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PROBABILISTIC FAILURE OF CERAMICS UNDER HIGH-VELOCITY IMPACT

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ABSTRACT

Failure of ceramic targets under an axisymmetric high-velocity impact has been studied experimentally and numerically. The results of the experimental investigations testify to the existence of a significant influence of the structure of ceramic materials on the process of their failure. The process becomes asymmetric, which can lead to rotation of the projectile with conservation of its initial direction of motion. There are still no models describing the asymmetric character of high-strength ceramic failure. The probabilistic approach to describing strength characteristics of materials is a possible approach to creating such models. A fracture model of brittle materials subjected to high velocity impact is presented. The verification of the model is carried out by comparing computational results with the data obtained from shock compression tests.

Keywords: probabilistic approach, high-strength ceramics, failure.

INTRODUCTION

The wide use of composite materials in the constructions designed for operation under dynamic loads causes a steady interest in the study of their properties (Jayakumar, 2016; Samsudin, 2015). Most of the composites include ceramic materials, so the experimental and theoretical investigations are intensively conducted to study the behavior of ceramic materials under dynamic loading (Branicio, 2008; Gorelskii, 2000; Grady, 1998; Rumyantsev, 2015). In the computational investigation the most important stage in the developing and studying the behavior of structural elements is the application of an adequate material model (Zelepugin, 2016). It concerns especially the ceramic materials exposed to shock-wave loading due to a difference in strength properties of such materials compared to metals and a substantial dependence of their properties on the microstructure of the material.

The results of the experimental investigations testify to the existence of a significant influence of the structure of ceramic materials on the process of their failure (Zelepugin, 2017). The process becomes asymmetric, which can lead to rotation of the projectile with conservation of its initial direction of motion. Failure asymmetry was mentioned in scientific works. In (Kilic, 2014) the asymmetry of the interaction between a bullet and perforated target was shown experimentally and numerically. In (Anderson, 2008) X-ray patterns illustrating the asymmetry of the target-material failure during the process of elongated rod penetration into a SiC ceramic target were presented. There are still no models describing the asymmetric character of high-strength ceramic failure. Probabilistic approach developed in (Gerasimov, 2016) for describing the strength characteristics of materials is a possible approach to creating such models.

EXPERIMENTAL RESULTS

In this work, failure of ceramic and ceramic-containing targets was studied experimentally on the ballistic stand of the Scientific Research Institute of Applied Mathematics and Mechanics at Tomsk State University. The conditions for carrying out the experiments were chosen as follows. On the ballistic path, a standard SKS carbine was used with a 7.62×39 cartridge (a bullet with a steel core with an ogival head), the distance from the target was ~0.5 m, and the bullet speed was 760 ± 3 m/s. Special attention in the experiments was paid to the fulfillment of the axial symmetry condition for the bullet's impact on the target. The experiments included X-ray radiography of the process and estimation of the speed of the deformed bullet core in the after-penetration space and character of the target failure. For the targets under study, we took a ceramic target of boron carbide B_4C, TiB_2-B_4C-based ceramic composite, and three-layer target consisting of the face and back plates of VT4 titanium alloy and middle layer of B_4C ceramics.

Figure 1 presents the X-ray patterns of TiB_2-B_4C-based ceramic-composite failure. The composite thickness was 6.4 mm. The process of composite destruction in time proceeds as follows. At the initial stage of the collision, the head of the bullet core is deformed. In this process, the bullet shape is symmetric, which is illustrated by the X-ray patterns in Figure 1. After the shock wave reaches the back surface of the target and reflects from it in the form of the unloading wave, the process of microdamage accumulation and macrodamage formation begins in the target. The material of the ceramic composite loses strength characteristics in the region of damage and transits into the destructed state. The tensile loads act first of all on the region along the impact axis. As a result, the deformed bullet core begins to penetrate into the target weakened by the unloading wave. By 50 μs the bullet core perforates the target, destructs the spallation plate and becomes a leading element in the after-penetration flow. The target still retains integrity beyond the contact zone. The process of the target failure continues and a flow of debris with different shapes and sizes is formed. As the final result, the target is destroyed completely.

