Influence of Loading Conditions on Dynamics of Crack Propagation in Polymethylmethacrylate

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Abstract. The results of experimental investigation of crack propagation in PMMA plate samples under quasi-static and dynamic loading are presented. The quasi-static loading was carried out using a tensile-testing machine. The dynamic loading was carried out by means of the installation of conductor explosion.

The results of both dynamic and quasi-static experiments show the unstable behavior of the instantaneous crack velocity. However the mean speed of the crack tip propagation depends on the type of the load.

Introduction

Crack propagation in quasi-brittle and brittle materials has been studied for many decades. However, there is no complete understanding of the crack development process.

According to the classical concepts of fracture mechanics, the crack speed is a monotonic function of time. This assumption is based on the results of many experiments. Nevertheless some more recent experiments showed the unstable behavior of the crack tip velocity. For example, Fineberg et al. [1] showed the unstable behavior of the crack speed at quasi-static tests of PMMA plates. Kostandov et al. [2] obtained the step-wise crack propagation in PMMA plates under impact loading on the notch edges.

The results with the unstable crack behavior were obtained in different laboratories, under different loading conditions, and by different methods. This fact can affect the assessment of the differences in crack propagation under various loads. Therefore, there is an interest to conduct the similar tests with the uniform method of crack registration.

We present the results of experimental studies of the dynamics of crack propagation in plane samples of PMMA under quasi-static and dynamic loading. The quasi-static loading was carried out by a slow uniaxial tension of the samples with a starter notch. The dynamic load was carried out by means of electrical explosion of a wire between the edges of the notch in the sample.

Experimental Methods

Our experiments were performed on the samples of PMMA with the parameters: density ρ = 1180 kg/m^3, longitudinal sound velocity C_L = 2750±25 m/s, transverse sound velocity C_{TR} = 1400±25 m/s, modulus of elasticity E = 5.9 GPa.

The quasi-static loading was carried out on a tensile testing machine. The dumbbell-like plane samples with the dimensions of a working part of 93×35×5 mm were used. To initiate the crack, a notch was made by a razor blade in the middle of the working area. The notch depth was 0.4 - 1.3 mm.

The dynamic loading was realized by means of the installation of electrical explosion of conductors. The capacitor capacity was C = 1.0 μF; the charge voltage, $U \leq 25$ kV; the stored energy, $E \leq 312$ J. The samples were in the form of square plates (200×200×5 mm) with a side notch. The notch was

50 mm in length and 0.5 mm in width. The size of the samples was selected so that to remove the influence of reflected waves on the process of crack propagation during the registration time. The exploding wire (∅ 0.2 mm) was placed between the edges of the notch perpendicular to the plane of the plate at the distance of 24-31 mm from the notch base. A lavsan film was used to create the acoustic contact between the wire and notch edges. The same sample was used several times.

The registration of the crack front extension was carried out by means of the streak camera (K008) using the method of slit-type scanning of the image. The camera recorded the space-time scan of a beam of light reflected from the surface of the growing crack. In the quasi-static tests, the synchronization of the camera was made on the change of intensity of a laser beam passing through the notch base. In the case of dynamic loading, the synchronization was carried out on the signal from a current sensor. The detailed diagrams of the experiments are presented in [3].

The slit scan of the caustic was carried out for a qualitatively analysis of stress waves at the crack tip. In addition, in the quasi-static tests, the acoustic emission signals were registered on the lateral surface of the sample. These data allowed us to obtain a qualitative picture of the dynamic stress field at the crack tip and to analyze the parameters of elastic waves emitted during crack motion.

