NOTE

Computer Simulation of Conic-Shaped Patterns on Fracture Surfaces of Polymers

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ABSTRACT: Fractographic analysis, using scanning electron microscopy, is an important method to study polymer fracture behavior. There are several distinctive patterns on fracture surfaces, such as radial striations, regularly spaced 'rib' markings, and conic-shaped patterns. The conic-shaped pattern is the intersection locus of a moving planar crack front and a radially growing circular craze or secondary crack front. In this paper, the effects of the ratio of crack velocity to growing craze or secondary crack velocity on the shape of intersection loci are discussed using computer simulations. It is shown that when the ratio of crack velocity to craze or secondary crack velocity ($\dot{a}/\dot{c}$) increases progressively, the fracture surface pattern changes from a parabola or a prolate parabola to an ellipse and finally to an approximate circle. Therefore, the crack growth velocity can be estimated based on the fracture surface morphology and then related to the fracture processes as well as to the ductile–brittle transition or toughening mechanism of brittle polymers. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 89: 1722–1725, 2003

Key words: fracture; fractionation of polymers; electron microscopy; crazing; simulations

INTRODUCTION

Polymer glasses are attractive materials for many engineering applications because they are low in density, have excellent mechanical properties, and are easily fabricated by processes such as injection molding, extrusion, and vacuum forming. Their stiffness and strength must satisfy the structural needs. Therefore, the failure theory of polymers attracts many researchers' attention. During the fracture process, a craze or shear yielding zone usually forms at a crack tip.[1] The initiation, growth, and breakdown of crazes or shear yielding zones are thus central to the understanding of the fracture mechanics of polymer glasses. There are two main methods to study the process of craze growth and craze breakdown. One is optical interferometry, which is used to measure the size and shape of single crack tip crazes in transparent polymers.[2, 3] The results of interferometric measurements are used in connection with fracture mechanics models and mathematical or numerical methods for calculations of stress in the microregion at the crack tip and give qualitative and quantitative descriptions of deformation and fracture processes. The other method is fractographic analysis of fracture surfaces, which is an important and often used method to investigate the failure mode and damage-fracture mechanism of materials.[4–12] The fracture process of many glassy polymers is usually associated with craze formation and governed by craze growth and breakdown. There are several distinctive patterns on fracture surfaces, such as radial striations, regularly spaced 'rib' markings, conic-shaped patterns, etc. These patterns are related to distinctive deformation and fracture mechanisms. The conic-shaped pattern is thought to be the intersection locus of a moving planar crack front and a growing circular craze or secondary crack front.[1, 9–11] These conic-shaped patterns include parabolas, ellipses, and circles. They are related to the crack and craze growth speeds; namely, there exist different distinctive conic patterns on fracture surfaces due to different crack or craze growth speeds. In this paper, the effects of the ratio of crack velocity to craze or secondary crack velocity on the shape of intersection loci are discussed using computer simulations. The purpose of this study is to determine the interrelationship between the facture surface morphology and the crack or craze growth behavior.

DISTINCTIVE PATTERNS ON FRACTURE SURFACES OF POLYMERS

For a slow moving crack/craze entity in polymethyl methacrylate (PMMA), crack growth takes place by breakdown of the craze along its midrib, which leaves a relatively smooth fracture surface[13, 14] and dissipates a relatively small amount of energy to create new surfaces. During the continuous loading, the crack growth speeds up, and the fracture sur-

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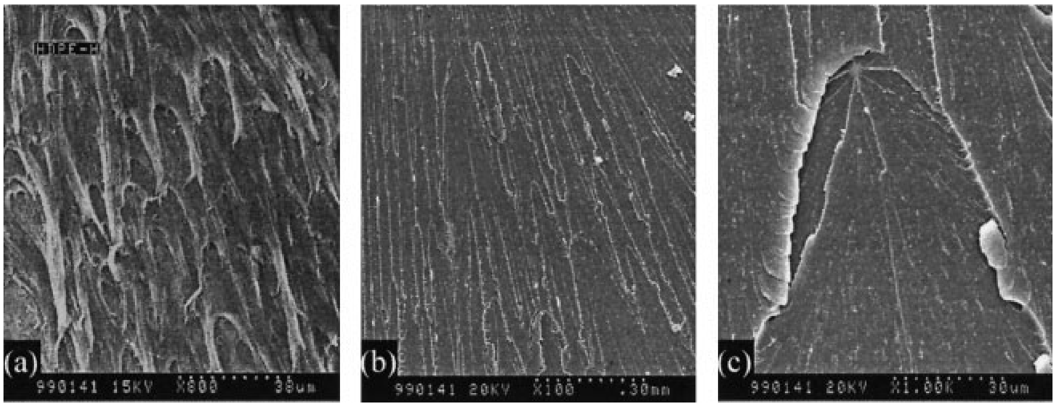

