THE SHOCK WAVE COMPACTION OF CERAMIC POWDERS

by

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Original scientific paper
https://doi.org/10.2298/TSCI19S2471B

Joint theoretical and experimental investigations have allowed to realize an approach with use of mathematical and physical modeling of processes of a shock wave compaction of ceramic powders. The aim of this study was to obtain a durable low-porosity compact sample. The explosive compaction technology is used in this problem because ceramic powders such as boron carbide and aluminum oxide is an extremely hard and refractory material. Therefore, its compaction by traditional methods requires special equipment and considerable expenses. In order to better understand the influence of the loading conditions and, in particular, to study the effect of detonation velocity, explosive thickness and explosion pressure on the properties of the final sample, the problem of compaction of the powder in an axisymmetric case using the conditions of the above experiments have been numerically solved. Thus, using the technology of explosive compaction, compact samples of boron carbide and aluminum oxide are obtained. On the basis of experimental and numerical studies of shock waves propagation, the optimum scheme and parameters of dynamic compaction of boron carbide and aluminum oxide are determined in order to maximize the density and the conservation of the samples after dynamic loading.

Key word: *ceramic powder, explosive, boron carbide, aluminum oxide*

Introduction

At present, ceramic materials are widely used, both in civil and military applications (for example, in power engineering, metalworking, medicine (for prosthetics of teeth, joints), rocket technology, in engine components, armor protection, *etc*.). However, the high fragility of ceramics limits its use as a structural material.

A promising direction to improve the properties of such materials is the introduction of highly disperse fillers [1], into the ceramic matrix, which provide a significant change in their physical properties [2]. At the same time, for a number of applications, it is necessary to develop functionally graded materials (FGM) with a continuous or discrete-continuous change in properties. In particular, the development of FGM is necessary when combining materials with sharply differing values of physicochemical parameters [3, 4], for example, in compounds of metals and ceramics. Compacting of ceramic powders with the use of dynamic

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processes is widely studied from the point of view of manufacturing ceramics with unique properties and microstructures [5-7]. In these studies, the effects of pressure and temperature on the properties of sintered ceramics were studied. At the same time, there is a limited number of works in which the processes of dynamic compaction of ceramics in quantitative expression are investigated, and also physical processes associated with pouring of pores are investigated. In addition, there is no understanding of the influence of the loading rate on the process of compacting ceramic powders. A common characteristic of studies of the dynamic loading of highly porous materials are significant experimental difficulties that lead to large scatter and ambiguous experimental data. In addition to the experimental study of the dynamic loading of powders, many models have been created to describe the dynamic behavior of porous materials and powders during compaction [8, 9]. Each of these models contains three main elements: the equation of state for describing the pressure-density relationship, which includes non-linear compaction effects; yield surface describing the strength dependence of the undamaged and destroyed material depending on the pressure, and the fracture model describing the transition of the material from the undamaged to the destroyed state. As for the applicability of these models to the description of the dynamic compression of porous ceramic materials, recently there have been a limited number of papers devoted to this topic. We note the paper [10], in which the compaction of boron carbide B_4C in a flat formulation was numerically studied. The results of finite element modeling of the production of ceramic superconductors by explosive compaction are presented in [7, 11].

Explosive compaction

Experiments have been carried out on explosive compaction of ceramic powders B_4C and Al_2O_3, as well as its mixtures with multiwall carbon nanotubes (MWCNT) using the standard cylindrical scheme with central mandrel [12]. In [13] experiments on compacting powder were conducted to compare the different schemes of compaction to select the appropriate loading modes for obtaining a sample uniform in its physical and mechanical properties with density close to the theoretical maximum density (TMD). According to [13], the B_4C and Al_2O_3 powder, compacted with the standard cylindrical configuration has the most homogeneous structure and the best connection between the particles. It has no pronounced Mach area. All the experimental data have been included as summary data in tab. 1. The powders, the mixture and the structures of the explosive compacts were examined with scanning microscope. The original Al_2O_3 and the B_4C powders are shown at fig, 1.

