AIP Conference Proceedings

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Citation: AIP Conference Proceedings **1783**, 020081 (2016); doi: 10.1063/1.4966374
View online: http://dx.doi.org/10.1063/1.4966374
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1783?ver=pdfcov
Published by the AIP Publishing

Numerical Investigation of Effective Mechanical Properties of Metal-Ceramic Composites with Reinforcing Inclusions of Different Shapes under Intensive Dynamic Impacts

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Abstract. In the present paper, the results of numerical simulation of high-rate deformation of stochastic metal-ceramic composite materials Al–50% B_4C, Al–50% SiC, and Al–50% Al_2O_3 at the mesoscopic scale level under loading by a plane shock wave are presented. Deformation of the mesoscopic volume of a composite, whose structure consists of the aluminum matrix and randomly distributed reinforcing ceramic inclusions, is numerically simulated. The results of the numerical simulation are used for the investigation of special features of the mechanical behavior at the mesoscopic scale level under shock-wave loading and for the numerical evaluation of effective elastic and strength properties of metal-ceramic composites with reinforcing ceramic inclusions of different shapes. Values of effective sound velocities, elastic moduli and elastic limits of investigated materials are obtained, and the character of the dependence of the effective elastic and strength properties on the structure parameters of composites is determined. The simulation results show that values of effective mechanical characteristics weakly depend on the shape of reinforcing inclusions and mainly are defined by their volume concentration.

INTRODUCTION

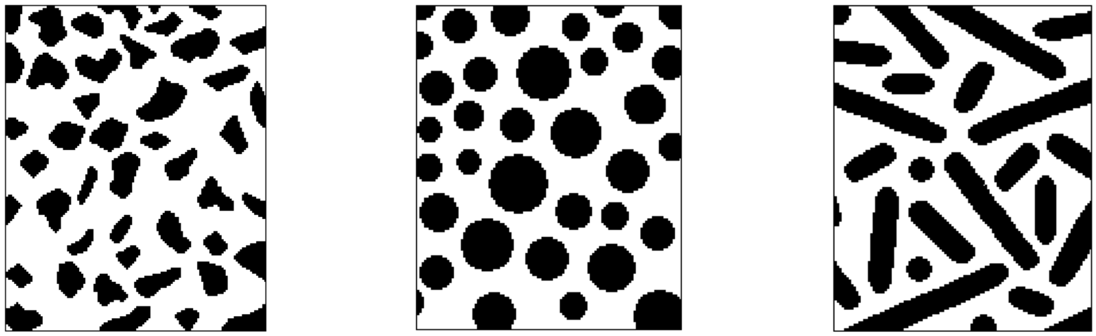
Metal-ceramic composite materials are widely used now in various fields of industry and are often used under extreme operating conditions. In this connection, it is necessary to adequately evaluate the elastic and strength properties and predict the mechanical behavior of these materials under intensive energy impacts.

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

It is shown experimentally that the mechanical behavior of composites under intensive dynamic loadings differs qualitatively from the behavior of their components under the same conditions [1–5]. The analysis of the structure of experimental specimens after loading testifies that special features of the mechanical behavior of composites is due to the influence of the evolution of their structure during high-rate deformation of the materials. However, the degree and nature of this influence are still incompletely understood. Therefore, the problem of studying mechanical properties and predicting the mechanical behavior of composite materials under intensive dynamic loading conditions remains relevant.

The present paper aims at the numerical simulation of the mechanical behavior of stochastic metal-ceramic composites at the mesoscopic scale level under loading by plane shock waves and at the study of effective elastic and strength properties of composites with different structure parameters.

Advanced Materials with Hierarchical Structure for New Technologies and Reliable Structures 2016
AIP Conf. Proc. 1783, 020081-1–020081-4; doi: 10.1063/1.4966374
Published by AIP Publishing. 978-0-7354-1445-7/$30.00



(a) (b) (c)

FIGURE 1. Simulated areas of the two-phase heterogeneous medium with the model structure composed of the matrix (light region) and reinforcing inclusions (dark regions) of different shapes: (a) the arbitrary shape, (b) the spherical shape, and (c) the shape of short fibers. The average size of inclusions is (a) the characteristic dimension 5 μm, (b) the diameter of spheres 5 μm, (c) the diameter of fibers 1 μm, and their length 10 μm. The volume concentration of inclusions is 50%

SIMULATION OF THE MECHANICAL BEHAVIOR OF THE METAL-CERAMIC COMPOSITE MATERIAL AT THE MESOSCALE LEVEL UNDER SHOCK-WAVE LOADING AND DETERMINATION OF EFFECTIVE MECHANICAL PARAMETERS

In this paper, loading of a plate of stochastic metal-ceramic composite material consisting of the metal matrix and reinforcing ceramic inclusions by a plane shock wave 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 front.

The physical-mathematical model of the two-phase condensed heterogeneous medium with an explicit description of its structure [6] is used to describe the mechanical behavior of the composite at the mesoscopic scale level under the considered loading conditions.

The used model represents a 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.