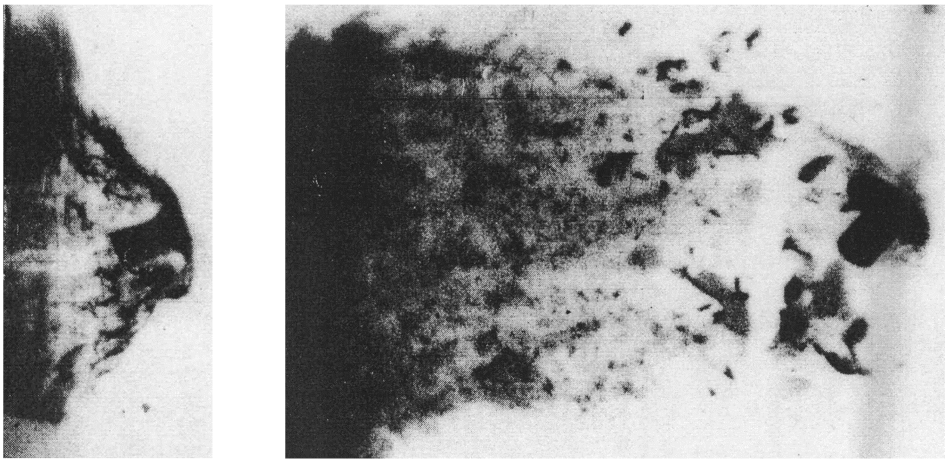

Fig. 1 - X-ray pattern of penetration into a target of TiB_2–B_4C based ceramic composite at (a) 50 and (b) 200 μs.

Results of experiments testify to the significant influence of the structure of ceramic materials on the process of their failure. The process becomes asymmetric, which can lead to rotation of the projectile with conservation of its initial direction of motion. The probabilistic approach for describing the strength characteristics of materials is a possible approach to creating models describing the asymmetric character of high-strength ceramic failure.

MODEL OF BRITTLE FRACTURE

In this work, a wide-range model is proposed to describe the brittle fracture of materials (ceramics, intermetallics, glass) at relatively low loading velocities (the velocity is about several hundred m/s) and sufficiently high loading velocities (about several thousand m/s). The model considers the possibility of the material fracture after exceeding the Hugoniot elastic limit in the shock wave, as well as the strength material characteristics (dynamic yield point) versus the achieved level of damage.

Unlike metals, the failure of which occurs under tensile loading, the modeling of brittle fracture requires considering both stages of loading such as compression and tension. In this work the dependence of the dynamic yield point for modeling of the brittle material fracture during compression is given by:

$$\sigma = \begin{cases} \sigma_0, & if\ \sigma_z \geq P_{fr} \\ K_f \sigma_0, & if\ \sigma_z < P_{fr} \end{cases} \tag{1}$$

Here σ_z is the stress component in the shock wave ($\sigma_z < 0$ for compression); P_{fr} is the material constant ($P_{fr} < 0$). The coefficient K_f can be varied from 0 to 1. When $K_f = 0$, the dynamic yield point in the shock wave drops to zero after exceeding the Hugoniot elastic limit, which is typical for completely brittle fracture (for example, boron carbide), when $K_f = 1$ the character of deformation is completely plastic, and the dynamic yield point in the shock wave is not changed during compression. The intermediate values K_f allow the combined plastic deformation and brittle fracture to be described.

Under tensile loading, the dependence of the dynamic yield point in the modeling of brittle fracture is given by:

$$\sigma = \begin{cases} \sigma_0 \left(1 - \frac{V_f}{V_4}\right), & if\ V_f < V_f^k \\ \sigma_f, & if\ V_f^k \leq V_f < V_4 \\ 0, & if\ V_f \geq V_4 \end{cases} \tag{2}$$

where V_f is the specific volume of microdamages (cracks) defined by the spall fracture model (Kanel', 1996), V_4, V_f^k, σ_f are the constants.

For comparison, the dynamic yield point versus the damage level in the modeling of the behavior of plastically deformable materials is as follows (Kanel', 1996):

$$\sigma = \begin{cases} \sigma_0 \left(1 - \dfrac{V_f}{V_4}\right), & if\ V_f < V_4 \\ 0, & if\ V_f \geq V_4 \end{cases} \tag{3}$$

VERIFICATION OF THE MODEL

Verification of the model was carried out by comparing with the experimental data obtained in the Sandia National Laboratories (Grady, 1998). The installation that produced a plane loading front in the sample for the specified time interval of the process was used in the experiments. The projectile was a ceramic plate made of a material identical to the material of the target. The projectile was accelerated by a gunpowder (89 mm internal diameter) or a two-stage light gas installation at velocities providing the peak pressure in the sample from 3 to 70 GPa (0.4 - 2.4 km/s for the gunpowder installation and higher for the light gas installation). The ceramic projectile velocity was measured using three electric sensors (velocity pins).

Four similar sensors (flush pins) controlled the plane of impact, and the deviation was usually less than 10^{-3} radians. The lithium fluoride window (LiF) was attached to the rear surface of the ceramic target by using epoxide resin with a layer sickness of 10 - 20 microns for observations with the use of a laser interferometer. The laser interferometer recorded the rear surface velocity of the ceramic sample through the window versus time of the process, including both the increase in the velocity of the rear surface due to the arrival of a compression wave and the decrease in the velocity due to the arrival of the unloading wave from the rear surface of the projectile.

