THE EFFECT OF DAMAGE DISSEMINATION ON FRACTURE PROPAGATION

J. Botsis, A. Chudnovsky and A. Moet

Department of Macromolecular Science, Case Western Reserve University, Cleveland, OH 44106, USA

ABSTRACT

Fatigue crack propagation (FCP) experiments conducted on thin, single edge notched polystyrene specimens show that an intensive zone of damage (crazing) surrounds and precedes the main crack. Damage accumulation, within the zone ahead of the crack tip (i.e., the active zone), takes place prior to crack advance. The width of the active zone is found to increase by an order of magnitude during slow crack propagation. Crack propagation kinetics plotted as a function of the energy release rate display the well known S-shape behavior. A considerable difference in the critical energy release rate is observed in identical specimens fatigued under different loads. This difference is attributed to the difference in craze density at the critical crack length. Experimental results are in good agreement with the Crack Layer (CL) theory.

KEYWORDS

Fatigue crack propagation; damage; crazing; crack layer; active zone; energy release rate.

INTRODUCTION

Concepts of fracture mechanics are extensively used to study crack propagation in polymeric materials. Assuming that a crack starts from a known defect, several models have been proposed to relate the crack speed to some function of the stress intensity factor or the energy release rate. Both are functions of the crack length, applied stress and specimen geometry. The basic assumption is that fracture propagation can be described by a single geometric parameter, i.e., the crack length. Limitations of this approach become clear when FCP is considered over a wide range of propagation rates. Recent work has shown that damage in the form of crazes (Botsis, Moet and Chudnovsky, 1983; Chudnovsky and co-workers, 1983) and shear bands (Mills and Walker, 1980; Takemori and Kambour, 1981) accompanies crack propagation. These transformations constitute major energy sinks (Haddaoui, Chudnovsky and Moet, 1983; Chudnovsky and co-workers, 1983) and ought to be taken into account for proper characterization of the materials to crack propagation.

This paper examines the effect of damage dissemination on the resistance of the material to FCP within the framework of the crack layer (CL) theory (Chudnovsky, 1983).

EXPERIMENTAL METHODS

Single edge notch tension specimens 20 x 80 x 0.25mm of plane isotropic polystyrene (PS) were used in this investigation. The details of specimen preparation can be found elsewhere (Botsis, Moet and Chudnovsky, 1983). Fatigue experiments were performed on an MTS-800 machine onto which a traveling optical microscope, equipped with a motor driven camera, was attached. Tests were conducted at room temperature in a laboratory atmosphere using a sinusoidal waveform at a frequency of 0.2Hz. The energy release rate J was calculated as K^2/E, where E is the tensile elastic modulus of the material, which was determined experimentally (E = 2.2 MPa). The stress intensity factor K was calculated by using the formula $K = \sigma\sqrt{\pi\ell}\cdot f(\ell/B)$, where σ is the applied stress, ℓ is the crack length, B is the width of the specimen and $f(\ell/B) = 1.12 - 0.231(\ell/B) + 10.55(\ell/B)^2 - 21.72(\ell/B)^3 + 30.39(\ell/B)^4$ (Tada, Paris and Irwin, 1975). Crack propagation data were obtained from micrographs taken at appropriate intervals of cyclic load excursions. The micrographs were taken without interrupting the experiment. Complementary kinetic data were obtained from subsequent fractographic analysis of fracture surface and crack layer profile using optical microscopy (Botsis, Moet and Chudnovsky, 1983). Hence our measurements cover the rate of crack extension for the whole range of slow crack propagation. The distribution of crazes within the active zone was determined from high magnification micrographs of thin sections (25 - 50μm thick) which were prepared by standard metallographic and polishing procedure.

RESULTS

FCP kinetics is observed under two loading conditions. Whereas the frequency and load ratio are the same, the level of the mean stress σ_m is 16.0 MPa for the first experiment and 10.7 MPa for the second. The rate of crack extension plotted against the energy release rate, J_1, for both experiments is shown in Fig. 1. The data display the S-shaped character well recognized for other materials (Beevers and co-workers, 1975; Kunz and Beaumont, 1975; Nguyen and Moet, 1984). The data also indicate that the critical energy release rate, J_{1c}, measured from crack growth rates under σ_m = 10.7 MPa is almost twice that measured at σ_m = 16.0 MPa. This emphasizes the recently realized phenomenon that critical energy release rate is not a material constant (Kauch, 1978; Bakar, Moet and Chudnovsky, 1983; Haddaoui, Chudnovsky and Moet, 1983).

