Crack Propagation in PMMA Plates under Various Loading Conditions

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Abstract The experimental results of the dynamics of crack propagation in polymethylmethacrylate plates under quasi-static and dynamic loading are presented. Registration of the cracks was made by the method of slit-scanning of an image using a streak camera. Either a crack trajectory or caustic at the crack front was recorded in the experiments. It is shown that crack front extension has a stepwise character for any type of loading. However the average speed at the quasi-static loading increases smoothly up to the maximum value, and the average speed at pulsed loading takes the maximum value rather instantly. The value of the stress intensity factor at the moment of crack start under dynamic loading essentially exceeds the corresponding value for quasi-static loading. Furthermore, under dynamic loading, the crack speed depends on the thickness of the sample.

Keywords Crack propagation, Dynamic loading, Quasi-static loading

1. Introduction

Despite the fact that our knowledge constantly updates with experimental data about the process of fracture, questions about the conditions of initiation, propagation and stop of fracture remain actual. The problem is compounded by the fact that the data, which are used to develop the theoretical approaches, have been obtained at different scales, with different spatial and temporal resolution of recording equipment, under various load conditions and energy exchange of a sample and external environment.

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. Experimental results on quasi-static tensile of plates with a notch [see e.g. 1] lead to the conclusion that the speed of a crack is a monotonic function of time, and the relationship between the speed of a crack and the stress intensity factor can be described by an L-shaped curve. Studies of cracks in plates under dynamic load [2] showed that the speed of a crack is constant, but the corresponding stress intensity factor can change. In papers [3, 4] showed that the speed of a crack is unstable and stepwise. Such divergence of results suggests an idea about need of carrying out "systematizing" experiments which will allow to look at the behavior of strength characteristics of a material in terms of the scale factors, structural features and characteristics of energy input into the material.

In this work we have made an attempt to conduct the generalizing study of crack propagation process in brittle and quasi-brittle materials under quasi-static and dynamic loads. The loading schemes have been applied by analogy to the schemes in [1-4]. The quasi-static loading was carried out by slow uniaxial tension of plane samples with a starter notch. The dynamic load was carried out by means of electrical explosion of a wire between edges of a notch in a plane sample. Polymethyl methacrylate was chosen as the model material. PMMA shows quasi-brittle fracture and its transparency gives the chance to see a crack extension and to control it by photo recording methods. Crack propagation was registered by a streak camera which allowed to receive the time sweep of crack trajectory with the resolution 40-400 ns.

2. Experimental Technique

Our experiments were performed on the samples of injection molding 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 the 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 setup for 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 and 98×128 mm) with a side notch. The sample thickness was 5, 8 and 10 mm. The notch was 50 mm in length and 0.5 mm in width. The size of the greater samples was selected so that to remove the influence of reflected waves on the process of crack propagation during the registration time. The localized pressure pulse was generated by electrical explosion of a wire. 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 crack front extension was carried out by means of a streak camera (K008) using the method of slit-type scanning of an image. For this purpose, a beam of light was directed at the expected place of crack propagation at an angle to the plane of the sample. The camera recorded the space-time scan of the 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 [5].

The registration of caustic near with a crack tip was carried out on the basis of schemes of receiving shadow optical images described in [6]. The change of caustic was registered by scanning the real image with help the streak camera. However, the diameter of caustic was registered along crack extension rather than across (as generally accepted). Note that it may affect quantitative estimates because of the large singularity at the back of caustic.

The calculation of the stress intensity factor was made according to the following formula [6]

$$KI(t) = \frac{2\sqrt{2\pi}F(v)}{3(3.17)^{5/2} z_0 c d} D(t)^{5/2},$$
$$F(v) = \frac{[4\alpha_1\alpha_2 - (1+\alpha_2^2)^2]}{[(\alpha_1^2 - \alpha_2^2)(1+\alpha_2^2)]}, \ \alpha_j = (1 - \frac{v(t)^2}{c_j^2})^{1/2} \quad (j = 1,2) \tag{1}$$

where KI is the stress intensity factor of a crack in tension; $D(t)$ is the change in the diameter of the caustic; z_0 is the distance from the object to the image; c is the shadow optical constant; d is the thickness of the sample; c_1 and c_2 are the speeds of longitudinal and transverse waves respectively; $v(t)$ is the speed of the crack.