Figure 1 Parabola patterns on tensile fracture surfaces: (a) the fracture surface of high-density polyethylene; (b) the fracture surface of epoxy resin; and (c) a higher magnification of the features in (b).

faces have regularly spaced 'rib' markings perpendicular to the direction of crack growth.[15, 16] This pattern appears to be related to a type of stick/slip propagation due to either crack bifurcation or the effect of stress waves.[15] The transition between these two distinct types of surface morphology can be very abrupt. More features exist on the fracture surfaces of some other materials, such as polystyrene (PS), polycarbonate (PC), acrylonitrile–butadiene–styrene (ABS) copolymer, polypropylene (PP), high-density polyethylene (HDPE), and epoxy resin.[4–17] Conic-shaped patterns[9–11,17] are often seen on the fracture surfaces when relatively slow crack growth has taken place, as shown in Figure 1. For rapidly moving cracks in these materials, irregular 'mackerel' or 'patch' patterns are found on fracture surfaces.[1, 8,11,14]

The conic-shaped surface patterns are thought to be the intersection loci of the moving planar crack front and growing circular crazes or secondary cracks, as illustrated schematically in Figure 2. The parallel lines represent the moving crack front and the concentric circles represent the radially growing craze or secondary crack front. It can be seen in Figure 2 that the points of intersection in time sequence form a conic-shaped pattern, aligned with the bow of the conic section pointing towards the moving crack. Craze or secondary crack initiates at the focal point of the conic section. The initiation site, which is the location of stress concentration due to material inhomogeneity (e.g., secondary particles), can be clearly seen in Figure 1(c). The number of conic-shaped patterns is dependent on the degree of material inhomogeneity and the loading conditions. It has been shown that the shape of conic section is dependent on the ratio of crack velocity to craze or secondary crack velocity, $\dot{a}/\dot{c}$.

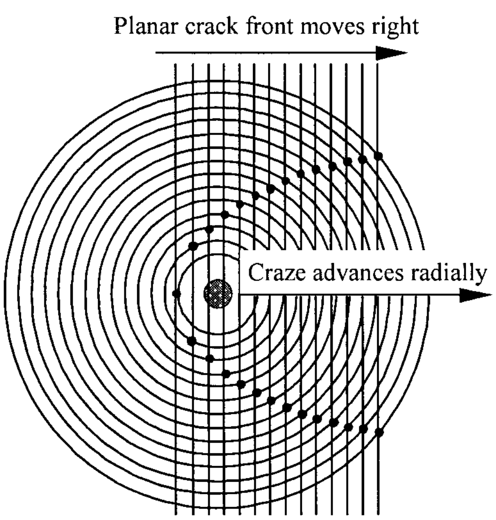

Figure 2 Schematic drawing of conic-shaped pattern.

COMPUTER SIMULATION OF CONIC-SHAPED PATTERNS

The computer simulation of conic-shaped patterns on fracture surfaces based on their formation mechanisms is given next. In methodology terms, this simulation involves a system of equations that describe the motion of the moving fronts of main crack and crazes or secondary cracks. As shown in Figure 2, the main crack is supposed to propagate right with velocity of $\dot{a}$, and the craze or secondary crack advances radially with velocity of $\dot{c}$. The hatched circle in Figure 2 indicates the craze initiation site. The radius of the craze or secondary crack front (represented by a circle in Figure 3) is assumed to reach r_0 at the instant when the main crack front first meets the front of craze or secondary crack (i.e., when the first left line is exactly the tangent line of the smallest circle shown in Figure 2). By constructing a coordinate system with its origin at the craze initiation site and the x-axis parallel to the crack growth direction (see Figure 3), the control equations for crack front growth and craze front advance are as follows:

$$x = -r_0 + \dot{a}t \qquad \text{for crack front growth} \tag{1}$$

$$x^2 + y^2 = (r_0 + \dot{c}t)^2 \qquad \text{for craze front advance} \tag{2}$$

in which t is time. Substituting eq. 1 into eq. 2 yields

$$\left(\frac{x}{r_0}\right)^2 + \left(\frac{y}{r_0}\right)^2 = \left(1 + \frac{\dot{c}}{\dot{a}} + \frac{\dot{c}}{\dot{a}}\frac{x}{r_0}\right)^2 \tag{3}$$

Equation 3 is the control equation for the intersection loci of the moving planar crack front and growing circular crazes or

