Deformation and Damage Accumulation in a Ceramic Composite under Dynamic Loading

M V Korobenkov[1,3], S N Kulkov[1,2], O B Naymark[4], U V Khorechko[5] and A V Ruchina[5]

[1] National Research Tomsk State University, Tomsk, Russia
[2] Institute of Strength Physics and Materials Science SB RAS, Tomsk, Russia
[3] Institute of Marine Technology Problems FEB RAS, Vladivostok, Russia
[4] Institute of Continuous Media Mechanics UB RAS, Perm, Russia
[5] National Research Tomsk Polytechnic University, Tomsk, Russia

[1]E-mail: korobenkov@ftf.tsu.ru

Abstract. Methods of computer modelling were used to investigate the processes of deformation and microdamage formation in ceramic composite materials under intense dynamic loading. It was shown that there was no damage caused by dynamic compression in the vicinity of phase borders of a nanostructured aluminum oxide matrix and reinforcing particles of tetragonal zirconium dioxide. Also, the local origination of microdamages occurs only in the zones close to micropores.

Keywords: ceramic composites, dynamic exposure, computer modelling

1. Introduction

By the present day, the range of application of structural ceramics combining high hardness, thermal resistance, wear strength and chemical inertness has appreciably expanded. This is due to a successful development of technologies for the production of ceramic composites on the basis of powders with nanocrystallic structure, which enables mass production of materials with augmented strength and crack resistance that are successfully implemented in oil and gas industry, and are used as protective coating. The use of new generations of ceramic materials demanded the creation of adequate models of their mechanical behavior under high dynamic loading. The fracture of brittle ceramic materials usually occurs in dynamic regime and is accompanied by a fast change of the local stress condition. However, the determination of the influence of geometrical factors on the mechanical behavior is a complex challenge.

The available experimental data is not enough for determining the influence of geometrical factors. In this connection, the solution of the problem on predicting the properties of ceramic composites on the basis of computer modelling is a promising task. This is conditioned by the ability of computer modelling of mechanical behavior of heterogeneous condensed media to improve the understanding of regularities describing the deformation, development of damage and fracture of ceramic composites under severe dynamic exposure.

The physical and mathematical model for studying the kinetic processes of damage and fracture of composites with an oxide ceramic matrix filled with submicron impurities accounts for the results obtained after investigating the microstructure of materials at different scale levels [1]. The numerical modeling of deformation and fracture was performed with the use of either the discrete-continual particle method or the finite difference method with the accuracy of second order.

2. Computational Model

The model volume of a structural inhomogeneous medium (RVE) is filled with particles of identical effective size *d*. Physicomechanical properties of each particle are set according to its attribution to matrix phase, grain boundary phases (matrix grain-to-matrix grain, matrix grain-to-reinforcing particle), reinforcing particles. The volume of microcracks is filled with pseudoparticles, the mass density is zero. Introduction into the model of the pseudoparticles allows modelling free surfaces in a microcrack without altering the calculation algorithm. The lack of estimated stresses on the surface of a crack will be carried out automatically during the calculation of particle-pseudoparticle couples.

The complete system of equations describing nonstationary loading in relation to model volume includes conservation equations for weight, impulse and energy, and kinematic equations defining ratios, initial and boundary conditions.

As a criterion of brittle local fracture of particles that form composite ceramic material, the following condition was adopted:

$$\sigma_1 \geq \sigma_{tension}, \tag{1}$$

where σ_1 is the main component of the stress tensor, $\sigma_{tension}$ is the tensile strength of the ceramic matrix condensed phase, grain boundary phases, phase of reinforcing particles, under quasi-static or dynamic deformation conditions.

To evaluate $\sigma_{tension}$, the data from [2, 3] were used.

The present work uses media damage parameter *D* considered as a result of accumulation of damage increments during the microstructure evolution at lower scale level over the time from t_0 to $t_0 + m\,\Delta t$ [4–7]:

$$D = \sum_{i=1}^{m} \frac{\left[\Delta\varepsilon_{eq}^{p}\right]_i}{\varepsilon_f}, \tag{2}$$

Where $\Delta D_i = \frac{\left[\Delta\varepsilon_{eq}^{p}\right]_i}{\varepsilon_f}$ is the increment of the damage parameter over the deformation time Δt,

ε_{eq}^{p} is the intensity of inelastic deformation,

ε_f is the ultimate strain at the moment of macroscopic fracture.

