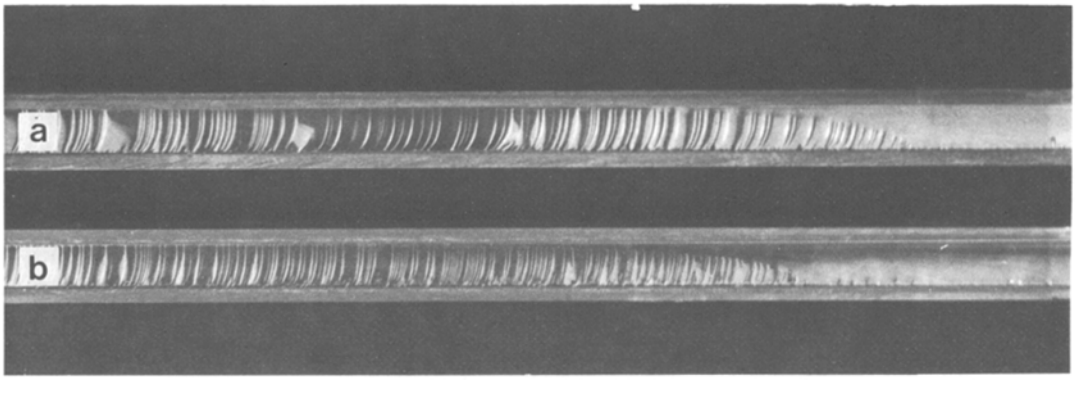

Figure 2 Fracture surfaces: PMMA in air. Cross-head speeds (a) 1 mm min^{-1}, (b) 20 mm min^{-1}.

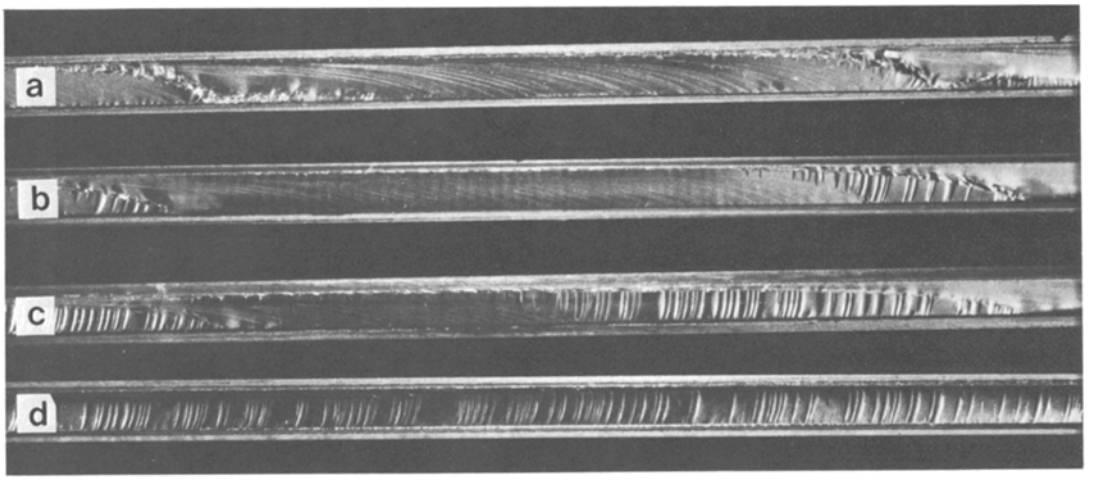

Figure 3 Fracture surfaces: grease-coated PMMA in methanol. Cross-head speeds (a) 1, (b) 5, (c) 20, and (d) 50 mm min^{-1}.

type, they here take on a relatively complex curvature imposed by the testpiece geometry. The observation of rib markings on double-torsion testpieces in PMMA does not appear to have been reported before, but it is interesting to note the great similarity between Fig. 2 and the illustration of a stable fracture in expoxy resin by Young and Beaumont (Fig. 3b of [9]).

