Numerical Simulation and Experimental Study of Explosive Compaction of Tungsten Powder

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Abstract: - Explosive Compaction is an alternative way for densification of powders in powder metallurgy technique. It is often used to consolidate and form the metal powders which are difficult to work. In this paper, the explosive compaction process was applied to compact and densify the tungsten powder. Prior to the

1 Introduction

Refractory materials such as tungsten have wide applications in various industries. Due to the special characteristics of these materials like high melting point temperature and high hardness, the production of the engineering parts made by these materials is very difficult. Although the powder metallurgy technique is one of the important technologies applied for production of tungsten parts, but achievement of high density and hardness is not possible by this method [1]. To prepare high quality parts, the explosive compaction technique is an alternative way, especially for consolidation of tungsten powder. Previous studies have reported that by utilizing the shock waves which are generated by detonation of an explosive material, the production of denser compact pieces with high quality is possible within microseconds [2-8]. Passing the high pressure shock waves through the powder medium, would cause the localized heating to generate on powder surface and a layer of powder surface would melt. By compaction of these powder particles, it is possible to obtain a strong bond between the particles [9, 10]. There are some major parameters such as the detonation velocity of explosive material, the pressure of compaction, the ratio of the mass of the explosive to the mass of the powder, etc. which could effect the process and were investigated and studied for different materials by various researchers in the past [10-17]. To reduce the experimental costs in determination the effect of important parameters of the process, computer simulation has been applied [11].

In the present investigation, a setup of explosive compaction was assumed and the numerical simulation of the process for consolidation of tungsten powder was conducted using the LS-DYNA program [18]. Figure 1 shows the assumed compaction setup in the present analysis. Experimental setup for compaction of tungsten powder was designed and optimized using the computer simulation results.

Several explosion tests were performed for compaction of tungsten amorphous powder with 40 micron mean grain size by using the C4 as an explosive material.

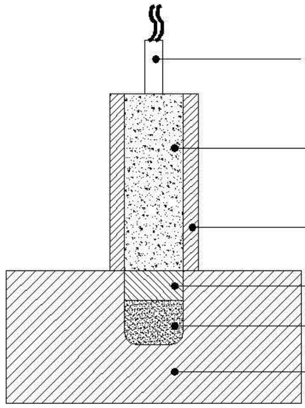

Fig.1: The setup used in simulation of the explosive compaction

2 Numerical simulation of the process

In order to utilize the computer simulation, it was necessary to determine the several parameters appearing in general theory of explosion synthesis [18]. First of all is the Equation of State (EOS) for tungsten powder. In order to exactly determine the EOS for the powder, instrumented gas gun experiments must be perform. However, reliable calculation method can be applied for determination of EOS of the powder. Meyers [17] suggested a theoretical method for calculation of EOS of the powder by using EOS of the solid, based on the Mie-Gruneisen equation which is given by

$$P=P_H+g/V(E-E_H) \quad (1)$$

where P_H and E_H are the pressure and specific internal energy of EOS of solid, g is the Mie-Gruneisen constant, V is the specific volume of the material and P and E are the pressure and specific internal energy for the powder.

Using the equation (1) and by applying the three equations for the conservation of mass, momentum, and energy for both the solid and the powder, EOS of the powder could be obtained as follows:

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

Where V_0 is the specific volume of the solid, V_{00} is the initial specific volume of the powder, C_0 is the sound speed in the solid and S is a constant obtained from EOS of the solid. The physical properties and EOS parameters of tungsten powder is as follows [19, 20]:

C_0= 4.03 Km/s, $V_0=5.19\times10^{-5}$ m^3/kg, S=1.24, g_0= 2S-1= 1.48

For the tungsten powder with the initial density of about 7.8 g/cm^3, the required parameters to drive an EOS expression by using the above constants could be calculated as follows:

$V_{00}=1/7800=12.82\times10^{-5}m^3/kg$,
$g_0/V_0=g/V=1.48/5.19\times10^{-5}=28516$

Using the above calculated parameters, the EOS of tungsten powder with a density of 7.8g/cm^3 was determined as follows:

$$P = \{[2V-28516(5.19\times10^{-5}V-V^2)](16.24\times10^6)(5.19\times10^{-5}-V)\}/\{[2V-28516(1.282\times10^{-4}V-V^2)][5.19\times10^{-5}-1.24(5.19\times10^{-5}-V)]^2\} \quad (3)$$

The other requirement for the computer simulation process is the EOS of explosive material. The JWL equation [18] of the state for C4 explosive material is as follows:

$$P = A\,(1-w/R_1V)\,e^{-R_1V} + B\,(1-w/R_2V)\,e^{-R_2V} + wE/V \quad (4)$$

where A, B, R_1 and R_2 are constants and for the C4 explosive material, they are equal to [21]:

