UDC 539.4

Fracture of Polymethylmethacrylate under Pulse Loading Conditions

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УДК 539.4

Разрушение полиметилметакрилата при импульсном нагружении

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Экспериментально исследовано распространение трещины в полиметилметакрилате при ударном нагружении импульсным магнитным полем. Проанализированы поверхности динамического разрушения полиметилметакрилата в зависимости от расстояния от надреза с помощью микроструктурных методов исследования. Построена диаграмма изменения типа разрушения в зависимости от длительности импульса.

Ключевые слова: полиметилметакрилат (ПММА), разрушение, импульс, динамическое нагружение.

Introduction. At present there are numerous studies of the fracture surface dedicated to the determination of the location of the onset fracture of a given structure together with the probable cause for its failure. Although every fracture surface is different, the advantage of fracture surface analysis in the determination of various fracture processes stems from the fact that a close relation exists between the deterministic dynamics of crack and the fracture surface that it leaves behind. However, in many cases, the mechanisms leading to particular intrinsic surface features are not revealed. In this study based on fractographic analysis of a model material, an attempt is made to uncover these fundamental mechanisms and to validate their generality.

Material and Experimental Technique. The subject of investigation was polymethylmethacrylate material (PMMA) with the following mechanical properties: $c_1 = 1970$ m/s, $c_2 = 1130$ m/s, $K_{Ic} = 1.47$ MPa$\sqrt{\text{m}}$, where c_1 and c_2 are longitudinal and transverse wave elastic velocities, respectively, while K_{Ic} is the critical stress intensity factor. Crack propagation in PMMA has been investigated experimentally under shock loading conditions generated by pulse magnetic field [1]. The loading scheme provided uniformly spread pressure along the crack faces. Plain 10-mm-thick specimens of PMMA with a notch of 3 mm width and 10 cm length were used. Speed photo camera SFR-2 was used as photo register. Pressure amplitude constituted $P = 140$–320 MPa.

PMMA was selected for investigations because of its transparency, which permits to observe crack propagation and to test it. From many studies of fracture surfaces formed in brittle materials, it was found that the surface created by the process of dynamic fracture has a characteristic structure in brittle amorphous materials. Such a structure, defined as “mirror, mist, parabolic surface markings, or hackle,” has been observed to occur in materials as diverse as glass, ceramics, noncrosslinked glassy polymers, such as PMMA and others [2].

Using microstructural investigation, the dynamic fracture surfaces of a brittle amorphous material was analyzed depending on distance from the notch tip.

Results and Discussion. Results obtained by speed photo register (SPR-2) for typical picture of crack movement are presented in Fig. 1, which illustrates a steplike pattern of the crack propagation. Test with SPR-2 measurements have demonstrated the dependence of crack starting time on loading amplitude applied. This is illustrated in Fig. 2. It is easy to see a delay in fracture, which corresponds to the distance between the calculated curve or experimental point and the dotted line.

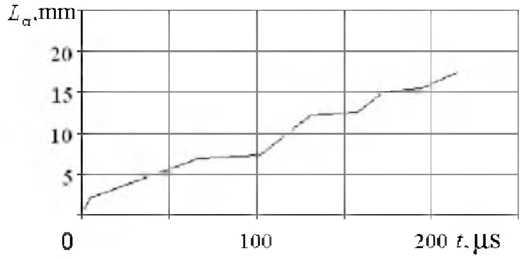

Fig. 1. Dependence of crack length on time.

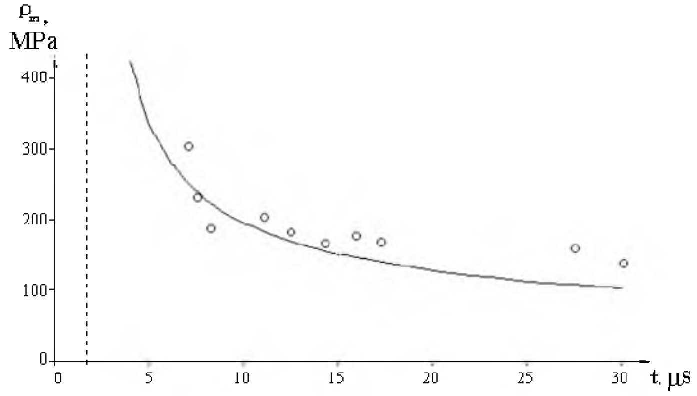

Fig. 2. Loading pulse amplitude vs time from fracture start.

Propagating from the notch tip, fracture pattern varies from fiber, quasi-fiber to cup fracture like fracture types in metals. Diagram of various types of fracture depending on the pulse loading duration and the distance from notch tip is presented in Fig. 3. This dependence has periodical character under loading of microsecond duration pulses of threshold amplitude. An illustration of the differences in fracture behavior and typical kinds of fracture type with their location along the main crack is given in Fig. 4. It can be clearly seen that the fracture pattern changes.

The fracture energy, or the energy required for creation of a unit fracture surface, is of tremendous practical and fundamental importance. For this reason, evaluation of the fracture energy as a function of the crack propagation speed have been done. Surface fracture energy was evaluated, using the cup size and specific surface fracture energy. Its dependence on distance from notch tip was defined. The results are given in Table 1.

