

Numerical simulation of mechanical behaviour and prediction of effective properties of metal matrix composites with consideration for structural evolution under shock wave loading

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Abstract. Mechanical behaviour of stochastic metal-ceramic composite materials under shock wave loading was numerically simulated on mesoscopic scale level. Deformation of mesoscopic volumes of composites whose structure consisted of a metal matrix and randomly distributed ceramic inclusions was simulated. The results of numerical simulation were used for numerical evaluation of effective elastic and strength properties of metal-ceramic materials with different values of volume concentration of ceramic inclusions. The values of the effective mechanical characteristics of investigated materials were obtained, and the character of the dependence of the effective elastic and strength properties on the structure of composites was determined. It is shown that the dependence of the values of the effective elastic moduli on the volume concentration of ceramic inclusions is nonlinear and monotonically increasing. The values of the effective elastic limits increase with increasing concentration of the inclusions, however, for the considered composites, this dependence is not monotonic.

1. Introduction

Now metal-ceramic composite materials are widely used 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 simulation of deformation of composite materials, composites are often taken as homogeneous or quasi-homogeneous. However, these materials present a complex of components with different physical and mechanical properties. The components form the structure of composites. The structure and its evolution during deformation can have a significant influence on the mechanical properties and mechanical behaviour of composite materials [3, 4]. However, the degree and nature of this influence is still incompletely understood. Therefore, the problem of studying mechanical properties and predicting mechanical behaviour of composite materials under intensive dynamic loading conditions remains relevant.

In this connection, the present paper aims at the numerical simulation of mechanical behaviour under loading by plane shock waves and study of effective elastic and strength properties of metal-ceramic composites with consideration for structural evolution during deformation of composites.



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

The paper employs a plate of the composite material consisting of a matrix and reinforcing inclusions to simulate loading by a plane shock wave. The simulation is performed on a rectangular fragment of the plane section of the plate along the direction of the shock wave front.

The mechanical behaviour of the composite under the considered loading conditions is described using the physical and mathematical model of the two-phase condensed heterogeneous medium with an explicit description of its structure [5-7]. 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 aluminium matrix.

The used physical and mathematical model assumes the heterogeneous medium as a set of interrelated structural elements, namely, a matrix and inclusions. Inclusions are arbitrary in shape and randomly distributed in the matrix. Mechanical interaction between structural elements occurs along internal contact surfaces, i.e., matrix - inclusion interfaces. Within interfaces of each structural element the medium is taken as homogeneous and isotropic while in transition through the interface physical and mechanical properties of the medium change abruptly. Geometry of the simulated area and the number of structural elements are so chosen as to determine effective values of parameters of the mechanical state of the medium by averaging of calculated local values. The simulated areas of the two-phase heterogeneous medium with the model structures are shown in figure 1.

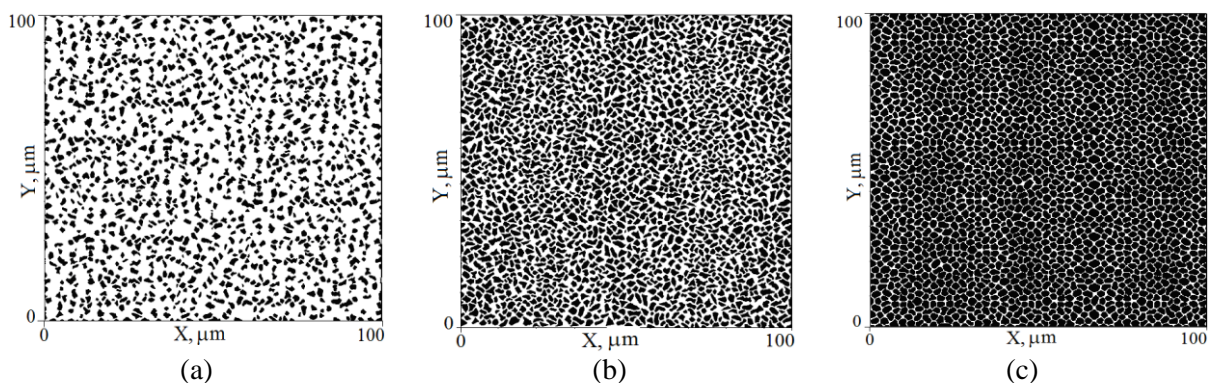


Figure 1. Simulated areas of the two-phase heterogeneous medium with the model structure of the composite composed of the matrix (light region) and arbitrary-shaped inclusions (dark regions). The characteristic size of inclusions is 5 μm , the volume concentration is: (a) 25%, (b) 50%, (c) 75%

Effective parameters of the mechanical state 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. A method for determining effective parameters of the mechanical state is described in [8, 9].