A = 6.0997, B = 0.1295, R_1 = 4.5 and R_2 = 1.4

V is the relative volume during the initial stage of reaction which is defined as r_0/r, and E is the internal energy per unit volume. For the C4 explosive material, w is defined as $w=n-1$ where n is the explosive adiabatic exponent which could be approximately considered as 3[19]. Therefore the value for w would be equal to 2. The pressure (P_{cj}) and the particle velocity (u_p) of explosive material is defined from the Chapman- Jouget equation as follows [17,19]:

$$P_{cj} = (r_0D^2)/(n+1) \quad (5)$$
$$u_p = D/(n+1) \quad (6)$$

where D is the detonation velocity and is equal to 8193 m/s, ρ_0 is the initial density of the explosive material and is equal to 1.6 g/cm^3 [21].

Using the above equations, the necessary coefficients and constants for the computer simulation of the compaction process were calculated and the simulation was performed using the LS-DYNA program. Figure 2 shows the simulation and the constructed model with the required meshing.

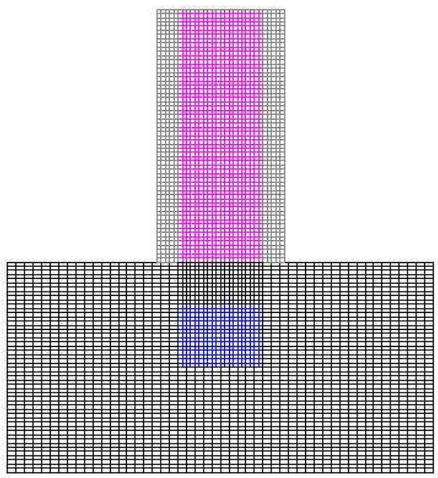

Fig. 2: Simulation model and the constructed meshing

3 Experimental procedure

Using the results obtained from the simulation model, an optimum experimental setup for the explosive compaction of the tungsten powder was designed and a number of tests were conducted. To perform experimental works, the setup was assembled by using different components and the multi-purpose commercial adhesive was applied to join these components. The compaction setup consists of several components, i.e. an electrical detonator, explosive material, an explosive container, a punch, a powder container, tungsten powder and a momentum trap. The explosive material used in the present study was C4 with a detonation velocity of 8193 m/s. The amorphous tungsten powder with a mean grain size of 40 micron was prepared and placed in the powder container. By ignition of the electrical detonator, the compaction process was successfully performed and several samples were produced. In order to eject the product from the container, the powder container was precisely machined using turning operation. After releasing the specimens from the setup, their properties such as the density and the hardness were measured and the fragment surfaces of cross sectional area of the specimens were analyzed using the scanning electron microscope (SEM).

4 Results and discussion

4.1 computer simulation results

The computer simulation of the process was conducted for the various setup and the various process parameters such as the ratio of the mass of the explosive to the mass of the powder (M_E/M_p), the thickness of the punch, the kind of the explosive material, and the dimensions of the explosive material. The results of the computer simulation were indicated that the ratio M_E/M_p is the most important parameter in the explosive compaction process and for the compaction of the tungsten powder, this ratio must be consider between 1 to 2. To prevent the reflected explosive wave from the end of the powder container which was observed in the simulation process, a momentum trap was used in experimental setup. When explosion of the explosive material was initiated from a single point, a spherical front detonation wave was propagated through the explosive material and as the wave was propagated along the explosive material, the spherical front wave was changed to semi-planar shape. To compact a homogeneous part, a planar wave must be passing through the powder. In the simulation process, fully planar passing wave was not observed in the explosive material and the powder. To prevent the propagation of the spherical front part of detonation wave and passing the fully planar wave through the powder medium, the diameter of the explosive material was changed and increased from 20 to 30 mm. Another optimization of the experimental setup was the reduction of the thickness of the punch in order to reduce the loss of energy in the shock wave. Fig. 3 shows the final model and constructed mesh used for simulation of compaction process after optimization of the setup. Therefore, the computer simulation results were useful in optimizing the parameters for the experimental test setup.

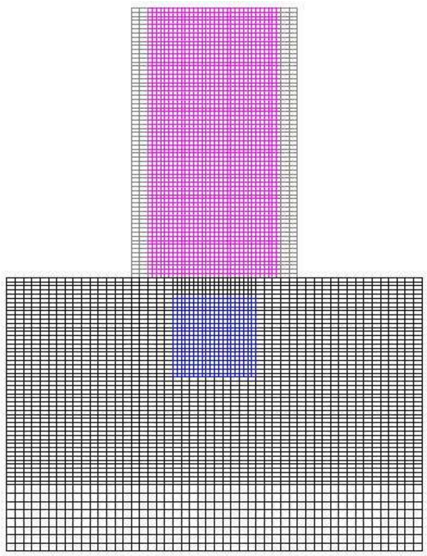

Fig. 3: Final simulation model and constructed mesh for the optimum setup

4.2 Experimental results

Figure 4 shows the optimum test setup used for the compaction of the tungsten powder in the present analysis.