3. Results and Discussion

3.1. Quasi-static Tests

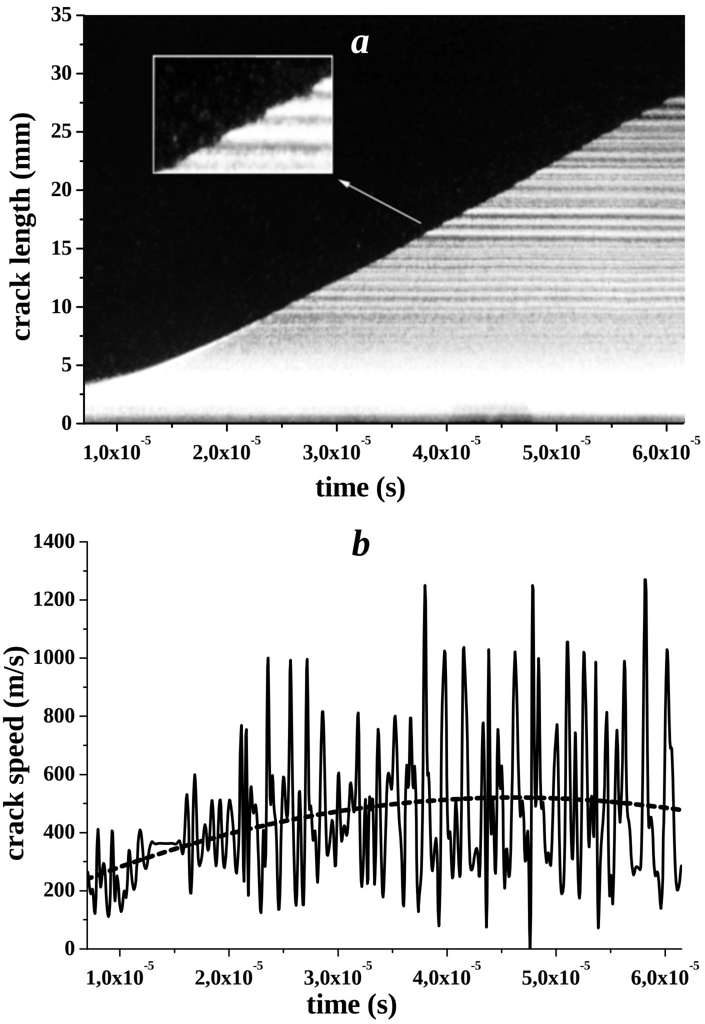

Figure 1. Crack propagation under quasi-static tension of plane samples of PMMA: a) slit scan of the crack tip trajectory; b) fluctuation of the crack front speed; dashed line is the mean speed (polynomial fitting).

Fig. 1a shows the typical trajectory of the crack front under quasi-static tensile of PMMA plates with a notch. The speed of the crack front is shown in Fig. 1b. The speed was obtained by differentiating of the crack trajectory according to the formula of the central difference derivative. Note that the applied scheme synchronization does not allow you to capture the initial part of the crack trajectory.

Comparison of the crack trajectory and the fracture surface shows that the beginning of an unstable behavior of the crack corresponds to the beginning of the "ribbed" surface structure [3,7] with the distance between the ribs about 1 mm. The most pronounced oscillation frequency of the crack front speed is in range of 400-700 kHz. The similar dependence of crack propagation speed was also obtained in [3]. In this work, the speed of a crack was determined by change in electrical resistance of an aluminum layer deposited on the sample surface. It was shown that the crack front oscillations correlated with the profile of the fracture surface, and the critical speed of the transition to the unstable regime $V_c = 0.34C_R$ (C_R is the Rayleigh wave speed) does not depend on the geometry and thickness of a sample and the tensile rate.