Table 1, Experimental details

	B_4C	Al_2O_3
Explosive	Hexogen–ammonite 1:1.5	Ammonite-soda 2:1
D, [ms^{-1}]	4600	2830
Sintering	1000 °C for 3 hours	900 °C for 3 hours
ρ_0, [% TMD]	51	40
Particle size	60 μm	10–100 μm

The explosive loading process using the standard cylindrical configuration is performed by plastic deformation of the container along with porous material therein at detonation of contact explosive charge in the mode of running load. The shock wave propagates in

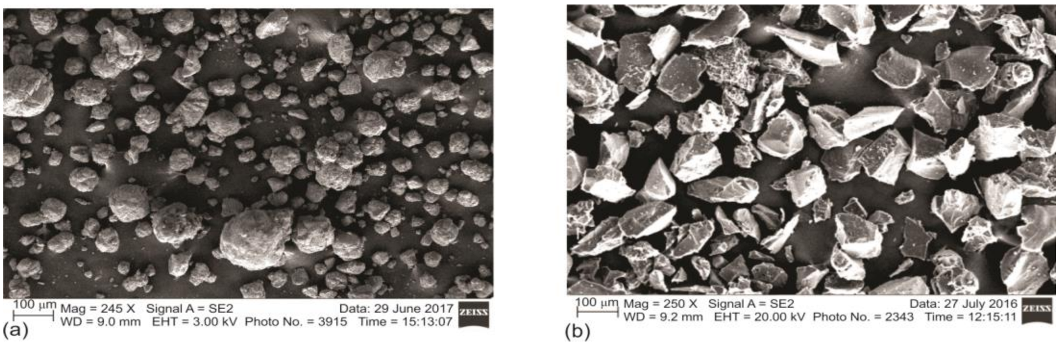

Figure 1. Initial aluminum oxide (a) and boron carbide (b) powders

the loaded sample with great speed and defines the boundary between the compressed and the undisturbed material. At that, position of the shock wave varies with the time. Due to the radial component and the cylindrical geometry, the shock wave converges as it spreads in the powder. The area on which the shock wave acts is reduced and, hence, the energy density increases. Apparently, the pressure and shock wave velocity were approximately constant over the radius. The compaction process has not been able to densify the powder to full density because to insufficient pressure in the shock wave during compaction. The density of the material, calculated from the reduction in diameter of the cylinder, is 87% of the TMD and no bonding, apart from mechanical interlocking, has occurred. Microstructures of the compact after consolidation by oblique shock wave are shown in figs. 2 and 3 for B_4C and Al_2O_3, respectively.

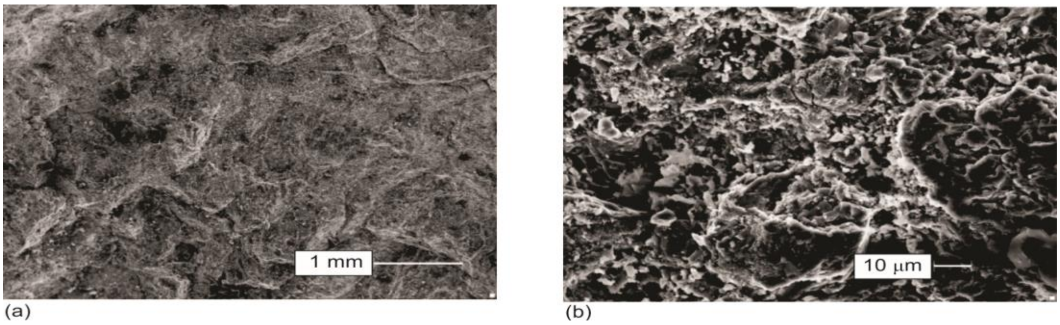

Figure 2. The microstructure of a compact of B_4C; (a) resolution 1 μm, (b) resolution 10 μm

