Computer simulation of damage to metal-ceramic composites under shock 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 mesoscale 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 processes of the nucleation and growth of damages on mesoscale level of metal-ceramic composites under the loading by shock pulses. The sizes of representative volume give the possibilities to enter effective mechanical parameters of a composite material. 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 problem is solved in 2D statement with application of finite-difference method. The results of computer simulation show that the local tensile stresses can appear in unloading wave and can cause damages in ceramic particles. In the region of composite where two opposing unloading waves interacts (spall zone) the calculation predicts the existence of cracked ceramic particles, local damages in metal matrix and existence of mesoscale and macro-scale cracks.

1. Introduction

Metal-ceramic composite materials 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 numerically evaluate the elastic and strength properties and predict the mechanical behaviour of these materials under intensive energy impacts.

In the simulations of mechanical behaviour, the composites are often taken as homogeneous or quasi-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 properties and the mechanical behaviour of composite materials.

The results of experimental investigations show that the actual strength of the metal-ceramic composites under shock loading is lower than the theoretical strength estimates. The results of investigations of microstructure in the composites after loading show the fractured ceramic particles and cracks between particles and matrix. This specificity of the mechanical behaviour of composites can be caused by processes on mesoscale level.

The present work aims at the numerical simulation of the mechanical behaviour of stochastic metal-ceramic composites on mesoscopic scale level under loading by shock pulses and study processes of the nucleation and growth of damages on mesoscale level of composites with different structure parameters.
2. Simulation of damage to the metal-ceramic composite under loading by the shock pulse

In this paper, the loading by a shock pulse 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 pulse.

The physical-mathematical model of the two-phase condensed heterogeneous medium with an explicit description of its structure is used to describe the mechanical behaviour 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 behaviour of ceramic inclusions and the Johnson–Cook model of the elastic-viscoplastic medium for the metal matrix.

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

![Figure 1](image)

**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) 50%, (c) 75%.

Dimensions of the simulated area and the number of structural elements are chosen in such a way as to determine the effective values of parameters of the mechanical state of the medium. Effective mechanical properties 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 model of the behaviour of the composite material under shock 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. Results of the computer simulation of damage to metal-ceramic composites

Propagating in a composite material the shock pulse interacts with the inner boundaries of structural elements. These processes cause the distribution of local values of the parameters of the mechanical state on mesoscale level.

The results of computer simulation show that there is a strong variation of stresses and strains at the mesoscale level in metal-ceramic composites under shock pulse loading. The distribution of stresses depends on mesoscale structure of composites, but has no essential dependence on the shock pulse 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) in the shock pulse at the mesoscale in the metal-ceramic composite Al-75%B₄C.

The results of calculations forecast the existence of the local tensile stresses in unloading wave. The strength of ceramics is very different in compression and in tension. For this reason, some local damages appear in ceramic particles after passing of unloading wave. The figure 3 shows that local tensile stresses may appear in unloading wave in the composite Al-75% B₄C and the figure 4 shows that this may be the reason of the appearance of damages in ceramic particles.

Figure 3. The structure of shock pulse in metal-ceramic composite Al-75%B₄C: \( P_{\text{max}} \) is maximum pressure, \( <P> \) is effective pressure, \( P_{\text{min}} \) is minimum pressure.

Figure 4. Damages in ceramic particles after the passage of a shock pulse due to local tensile stresses in the unloading wave.

There are more significant damages of the metal-ceramic composite in the region where two opposing unloading waves interact (spall zone). The calculation predicts the existence of cracked ceramic particles, local damages in metal matrix and the existence of mesoscale and macro-scale cracks. The spall zone in metal-ceramic composite has larger dimensions than in metals and ceramics. There is the effect of bridging meso-cracks in composite materials under loading by shock pulses. The efficiency of strengthening of metal-ceramic composites depends on not only the concentration of ceramics but on meso-structure of composites.

The figures 5 and 6 show the formation of the spall zone in composite Al-75% B₄C under tensile stresses. The volume of the damaged composite material catastrophically increases in the spall zone. There are three kinds of damages in spall zone: (i) cracks in ceramic particles; (ii) cracks between ceramic particles and matrix; (iii) damages in aluminium matrix.
Figure 5. The structure of shock pulse under spallation in metal-ceramic composite Al-75%B4C: (1) effective pressure <P>, (2) minimum pressure P_{min}, (3) maximum pressure P_{max}, (4) the specific number of damaged cells, (5) the specific number of damaged ceramic mesh cells, (6) the specific number of damaged aluminium matrix mesh cells.

Figure 6. The structure of spall zone in metal-ceramic composite Al-75%B4C: (1) damage of ceramic particles, (2) damage of aluminium matrix.

Cracks between ceramic particles and matrix and damages in aluminium matrix may appear under tensile stresses when two opposing unloading waves interact. Cracks in ceramic particles may appear under local tensile stresses in unloading wave.

4. Conclusion
The simulation results show:
- there is a strong variation of local values of stresses at the mesoscale level in metal-ceramic composites under shock pulse loading and local tensile stresses may appear in unloading wave and may be the reason of the appearance of damages in ceramic inclusions;
- the spall zone in composites has larger dimensions than in metals and ceramics, there are cracks in ceramic particles, cracks between particles and matrix, damages in the matrix in spall zone;
- the efficiency of strengthening of metal-ceramic composites depends on not only the concentration of ceramics but on meso-structure of composites.

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