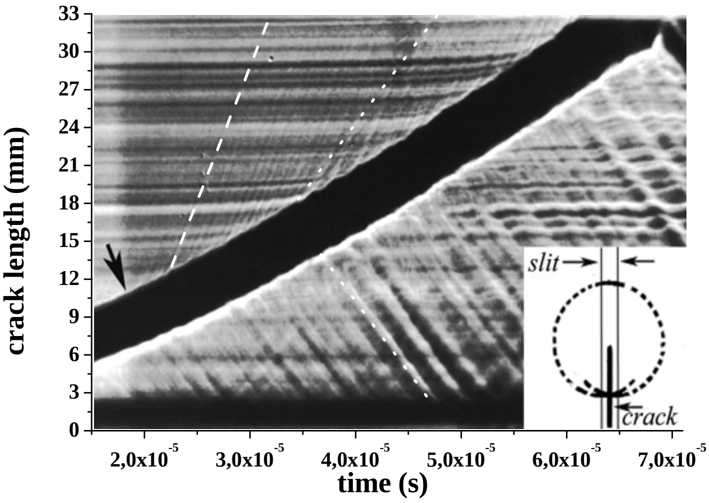

Figure 2. Slit scan of the stress-wave pattern at a crack tip under quasi-static tension of plane samples of PMMA.

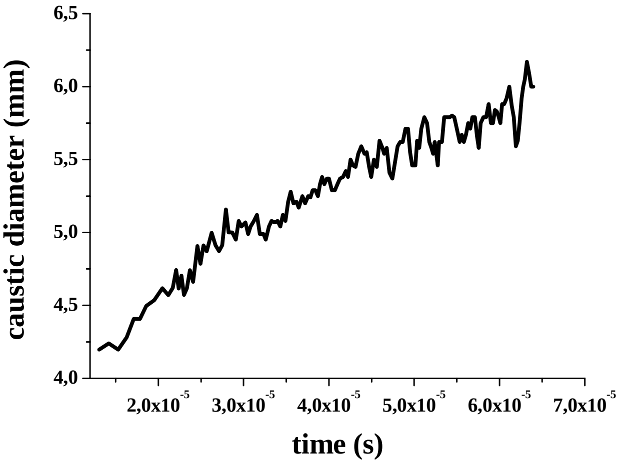

Figure 3. The caustic diameter at crack propagation in quasi-static tests.

The temporary scan of the caustic image was made to track change of stress fields in the process of crack propagation, Fig. 2. There is a clear qualitative picture, namely that elastic waves travel from the crack tip with a certain frequency. This frequency falls into the frequency range obtained during the registration of the crack trajectory (Fig. 1). The black arrow indicates the beginning of a distinct emission of elastic waves from the crack tip. There are two sets of lines that correspond to the longitudinal (dash line) and transverse speeds (dotted line). Fig. 3 shows the change of the caustic diameter at the crack propagation.

3.2. Dynamic Tests

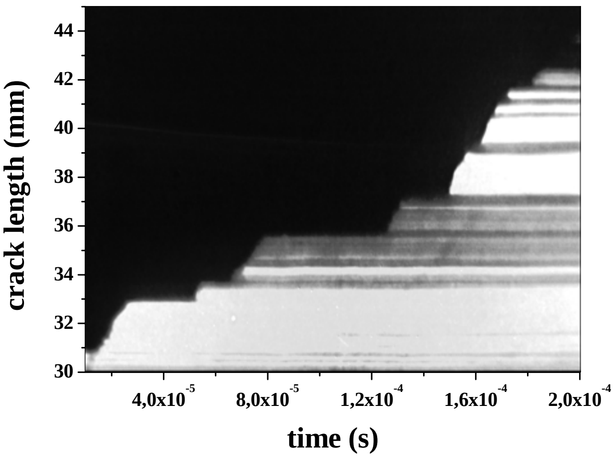

Figure 4. Crack propagation in case of dynamic loading of plates with a notch.

Fig. 4 shows the typical trajectory of crack extension obtained under pulsed pressure on the edges of the notch in the plates of PMMA. The stepped form of crack trajectory is associated with an arrival of elastic waves reflected from lateral faces of a sample. Therefore, the greatest interest is the first step of crack development without influence of reflected elastic waves. For this purpose the samples were made with such sizes that energy of reflected waves was not enough to re-start the crack. The typical trajectory of cracks obtained in these samples is shown in Fig. 5a; and the corresponding crack speed is shown in Fig. 5b.

