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Consolidation of bulk TiB_2 by underwater explosive compaction

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ABSTRACT

Underwater shock compaction of titanium diboride (TiB_2) powder has been performed, complemented by a numerical simulation with AUTODYN hydro code. Density, micro hardness and microstructure of the specimens were investigated. TiB_2 specimens without any cracks were successfully consolidated up to high density of about 98% of the theoretical value and a micro hardness of about 2550 Vickers.

1. Introduction

Refractory materials such as titanium diboride have wide applications in various industries. With properties such as high melting point (3225 °C), low density (4.5 g/cm^3), high hardness (25 GPa), good thermal conductivity (96 W/m/K), high electrical conductivity (22 × 106 Ω cm) and considerable chemical stability, titanium diboride is one of the candidate materials for high temperature structural and wear applications [1]. The interest in TiB_2 enormously increased because of these properties, but its applications seem to be limited because of the pertaining difficulties during machining. Today, TiB_2 is only considered for special applications such as electrode material for salt-bath electrolysis in aluminum production [2], for impact-resistant armor targets [3] or as a constituent in hard metal cutting tools and wear parts [4,5].

There have been a number of studies on TiB_2 powder sintering. Demirskyi et al. [6] sintered TiB_2 by microwave under 1600–1700 °C. The density and hardness of the samples were respectively observed to be 98.5 and 24.5 Vickers. Rabiezadeh et al. [7] sintered nano-powder TiB_2 by pressureless and hot press method. Sintering of the samples took 2 h. For the pressureless method, it was done under 1900 centigrade degrees and for the hot press method, 1700 °C. In the former method, a density of 82.3% and in the latter, a density of 92% and a hardness of 25.9 GPa was achieved. Karthiselva et al. [8] sintered TiB_2 by RSPS method under 1400 °C temperature and 50 MPa pressure and 10 min hold time. They reached to a nano-hardness of 26 GPa.

To prepare high quality parts, the explosive compaction technique is an alternative way for consolidation of hard material powder such as TiB_2. According to previous studies, production of denser compacts with high quality within microseconds is possible by utilizing shock wave, which is generated by the detonation of an explosive material [9–12].

The technique of underwater shock compaction was developed by Chiba et al. [13] in which by passing of high pressure shock wave through the powder medium, localized heating is generated and a layer of powder surface is melted. The powder surfaces undergo melting and solidifying process in a few microseconds [14]. In comparison to the traditional powder metallurgy, the main advantage of this technique is the production of denser compacts without any additives such as binder [15]. In addition, due to absence of heating, this method creates fully dense materials without grain growth [11].

Based on the best knowledge of the author, there had been no articles conducted on TiB_2 sintering by underwater explosive compaction method, thus this research studies this kind of TiB_2 sintering. In the present investigation, a numerical simulation of the process for consolidation of TiB_2 powder was conducted by hydro code software, AUTODYN.

As Mayer [16] mentioned, the dynamic pressure to consolidate TiB_2 powder is approximately 35 GPa. Several explosion tests were performed for consolidation of titanium diboride powder (with mean grain size of 5 μm and via HMX explosive material).

2. Numerical simulation of the process

Computational simulations were performed in 2D axial- symmetric by using the hydro code AUTODYN. In order to utilize the

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Table 1
The JWL equation of state parameters for HMX explosive [18].

A (GPa)	B (GPa)	R_1	R_2	ω	E (GJ/m^3)
778.3	7.071	4.2	1	0.3	10.5

computer simulation, it was necessary to determine several parameters appearing in the general theory of explosion synthesis. The basic requirement for computer simulation is the equation of state (EOS) of explosive material and TiB_2 powder. The JWL [17] equation of state for HMX explosive is as follows:

$$P = A(1 - \omega/R_1V)e^{-R_1V} + B(1 - \omega/R_2V)e^{-R_2V} + \omega E/V \quad (1)$$

where A, B, R_1, R_2 and ω are constant parameters which they are reported in Table 1 [18]. V is the relative volume during the initial stage of reaction and E is the internal energy per unit volume.