The criterion of local fracture of a particle of the matrix is as follows:

$$D = 1. \tag{3}$$

3. Results and Discussion

The modeling results showed that there are local areas of tensile stresses occurring during the propagation of a compression wave in the sample after the heterogeneous media compression with high speed of deformation in the front of shockwaves (Figure 1).

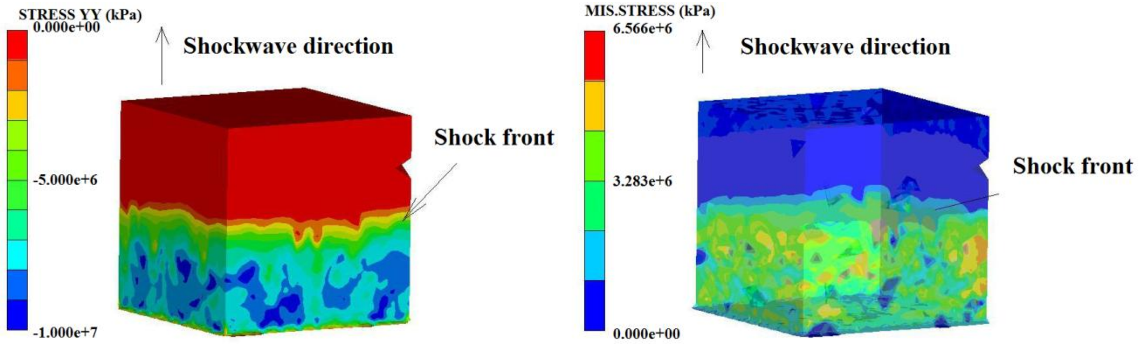

Figure 1. Distribution and strength of shear stresses during the shockwave propagation in Al_2O_3-(15vol.%t-ZrO_2) composite material

In the case of elastic-brittle behavior of ceramic composites, the size of J-integral corresponds to the energy stream flowing to the top of the crack. In this case,

$$J = J_{1C} = G, \tag{4}$$

where the J_{1C} is fracture toughness, G is the crack energy release rate.

Figure 2 depicts the distribution of specific energy of damage origination in a model volume of Al_2O_3-(15vol.%t-ZrO_2) composite behind the front of the shockwave over consecutive moments of time. The values of specific energy of damage formation calculated in the course of the modelling of dynamic loading of a composite model volume can be used for fracture toughness determination.

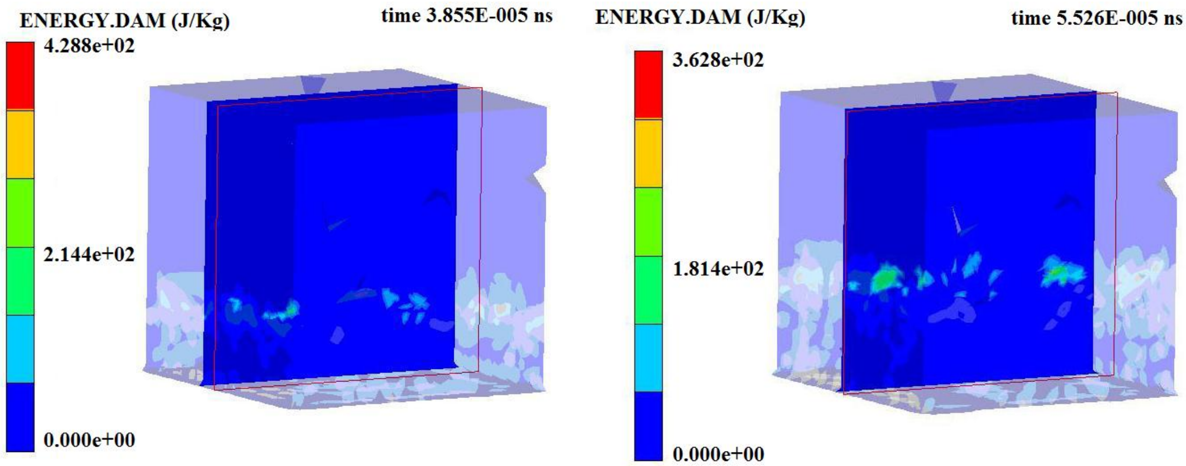

Figure 2. Specific work of damage origination behind the front of shock compression

The loss of shear strength of the nanocomposite during high-speed deformation could be caused by the localized propagation of damages or microcracks. The complete loss of shear strength of a model volume will be reached in the case of its fragmentation when the damage parameter averaged over the volume becomes less than criterial value equal to 1.