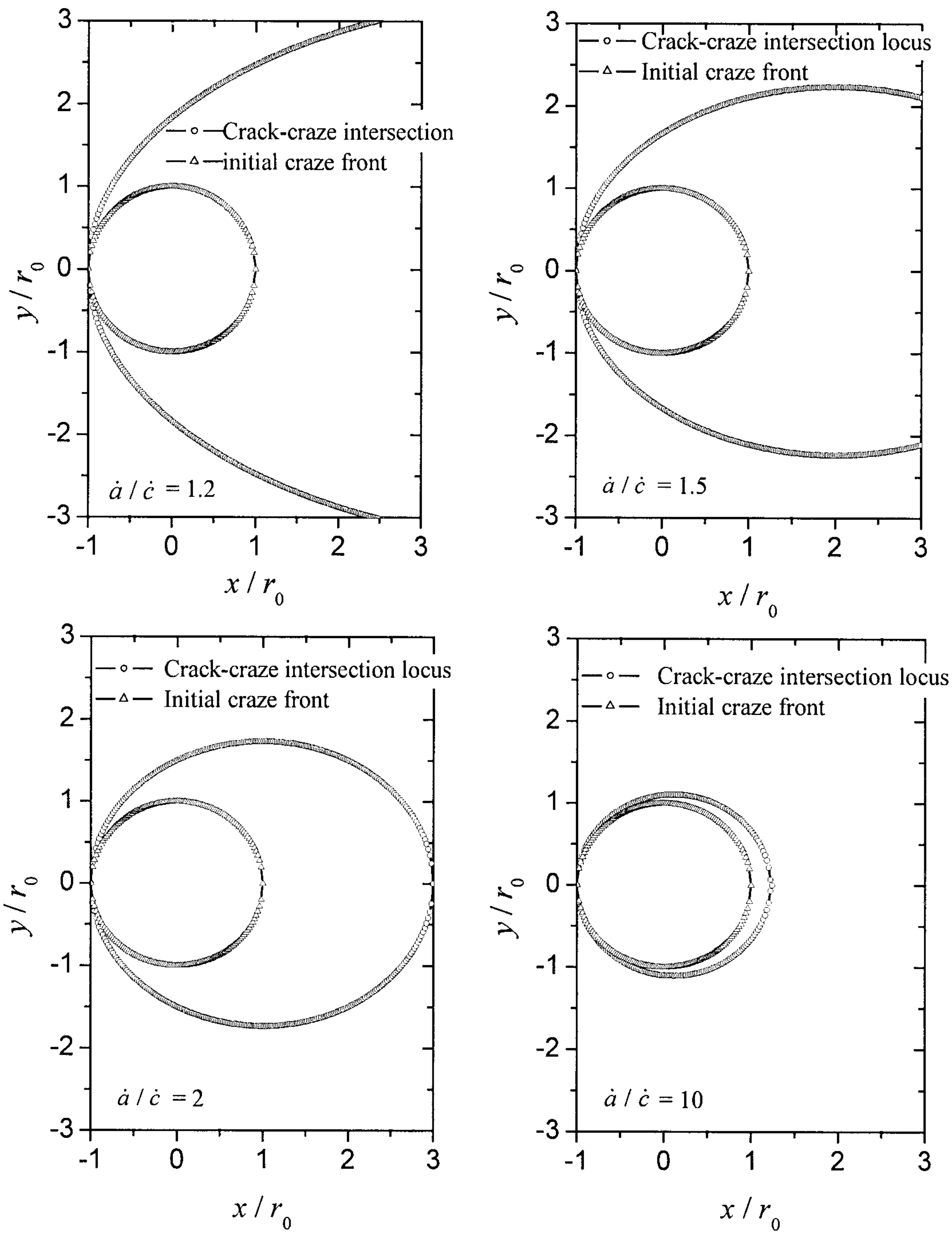

Figure 3 Computer simulation of conic-shaped patterns on fracture surfaces for different $\dot{a}/\dot{c}$.

secondary cracks. It has a conic form, but the specific shape depends on the ratio of crack velocity to craze or secondary crack velocity, $\dot{a}/\dot{c}$.

The variations in the shape of the conic-shaped patterns for different $\dot{a}/\dot{c}$ velocity ratios, where the coordinate origin is located at the initiation site of the craze or the secondary crack and the simulated patterns are limited in a rectangular area with size of $4r_0 \times 6r_0$, are shown in Figure 3. When the ratio $\dot{a}/\dot{c}$ increases progressively, the fracture surface pattern changes from a parabola or a prolate parabola to an ellipse and finally to an approximate circle. It is evident from eq. 3 that the geometric drawing of the equation is a near circle if the $\dot{a}/\dot{c}$ ratio becomes large enough.

