Explosive compaction of aluminum oxide modified by multiwall carbon nanotubes

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Abstract. This paper presents experiments and numerical research on explosive compaction of aluminum oxide powder modified by multiwall carbon nanotubes (MWCNT) and modeling of the stress state behind the shock front at shock loading. The aim of this study was to obtain a durable low-porosity compact sample. The explosive compaction technology is used in this problem because the aluminum oxide is an extremely hard and refractory material. Therefore, its compaction by traditional methods requires special equipment and considerable expenses.

1. Introduction
Ceramics are usually chemically inert, hard, refractory and have a relatively low density in comparison with metals. Therefore, they form an interesting group of materials for high-tech applications. Hardness and refractivity exclude the possibility of their processing by casting, forging and machining, as is usually the case for metals and many polymers.

Instead, the technical ceramics are usually synthesized in the form of powders and further processed by precompiling them in green form and then sintering at high temperature in the furnace for their final compaction. A high-temperature process is usually required, since sintering is a process controlled by diffusion. The growth of grain and the shift of the chemical composition to a more thermodynamically stable one are inevitable during this process.

Thus, materials consisting of metastable phases and very small size particle (nanocrystalline, high-alloy and amorphous powders) cannot be processed using sintering without some loss of their original, often unique properties. Also, materials that have a low self-diffusion coefficient or decompose at high temperatures cannot be processed in this way. For these materials, as well as for unintentionally reacting material mixtures, alternative methods of compaction should be used. One of such methods is shock or explosive compaction of powders, in which the compaction of the powder occurs in a shock wave.

In a number of works, composite ceramic materials based on nano-sized oxides Al2O3, TiO2, ZrO2, MgO modified with carbon nanotubes were studied [1–6]. They showed that the insertion of small amounts of additions of carbon nanotubes (1–10 mass%) into dielectric ceramics drastically changes its electromagnetic properties leading to an increase in conductivity by several orders of magnitude. This opens the possibility of using such composite materials along with chemical, thermal and mechanical ones. It is necessary to provide certain electrophysical
Figure 1. Original Al₂O₃ powder.

Figure 2. Initial mixture of MWCNT–Al₂O₃.

characteristics. At the same time, different values of conductivity are required for different applications. In this paper, an attempt was made to obtain a composite material based on Al₂O₃ ceramics modified by multiwall carbon nanotubes by explosive compaction.

2. Explosive compaction of Al₂O₃ modified by multiwall carbon nanotubes

Experiments have been carried out on explosive compaction of ceramic powder Al₂O₃, as well as its mixtures with carbon nanotubes. The powder, the mixture and the structure of the explosive compacts were examined with the MERLIN Compact scanning microscope. The original Al₂O₃ powder had granules of size of 10 ÷ 100 µm (figure 1).

The bulk density was 1.56 g/cm³ or +40% of the theoretical maximum density (TMD). Multi-walled carbon nanotubes were supplied as an aqueous suspension containing 0.2% nanotubes by weight. For the experiment, 60 g of the powder were mixed with 40 ml of the suspension, then the mixture was dried and processed in a ball mill for 1 hour. Thus, the content of MWCNT in the mixture was 0.13% by weight. Figure 2 shows the mixture after drying.

Further, the pure Al₂O₃ powder and the mixture were compacted by explosion in ampoules of conservation according to the standard cylindrical scheme (figure 3) [7–9]. 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 (figure 4). The shock wave propagates in the loaded sample with a great speed and determines the boundary between the compressed and the undisturbed material. At that, the position of the shock wave varies with time. Due to the radial component and the cylindrical geometry, the shock wave decays as it spreads in the powder. The area on which the shock wave acts reduces and hence the energy density increases.

As the explosive we used the mixture of ammonite with soda 2 : 1 by weight. The detonation velocity was measured by an electrocontact method and amounted to 2830 m/s. After compacting, the samples were heat-treated at 900°C for 3 hours. This sintering temperature was insufficient, so the compacts had a low strength and a porous structure. The compact density was 3.5 ± 0.1 g/cm³ or 86% of the TMD. Figure 5 shows the microstructure of a compact of pure Al₂O₃ after explosive loading.

The microstructure of mixture of Al₂O₃ with carbon nanotubes after explosive loading is shown in figure 6.

Also from compacts, samples of size of 5 × 5 × 5 mm were cut out and their electrical resistance was measured by the LCR-meter Instec LCR-816. For a compact of pure Al₂O₃, it
3. Calculation results and discussion

For the numerical simulation of propagation of shock waves, a complete system of equations of deformation of the porous elastic-plastic material was solved [10]. The methods for numerical modeling of explosive loading of porous materials are described in detail in [11,12]. In this paper, we used the few-parameter equation of state adequately describing the physics of collision at high pressures and temperatures [13–15], which made it possible to calculate the shock-wave processes with a minimal number of physical parameters as the initial data. The geometrical dimensions and the values of physical parameters correspond to the experimental data mentioned above.

With the results obtained in [13,14], the Hugoniot for aluminum oxide have been constructed (figure 7). The presented comparison of the results obtained in this study with known experimental data [16–23] shows that the error in calculating of the parameters of the Hugoniot does not exceed 5–10%.

Joint theoretical and experimental studies allowed us to implement an approach based on mathematical and physical simulation of shock-wave loading of powdered materials. The Hugoniot curve of the aluminum oxide was constructed. Thus, the technology of explosive compaction was used to obtain compact samples of aluminum oxide. The above research allows us to draw the following conclusions:
Figure 7. The Hugoniot curve for aluminum oxide. Experimental data: △ – [22], □ – [24], ○ – [25], × – [26], ♦ – [27].

- When the aqueous suspension is a mixture of multiwall carbon nanotubes and Al₂O₃ powder, the distribution of nanotubes is fairly uniform.
- It is possible to obtain a composite Al₂O₃ modified by multiwall carbon nanotubes by the explosive method followed by sintering.
- Even in the case of a low content of multiwall carbon nanotubes in compacts (0.13%), the electrical conductivity increases by four orders of magnitude.

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