The maximum fluctuations of the crack speed, as well as in the quasi-static tests, fall on the rougher area of the fracture surface. Unlike the quasi-static [3, 8] or the dynamic [9, 10] tests, here the return order of formation of characteristic zones of fracture surface is observed: fragmentary (large pieces), scaly, parabolic and mirror.

The scan of caustic in the dynamic tests is complicated by presence of elastic waves emanating from the point of application of pressure to the crack edges, and presence of "residual" caustic before and after crack propagation, Fig. 6. In Fig. 7 shows the characteristic change of the stress intensity factor at the crack tip and the corresponding change of the crack speed. It can be seen that the stress intensity factor, at which began the crack extension, substantially exceeds the static value K_{Ic} for a crack start.

The caustic at the crack tip begins to increase after the arrival of the Rayleigh wave; and the crack starts only through some microseconds. In general, the stress intensity factor decreases after the crack start together with the average speed of the crack.

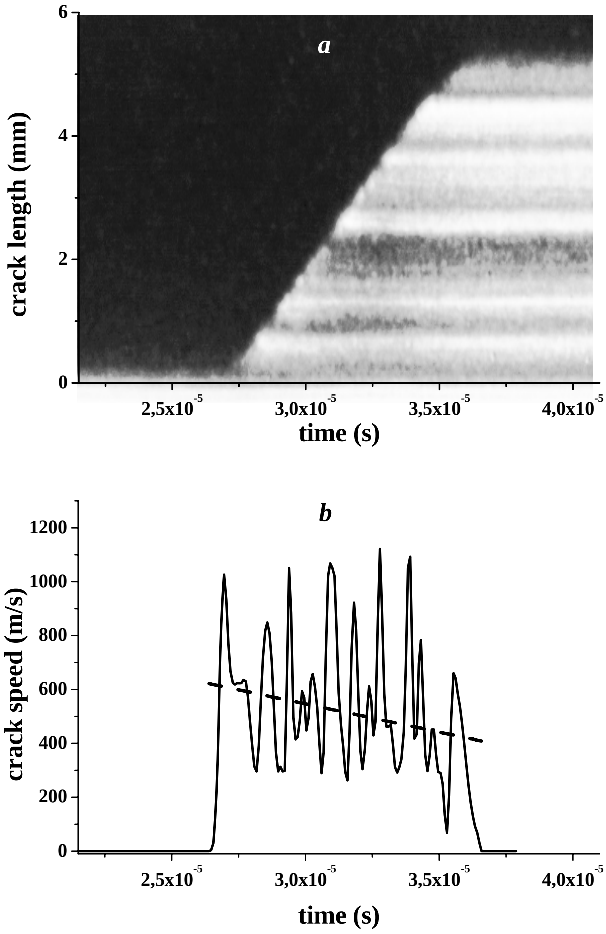

Fig. 5. Crack propagation under a localized pulse load on notch edges: a) slit scan of the crack tip trajectory; b) fluctuation of the crack front speed (dashed line - the mean speed).

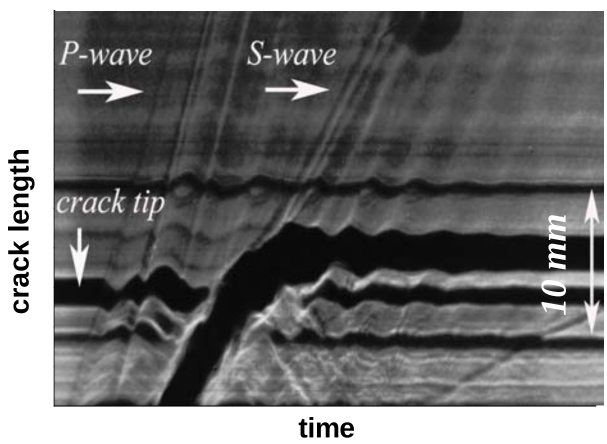

Figure 6. Stress waves in dynamic tests.