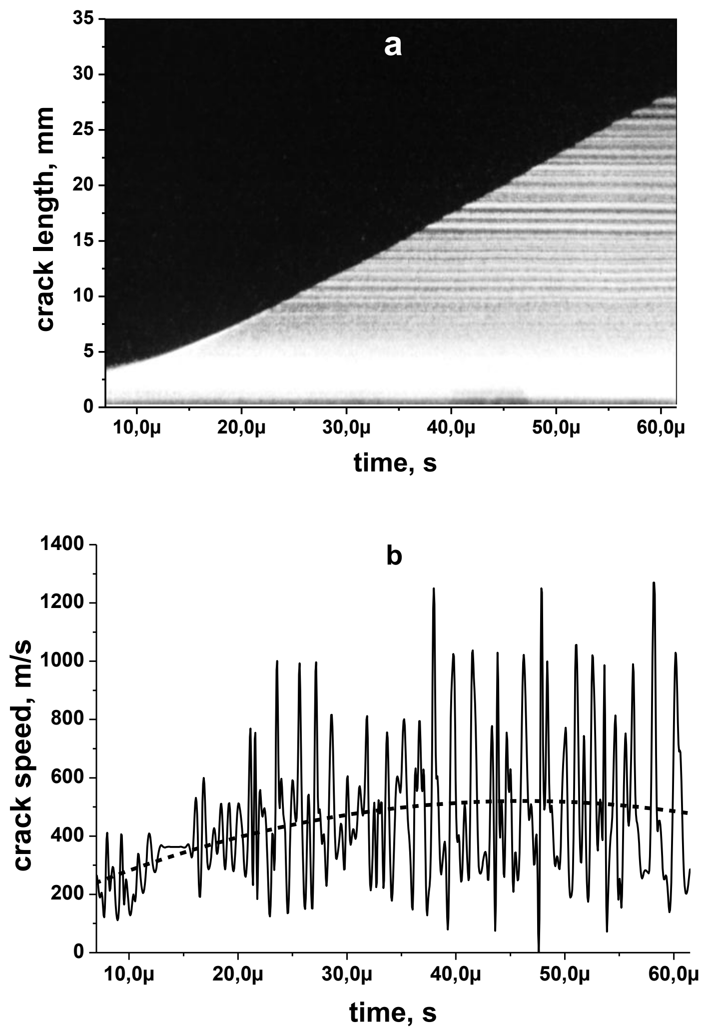

Fig. 1. Crack propagation under quasi-static rupture of plane samples of PMMA:
a) slit scan of the crack tip trajectory; b) fluctuation of the crack front speed (dashed line - the mean speed).

Test Results

Quasi-static Tests. The typical scan of the crack front trajectory is shown in Fig. 1, a. The speed of the crack tip propagation, obtained by differentiating the trajectory, is shown in Fig. 1, b.

The similar dependence of a crack speed was obtained in [1]. Fineberg et al. showed that the oscillations of the crack front correlate with the profile of the fracture surface, and the critical speed of the transition to the unstable mode of $V_c = 0.34C_R$ (C_R is the Rayleigh wave speed) does not depend on the geometry, sample thickness and applied load.

Our synchronization method made it possible to capture only the portion of the unstable crack propagation. However there is a similar correlation between the velocity oscillations of the crack, the fracture surface profile and the frequency of the acoustic emission signal.

The beginning of the most expressed unstable behavior of the crack corresponds to the beginning of the "ribbed" profile of the surface [1] with the distance between ribs about 1 mm. The most pronounced frequencies of the crack front velocity oscillations fall into the range 400–700 kHz. The stress-wave picture of the process of the crack propagation is shown in Fig. 2. The black arrow indicates the beginning of the well-defined emission of elastic waves from the vicinity of the crack tip. It is seen that the oscillations of the caustic diameter are accompanied by the emission of elastic stress waves.

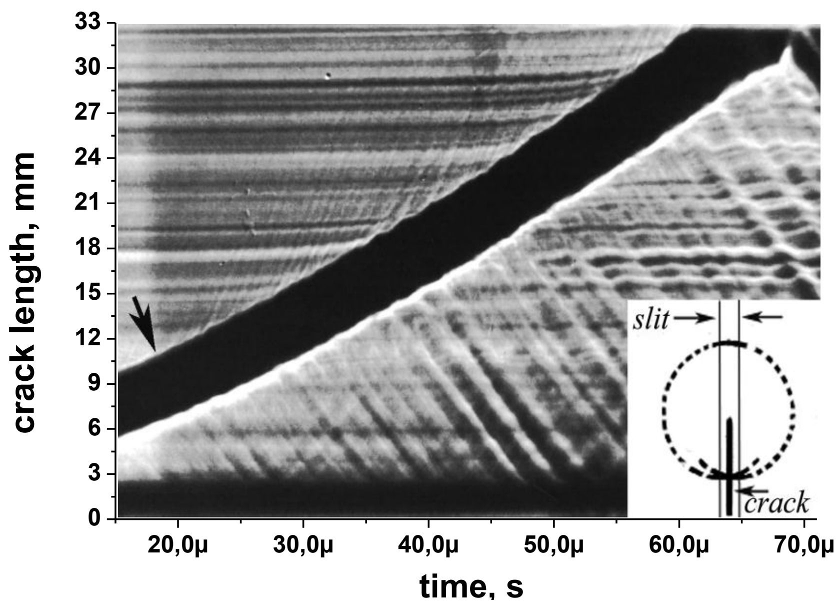

Fig. 2. Slit scan of the stress-wave pattern at a crack tip under quasi-static rupture of plane samples of PMMA.