In order to understand this behavior, a systematic examination of the micromechanisms of fracture is undertaken, within the framework of the CL theory (Chudnovsky, 1983; Chudnovsky and Moet, 1984). The theory treats the crack and the surrounding damage as a single entity, i.e., a CL. A typical optical micrograph of a well developed CL is shown in Fig. 2. During slow crack propagation crazing surrounds and precedes the crack. Craze accumulation within the area ahead of the crack tip, i.e., the active zone, takes place

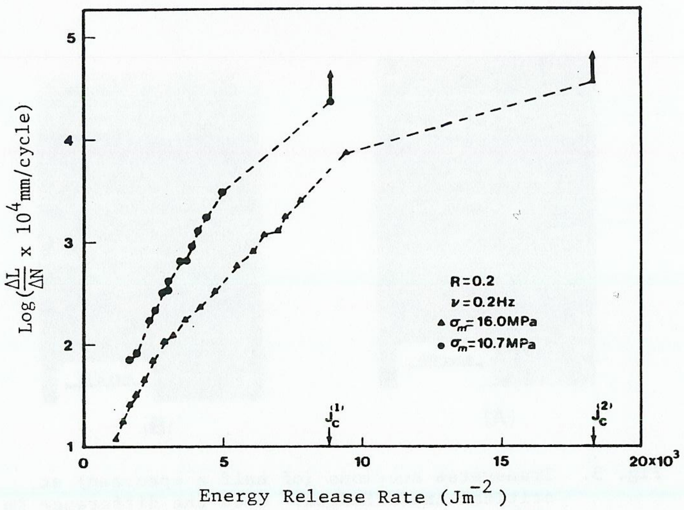


Fig. 1. Fatigue crack propagation vs. energy release rate for two levels of σ_m.

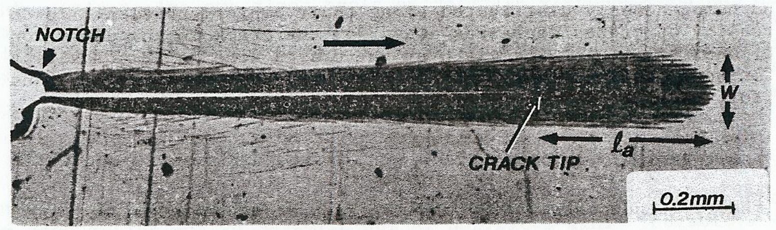
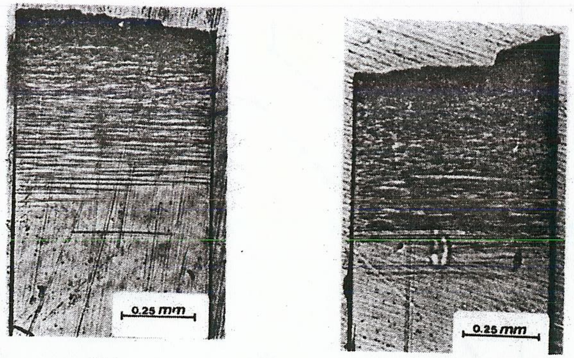


Fig. 2. Transmission optical micrograph showing a well developed CL during slow propagation. Horizontal arrow indicates the direction of propagation.

prior to CL growth. Craze accumulation within the active zone is inferred from the progressive darkness of this zone during fatiguing. CL propagation occurs as a sequence of discontinuous advances of the active zone leading the crack. This sequence persists during slow CL growth, at the end of which uncontrolled (avalanche-like) propagation occurs. The transition from slow to avalanche-like crack propagation characterizes the critical state of the CL. From initiation to critical CL propagation, the size of the active zone increases by an order of magnitude. The critical value of J_{1c} for the lower loading level is two-fold that of the higher level. The CL theory associates J_{1c} with the extent of damage. In order to obtain information about the extent of damage within the CL, transverse sections at the location of the critical crack tip are examined under optical microscope. Micrographs of these sections are shown in Fig. 3.



