UDC 539.4

Investigation of Fracture of Spheroplastics under Static and Dynamic Loading Conditions

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УДК 539.4

Исследование разрушения сферопластика при статическом и динамическом нагружении

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Проведено экспериментальное исследование статического и динамического разрушения композиционного материала (сферопластика), состоящего из матрицы (полиэстер) с наполнителем в виде стеклосфер. Распространение трещины исследовано при нагружении импульсным магнитным полем. Проанализированы микроструктурные особенности динамического разрушения.

Ключевые слова: сферопластик, разрушение, импульс, инкубационное время.

Introduction. The effect of pulse loading on heterogeneous porous medium is not studied in full, although shock compression of porous matters is widely used in shock wave physics. Interest in porous materials is caused by the necessity to describe their behavior within the framework of the thermonuclear synthesis and, moreover, with the needs of creation of new materials for damping of pulse loads. Porous heterogeneous materials containing glass microspheres are of great practical interest. Such materials show good constructional and dielectric properties, as well as high resistance to shock loads. Dynamic strength of materials containing 42% of glass microspheres by volume or 27.7% by weight with epoxy binder was analyzed in [1] and assessed as 0.24 GPa. Due to the reinforcement of plastic binder by glass microspheres, density of the new material decreases significantly, while the damping properties are improved as well. Addition of microspheres is a proper method to creation of heterogeneous materials with controlled properties.

An approach based on the notion of incubation time [1] and a new testing method were used to evaluate the dynamic crack resistance of the material. According to the applied approach, the principal parameter responsible for critical characteristics of dynamic fracture is the incubation time τ, which has to be determined individually for each material and can be found from tests on macrocracked specimens.

Material and Experimental Technique. The specimens were manufactured as square plates $120\times120\times(9-16)$ mm containing a precracked notch that was loaded on its faces by a controllable uniform pulse pressure with semi-sinusoidal history. The controllable impact loading was provided by an installation [2], based on the pulse current generator, so that the magnetic field produced a mechanical pressure, which generated dynamic stress waves, fracture and crack propagation processes. In the present paper, the basic principles and characteristics of the above installation, which is able to produce controllable pulses of the order of 1 GPa with duration of the order 1 μs, are described.

The material under investigation was spheroplastics (SPH) that has a matrix of polyester resin containing a filler of glass microspheres. In different specimens, the size of spheres varied in intervals from 6–60 μm and also from 12–60 μm with average diameters of 21–31 μm. The SPH density was $\rho = (0.79 \pm 0.01) \cdot 10^3$ kg/m^3.

The static characteristics of the material are established on the basis of data obtained by a standard static testing machine. The elastic modulus obtained from a standard test is $E = 2400 \pm 50$ MPa. The material ultimate strength turned out to be equal $\sigma_c = 12.4 \pm 0.9$ MPa. The critical value of the stress intensity factor (or static fracture toughness) obtained from static tensile tests on specimens containing central cracks is $K_{\text{I}c} = 0.52 \pm 0.03$ MPa$\sqrt{\text{m}}$. The longitudinal wave velocity is $c_\perp = 2450$ m/s.

Results and Discussion. Two values of pulse duration T were considered: 2.76 μs and 4.4 μs. The basic characteristic taken from experiments is threshold amplitude of pulse that turned out to be equal 16.8 MPa and 11.2 MPa correspondingly for the above durations. The incubation time of the SPH, that was found from values of threshold amplitudes according to the method described in [1, 2], is $\tau = 5.0 \pm 0.3$ μs.

In compliance with the incubation time approach, two material constants $K_{\text{I}c}$ and τ describe static and dynamic crack resistance of the material on the given scale level, respectively. The critical parameters of the external loading for the given construction, which is loaded symmetrically (regarding the crack line) can be evaluated by means of the criterion [1, 2]:

$$\int_{t-\tau}^{t} K_{\text{I}}(s)ds \le \tau K_{\text{I}c},$$

where $K_{\text{I}}(t)$ is the stress intensity factor as a function of time, which is to be found from the solution of the appropriate dynamic boundary problem.

The dynamic fracture toughness $K_{\text{I}d} = K_{\text{I}}(t_*)$, where t_* is time to fracture, can be considered as a calculated parameter that generally is not needed for solving a fracture problem. Within the framework of the incubation time theory, the dynamic fracture toughness is an unstable characteristic depending on the history of loading and other conditions of problem. The same is confirmed by numerous experimental observations. In our particular case for the above threshold pulses, we got: $K_{\text{I}d} = 0.7K_{\text{I}c}$ for $T = 2.76$ μs, and $K_{\text{I}d} = 0.74K_{\text{I}c}$ for $T = 4.4$ μs. It is important that for the threshold pulses the fracture occurs in the stage of decreasing of the stress intensity factor at the crack tip.