3. Investigation of the effective elastic and strength properties of metal-ceramic composites

The model of mechanical behaviour of the composite under shock-wave loading and method for determining effective parameters of the state are employed to predict effective mechanical properties of metal-ceramic composites Al-B₄C and Al-SiC. Composites contain 25%, 50% and 75% ceramic inclusions by volume.

The simulation results for propagation of plane shock waves in metal-ceramic composites are drawn on to plot dependencies of effective shock wave velocity $\langle D \rangle$ on effective mass velocity $\langle U_y \rangle$ (figure 2). The plotted dependences in the considered range of shock compression are linear $\langle D \rangle = C_B + \lambda \langle U_y \rangle$, which agrees well with the experimental and theoretical data. The results prove that concentration of ceramic inclusions affects bulk sound velocity C_B and proportionality factor λ .

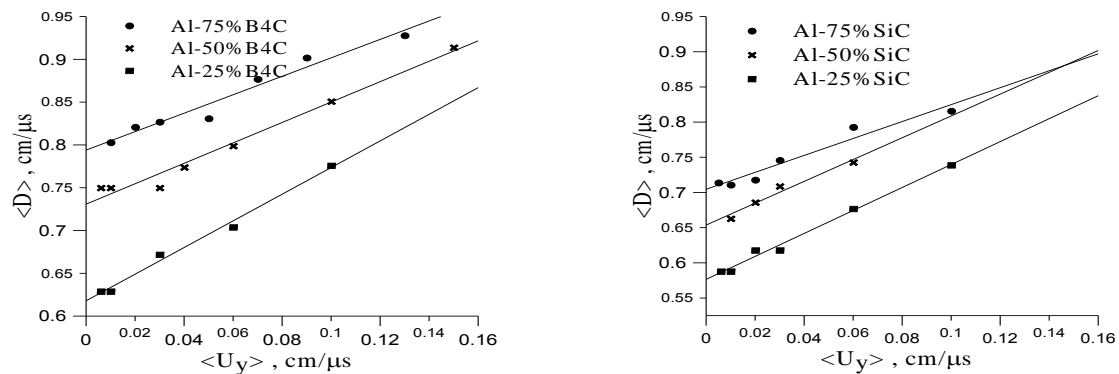


Figure 2. Values of effective shock wave velocity $\langle D \rangle$ versus effective mass velocity $\langle U_y \rangle$ in composite materials. Solid lines exhibit linear approximation of the simulation results

The numerical simulation of the loading by a plane shock wave of composites makes it possible to determine values of effective bulk, longitudinal and shear sound velocities of investigated materials. The simulation data on effective sound velocities are used for determining values of effective elastic modules of composites under normal conditions. The dependences of values of the effective bulk modulus on volume concentration of ceramic inclusions are presented in figure 3.

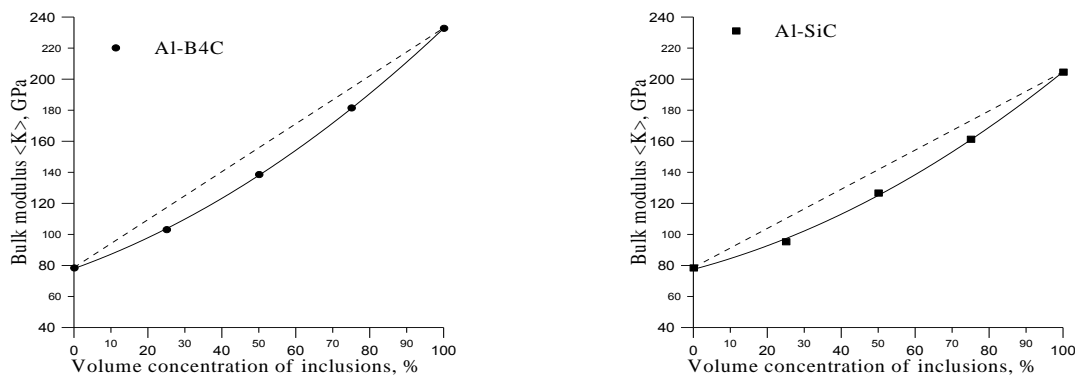


Figure 3. Values of effective bulk modulus versus concentration of inclusions in composite materials. Solid lines exhibit the square approximation of the simulation results, dotted lines exhibit linear approximation of component's properties of investigated composites

Values of the effective shear modulus in dependence on volume concentration of ceramic inclusions are presented in figure 4.