Fragments of the simulated areas of the two-phase heterogeneous medium with inclusions of different shapes are shown in Fig. 1.

A method for determining effective parameters of the mechanical state of the heterogeneous medium loaded by a plane shock wave was previously described [7, 8].

Effective parameters of the mechanical state are determined by volume averaging of values of local state parameters in thin flat layers perpendicular to the shock front direction. Examples of the effective elastic and strength characteristics determined by this method for a series of metal-ceramic composites are presented in the next section.

INVESTIGATION OF THE EFFECTIVE ELASTIC AND STRENGTH PROPERTIES OF METAL-CERAMIC COMPOSITES AL–50% B_4C, AL–50% S_IC, AND AL–50% AL_2O_3 WITH REINFORCING INCLUSIONS OF DIFFERENT SHAPES

The model of the behavior of the composite material under shock-wave loading and the method for determining effective parameters of the mechanical state are used for the numerical evaluation of effective elastic and strength characteristics of stochastic metal-ceramic composites Al–50% B_4C, Al–50% SiC, and Al–50% Al_2O_3 with reinforcing ceramic inclusions of different shapes.

The numerical simulation of loading of composites by a plane shock wave at the mesoscopic scale level makes it possible to determine values of effective longitudinal, bulk and shear sound velocities and Hugoniot elastic limits for the investigated materials. Values of the effective sound velocities are used for determining values of the effective bulk, shear and Young's moduli of the composites under normal conditions. The results are shown in Tables 1–3.

TABLE 1. Calculated values of the effective mechanical characteristics of the metal-ceramic composite material Al–50% B_4C with reinforcing inclusions of different shapes

Effective mechanical properties of the composite material	**Composite material with reinforcing inclusions of arbitrary shape**	**Composite material with reinforcing inclusions of spherical shape**	**Composite material with reinforcing inclusions in the shape of short fibers**
Mass density ρ_0, g/cm^3	2.64	2.64	2.64
Longitudinal sound velocity C_l, km/s	8.8	8.8	8.9
Bulk sound celocity C_b, km/s	7.25	7.26	7.23
Shear sound celocity C_s, km/s	4.32	4.31	4.4
Bulk modulus K, GPa	138.8	139.1	138.1
Shear modulus μ, GPa	49.3	49.1	51.1
Young's modulus E, GPa	132.3	131.7	136.4
Hugoniot elastic limit σ_{HEL}, GPa	0.54	0.54	0.55

TABLE 2. Calculated values of the effective mechanical characteristics of the metal-ceramic composite material Al–50% SiC with reinforcing inclusions of different shapes

Effective mechanical properties of the composite material	**Composite material with reinforcing inclusions of arbitrary shape**	**Composite material with reinforcing inclusions of spherical shape**	**Composite material with reinforcing inclusions in the shape of short fibers**
Mass density ρ_0, g/cm^3	2.97	2.97	2.97
Longitudinal sound velocity C_l, km/s	8.05	8.02	8.07
Bulk sound celocity C_b, km/s	6.54	6.56	6.53
Shear sound celocity C_s, km/s	4.06	4.03	4.11
Bulk modulus K, GPa	126.9	126.8	126.5
Shear modulus μ, GPa	49.1	47.8	50.1
Young's modulus E, GPa	130.2	129.4	132.5
Hugoniot elastic limit σ_{HEL}, GPa	0.548	0.547	0.551

TABLE 3. Calculated values of the effective mechanical characteristics of the metal-ceramic composite material Al–50% Al_2O_3 with reinforcing inclusions of different shapes

Effective mechanical properties of the composite material	**Composite material with reinforcing inclusions of arbitrary shape**	**Composite material with reinforcing inclusions of spherical shape**	**Composite material with reinforcing inclusions in the shape of short fibers**
Mass density ρ_0, g/cm^3	3.24	3.24	3.24
Longitudinal sound velocity C_l, km/s	7.01	7.01	7.03
Bulk sound celocity C_b, km/s	5.94	5.94	5.93
Shear sound celocity C_s, km/s	3.22	3.21	3.26
Bulk modulus K, GPa	114.1	114.1	113.8
Shear modulus μ, GPa	33.5	33.3	34.3
Young's modulus E, GPa	92.1	91.1	93.7
Hugoniot elastic limit σ_{HEL}, GPa	0.6	0.6	0.61

CONCLUSION

The simulation results showed that values of the effective mechanical characteristics of stochastic metal-ceramic composites Al–50% B_4C, Al–50% iC, and Al–50% Al_2O_3 weakly depend on the shape of reinforcing inclusions and mainly are defined by their volume concentration.

Calculated values of effective mechanical characteristics of composites with inclusions of a spherical shape and composites with inclusions of an arbitrary shape coincide with an accuracy of 1%. For composites with reinforcing inclusions in the shape of short fibers, with the fiber diameter to length ratio equal to 1/10, the determined values of longitudinal sound velocities and Hugoniot elastic limits are higher. This is due to the effect of orientation of fibers, and due to the fact that the speed of propagation of elastic waves in all considered ceramic compounds is much higher than the corresponding values for the aluminum matrix.

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