About mechanical behaviour of metal matrix composites under shock wave loading

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Abstract. In this work the results of studying of the mechanical behaviour of metal-ceramic composites with an aluminium matrix on meso-scale level are submitted. Computer simulation of mechanical reaction of representative volume of composite material, considered as ensemble of the interacting structural elements (ceramic particles and metal matrix), is used for studying mechanisms of deformation on meso-scale level of metal-ceramic composites under the loading by shock waves. The mechanical behaviour of aluminium matrix is described by the model of the damaged elastic-plastic medium. The model of the damaged brittle solid is used for ceramics. The absence of macroscopic and mesoscopic voids and cracks in the material before loading is assumed. Ideal adhesion of ceramic material to metal is supposed at the initial condition. The problem is solved in 2D statement with application of finite-difference method. Results of numerical simulation of the mechanical behaviour of metal-ceramic composites under shock wave loading have shown the formation of non-stationary and essentially non-uniform fields of stresses and strains at the meso-scale level. The generation of a dissipative structure on the meso-scale level of the composites under shock wave loading was revealed in the simulations.

1. Introduction

Metal-ceramic composites are widely used now in various fields of industry and are often used under extreme operating conditions [1, 2]. In this connection, it is necessary to adequately predict the mechanical behavior of these materials under intensive energy impacts.

The experimental results show, that the mechanical behaviour of composites at high strain-rates qualitatively differs from the behaviour of its components under the same conditions. This specificity of the mechanical behaviour of composites can be caused by processes on meso-scale level.

In the simulations of mechanical behavior the composites are often taken as homogeneous, but these materials represent a complex of components with different physical and mechanical properties. The components interconnected on inner contact surfaces form the structure of composites. The structure and its evolution during deformation can have a significant influence on the mechanical behavior of composite materials.

The present work aims at the numerical simulation of mechanical behavior of stochastic metal-ceramic composites under loading by shock waves and study mechanisms of deformation on meso-scale level of composites with different structure parameters.

In this work the loading by a shock wave of a plate of stochastic metal-ceramic composite material consisting of a metal matrix and reinforcing ceramic inclusions is considered. The numerical
simulation is performed on a rectangular fragment of the plane section of the plate along the direction of the shock wave.

2. Simulation of the mechanical behaviour of metal-ceramic composite

The physical-mathematical model of the two-phase condensed heterogeneous medium with an explicit description of its structure is used to describe the mechanical behavior of the composite on mesoscopic scale level under the considered loading conditions.

The used model represents the heterogeneous medium as a complex of interconnected structural elements – matrix and inclusions. Inclusions have different shapes and are randomly distributed in the matrix. Within interfaces of each structural element, the medium is taken as homogeneous and isotropic while in transition through the interface mechanical properties of the medium change abruptly. The Johnson–Holmquist model of the damaged elastic-brittle medium is used for the mechanical behavior of ceramic inclusions and the Johnson–Cook model of the elastic-viscoplastic medium for the metal matrix.

Dimensions of the simulated area and the number of structural elements are chosen in such a way as to determine effective values of parameters of the mechanical state of the medium. Effective mechanical parameters of the heterogeneous medium loaded by a plane shock wave are determined by volume averaging of local values of the state parameters in thin flat layers perpendicular to the shock front direction.

The physical-mathematical model and the method for determining effective parameters are described in [3, 4].

The fragments of simulated areas of the two-phase heterogeneous medium with different concentration of inclusions are shown in figure 1.

![Figure 1. Simulated areas of the two-phase heterogeneous medium with the model structure of the composite composed of the matrix (light region) and arbitrary-shaped inclusions (dark regions). The characteristic size of inclusions is 5 µm, the volume concentration is: (a) 25%, (b) 75%](image)

The model of the behaviour of the composite material under shock wave loading and method for determining effective parameters of the mechanical state are adopted here for metal-ceramic composites Al-B₄C, Al-SiC and Al-Al₂O₃ with different concentration of inclusions.

3. Investigation of the mechanical behaviour of metal-ceramic composites

Propagating in the composite material the shock wave interacts with inner boundaries of structural elements. These processes cause the distribution of local values of parameters of the mechanical state at the meso-scale level. The results of computer simulation show that there is a strong variation of stresses and strains at the meso-scale level in metal-ceramic composites under shock wave loading.
The distribution of stresses depends on meso-scale structure of composites, but has no essential dependence on the shock wave amplitude. The figure 2 shows the distribution of pressure and strains in the composite Al-75%B₄C.

![Figure 2. The distributions of local values of pressure (a) and strain (b) at the meso-scale level in the metal-ceramic composite Al-75%B₄C under shock wave loading](image)

Deformation of composites in the shock wave front is accompanied by a change in the initial orientation of the structural elements. In this process, it is possible to form a dissipative structure from volumetric blocks, including a certain number of inclusions, which are displaced as a whole. The simulation results reveal the formation of the dissipative structure in the shock wave front at the meso-scale level of the metal-ceramic composites. The figure 3 shows the formation of the dissipative structure at the meso-scale level of the composite Al-75%B₄C. Simulation results indicate that the scale of the dissipative structure depends on the amplitude of the shock wave.

![Figure 3. Calculated field of particle velocity at the meso-scale level in the metal-ceramic composite Al-75%B₄C under shock wave loading. Nucleation of the dissipative structure under intensive shock compression of the composite](image)

Formation of the dissipative structure is accompanied by the formation of the bimodal distribution of velocities of material particles in the shock wave at the meso-scale level of the composite. The simulation results reveal the formation of the bimodal distribution of velocities of material particles in the shock wave at the meso-scale level of the composite Al-75%B₄C, as one can see in figure 4. Distribution function of particle velocities behind the front of shock wave is similar to logarithmically normal distribution function.
Figure 4. The distribution of particle velocity in the shock wave at the meso-scale in the metal-ceramic composite Al-75%B4C. Formation of bimodal distribution of particle velocity

4. Conclusion

The simulation results show:

- there is a strong variation of local values of stresses and strains at the mesoscale level in metal-ceramic composites under shock wave loading and the distribution of stresses depends on mesoscale structure of composites, but has no essential dependence on the shock wave amplitude;
- deformation of composites in the shock wave front is accompanied by a change in the initial orientation of the structural elements, in this process, it is possible to form a dissipative structure from volumetric blocks, including a certain number of inclusions, which are displaced as a whole, the scale of the dissipative structure depends on the amplitude of the shock wave;
- formation of the dissipative structure leads to the formation of the bimodal distribution of velocities of material particles in the shock wave at the meso-scale level of the composite, distribution function of particle velocities behind the front of the shock wave is similar to logarithmically normal distribution function.

Acknowledgements

The work was carried out with the support of the Tomsk State University Competitiveness Improvement Program and partly within the framework of the Fundamental Research Program of the State Academies of Sciences for 2013–2020, line of research III.23.

References

[1] Gömze L A and Gömze L N 2013 IOP Conf. Ser.: Mater. Sci. Eng. 47 012033 http://dx.doi.org/10.1088/1757-899X/47/1/012033
[2] Kulkov S N, Buyakova S and Gömze L A 2017 J. Phys.: Conf. Ser. 790 012015 https://doi.org/10.1088/1742-6596/790/1/012015
[3] Karakulov V V, Smolin I Yu and Skripnyak V A 2016 AIP Conf. Proc. 1783 020081 http://dx.doi.org/10.1063/1.4966374
[4] Karakulov V V, Smolin I Yu and Kulkov S N 2017 IOP Conf. Ser.: Mater. Sci. Eng. 175 012029 http://dx.doi.org/10.1088/1757-899X/175/1/012029