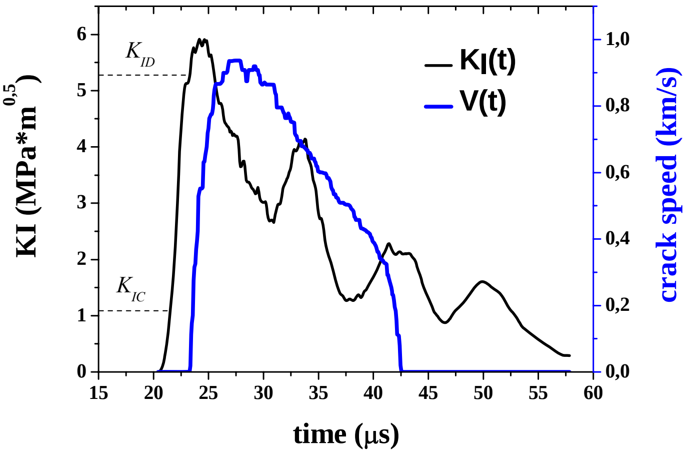

Figure 7. The dynamic stress intensity factor and the corresponding crack speed in dynamics tests.

3.3. Discussion

The results obtained by a single method for recording of dynamics of a crack in plates of PMMA allow to mark out similarities and differences in stages of a fracture process in fragile and quasi-fragile materials under quasi-static and dynamic loads. The slit scan of the development process of a crack front allows to estimate the crack speed on different time intervals, and thus the spatial scale (either the section of a crack front or the all front).

The experiments demonstrate the general property of spasmodic development of a crack front and qualitative agreement with the results obtained by other authors [3, 4]. The average speed of crack propagation in our experiments, both in the quasi-static and dynamic tests, did not exceed $0.5C_R$, but the instantaneous crack speed could approach the Rayleigh wave speed C_R on the "jumps".

The oscillations of the crack front speed correlate with changes of a profile of fracture surface. The observed dynamics of cracks may be related to a pre-fracture zone before the tip of a main crack [9-12], i.e. development of micro damages ensemble in the area of high stresses. The characteristic view of such pre-fracture zone, registered in the dynamic tests after stopping a crack, is shown in Fig. 8.

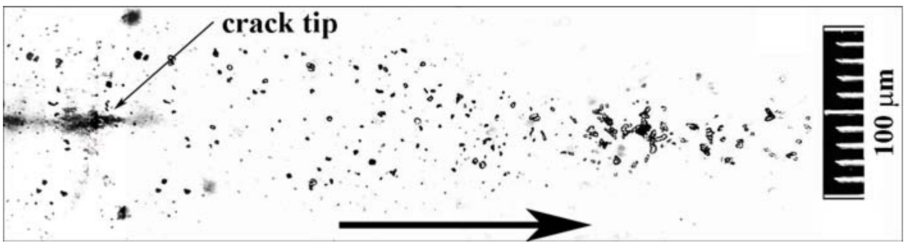

Figure 8. Magnified view of the pre-fracture zone before a crack tip. The photo was made after stopping the crack in dynamic tests. The arrow indicates the direction of crack propagation.

The principal difference between the two ways of loading is the behavior of the average speed of cracks. Under quasi-static uniform extension of the plates, the average speed over smoothly reaches a maximum value. This fact is consistent with the results of [1]. In the case of pulse pressure on the notch edges, the average speed takes a maximum value almost instantly and then can be considered by a constant. That was observed in [4].

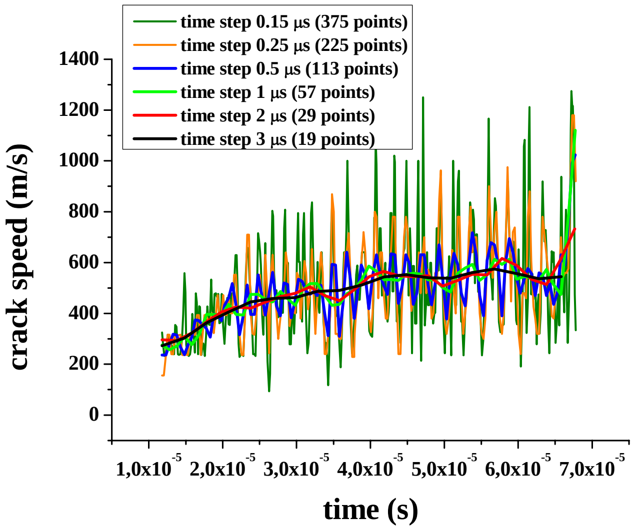

Figure 9. Speed of crack front extension depending on a time interval of registration of the crack front position.