The SPH fracture mainly took place in-between glass microspheres. Crack propagated along the binder rounding spheres. Only in separate cases, it crossed sphere as illustrated in Fig. 1. Uneven grains of filler can be seen in this figure.

Table 1

Crack Length and Filler Size

Specimen	Crack length, mm		Filler size, μm
	First crack	Second crack	
1	24.0	27.0	48.5
3	9.6	11.9	35.1
4	7.0	11.0	21.1
6	9.0	11.2	30.5

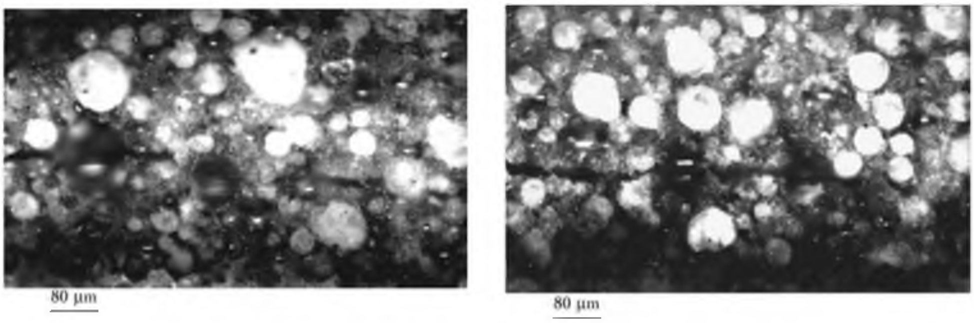

Fig. 1. Crack propagation in the composite material filled with glass microsheres.

Fig. 2. Microstructure of the fracture surface of the composite material filled with glass microsheres.

Two cracks, as a rule, propagate from the notch tip in specimens: one goes along the notch, another – under some angle to the notch. Their sizes vary in the range of 7–27 mm depending on the loading conditions. The crack abruptly changes the direction of its propagation in different specimens at the distance 2 or 4 mm from the fracture starting to deviate from the previous one at the angle of 8–10°. Then crack changes its direction once again approximately at the same distance and under the same angles. A summary of fractographic SPH investigations is given in Table 1.

As it follows from the results given in Table 1, the smaller filler grain size, the smaller crack length. It can be explained in the following way: higher quantity of glass spheres creates more barriers for crack movement.

More detailed microstructure is shown in Fig. 2. Traces of plastic flow of binder and microcracks can be seen in some places around glass spheres. Under more magnification binder deformation can be seen with pronounced features of hackle or parabolic fracture.

Conclusions

1. A new testing method was proposed, which allows qualitative and quantitative evaluation of the dynamic crack resistance of materials.

2. A new approach was developed, according to which the principal parameter controlling the critical characteristics of dynamic fracture is the incubation time τ that is to be determined individually for each material and can be found from tests on macrocracked specimens.

3. It has been found that for threshold pulses, the fracture event occurs at the stage of decreasing of the stress intensity factor $K_{\mathrm{I}}(t)$ at the crack tip.

4. Comparison of fracture properties of various materials demonstrates that the heterogeneous composite material such as a composite material filled with glass microspheres has similar characteristics as PMMA.

5. The peculiarities of dynamic crack propagation in the composite materials filled with glass microsphere and the microstructural aspects of their fracture were defined:

- The smaller filler grain size, the smaller crack length. This can be attributed to the fact that more quantity of glass microspheres creates more barriers for the crack propagation.
- Two cracks, as a rule, propagate from the specimen notch: the first one propagates along the notch, while the second – under some angle to the notch. Their sizes change in the range of 7–27 mm depending on the loading conditions.

Acknowledgements. The work was supported by the RFBR (Grants 99-01-00718, 97-01-05009, 00-01-00484), the Federal Special Program “Integration,” and the Educational Fundamental Research Center (Grant 97-0-4.3-28).

Резюме

Проведено експериментальне дослідження статичного і динамічного руйнування композиційного матеріалу (сферопластик), що складається з матриці (поліестер) з наповнювачем у вигляді скляних сфер. Поширення тріщини досліджувалося при навантаженні імпульсним магнітним полем. Проаналізовано мікроструктурні особливості динамічного руйнування.

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Received 14. 11. 2001