In the considered Al_2O_3-(t-ZrO_2) model ceramic composites, the local origination of microdamage occurs only in the zones close to microcavities (micropores) in the case of high-speed deformation. There was no damage origination detected under shock compression in the vicinity of phase boundaries of Al_2O_3 nanostructural matrix and the reinforcing particles.

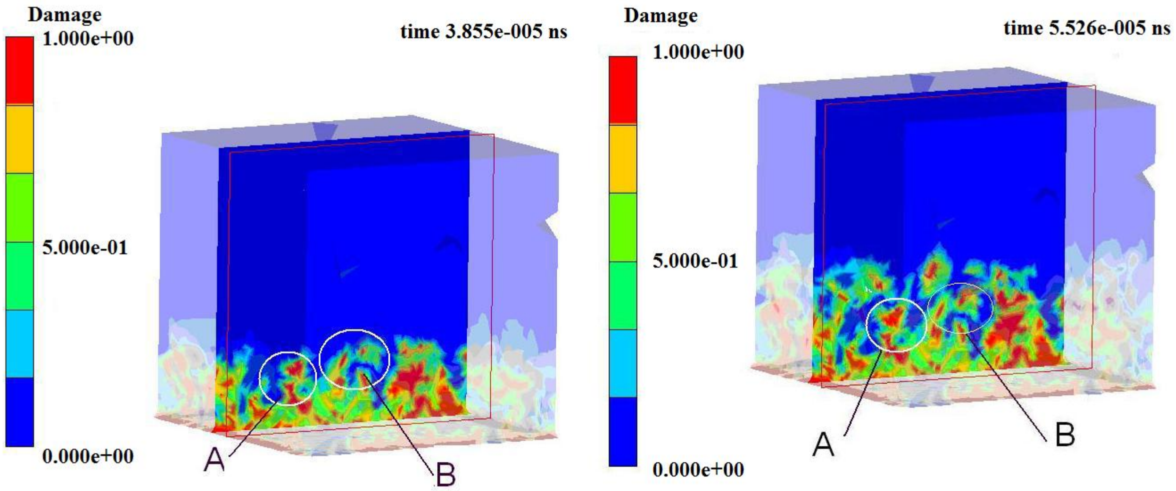

Figure 3. Distribution of damage in the structure of Al_2O_3-(15vol.%t-ZrO_2) composite model volume behind the shockwave front at consecutive moments of time of 0.0385 and 0.0553 ns

The results shown in Figure 3 for consecutive moments of time testify the formation of local damages of the ceramic matrix in the zone of shock transition. There was no considerable alteration detected to the size and configuration of local damage areas, for example, to area A and B in Figure 3, after the increase of time of hydrostatic compression by the shockwave front.

4. Conclusions

The modeling of compression wave distribution in a composite has demonstrated the formation of tensile strain areas. This leads to the emergence of microdamage at mesoscopic level in zones close to microvoids. At the amplitude of compression impulses not exceeding the limit of elasticity of a high density condensed matrix, the damage behind the front of shockwaves remains stationary and localized at the microscopic level. Possible formation of microcracks behind the front of a shockwave is connected with the presence of pore clusters. The zones of local damage get elongated; the orientation of axes of which is defined by the direction of the maximum shear stress.

The presence of submicron reinforcing particles near a pore cluster leads to the change in the shape of local damage area, while the increase of the relative number of damaged particles can be defined as the formation of a shear mesocracks in a model volume of the composite.

Thus, the modeling has shown that the value of effective shearing resistance is higher for the composite with higher concentration of particles. The obtained data agree well with the measurements of static strength characteristics of the considered class of composites [8].

Acknowledgments

The work was performed within the implementation of Tomsk State University Competitiveness Improvement Program and with partial financial support of the Ministry of Education and Science of the Russian Federation within State task # 16.2004.2014 / K.

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