Explosive compaction of WC+Co mixture by axisymmetric scheme

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Abstract. This paper is devoted to the problem of development and optimization of schemes for explosive compaction of mixtures of solid powder materials with metal bond. For this purpose, experiments were conducted on explosive compaction of mixtures of tungsten carbide (WC) and cobalt (Co) using a simple cylindrical compaction system. In addition, a numerical simulation of shock waves propagation in two-phase porous medium WC+Co was carried out. Based on experimental and numerical studies of shock wave propagation, the optimal modes of explosive compaction of two-phase powder media, representing mixtures of solid powder materials with metal bond, were found. It is shown that the most preferable compaction mode for obtaining a uniform durable compact of a mixture of powders WC+Co with ratio 9:1 by volume in axially symmetric scheme with central mandrel corresponds to the detonation velocity of 4.6 km/s followed by sintering.

1. Introduction

In creation new materials, including composite ones, the methods of explosive compaction of powder heterogeneous systems occupy an important place, because, due to short-term exposure to high temperatures and pressures, this method allows one mainly to preserve the structure and properties of the starting powders. This condition is important for compression, e.g., of submicrocrystalline or amorphous powders. The interest to these problems is connected with the ability to create new materials with controlled properties.

Tungsten carbide has numerous applications due to a combination of its physical and mechanical properties (high melting point, high hardness, low friction and chemical resistance to corrosion and oxidation) [1]. Tungsten carbide is the most widely used as the basis for solid alloys. Introduction of the metal phase, particularly cobalt, leads to an increase in fracture toughness of the resulting sample.

2. Experimental study of the structure of compacts

Experiments on explosive compaction were conducted using a simple cylindrical compaction system with a central mandrel. The method of the explosion experiments are described in detail in [2–4]. The initial cobalt powder was agglomerated with size of 50–100 µm consisting of particles with average size of 1 µm. The tungsten carbide powder had average particle size of 6–7 µm. For a better homogeneity of the mixture, before blending, the cobalt powder was milled...
Figure 1. The Hugoniot of the mixture WC+Co with ratio 9:1 by volume, $D = 0.244 + 1.554U$.

Table 1. Explosive detonation velocities.

| Sample | Explosive               | Detonation velocity, km/s |
|--------|-------------------------|----------------------------|
| 1      | Hexogen                 | 5.4                        |
| 2      | Hexogen-ammonite 1:1.5  | 4.6                        |
| 3      | ammonite                | 3.4                        |

in a ball mill for 7 hours. Then, the powders WC+Co were mixed in ratio 9:1 by volume in a ball mill as well for 7 hours. Before that, the Hugoniot of the mixture (figure 1) were measured by a contactless electromagnetic method [5]. Some samples after the compaction were thermally processed directly in the container. The compacts structures were investigated using scanning electron microscope LEO-420.

In all the experiments, the diameter of the container was 28 mm, wall thickness was 3 mm, and the central mandrel diameter was 14 mm. Length of the mixture filling was 120 mm. The WC+Co mixture ratio was 9:1 by volume. It had the bulk density of 7.46 g/cm$^3$, or 52% of the monolith density. The thickness of the explosive charge (EC) was 10 mm. Hexogen, ammonite, and their mixture with ratio 1:1.5 by mass were used as the EC. In all the experiments (table 1), the detonation velocity was measured. For hexogen, it was 5.4 km/s (sample 1), for the hexogen-ammonite mixture it was 4.6 km/s (sample 2), and for the ammonite it was 3.4 km/s (sample 3). Samples 2 and 3 were sintered after compaction directly in the containers for 3 hours at temperature of 900°C. Electronic images of the fractographs are shown in figure 2.

Studies of the compacts fractographs showed that sample 1 had a loose structure with a pronounced Mach area. There was no strong bond between the particles even in the Mach area, where cobalt particles melting was observed. Sample 2 has the most homogeneous structure and the best connection between the particles. It has no pronounced Mach area. Sample 3 has no Mach area either, and the bond between the particles is worse than in sample 2, due, apparently, to insufficient pressure in the shock wave during compaction. Thus, the studies have shown that the most preferable compaction mode for obtaining a uniform solid compact of power mixture WC+Co with ratio 9:1 by volume in a simple cylindrical compaction system with a central mandrel corresponds to sample 2 followed by sintering.

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Figure 2. The structures of the cross sections of the samples: a – structure of sample 1 over its thickness, b – the same sample in the Mach area, c – sample 2, d – sample 3 after sintering.

3. The calculation results and discussion

For the numerical simulation of the shock waves propagation, the complete system of equations for deformation of the porous elastic-plastic material was solved [6]. The method for numerical modeling of explosive loading of porous metallic materials is described in detail in [7, 8]. In this paper, we use the few-parameter equation of state [9, 10] that adequately describes the physics of collision at high pressures (up to 10 Mbar) and temperatures (up to 10,000 K), which allowed the calculation of shock-wave processes with the minimum number of physical parameters as the initial data. To describe the behavior of multicomponent medium in the shock wave, we used the mixtures approach [11]. The Hugoniot of a mixture is given by a linear relationship between the shock velocity $D_{mix}$ and the particle velocity $U_{mix}$:

$$D_{mix} = a_{mix} + \lambda_{mix} U_{mix},$$

then, we can write

$$P_{mix} = \frac{\rho_{0mix}a_{mix}^2}{\left[1 - \lambda_{mix}\left(1 - \rho_{0mix}/\rho_{mix}\right)\right]^2}, \quad V_{mix}(P) = \sum_{i=1}^{n} \alpha_i V_i(P),$$
α_i = \frac{m_i}{\sum_{i=1}^{n} m_i}, \quad \sum_{i=1}^{n} \alpha_i = 1,

where \( \rho_{0\text{mix}} = 1/V_{0\text{mix}} \), \( \rho_{\text{mix}} = 1/V_{\text{mix}} \) are the initial and current density; \( a_{\text{mix}} \) is the mixture speed of sound; \( \lambda_{\text{mix}} \) is linear Hugoniot slope coefficient; \( \alpha_i \) is the mass concentration. Values \( a_{\text{mix}}, \lambda_{\text{mix}} \) are taken from the experimentally determined Hugoniot of WC+Co mixture shown in figure 1.

Figure 3a shows the distribution of the porosity over the sample thickness for various modes of loading. The figure shows that at the detonation velocity of 3.4 km/s, the pores do not collapsed over the thickness of the loaded sample, which agrees well with the experimental data. Figure 3b shows the density distribution over the thickness of the loaded samples for various loading conditions. The most uniform distribution of density occurs at the detonation velocity of 4.6 km/s. The detonation velocity being 5.4 km/s, a sharp decrease in the density is observed in the upper part of the sample, which is associated with action of the unloading waves that manage to reflect from the free surface after the passage of the detonation wave.

4. Conclusion
Based on experimental and numerical studies of shock wave propagation, the optimal modes of explosive compaction of two-phase powder media, which are mixtures of solid powder materials with metal bond, are determined. It is shown that the most preferable compaction mode for obtaining a uniform solid compact of powder mixture WC+Co with ratio 9:1 by volume in a simple cylindrical compaction system with central mandrel corresponds to detonation velocity of 4.6 km/s followed by sintering.

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