The interaction of the projectile (ceramic plate 5 mm in thickness, 87.5 mm in diameter, the area D_1 in Figure 2(a) with the sample (ceramic plate 10 mm in thickness, 76.2 mm in diameter, the area D_2) was numerically investigated for comparison with the experimental data. The window of lithium fluoride located behind the sample and occupying the area D_3 was 25.4 mm in sickness and 50.8 mm in diameter.

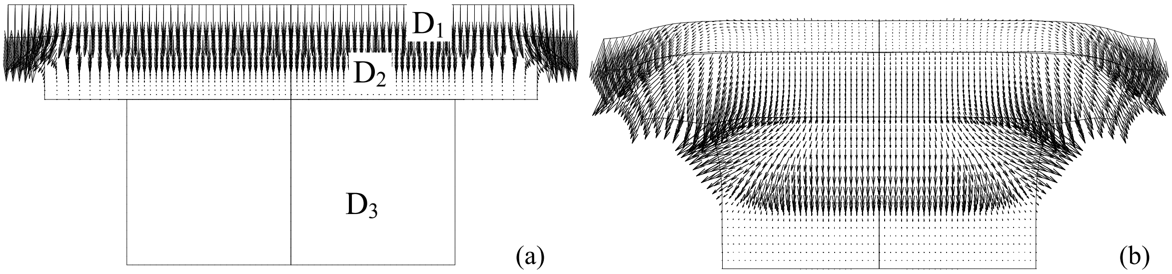

Fig. 2 - Computed configurations of the AD995 ceramic projectile (D_1) - AD995 ceramic plate (D_2) - LiF window (D_3) assembly and the velocity fields at the time of (a) 0.5 and (b) 3.5 μs.

The numerical computations were carried out using the research computer code based on the modified finite element method without construction of the global stiffness matrix (Gorelski, 1997; Johnson, 2011). For modeling of high velocity impact loading, a model of a damaged medium characterized by the presence of microcavities (pores or cracks) is used. The total volume of the medium comprises the undamaged part and microcavities of zero density. The damage level of the medium is characterized by the specific volume of pores V_f. The system of equations governing the nonstationary, adiabatic (for both elastic and plastic deformations) motion of a compressible medium with allowance for the evolution of microdamages comprises the continuity equation, the equation of motion, the energy equation.

Pressure in the undamaged substance is a function of specific volume of the undamaged substance and specific internal energy, and over the entire range of loading conditions it is determined by the Mi-Grüneisen equation of state. The constitutive relations connect the components of the stress deviator and strain rate tensor, and include the Jaumann derivative. The von Mises yield criterion is used. The critical value of the specific energy of shear deformations is used as a criterion of erosive material damage. The sliding boundary conditions are imposed to the contact surfaces between the projectile and the sample, as well as between the sample and the window of lithium fluoride. The material constants used in the computations can be found in (Zelepugin, 2016).

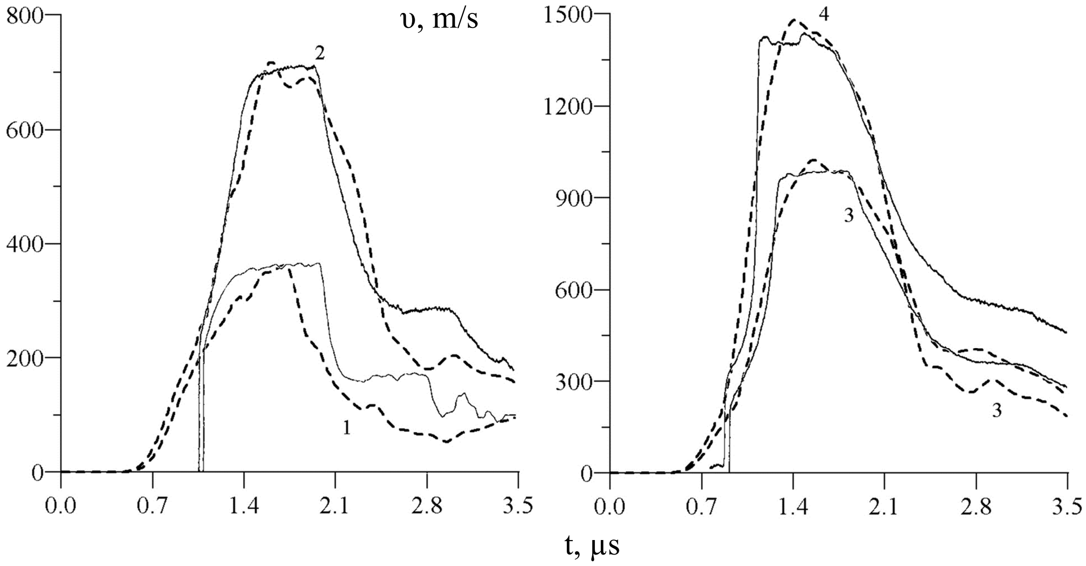

Fig. 3 - Rear surface velocities of the ceramic target for different loading velocities (curve 1 corresponds to the impact velocity υ_0 = 544 m/s; 2 - υ_0 = 1070 m/s; 3 - υ_0 = 1573 m/s; 4 - υ_0 = 2329 m/s). The solid lines correspond to the experiment (Grady, 1998), the dashed lines correspond to the computation.