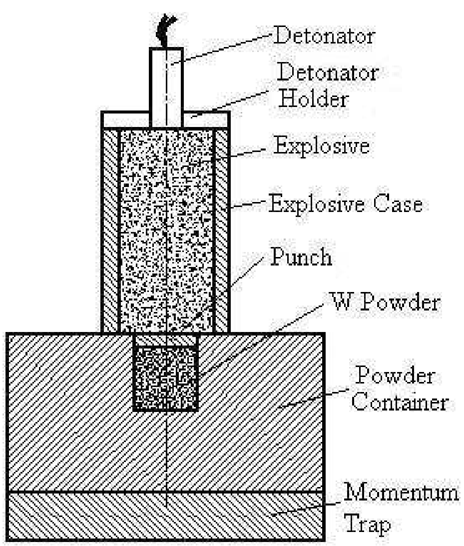

Fig. 4: Schematic illustration of optimum explosive compaction setup

Several cylindrical specimens were made using tungsten powder. All of the specimens were 20 mm in diameter and had various thicknesses. Figure 5 shows typical specimens produced by the explosive compaction method using the optimum setup.

Fig. 5: Explosive compacted tungsten specimens

Experimental tests were performed by the various explosive ratios from 0.5 to 2, in order to determine the optimum explosive ratio for the explosive compaction of the tungsten powder. The densities of the samples obtained were measured by the densitometer instrument. Figure 6 illustrates the variation of the density of the tungsten specimens obtained versus the explosive ratio.

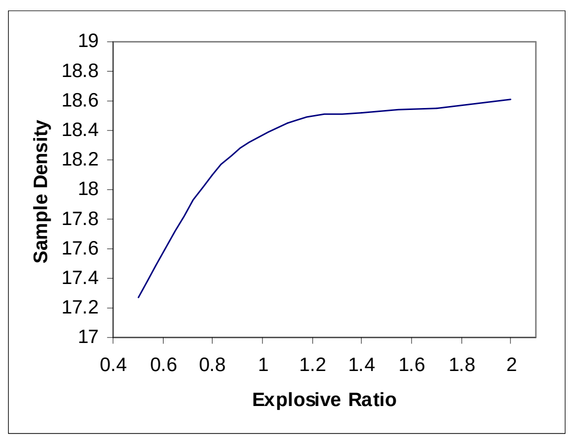

Fig. 6: Variation of spcimens density with the explosive ratio

The maximum density of the specimens obtained in the experimental test was about 18.6 g/cm^3 which it was equal to 96% of the tungsten theoretical maximum density (TMD). In the previous investigations by the author [1] for the densification of the tungsten powder using the conventional powder metallurgy method, it was indicated that the maximum density which could be obtained by powder metallurgy was 17.1 g/cm^3, in which it was lower than the minimum density obtained by the explosive compaction method used in the present analysis. As shown in Fig. 6, by increasing the explosive ratio from 0.5 to 1.2, the density of specimens increased very quickly and reached to 18.4 g/cm^3 and by increasing the explosive ratio from 1.2 to 2 the density of specimens increased slowly. Increasing the explosive ratio beyond 2, would destruct the test setup. Therefore considering the explosive ratio of 1.5 seems to be an optimum ratio. In addition to the density measurements, the micro hardness of the obtained specimens was also measured. Figure 7 illustrates the variation of the hardness of the specimens versus the explosive ratio.

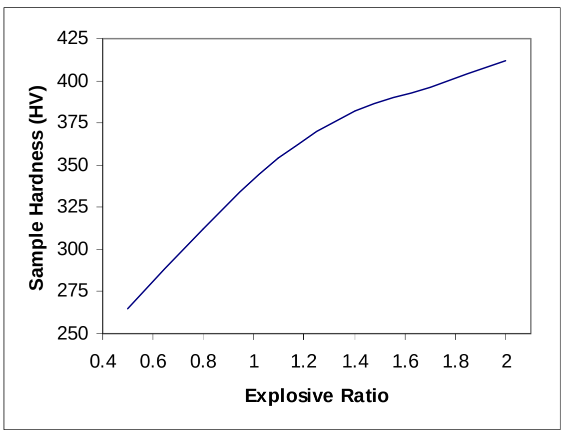

Fig. 7: Variation of specimen hardness with the explosive ratio

By increasing the explosive ratio, the thickness of molten layer of powder surface was increased and a strong bonding between the powders was obtained. Thus, as it was shown in Fig. 7, by increasing the explosive ratio, the hardness of the specimens was increased. The maximum value obtained for the hardness in former studies [1] on the conventional powder metallurgy specimens of the same material was 221 Vickers, which is too low compare to the maximum hardness obtained in the present investigation obtained by the explosive compaction (410 Vickers).