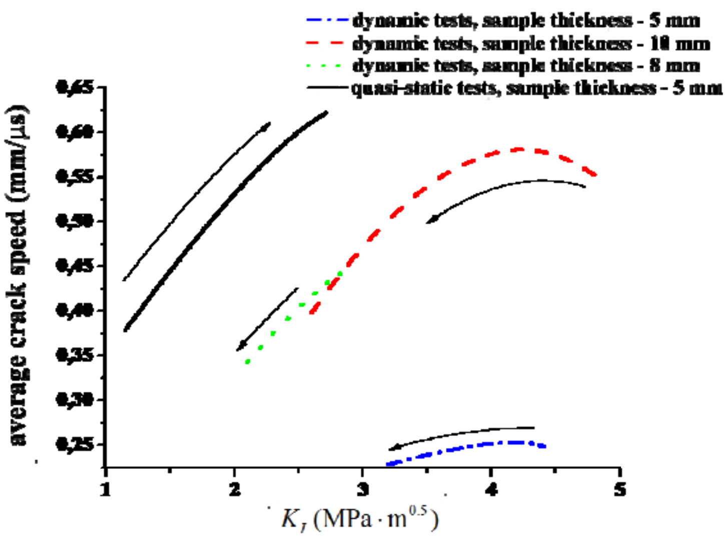

Figure 10. Average crack speed versus instantaneous stress intensity factor in plates of PMMA under different loading conditions.

The difference of experimental results for the same character of loading (see e.g. 1 and 2, 3 and 4) can be explained by resolution of recording equipment. Fig. 9 shows the crack speed in the quasi-static tests at different time intervals of the "fixing" moments of the crack locations. In [2, 4] "continuous" registration of a crack front position was applied (the electric signal from a resistive bridge or the slit scan of an image), while in [1, 3] single shooting with a given frame rate was used. Moreover, in [2, 4] the position of the crack front was registered, while in [1, 3] caustics or isochromatics, which are integral characteristics of stress fields at the crack tip, were captured.

Another one important difference between the results at the different loading conditions is the values of the fracture characteristics. The stress intensity factor at the moment of the crack start in the dynamic tests significantly exceeds its analog in the quasi-static tests. Figure 10 shows dependence of the average speed of the crack on the dynamic stress intensity factor. It is clear that the shape of the curve depends on the method of obtaining mean values of the crack speed and the SIF. In this case, the average was obtained by means of polynomial approximation.

The dash curves were received in the dynamic tests at the same charge of the condenser, but at different thickness of the samples. It can be seen that the crack speed depends on the state of stress at the crack tip. Reduction of the thickness of the sample leads to reduction of the crack speed.

In contrast to the quasi-static tests, the stress intensity factor and the average crack speed in the dynamic tests decrease with crack growth that well correlates with change of a roughness of the fracture surface. This fact can be explained by the quantity of input elastic energy in the crack tip. In case of the quasi-static tests there is a constant supply of mechanical energy in the system "grips-sample". However, in the case of a dynamic load on the crack (such source of loading as a pulse laser, an explosion of explosives or a conductor, etc.), only the final quantity of energy injects in a sample; and the fracture characteristics are defined by the pulse energy and the possible rate of absorption of this energy in the area of the crack tip.

4. 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 front speed has a stepwise 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. At the same time the limiting value of the stress intensity factor under impact loading of a crack significantly exceeds its limit value for quasi-static loading.

The analysis shows that the differences observed in experimental results on study of crack propagation can be explained by the different time resolution of recording equipment. Moreover, results significantly depend on duration and intensity of loading, as well as on the stress state in the area of fracture.

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