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Thermal wave imaging of propagating cracks in polymers

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Abstract: Thermal wave imaging techniques, using both an Inframetrics IR740 Camera and a Santa Barbara Focal Plane InSb array camera, have been used to measure the temperature distributions around propagating cracks in polymer materials. Cracks have been initiated under tensile stress with various strain rates, and in several different polymer materials. The time-dependent thermal behavior is then studied. This behavior includes elastic cooling, followed by heating caused by plastic deformation in the stressed region prior to crack formation, and localized heating as the crack initiates and propagates, followed by diffusive cooling after failure. The full-field picture provides also information about the interaction of cracks with pre-existing flaws, and the dynamics of the interaction between two cracks.

1. INTRODUCTION

The initiation and propagation of fracture cracks can result in a large local temperature rise in the vicinity of the crack tip. This temperature rise strongly affects the nature of the near-tip deformation field, and hence can lead to a decrease in the dynamic fracture toughness of the material. For this reason, over the last two decades there has been a growing interest in investigating the thermal behavior of polymer materials during crack initiation and propagation [1]. The experimental techniques have included calorimeters [2], contact thermocouples [3], and, more recently, non-contact IR detectors [1,3]. These efforts, though proven helpful for understanding the crack behavior, were restricted to measuring this temperature rise at only a few points, and failed to get the full-field information around the crack tip. It has been pointed out by various authors [4,5], that it is important to get the full-field information on the temperature distribution around the crack tip in order to understand the crack propagation dynamics and fracture mechanisms.

In this paper we report full-field, real time, thermal-wave imaging of dynamically propagating cracks in polymer materials. This is accomplished by utilizing advanced IR cameras.

2. EXPERIMENTAL

A table-top tensile tester (PL-Polymer Laboratories) is used to apply tensile stress to notched polymer test coupons, using uniform strain rates which are varied up to 100 mm/minute. During the tensile test, the IR emission from the coupon is monitored as a function of time, by using either an Inframetrics IR740 Camera (8 μ m - 12 μ m spectral band/30 Hz frame rate) or a SantaBarbara 128 x 128 InSb focal plane array camera (3 μ m - 5 μ m spectral band/ up to 244 Hz frame rate). A block diagram of the experiment is shown in Fig. 1, and the geometry of the test coupons is shown in Fig. 2.

To convert the measured IR signal to surface temperature, it is necessary to know the emissivities of the samples. We have made such measurements in the 3 μ m - 5 μ m spectral band, and our results are summarized in Fig. 3.

Fig. 1 Block Diagram of Experiment

Fig. 2 Geometry of the test coupons.

Fig. 3. Measured emissivity data for the polymer test coupons at the $3\mu\text{m} - 5\mu\text{m}$ spectral band, the working range of the SantaBarbara focal plane array camera.

3. RESULTS

A typical set of images for a rubber-modified polystyrene coupon is shown in Fig. 4. The strain rate in this case is 40 mm/min. These images, taken with the IR740 camera, illustrate the typical behavior for a double-notched sample, such as that shown schematically in Fig. 2. The features include elastic cooling, heating caused by plastic deformation in the stressed region; localized heating as the crack initiates and propagates; and diffusive cooling after failure.

Figure 5 shows the result for a polycarbonate sample, taken by using the SantaBarbara camera. This sample is single edge-notched and contains a bubble. The images recorded show again the cooling down process ($t=0$), the local heating up around the notch and the bubble ($t=172$ ms), and the following crack propagation dynamics. Compared to Fig. 4, an additional feature seen here is that the result contains full-field images of the crack-bubble interaction dynamics. We also observed a much higher temperature rise at the crack tip for the polycarbonate sample, as compared to the rubber-modified polystyrene test coupons.

Figure 6 shows a typical set of images for the epoxy sample, using the SantaBarbara camera. Epoxy is much more brittle than the polycarbonate and the rubber modified polystyrene. For this reason a much faster crack propagation speed is observed with the same drawing speed.

In Fig. 7, we show the variation in temperature rise at the crack tip for the three materials tested, all measured with a drawing speed of 90 mm/min. These measurements were carried out on test coupons with a single notch, and the temperature rise calculations include corrections for the differences in emissivity (see Fig. 3). It can be seen that the crack tip temperature changes drastically from sample to sample (from about one degree Celsius for epoxy to several tens of degrees Celsius for polycarbonate), even though the geometry of the test coupons are similar and the experimental conditions are exactly the same.

Fig. 4. IR images for a rubber modified polystyrene test coupon. Drawing speed: 40 mm/min.

Fig. 5. IR images for a polycarbonate test coupon with a drawing speed of 80 mm/min.

The observed differences in thermal behavior are helpful for the understanding of the energy dissipation processes and the fracture mechanisms of polymer materials. For most polymers, the sources of the thermal events may be both the rupture of macromolecules and the deformational processes, with the effect of the latter much less pronounced for brittle materials (such as the epoxy test coupon) than for quasi-brittle or ductile ones (such as the polycarbonate sample). For this reason, the temperature rise at the crack tip is strongly dependent on the ratio of the plastic work transformed into heat, the volume of the heated zone, the crack velocity, and the toughness of the material which determines how much work is needed to break the macromolecules. Detailed discussions on the experimentally observed thermal events and their correlation with the energy dissipation and fracture mechanisms will be presented in our forthcoming papers.

Fig. 6. IR images for an epoxy test coupon with a drawing speed of 80 mm/min.

Fig.7. Temperature rise at the crack tip for the three materials tested. Drawing speed: 90 mm/min.

4. CONCLUSIONS

In conclusion we have demonstrated that thermal-wave imaging is a powerful technique for investigating fracture related problems for polymer materials, particularly the energy dissipation mechanisms and the crack propagation and interaction dynamics.

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