Dynamic Tests. The typical crack trajectory under the dynamic loading of the samples is shown in Fig. 3, a. The speed of the crack front is shown in Fig. 3, b.

The mean speed varies slightly and can be assumed to be constant. The maximum speed fluctuations, as well as in the quasi-static tests, correspond to the rougher area of the fracture surface. Unlike the quasi-static tests, the formation sequence of typical zones on the fracture surface here is reverse: rough fragmentary, flaky, parabolic, and mirror.

Note that the loading condition corresponds to the problem of sudden application of concentrated loads on the faces of a semi-infinite crack. According to the analytical solution, the crack starts to propagate after the arrival of the Rayleigh wave. The recorded moments of the start of the crack are in good agreement with the theory.

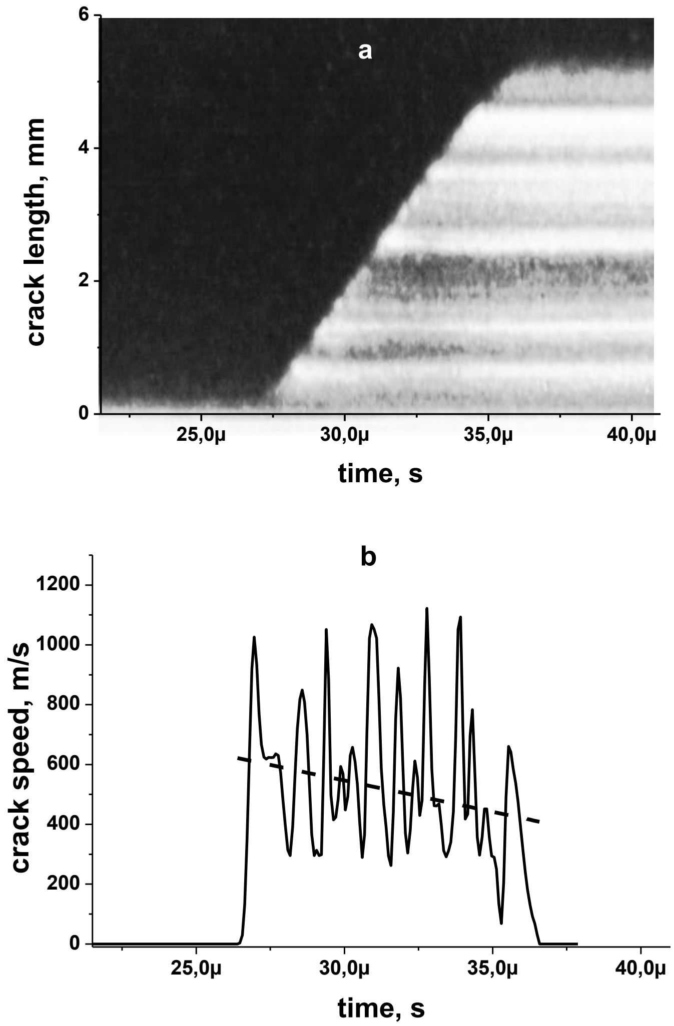

Fig. 3. Crack propagation under a localized pulse load on notch edges:
a) slit scan of the crack tip trajectory; b) fluctuation of the crack front speed (dashed line - the mean speed).

The slit scan of stress fields in the dynamic tests is shown in Fig. 4. Since PMMA is a viscoelastic material, then there is a small caustic at the crack tip before the arrival of the stress pulse. It is seen that the crack starts after the arrival of the transverse wave. Moreover, the caustic begins to move forward not from the crack tip, but along the edges of the notch. This could mean that the notch edges to move toward each other. However for the better analysis of the results and final conclusions, it is necessary to collect much more data statistics.

General Remarks. The data for the crack dynamics in the PMMA plates, which were obtained using the uniform technique for the crack registration, allow to reveal the similarity and difference between the stages of fracture under quasi-static and dynamic loading of brittle materials.

The mean speed of crack propagation in our experiments in both the quasi-static and dynamic tests did not exceed $0.5C_R$. However at the jumps, it could approach to the Rayleigh wave velocity.

The experiments demonstrate the common property of the quasi-stochastic behavior of the cracks at high speeds of crack front propagation. The experimental data agree qualitatively with the results obtained by other authors [1, 2]. Our results also confirm that the jumps in the crack front velocity correlate with changes in the structure of fracture surface.