To study the microstructure of the specimens, the fragment surfaces obtained for the specimens were analyzed by scanning electron microscope (SEM) and micrographs obtained were compared with the one obtained for the typical specimens prepared with the conventional powder metallurgy method in the former study [1]. Fig. 8 shows the SEM micrograph of the explosive compacted specimen and Fig. 9 shows the SEM micrograph of the specimen obtained by the conventional powder metallurgy method.

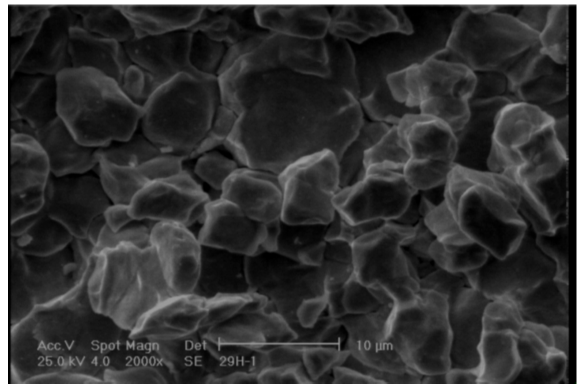

Fig.8: SEM micrograph of the explosive compacted tungsten specimen

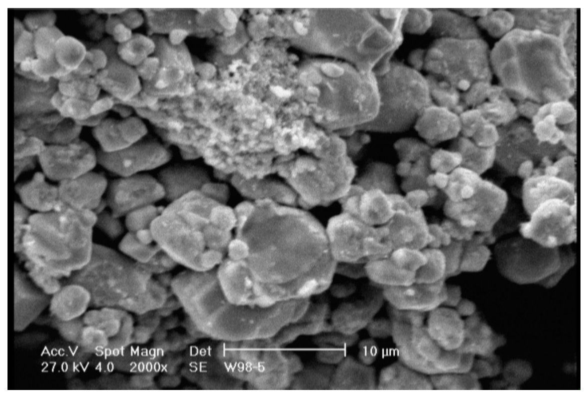

Fig.9: SEM micrograph of the powder metallurgy tungsten specimen

As it was shown in Fig. 8, in the explosive compacted specimen, the low porosity and the high quality bonding between the powder particles is obvious. Figure 9 illustrates large amount of the porosity and unsuccessfully bonding between powder particles. Thus, by comparison Fig. 8 and 9, it can be shown that the high quality specimens can be obtained by the explosive compaction method. Fig. 10 shows a higher magnification of the SEM micrograph for the compacted specimen to clearly indicate the strong bonding obtained by the explosive compaction process.

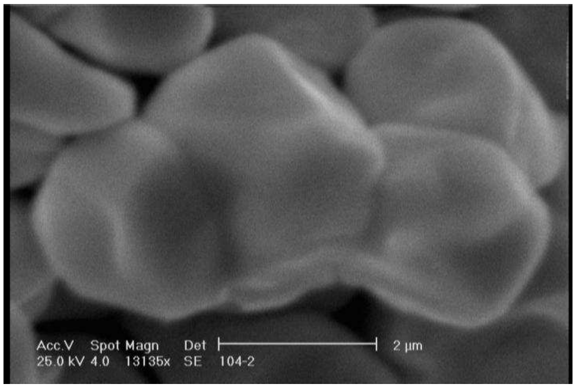

Fig.10: SEM micrograph of the explosive compacted tungsten specimen

A disadvantage that was observed in the explosive compacted sample was the existence of some cracks in the cross sectional area of the specimens. Hokamoto and Raghukandan et al [22-24] reported the usefulness of some method to reduce these cracks that was generated in the explosive compaction process.

5 Conclusions

A system for the explosive compaction of the tungsten powder using shock wave applied for the consolidation of the tungsten powder. The results indicated the usefulness of computer simulation for designing and optimizing the experimental setup. It was found that by using the explosive compaction system it is possible to produce a product with the high hardness (up to 410 Vickers) and the high density (18.5 g/cm^3) as well as high quality. Therefore it can be concluded that for manufacturing a high quality tungsten parts, it is better to apply the compaction method instead of using the conventional powder metallurgy method.

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