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TWO CRITICAL CRACK PROPAGATING VELOCITIES FOR PMMA FRACTURE SURFACE

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Abstract. Ultrasonic fractography and scanning electronic microscopy (SEM) are used to determine the direct relationship between the fracture surface morphology and the main crack velocity during the rapid rupture of polymethylmethacrylate (PMMA). Two critical crack velocities are found for the fracture. Quasi-parabolic markings will appear when the crack speed exceeds the first critical speed. Crack propagating at speed above the second critical speed leaves a thicket of small branches penetrating the surface behind them. Both critical speeds are functions of the thickness of the specimens.

1. Introduction. Surface microscopic morphology of PMMA and its relationship with crack velocity and dynamic stress intensity factor (DSIF) arouse much concern among investigators of various fields. High speed photography and caustics are usually used to determine the crack speed and the DSIF; Nevertheless, these two experimental methods are restricted to the surface boundary of the crack, therefore, it is hard to obtain the information inside the specimen by these two experimental methods. As a post-mortem examination method, the technique of ultrasonic fractography can be used to measure precisely the main crack velocity at any position of the fracture surface, so it is easy to connect directly the main crack velocity and the microscopic morphology. The crack velocity at any point on the fracture surface is determined by measuring the distance of the Wallner lines. The Wallner lines left on the fracture surface are the fronts of the main crack at various instants.

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Both experiments and numerical simulation in a simple atomic-scale model for Plexiglas [1] show that a critical crack velocity exists, slowly moving cracks tend to leave smooth surfaces, they travel calmly, their velocity increasing smoothly and slowly with time. Beyond a critical velocity, cracks move with wildly undulating speed and leave a thicket of small branches penetrating the surface behind them. The transition of the crack velocity is a function of the energy stored per unit length to the right of the crack [1]. The origin of the dynamical instability of the crack propagation is still not very clear, much more remains to be learned [1]. It has also been shown experimentally that the fracture surfaces of PMMA are tiled with conic markings [2], these markings are well known in the fracture of amorphous materials [3]. They are usually interpreted as being level differences resulting from an encounter between a microcrack and a main crack. It is one of the objectives of this letter to obtain the critical crack speeds for the appearance of the conic markings as well as the secondary microcracks of the fracture surface of PMMA.

2. Experimental results. The geometry of the crack front changes with the constraint conditions of the fracture surface boundary. Sheng and Takahashi [5] pointed out that the main crack front would propagate concavely if double pre-grooves are made along the line that the crack would propagate, as shown in Fig. 1. Fig. 2 is the fracture fractography of the specimen with double grooves, the concave curves on the fracture surface are the crack fronts at various instants. The crack speed distribution along the crack length is almost the same as that of the specimen without grooves. The curvature ahead of the crack tip increases with the crack speed.
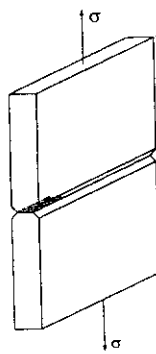

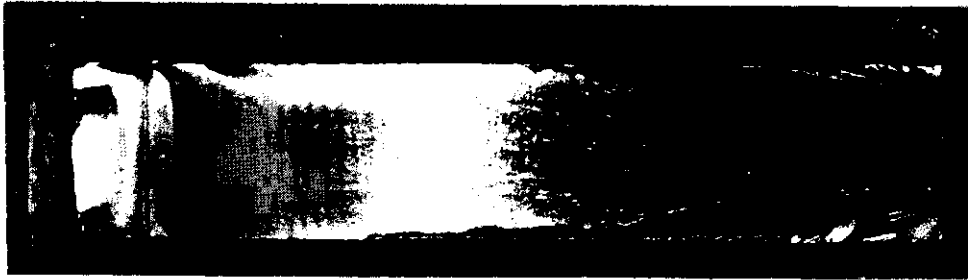Figure 1. PMMA specimen with double-grooves under tension.