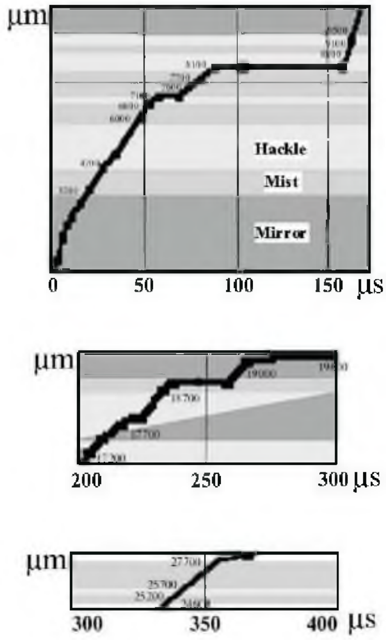

Fig. 3. Diagram of fracture type distribution depending on the pulse loading duration and distance from the notch tip.

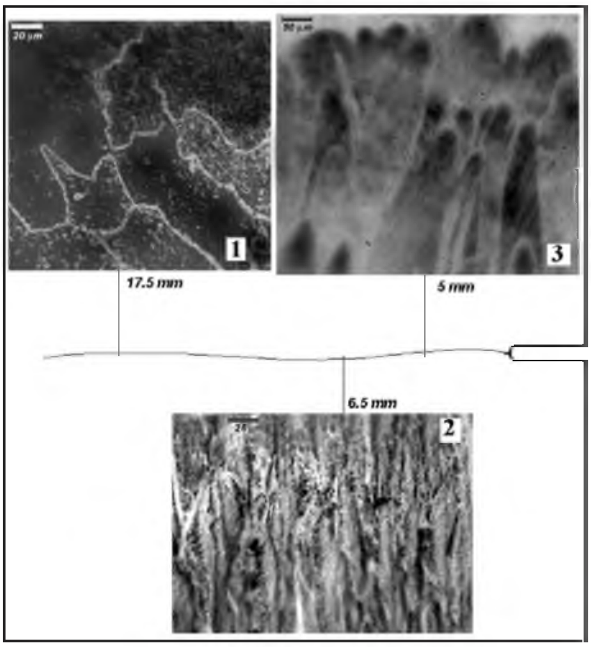

Fig. 4. Typical fracture types and their location along the main crack (*1* – mirror, *2* – mist, *3* – hackle).

ISSN 0556-171X. Проблемы прочности, 2002, № 3

T a b l e 1

Fracture Energy of the Cup Fracture

Crack length L_{cr}, mm	Cup size d, μm	Crack velocity V, m/s	Surface fracture energy $E \cdot 10^8$, J/cup
5.0	32	92.400	17.0
17.5	18	50.696	5.3
25.5	13	194.250	2.8

T a b l e 2

Mesocrack Inclination Angles

Crack length L_{cr}, mm	Inclination angle of mesocrack, deg	Crack velocity V, m/s
1.0	32	271.60
3.0	33	119.80
6.5	29	70.58
7.1	19	58.95
7.6	28	62.27
27.0	26	126.79

The formation and evolution of meso-branches are a major influence of the dynamics of a crack. The existence of mesocracks that branch away from the main crack was discovered only in the places with fiber and quasi-fiber fracture types. They did not find in the places of cup fracture. But character of mesocracks differs from ones presented in [2]. Inspection of the fracture surface in a given experiment shows that mesocrack inclination angle changes nonmonotonously depending on the distance from the notch tip. Mesocrack inclination angles and places of their nucleation were determined. As for crack velocity, it has nonmonotonous character depending on the distance from the notch tip, which is similar to the variation in the fracture pattern but different from the data presented in [3]. These results are presented in Table 2.

Conclusions. A new visualization technique for brittle fracture process under pulse loading of PMMA specimens was developed.

Peculiarities of brittle fracture process are experimentally defined for PMMA under microsecond pulse loading of threshold amplitude:

(i) length of propagated crack is proportional to the load amplitudes exceeding the threshold ones;

(ii) delay in the crack start with respect to the moment of reaching by loading stress its threshold value was determined;

(iii) periodicity of PMMA surface fracture pattern was defined under crack progress till its first stop;

(iv) diagram of fracture character changing depending on the pulse duration and distance from the notch tip was constructed;

(v) surface fracture energy per cup was evaluated, which decreases with increasing distance from notch tip;

(vi) mesocracks nucleate in the sites of “mirror-and-mist” fracture pattern, where less energy is required for the crack propagation;

(vii) mesocrack inclination angle with respect to the main crack does not depend on the crack propagation speed or the distance from the notch tip.

Р е з ю м е

Експериментально досліджено поширення тріщини у поліметилметакрилаті при ударному навантаженні імпульсним магнітним полем. Проаналізовано поверхні динамічного руйнування поліметилметакрилата у залежності від відстані від надрізу за допомогою мікроструктурних методів дослідження. Побудовано діаграму зміни типу руйнування у залежності від тривалості імпульсу.

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Received 14. 11. 2001