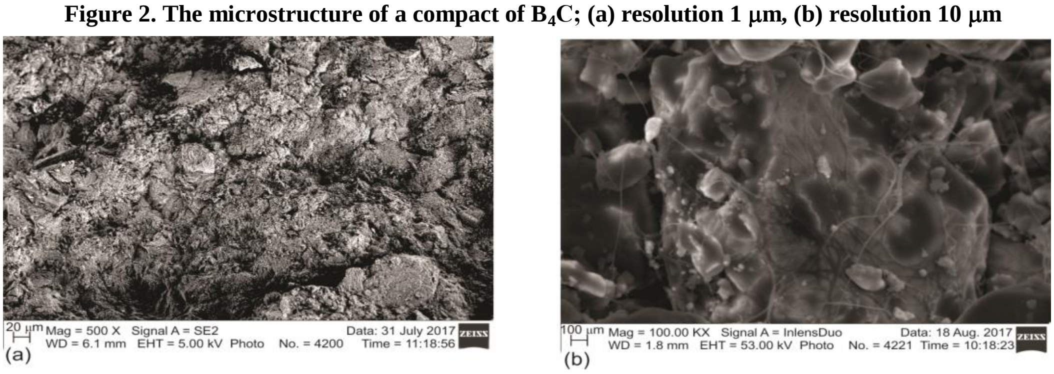

Figure 3. The microstructure of a compact of pure Al_2O_3 (a) and MWCNT-Al_2O_3 composite (b)

Numerical simulation

In order to better understand the influence of the loading conditions and, in particular, to study the effect of detonation velocity, explosive thickness and explosion pressure on the properties of the final sample, we numerically solved the problem of compaction of the powder in an axisymmetric case using the conditions of the above experiments. The technique of numerical simulation of explosive compaction of porous materials, which was used in this work is described in detail in [14, 15]. The modification of this technique as applied to the modeling of the explosive compaction of ceramic powders was performed for the first time. The problem statement according to experimental scheme is shown in fig. 4.

For the numerical simulation of the propagation of shock waves, a complete system of equations of deformation of the porous elastic-plastic material was solved [16] The action of the explosion products on the sample was modeled with a hydrodynamic pressure applied to the upper border of the sample. The pressure was calculated by the approximation formula for the pressure upon unrestricted dispersion of detonation products [17].

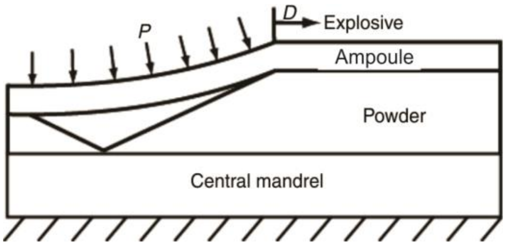

Figure 4. The problem statement

The symmetry axis is the axis of the container with the powder. On the symmetry axis rigid wall boundary conditions are set. The right boundary is considered to be free of stress, and at the left boundary condition of a rigid wall is put. Computation of the contact boundaries is performed by using a symmetric algorithm [18]. The calculations are carried out by the Wilkins scheme [19]. The shock wave propagates from left to right. Geometric dimensions and values of the physical parameters correspond to the experimental data mentioned above. For the numerical simulation of the propagation of shock waves in ceramic powders were taken into account three key elements as mentioned above: EOS to describe the dependence of the pressure - density, including a non-linear effects of compression; yield surface, which describes the dependence of the strength of intact and damaged material, depending on the pressure and the fracture model, which describes the transition of the material from the intact in the ruined state. The change in porosity is described relations Carroll-Holt [20]. To close the system uses small number of parameters equation of state [21-23], which allows you to make calculations of shock-wave processes with a minimal number of physical parameters as initial data. The stress state of the material presented in the form of Johnson-Holmquist [24]. The extent of the destruction of the material is expected to accumulate by increasing the plastic deformation of ceramics by the movement of the plastic deformation, using an expression similar to the Johnson-Cook damage model [25]. The calculations have been used the Hugoniots for aluminum oxide and boron carbide have been constructed in [21, 26].