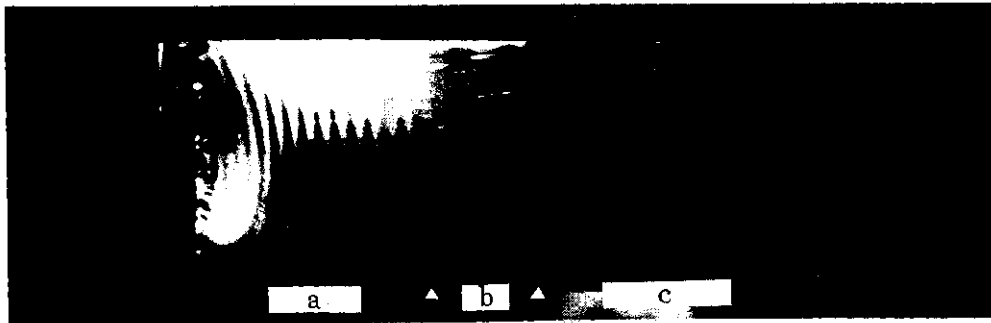Figure 2. Fracture fractography of the specimen with double-grooves.

Figure 3. Fracture fractography of the specimen with one-side groove.

Because of the spacing limitation, only the experimental result of 15mm thick, one-side grooved PMMA specimen is presented in this letter. SEM and ultrasonic fractography technique are used to determine the fracture surface microscopic morphology and the main crack speed. Then the microscopic morphology and the corresponding crack speed can be directly connected. Figure 3 is the photograph of the fracture surface morphology of the specimen under tension. The main crack propagates from left to right. In "domain a" of length 0~15mm, the main crack speed is comparatively slow, the crack speed increases monotonically from 135m/s to 196m/s, no quasi-parabolic markings are left on the fracture surface in this domain. In the range of 15mm~22mm (labeled as domain b), the crack speed increases from 196m/s to 235m/s. The first quasi-parabolic marking appears when the crack speed reaches a critical value--196m/s, however, there is not many quasi-parabolic markings in whole "domain b". In "domain c", the crack length is in the range of 22mm~40mm, the crack speed increases from 235m/s to 248m/s. The

density of the quasi-parabolic markings in "domain c" is obviously increased. It is also clear from Fig. 2 that the curvature at the crack tip decreases with the increase of the crack speed.
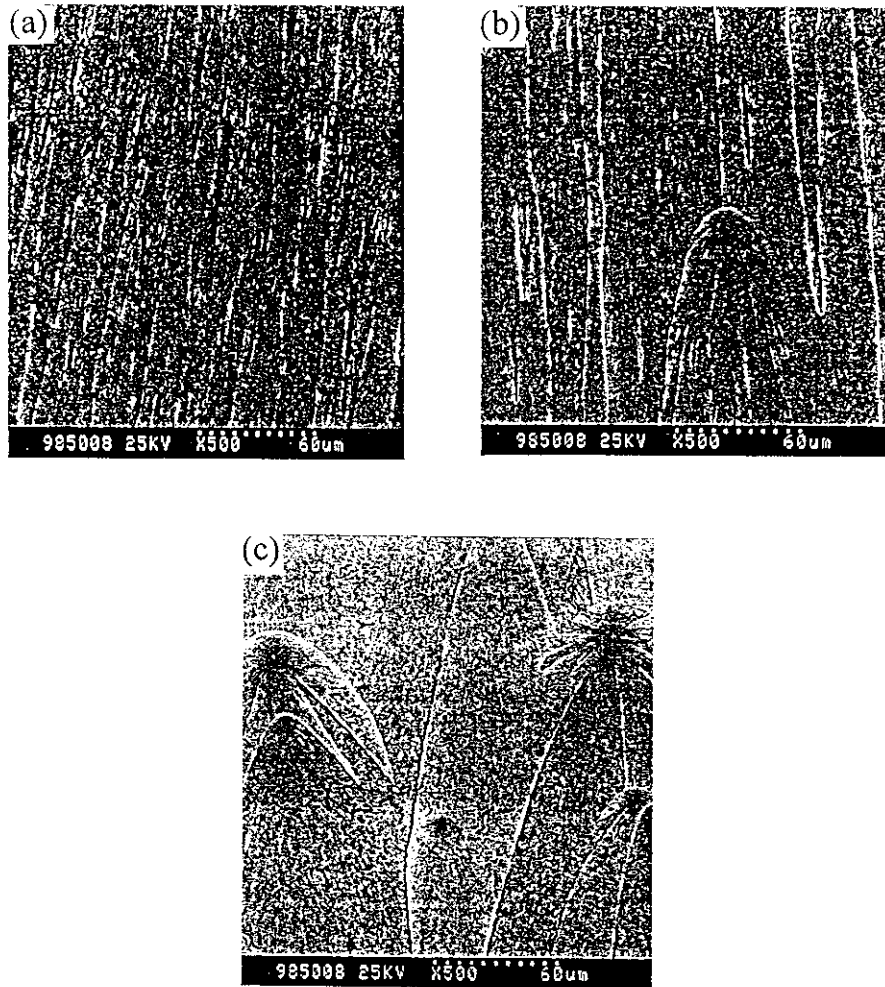