(A) (B)

Fig. 3. Transverse sections (of half a specimen) at critical crack length. Note the difference in craze density for the two loading levels: (A) σ_m = 16.0 MPa, (B) σ_m = 10.7 MPa.

The crazes are oriented perpendicular to the direction of the load application and homogeneously distributed along their own orientation. In contrast, the intensity of crazes decreases away from the crack in the direction of the applied load. Although, the width of the crazed zone is practically the same, for both loading levels, the intensity of crazing is significantly higher for the lower loading level.

DISCUSSION

The CL theory (Chudnovsky, 1983) models fracture propagation in terms of damage evolution. This evolution is approximated by the active zone movements: translation and rotation as a rigid body, isotropic expansion and shape changes. Detailed analysis of the results described in the previous section indicates that translation and expansion of the active zone are the dominant modes of propagation (Botsis, Chudnovsky and Moet, 1984a). In this report the translational mode of propagation is considered. The following constitutive equation for CL translation has been proposed (Chudnovsky and Moet, 1984).

$$\frac{d\ell}{dN} = \frac{\beta_1 W^{(i)}}{\gamma^* R_1 - J_1} \qquad (1)$$

Here β_1 is a phenomenological coefficient which expresses the fraction of the total dissipated work, $W^{(i)}$, expended on CL translation. The specific enthalpy of damage, γ^*, is taken as a material constant (Haddaoui, Chudnovsky and Moet, 1983) and J_1 is the energy release rate. The translational resistance moment, R_1, is an integral representation of damage along the trailing edge of the active zone (Chudnovsky and Moet, 1984). As J_1 approaches $\gamma^* R_1$,

$d\ell/dN$ becomes unlimited which corresponds to unstable CL propagation at which

$$J_{1c} = \gamma^* R_{1c} \qquad (2)$$

where J_{1c} and R_{1c} are the energy release rate and translational resistance moment at critical CL propagation. Considering an average craze density $\langle\rho\rangle$ [mm^2/mm^3] along the trailing edge of the active zone, the resistance moment can be expressed as

$$R_1 = \langle\rho\rangle\, W \qquad (3)$$

where W is the width of the active zone. Hence, eq. (2) may be written as

$$J_{1c} = \gamma^* \langle\rho\rangle\, W_c \qquad (4)$$

Here W_c is the width of the active zone at critical CL propagation. Substitution of eqs. (3) and (4) into eq. (1) yields

$$\frac{d\ell}{dN} = \frac{\beta_1 W^{(i)}}{\frac{W}{W_c} J_{1c} - J_1} \qquad (5)$$

The irreversible work, $W^{(i)}$, is the work done by the boundary forces on the displacements at the grips due to discontinuities associated within the active zone.
The coefficient, β_1, has been found to be inversely proportional to the life time of the active zone, i.e., $\beta_1 \sim (\ell a/\dot{\ell})^{-1}$, where $\dot{\ell}$ is the crack speed and ℓa the length of the active zone (Fig. 2). Further analysis suggests that the ratio, $\dot{\ell}/\ell a$, is proportional to the square of the energy release rate, i.e., $\beta_1 = \beta_0 J_1^2/(1 + \alpha)$, where α expresses the ratio of the fractions of irreversible work spent into expansion and translation of the active zone which is calculated from experimental data. The coefficient of proportionality, β_0, is the only fitting parameter used (Botsis, Chudnovsky and Moet, 1984b). Figure 4 shows the experimental results and theoretical predictions for the two levels. Evidently, eq. (1) is in good agreement with the experimental results for the entire range of slow CL propagation. The difference in the critical energy release rates, J_{1c}, can be easily explained in terms of the eq. (2) and the results shown in Fig. 3. Since the specific enthalpy of damage, γ^*, is a material constant, the different values of J_{1c} is due to the different values of R_{1c}. Indeed, image analysis of the sections shown in Fig. 3 indicates that the ratio of the average craze density is 0.45/0.84 = 0.53. This ratio is practically equal to $J_c^{(2)}/J_c^{(1)}$ which is in agreement with the prediction of eq. (2).