The fracture surface morphology near a crack root and its simulation result for a dual-edged notched PP specimen under tension with constant displacement rate are shown in Figure 4. In simulation we let $r_0 = 50$ μm and $\dot{a}/\dot{c} = 4/3$. It can be seen from Figure 4(a) that several crazes form near the crack root, due to stress concentration and material inhomogeneity, and distribute in a regularly spaced manner along the specimen width. During the continuous loading, the crazes grow and, simultaneously, the crack propagates

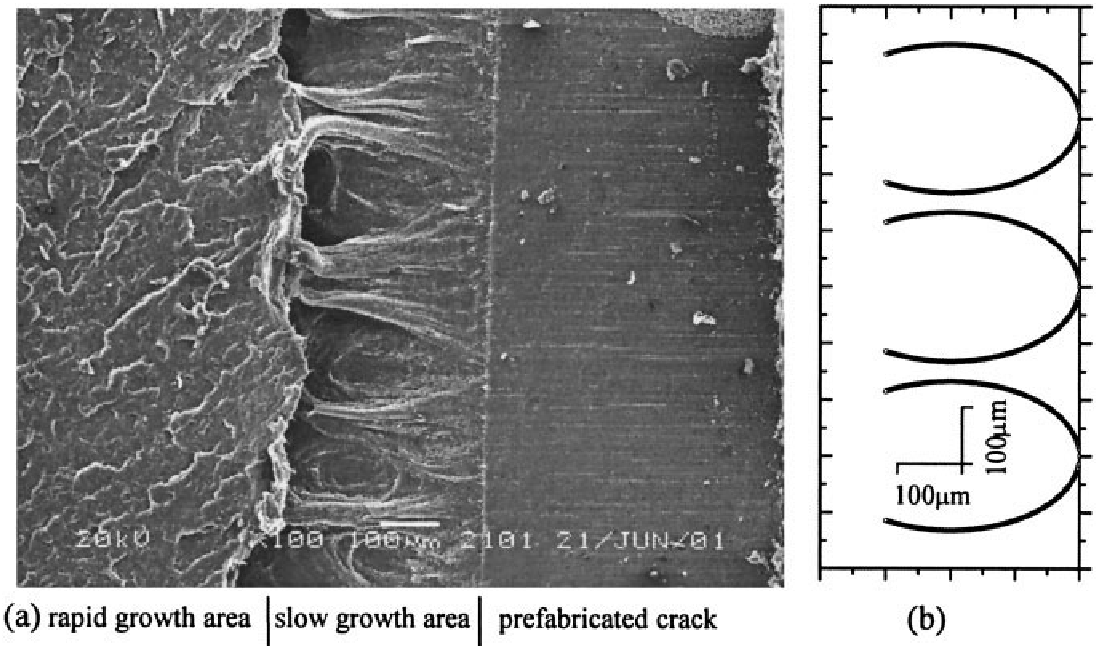

Figure 4 (a) Parabola pattern on fracture surface of polypropylene, and (b) computer simulation.

slowly. Parabola patters are formed when the fronts of crazes and cracks intersect each other. When the instability criterion for crack growth is met, the crack propagates at a very high speed and the crazes initiated near the crack front do not have enough time to grow. Thus, a large number of fine near circle patterns are left on the fracture surface (see Figure 5).

CONCLUDING REMARKS

Fracture surface morphology analysis is an important method to investigate the failure modes and damage–fracture mechanisms of polymers. The conic-shaped pattern is the intersection locus of a moving planar crack front and a radially growing circular craze or secondary crack front. Its shape is dependent on the ratio of crack velocity to craze or secondary crack velocity, $\dot{a}/\dot{c}$. Computer simulations indicate that when the $\dot{a}/\dot{c}$ ratio increases progressively, the fracture surface pattern changes from a parabola or a prolate parabola to an ellipse and finally to an approximate circle.

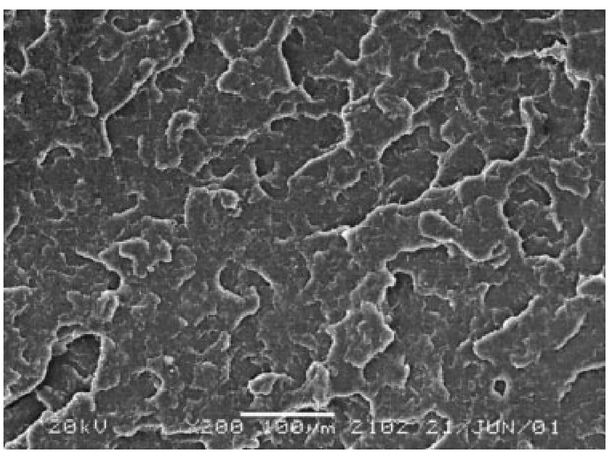

Figure 5 Surface patterns in rapid fracture region of polypropylene specimen in Figure 4(a).

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