Fig. 3 shows fracture surfaces representative of samples tested under methanol, but previously coated with grease, such that the liquid has access to the crack tip only by flow along the length of the crack. Features of interest are defined with reference to the schematic diagram (Fig. 1b). Rib markings are seen to lie between the smooth fast-fracture zone and the heavily crazed crack arrest region.

3.3. Relationship between fracture markings and crack arrest

We assert that after the dissipation of excess elastic energy by a crack jump, the expected and normal behaviour is stable propagation, whereas crack arrest is caused by and coincides with a change in material character in the crack tip region.

To support these assertions we hope to demonstrate:

(a) that under slip-stick conditions, rib markings are associated with stable crack propagation and not, for example, with vibrations of the crack front accompanying rapid deceleration:

(b) that a consistent explanation can be given for the occurrence and extent of stable propagation following a crack jump in a variety of circumstances;

(c) that the features which are described as "crack arrest zones" or "crazed zones" in Fig. 1b are indeed associated with deceleration and arrest of the crack and not simply with initiation of the subsequent crack jump.

3.3.1. Verification of the rib markings as associated with stable propagation

Optical macroscopy at magnifications of up to x 13 (Figs. 4 and 5) reveals no difference in detail between rib marks formed on dry (all-stable) samples and on immersed (slip-stick) samples.

Tests were performed under identical conditions on immersed grease-coated samples (Fig. 6a) and on samples left uncoated so that the liquid should

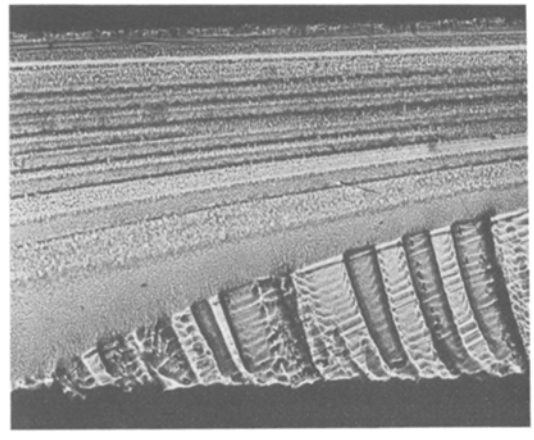

Figure 4 Rib-marks on dry (all-stable) sample. x13.

Figure 5 Rib-marks on immersed (slip-stick) sample. ×13.

have immediate access to the crack tip (Fig. 6b). Values of K_i and K_a, and the duration of the load transients, were such that the velocity/time history of the unstable propagations may be supposed identical. Rib markings, however, were entirely absent in the uncoated samples (magnified in Fig. 7), as would be expected if stable "after-growth" were suppressed by the environment.

3.3.2. Observations on the extent of stable "after-growth"

Fig. 3 shows the influence of testing machine cross-head speed upon the fracture appearance of grease-coated samples immersed in methanol. For cross-head speeds of 1, 5 and 20 mm min^{-1} (Fig. 3a, b and c, respectively), we observe a progressive increase in the lengths of the rib-marked regions following a given crack jump. It should be noted that, as previously reported [6], there occurs over this range of cross-head speeds a negligible variation in K_a, and a small, but consistent, decrease in K_i with increasing test rate.

The broad pattern of stick-slip fracture is, therefore, the same throughout, with about four crack jumps prior to final failure. Assuming that the rate of flow of liquid methanol along newly opened cracks of similar profile in PMMA is roughly constant, then the time available for stable "after-growth" is proportional to the length of newly-formed crack, since the crack jump is virtually instantaneous.

The velocity v_c of stable crack growth is directly proportional to machine cross-head speed, since K_a does not vary appreciably [6]. The model therefore predicts that for crack jumps of equal length, the length of the "rib-marked" region should be proportional to the testing rate. This prediction is supported, qualitatively, by Fig. 3a to c.

The onset of fully stable crack growth at a cross-head speed of 50 mm min^{-1} with otherwise identical conditions (Fig. 3d) provides further corroboration. It can be supposed that the velocity of stable propagation under these conditions ($da/dt \approx 8.0 \times 10^{-3}$ m sec^{-1})* is sufficient for the crack front to remain ahead of the advancing liquid.