Figure 4. Microscopic morphology of the fracture surface.

Fig. 4 shows a small portion of the microscopic morphology of the fracture surface of the specimen under tension. The main crack speed corresponding to Fig. 4(a) is 187m/s, the fracture surface begins to appear misty. The main crack speed corresponding to Fig. 4(b) is 196m/s, first quasi-parabolic marking appears on the whole fracture surface, this is the first critical velocity for the crack propagation

defined in this letter. The second critical velocity for the appearance of secondary microcracks for this specimen is found to be 209m/s. The speed of the main crack corresponding to Fig. 4(c) is 245m/s, from which we know that the density of the quasi-parabolic markings are obviously increased in this domain. It is noted from Fig. 4 (b) and (c) that the direction of the apexes of these markings are inverse to that of the crack propagation, a dark radiative zone is clearly seen inside each quasi-parabolic marking. Different dark zones may have different sizes, It is the size of the dark zone determines the shape of the marking. The larger the dark zone is, the less the curvature of the quasi-parabolic marking will be, and vice verse. The distance between the center of the dark zone and the apex of the quasi-parabolic marking is found in the range of $3\mu m \sim 20\mu m$.

3. Preliminary theoretical analysis. A series of tests show that the values of the two critical crack propagating velocities depend strongly on the thickness of the specimens. The functional relationship for the crack velocity V is expressed by

$$V = f(v, B, E, \rho, K_{Id}), \tag{1}$$

where E and ρ are the Young's modulus and the mass density, respectively, v

is the Poisson's ratio, B is the thickness of the specimen, and K_{Id} is the DSIF.

By Buckingham's π-theorem, equation (1) is changed into

$$Ca = f_1(v, Z), \tag{2}$$

where $Ca = \rho V^2 / E$ is the Cauchy number [5], $Z = E\sqrt{B} / K_{Id}$ is a nondimensional number first suggested in Ref. [6]. From equation (2), we know that the two critical conditions for the appearance of the quasi-parabolic markings and the secondary microcracks can be considered when Ca reaches a critical value. For most PMMA materials, v almost keeps constant, then equation (2) becomes

$$Ca = f_2(Z). \tag{3}$$

Equation (3) is instructive for the experiments and the analyses of the experimental results. It is known from the experiments that the values of the two critical crack propagating velocities increase with the thickness of the specimens, therefore, it would be reasonable to assume that a scaling relationship exists

between the two similarity parameters Ca and Z, i.e.,

$$Ca \sim Z^m, \tag{4}$$

where the exponent m is a positive real number to be determined by experiments. Then the scaling relation between the values of the critical crack propagating velocities and the thickness of the specimens is

$$V \sim Z^{m/2} \sim B^{m/4}. \tag{5}$$

4. Conclusions. We have presented experimental evidence indicating the existence of two critical crack propagating velocities for the fracture surface of PMMA. Quasi-parabolic marking appears at a critical crack velocity, termed the first critical crack propagating velocity in this letter. Secondary microcracks initiate at the second critical main crack velocity, control the subsequent main crack speed, and cause energy dissipation. The two critical crack propagating velocities are functions of the thickness of the specimens. Theories for these two phenomena do not yet exist, however we offer dimensional analyses for such problems, two governing similarity parameters are given. Systematic experiments are still required to determine the quantitative relation of equation (4) or (5), theoretical explanation to the experimental results in this letter remains open.

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