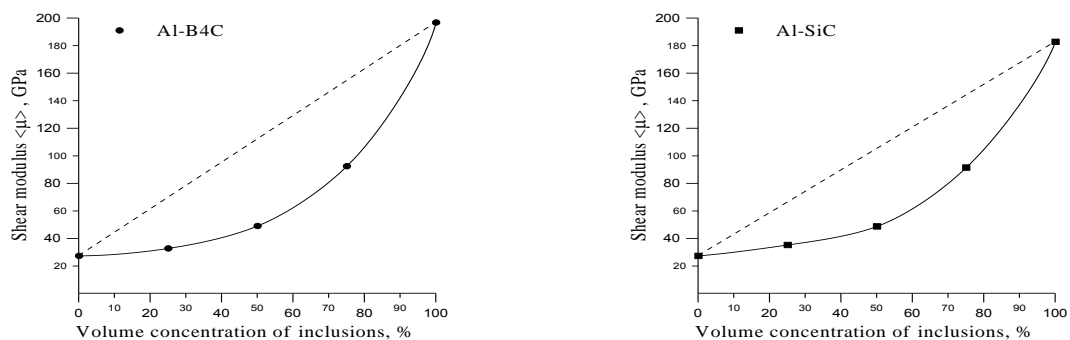


Figure 4. Values of effective shear modulus versus concentration of inclusions in composite materials. Solid lines exhibit the square approximation of the simulation results, dotted lines are linear approximation of component's properties of investigated composites

The influence of the concentration of ceramic inclusions on values of the effective Hugoniot elastic limit is also studied.

Values of the effective Hugoniot elastic limit in dependence on volume concentration of ceramic inclusions are presented in figure 5.

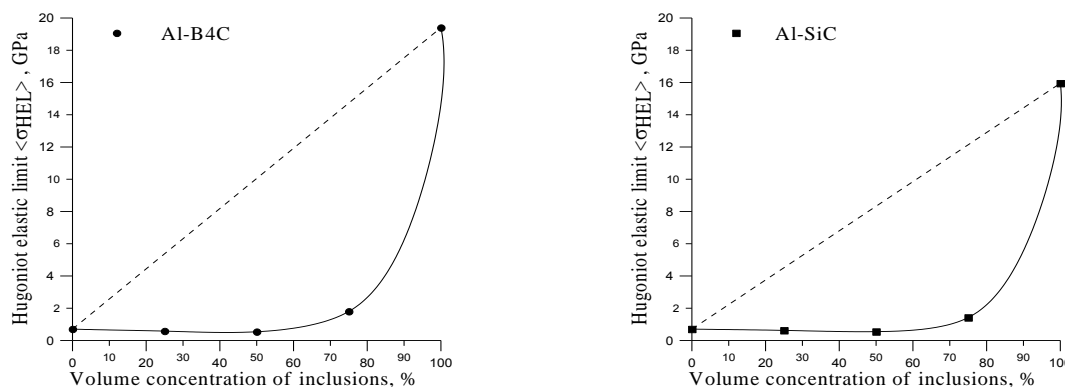


Figure 5. Calculated values of the effective Hugoniot elastic limit of composites as a function of volume concentration of ceramic inclusions. Solid lines exhibit the approximation of the simulation results, dotted lines exhibit linear approximation of component's properties of investigated composites

The effective Hugoniot elastic limit increases non-uniformly with growing concentration of inclusions, and its increment is maximal at high concentrations of inclusions.

4. Conclusion

The simulation results show that values of effective mechanical properties of the studied composites under shock-wave loading depend strongly on volume concentration of ceramic inclusions. The dependence of values of effective bulk and shear moduli of metal-ceramic composites on volume concentration of reinforcing ceramic inclusions is nonlinear and monotonically increasing.

The effective Hugoniot elastic limit demonstrates a weak dependence on the concentration of reinforcing inclusions up to 70%. This is explained by the fact that inelastic deformation develops at the shock front due to plastic flow of the aluminium matrix. At the inclusion concentration above 70% composites demonstrates a framework structure characterized by a negligible thickness of matrix layers or direct contact between particles. In this case, plastic deformation of the matrix is unable to ensure relaxation of increasing shear stresses. This causes the effective Hugoniot elastic limit to increase significantly, but not higher than the elastic limit in the corresponding polycrystalline ceramics.

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