Finally, it may be noted that where K_i and K_a are constant within a single test, as normally observed (Fig. 1a), successive crack jumps increase in length in a manner predictable from the test-piece geometry. The lengths of successive rib-marked zones are found to increase correspondingly, as the model predicts.

3.3.3. Crack arrest zones

Our observations show that the action of the liquid on "catching up" with the crack tip is extremely rapid. At the cross-head speeds employed in our tests, the time interval between the initiation of a crack jump and the subsequent

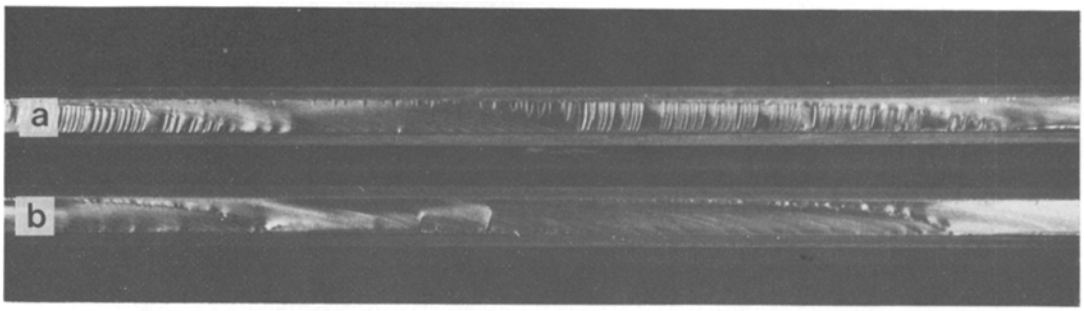

Figure 6 Fracture surfaces of immersed samples. Cross-head speed 20 mm min^{-1}. (a) Sample coated with grease. (b) Sample free of grease.

*Corrected value for the velocity of the crack front [10].

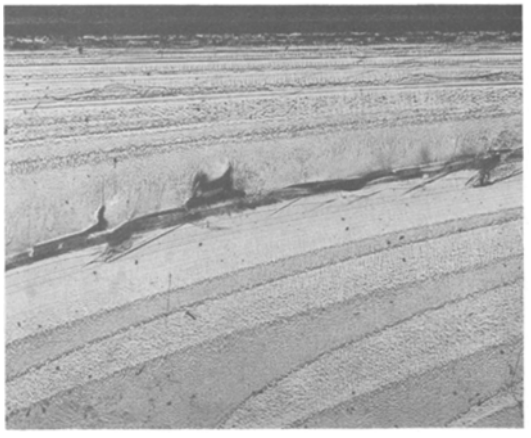

Figure 7 As Fig. 6b × 13.

arrest was a few seconds, much of this being occupied by stable crack growth. The time available for the final deceleration phase is very short, and the corresponding advance of the crack front very small.

Inspection of the arrest zone at higher magnification (Fig. 5) shows it to be a region of heavy deformation, with much surface roughening. It is instructive to compare this zone with the transition from stable to unstable propagation in a dry sample (Fig. 4) where no arrest occurs. In this case, no "crazed zone" is observed, and, taken together, the two types of fracture marking strongly suggest that the formation of a craze by the action of the methanol causes the crack to arrest.

4. Conclusions

In a close examination of the circumstances immediately following a fast crack "jump", fractography and high-resolution compliance studies have been employed. The evidence suggests that under the test conditions used, the crack continues to propagate in a stable manner before coming to rest. Thus the stress intensity factor normally identified as K_a (arrest) is probably identical with, and not simply close to, K_c (stable propagation).

In the model system, PMMA/methanol crack arrest occurs only when the crack tip material is modified by newly arrived liquid environment. The action of the liquid is very rapid. It appears to promote crazing, but liquid penetration to an appreciable depth is improbable in the time available.

For polymers in which unstable cracking occurs without benefit of liquid environment, crack branching at supercritical speed cannot be invoked as a mechanism of blunting and arrest. Instead, we must seek a mechanism based upon sudden blunting of a slowly moving sharp crack.

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