JOURNAL OF APPLIED POLYMER SCIENCE VOL. 15, PP. 209–212 (1971)

Crack Initiation in PVC for Subsequent Linear Elastic Fracture Mechanics Analysis

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Synopsis

Reproducible starter-cracks for subsequent linear elastic fracture mechanics analysis have been grown in PVC by fatigue cycling at 80 Hz. The crack growth rate has been related to the fracture surface markings and to the opening mode stress intensity factor (K_I) of the fatigue cycle. Termination of the fatigue crack growth when crack growth rate is constant ensures a smooth mirror fracture surface and a sharp crack tip.

INTRODUCTION

A fracture mechanics approach is being used increasingly to study the fracture of polymeric materials.[1,2] This approach requires that some method be available for the reproducible and controllable growth of starting cracks. These cracks may then be used for subsequent environmental stress cracking/crazing or fracture toughness studies. Berry's early work[3] on the fracture toughness of glassy polymers utilized a brittle starting crack initiated by driving a wedge into a saw cut in the edge of a sheet specimen. This method is unsatisfactory for the less brittle polymers, including PVC and the polycarbonate of bisphenol-A, because an unacceptable amount of plastic deformation occurs at the tip. Cooling specimens of PVC below the ductile-brittle transition temperature of −20°C[4] proves too drastic[5] as the wedge causes complete rupture of the sheet.

Work at Leeds has shown that a sufficiently sharp crack can be initiated in UPVC, and a number of impact-modified grades of PVC, by high-frequency cycling in tension (40–80 Hz). All the grades of PVC tested were satisfactorily fatigue notched using this method.

The following grades were studied: (a) a Geon (B.P.) grade of unplasticized PVC containing Breon 113 plus 3% mellite, plus 1% steric acid; (b) a Geon (B.P.) grade of modified PVC, referred to in ref. 6 as modification B; (c) an I.C.I. PVC, Corvic D60/11 plus 1.8% tribasic lead sulfate paste and 1.26% lead stearate powder, coded DL243; (d) as (c) plus 8% Dow chlorinated polyethylene modifier (C.P.E. 3614), coded DL244; (e) as (c) plus 8% Blendex 301 (ABS modifier); (f) an I.C.I. PVC, Corvic D60/11 plus 3% mellite 31.

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The metallurgical practice of fatigue notching for subsequent fracture toughness work was not applied to thermoplastics earlier, mainly for two reasons. First, thermoplastics are poor conductors of heat, and hence fatigue cycling results in a rise in temperature.[7] To keep this temperature rise small, low cycle rates are necessary and consequently fatigue notching could take a very long time. Secondly, thermoplastics are viscoelastic, and their properties will vary with time under stress. The properties may change appreciably under stress and during the time required for fatigue notching.

Fatigue cycling at high frequencies has a number of advantages:

(i) The time required for the growth of a crack of sufficient length is small.

(ii) The stresses required for the growth of a crack of sufficient length are lower.

(iii) The combination of shorter time and lower stress results in the creep of the specimen being negligible (Fig. 3 in ref. 8).

(iv) The lower stress reduces the heat rise to acceptable proportions (Fig. 9 in ref. 7).

RESULTS

A sheet specimen of PVC, 70 mm wide, 130 mm long and 3.5 mm thick, with a razor blade cut approximately 0.5 mm deep in the edge, is cycled between ca. 4.5 and 1.5×10^6 N m^{-2} (10^7 N m^{-2} = 1 hbar = 1.02 kgf/mm^2 = 1.45 klbf/in^2 = 1450 psi) at a rate of 40–80 Hz using a 2-tonf Amsler Vibraphore fitted with a 0.4-tonf dynamometer. Initiation of a fatigue crack from the razor blade cut occurs after a few minutes of cycling, at which point the applied stress may be reduced if necessary. The crack growth can be followed by a travelling microscope, and, in the case of transparent grades, a magnified image of the specimen can be projected on to a screen. A plot of crack length versus number of cycles is shown in Figure 1 for a specimen which was fatigued to failure. This specimen is not suitable for subsequent environmental stress cracking studies, as the crack has propagated beyond the linear growth region, but it is used to show the different areas present in a fatigue fracture surface. The point on Figure 1 at which the fatigue notching would have been terminated so that the specimen could be used for an environmental stress crazing test corresponds to a crack length of about 4 mm. Within the crack length range 3.0–4.5 mm, the crack growth rate, da/dN, is essentially constant with increasing stress intensity factor K_I, as is shown in Figure 2. There is no observable creep.