The effect of damage on CL propagation is expressed through the interplay of $\gamma^* R_1$ and J_1 of eq. (1). Whereas J_1 expresses the energy available, $\gamma^* R_1$ represents the energy required for CL translation. Therefore, the denominator of eq. (1), i.e., $\gamma^* R_1 - J_1$ is the energy barrier for the process. Accordingly a plot of the energy required, $\gamma^* R_1$, vs. the energy available, J_1, characterizes the evolution of the energy barrier during crack propagation

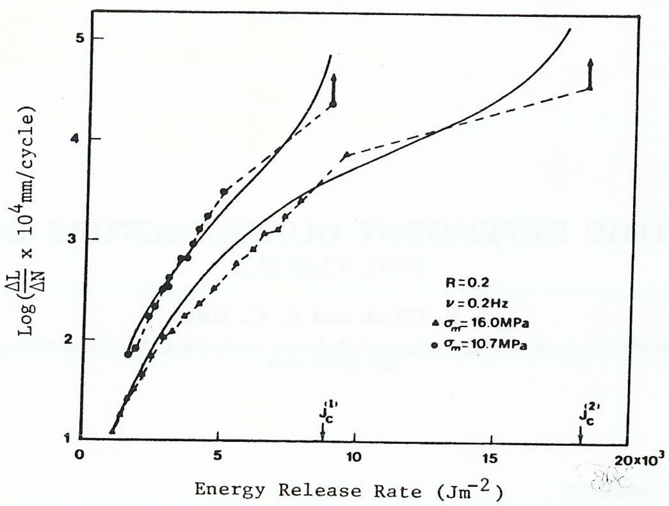


Fig. 4. Fatigue crack growth rates as a function of the energy release rate as predicted by eq. (1).

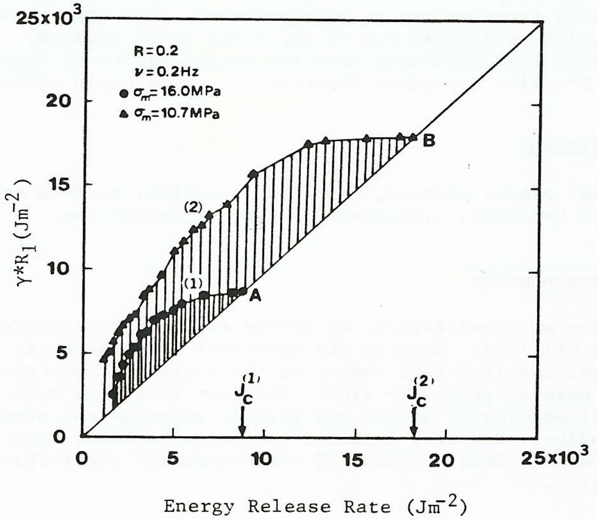


Fig. 5. Evolution of γ^*R_1 with the energy release rate for (1) σ_m = 16.0 MPa and (2) σ_m = 10.7 MPa.

history. Such a plot for the two experiments is shown in Fig. 5. The energetic barrier, $\gamma^*R_1 - J_1$, can be measured from the difference between the

respective γ^*R_1 curve and the bisector (shadowed area in Fig. 5). On the basis of this analysis, the S-shaped character of crack propagation curve can be explained. Prior to crack initiation a critical level of damage is usually attained (Botsis, Moet and Chudnovsky, 1983). Therefore, initiation of the crack within the damaged material requires a very small amount of energy as a result of which a very high speed of crack propagation is observed. At intermediate values of J_1, the average speed of crack propagation depends on the interplay between J_1 and γ^*R_1. This is evident from comparrison of Figs. 4 and 5 where higher damage density results in lower crack speed at the same value of J_1. Ultimate failure of the specimen occurs when the equality of J_1 and γ^*R_1 is met (eq. 2) and indicates that the critical energy release rate is dependent on the history of damage evolution.

The analysis presented above links material properties and microstructure (γ^*R_1) to conventional fracture mechanics (J_1).

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