In order to determine the EOS for TiB_2 powder, Meyers [16] offered a theoretical method for the calculation of EOS of the powder by using EOS of the solid based on the Mie-Gruneisen equation, given:

$$P - P_H = \gamma/V(E - E_H) \quad (2)$$

where P_H and E_H are the pressure and specific internal energy of EOS of solid, V is the specific volume of material, P and E are the pressure and specific internal energy for powder, γ is the Gruneisen constant which is obtained by the equation as follows:

$$\gamma_0 = 2S - 1 \quad (3)$$

The ratio γ/V is assumed constant, this implies that:

$$\gamma/V = \gamma_0/V_0 = cte \quad (4)$$

By applying three equations for the conservation of mass, momentum, and energy and using Eq. (2) for both the solid and the powder, EOS of powder is determined as follows:

$$P = [2V - (\gamma_0/V_0)(V_0V - V^2)]C^2(V_0 - V)/[2V - (\gamma_0/V_0)(V_{00}V - V^2)] \\ [V_0 - S(V_0 - V)]^2 \quad (5)$$

where V_0 is the specific volume of solid, V_{00} is the initial specific volume of the powder, C is the sound speed in solid, and S is a constant from the EOS of the solid. The EOS parameters and physical properties of TiB_2 are reported in Table 2 [19].

Using the above calculated parameters, the EOS of TiB_2 powder was determined as follows:

$$P = 2.09 \times 10^4 - 4.32 \times 10^7V - 2.26 \times 10^{11}V^2/4.66 \times 10^{-5} \\ + 0.6V + 0.18V^2 + 2.26 \times 10^3V^3 \quad (6)$$

3. Experimental procedure

By using computer simulation results, an optimum experimental setup for the explosive compaction of the TiB_2 powder was designed and a number of tests were conducted. Fig. 1 shows the assumed compaction setup. To carry out the experimental procedure, the illustrated setup was assembled by using different components. Multipurpose adhesive was applied to join these components. The explosive material used in the present study was HMX; with a detonation velocity of 8193 m/s. TiB_2 powder (Green World China Rong Feng, Purity > 99%) with a grain size of 5 µm (on average) was provided and put in the powder container. The XRD and SEM of the powder is illustrated in Figs. 2 and 3. As it can be noticed, the original powder is a mono phase TiB_2.

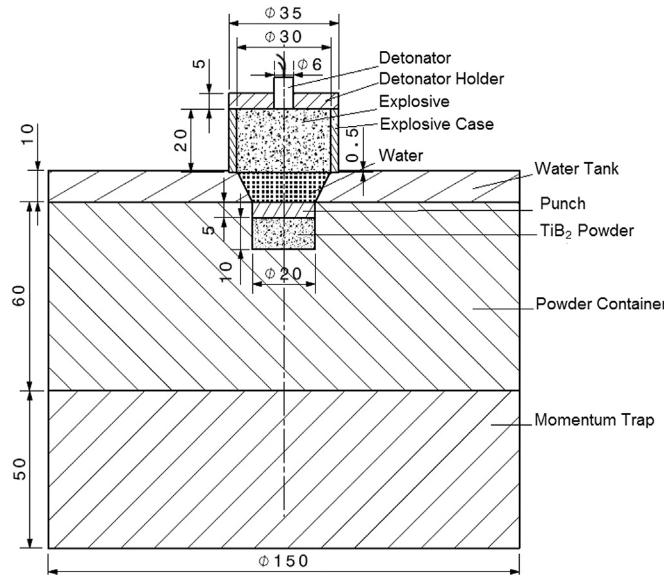

Fig. 1. Assumed setup of explosive compaction.

The consolidation process after ignition of the electrical detonator was successfully performed and several samples were produced. In order to eject the products from the container, the powder container was machined by turning operation. After acquiring the specimens, some of their properties such as density and micro hardness were measured. In addition, the fragment surfaces of cross-sectional area of the samples were analyzed by scanning electron microscope (SEM).

4. Results and discussion

4.1. Computer simulation results

Computer simulation of the process was conducted for various setups with variations of process parameters such as the ratio of explosive mass to powder mass (mass ratio) and the thickness of punch and water column.

According to the computer simulation, the discussed parameters are illustrated in Figs. 4–6. According to Fig. 4, the mass ratio is the most important parameter in explosive compaction process. For consolidated TiB_2 powder, it must be chosen in the range of 2.8–3.

In order to reduce the loss of the shockwave energy, as shown in Figs. 5 and 6, the optimal thickness of the experimental setup for punch was reduced from 8 to 5 mm and for water column was decreased from 20 to 10 mm.

4.2. Experimental results

Several cylindrical specimens were made of TiB_2 powder. All of the specimens are 20 mm in diameter, yet with various thicknesses. Fig. 7 shows the typical specimen was produced by underwater explosive compaction technique.

To determine the optimum mass ratio for explosive compaction of TiB_2 powder, experimental tests were performed by various explosive ratios from 1.5 to 3. The densities of the obtained

Table 2
Eos parameter and physical properties of TiB_2 [19].

C (m/s)	V_0 (cm^3/g)	V_{00} (cm^3/g)	S	γ_0
8486	0.223	0.372	0.85	0.7