Figure 2 shows the computed configurations of the test assembly (for AD995 ceramics) and the velocity fields at the time of 0.5 and 3.5 μs at the initial impact velocity of 1070 m/s. Figure 3 demonstrates the velocities of the contact surface between the ceramic sample and the lithium fluoride window for various initial impact velocities (curve 1 corresponds to the initial impact velocity υ_0 = 544 m/s; 2 - υ_0 = 1070 m/s; 3 - υ_0 = 1573 m/s; 4 - υ_0 = 2329 m/s). For comparison, the experimental curves are given in Figure 3 (Grady, 1998). The computed velocity profiles of the contact surface between the ceramic sample and the window of lithium fluoride are in good qualitative and quantitative agreement with the experimental data.

CONCLUSIONS

The computational brittle fracture model was presented for the materials subjected to high velocity impact. The verification of the model was conducted using the data obtained from shock compression tests. The results of the experimental investigations testify to the existence of a significant influence of the structure of ceramic materials on the process of their failure. The process becomes asymmetric, which can lead to rotation of the projectile with conservation of its initial direction of motion. The probabilistic approach to describing strength characteristics of materials is a possible approach to creating models describing the asymmetric character of high-strength ceramic failure.

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REFERENCES

[1] Anderson Jr. CE, Behner Th., Orphal DL, Nicholls AE, Templeton DW. Time-resolved penetration into pre-damaged hot-pressed silicon carbide. International Journal of Impact Engineering, 2008, 35, pp. 661-673.

[2] Branicio PS, Kalia RK, Nakano A, Vashishta P, Shimojo F, Rino JP. Atomistic damage mechanisms during hypervelocity projectile impact on AlN: A large-scale parallel molecular dynamics simulation study. Journal of the Mechanics and Physics of Solids, 2008, 56(5), pp. 1955-1988.

[3] Gerasimov AV, Dobritsa DB, Pashkov SV, Khristenko YuF. Theoretical and experimental study of a method for the protection of spacecraft from high-speed particles. Cosmic Research, 2016, 54, pp. 118-126.

[4] Gorelskii VA, Zelepugin SA, Tolkachev VF. Experimental and numerical study of ceramics destruction by high-velocity impact. Chemical Physics Reports, 2000, 18(10-11), pp. 2211-2217.

[5] Gorelski VA, Zelepugin SA, Smolin A.Yu. Effect of discretization in calculating three-dimensional problems of high-velocity impact by the finite-element method. Computational Mathematics and Mathematical Physics, 1997, 37(6), pp. 722-730.

[6] Grady DE. Shock-wave compression of brittle solids. Mechanics of Materials, 1998, 29(3-4), pp. 181-203.

[7] Jayakumar T, Annamalai K. Mechanical behavior of modified Al-Si-Cu-Mg alloy and reinforced with SiC under ambient to elevated temperature. ARPN Journal of Engineering and Applied Sciences, 2016, 11(7), pp. 4471-4477.

[8] Johnson GR. Numerical algorithms and material models for high-velocity impact computations. International Journal of Impact Engineering, 2011, 38(6), pp. 456-472.

[9] Kanel’ GI, Razorenov SV, Utkin AV. Fortov VE. Shock-wave phenomena in condensed matter. Moscow: Yanus-K, 1996.

[10] Kilic N., Bedir S., Erdik A., Ekici B., Tasdemirci A., Guden M. Ballistic behavior of high hardness perforated armor plates against 7.62 mm armor piercing projectile. Materials and Design, 2014, 63, pp. 427-438.

[11] Rumyantsev BV. Collective penetration of cumulative jets into brittle materials. Technical Physics, 2015, 60(4), pp. 614-617.

[12] Samsudin AH, Hussain AK, Mahmud J. Deformation and failure analysis of symmetric and antisymmetric graphite/epoxy laminate due to variations in fiber orientation. ARPN Journal of Engineering and Applied Sciences, 2015, 10(17), pp. 7336-7344.

[13] Zelepugin SA, Zelepugin AS, Khristenko Yu.F. Computational modeling of brittle fracture under dynamic loading, ARPN Journal of Engineering and Applied Sciences, 2016, 11(24), pp. 14560-14565.

[14] Zelepugin SA, Tolkachev VF, Zelepugin AS. Asymmetry of ceramic destruction under a high-velocity impact. Technical Physics Letters, 2017, 43(12), pp. 1071-1073.