The opening mode stress intensity factor K_I is given[9] by the relationship

$$K_I = Y \cdot \frac{Pa^{1/2}}{BW}$$

for various test specimen geometries. For the single-edge notched specimen considered here, P is the maximum applied load, B is the specimen thickness, W is the specimen width and a is the overall crack length; Y

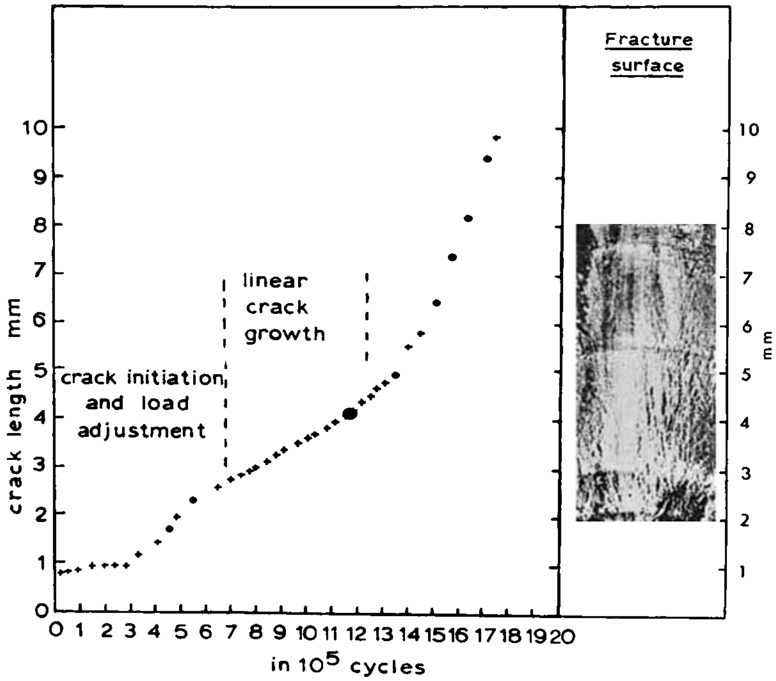

Fig. 1. Crack length vs. number of cycles for UPVC at 23°C.

is a compliance function and takes the form

$$Y = 1.99 - 0.41\left(\frac{a}{W}\right) + 18.7\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4.$$

For the specimen described in Figures 1 and 2, the crack growth rate da/dN is essentially constant at 2.7 nm/cycle over the range in K_I of 0.4 to 0.5 MN $m^{-3/2}$. The range of stress concentration factor for linear crack growth varies with the grade of PVC, but all the grades studied fell in the general range 0.25 to 0.6 MN $m^{-3/2}$ with crack growth rates of 2 to 10 nm/cycle.

An examination of the fracture surface of a fatigued specimen shows that the linear crack growth region has a mirror-like appearance to the naked eye. Microscopical examination (see Fig. 1), however, shows "river pattern" markings which extend slightly beyond the linear crack growth region. At a crack length of 7.0 mm (K_I = 0.69 MN $m^{-3/2}$), fatigue striations become apparent. The striations become increasingly difficult to resolve at higher crack lengths as the fracture surface becomes rougher. The discontinuities in Figure 1 at crack lengths 2.2 and 3.0 mm are caused by stopping the test to reduce the applied load after crack initiation. The discontinuities at crack lengths 5.6 and 5.8 mm were also caused by temporarily stopping the test.

Specimens removed from the Vibraphore while their crack growth characteristics remained linear showed good reproducibility in their sub-

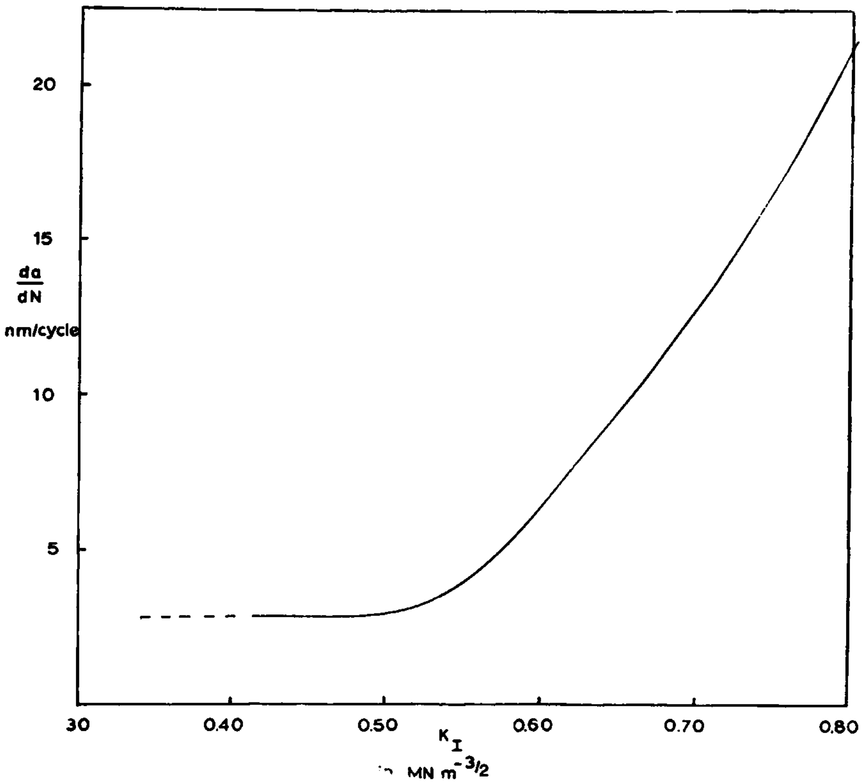

Fig. 2. Crack growth rate vs. plane strain stress intensity K_I.

sequent environmental stress crazing results.[5] Specimens subjected to nonlinear crack growth and subsequently tested for environmental stress crazing behavior did not show the same reproducibility.

We are grateful to the Gas Council for their encouragement and financial support for this work.

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Received April 21, 1970
Revised June 26, 1970