Typical isolines of pressure in compacted materials at various detonation velocities for the indicated loading parameters are shown in fig. 5. As a result of numerical simulation it is shown that as the shock-wave propagation velocity increases, the angle of incidence decreases and the reflected shock causes material destruction. As the velocity of the detonation wave increases, the angle of incidence of the incident shock wave increases and the incident shock wave is close to the normal shock and the amplitude of the reflection wave is almost zero.

The analysis shows that with a detonation rate of 2800 m/s, there is not enough compression in the transmitted shock wave, which is consistent with experimental data. Sample at fig. 5(c) is exposed to a significantly higher pressure, leading to the formation of a

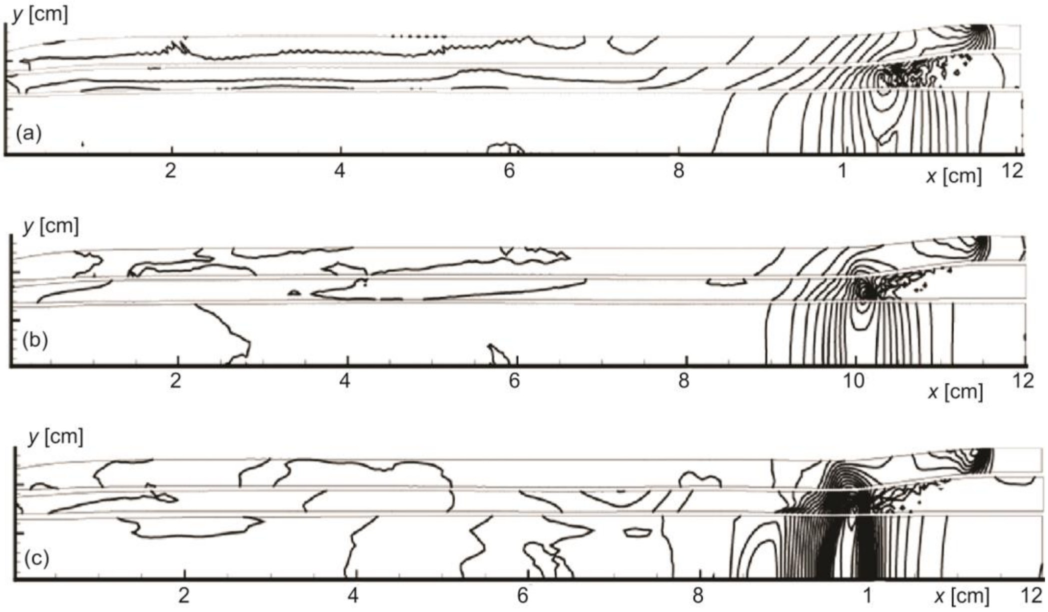

Figure 5. Pressure isolines. Detonation velocity: (a) 2800 m/s, (b) 4600 m/s, (c) 5400 m/s

Mach configuration at the powder boundary of the central mandrel. The formation of such a configuration leads to the destruction of the finished compact near the border with the central rod. The compaction mode with a speed of 4600 m/s is, apparently, optimal. This is confirmed by the results of the experiments and the distributions of the parameters over the thickness of the compacted samples obtained in the calculations.

Conclusion

Joint theoretical and experimental studies have allowed to implement an approach that uses mathematical and physical simulation of shock-wave loading of powdered materials. A numerical simulation of shock wave propagation and deformation of the experimental assembly has been performed. Thus, using the technology of explosive compaction, compact samples of boron carbide and aluminum oxide are obtained. On the basis of experimental and numerical studies of shock waves propagation, the optimum scheme and parameters of dynamic compaction of boron carbide and aluminum oxide are determined in order to maximize the density and the conservation of the samples after dynamic loading.

Acknowledgment

The study was conducted within the framework of the basic part of state task of the Khristianovich Institute of Theoretical and Applied Mechanics SB RAS (GR No. AAAA-A17-117030610136-3).

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Paper submitted: October 1, 2018
Paper revised: November 2, 2018
Paper accepted: December 7, 2018

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