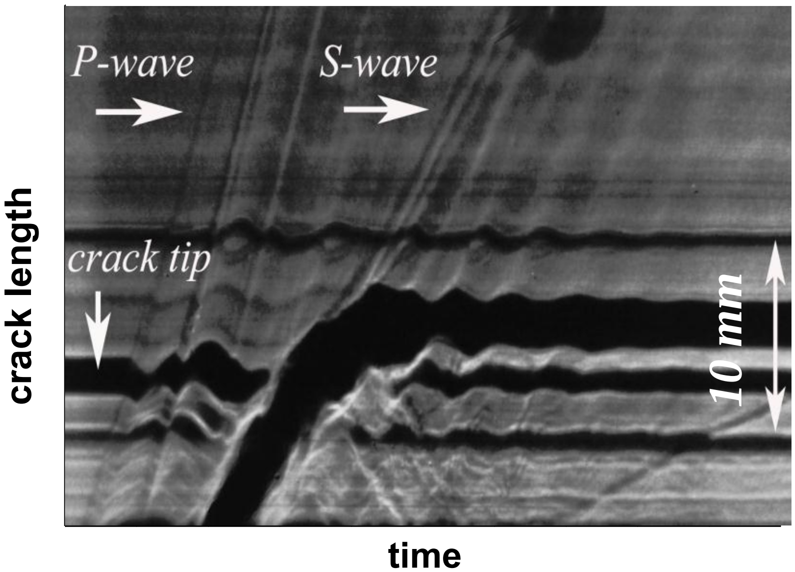

Fig. 4. Stress waves in dynamic tests.

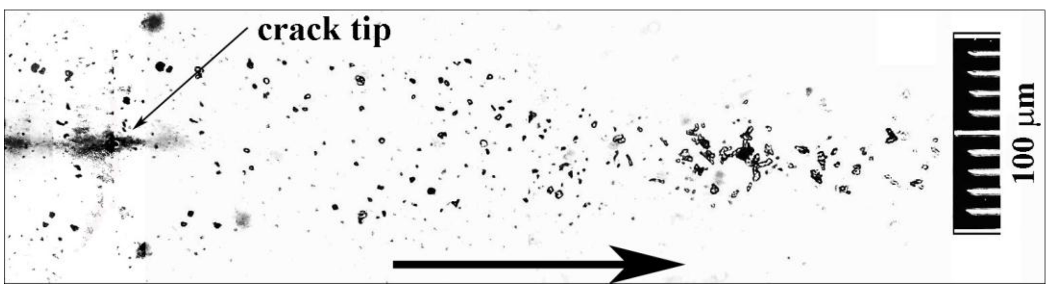

Fig. 5. Magnified view of the prefracture zone before a crack tip. The photo was made after stopping the crack in dynamic tests. The arrow indicates the direction of crack propagation.

The observed dynamics of crack propagation can be related to the formation of a prefracture zone before the front of a main crack [5-8], i.e., to the development of an ensemble of micro-damages in the area of high stress. Such area of micro-damages, registered during the dynamic tests after a crack stop, is shown in Fig. 5.

The principal difference between the two types of loading consists in the behavior of the mean speed of a crack tip. In case of quasi-static loading, the average speed increases relatively smoothly to its maximum value. This fact qualitatively coincides with the results of Dally et al. [9]. However, under dynamic loading, the average speed takes its maximum value almost immediately. The similar result was obtained by Ravi-Chandar and Knauss [10].

The unstable behavior of a crack is connected to mechanisms of energy dissipation in the area before the crack tip. The classical theory of fracture does not describe the behavior of such system. Averaging of the crack speed and the profile of fracture surface (or introduction of integral characteristics) may allow to use the equations of the linear theory of elasticity. Nevertheless the limiting characteristics of fracture (stress intensity factors, limit stress) will be determined by loading conditions, especially at high-intensity pulses with a wavelength much smaller sample sizes, as well as activation and further interaction of microdefects in the vicinity of a crack tip.

Summary
The study of the dynamics of crack propagation in plates of PMMA under quasi-static and dynamic loading was carried out.
It is shown that under both the quasi-static and dynamic testing conditions the change in the instantaneous crack speed has a quasi-stochastic character. However the behavior of the mean speed depends on the type of loading. In the case of quasi-static loading, the crack accelerates to its maximum value smoothly. In the case of pulse loading, the crack accelerates to its maximum value almost immediately.

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