Shock Compaction of Tungsten Carbide

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Tungsten carbide powder with 3.5 μ m average particle diameter was shocked by the indirect method to produce a quasi-isentropic plane compression wave normal to the cylinder axis. [1] Recovered specimens showed the evidence of melt and possible evaporation. For the lower temperature specimen, compacted structure possibly sintered through melt was observed and for the high temperature shock specimen newly formed triangular plates were observed.

[tungsten carbide, quasi-isentropic plane compression wave, triangular plate]

1. Introduction

Attempts to make compacted bodies of refractory materials by shock loading methods have been reported to date. [2] Although few successful results have been reported, no commercial product have been developed for the market. Simple trials were to explore the possibility of the industrial use of shock sintered ceramics. Usually, the main causes for the failures in making flawless compacts are considered to be strong supersonic shock waves. In order to avoid flaws in the compacts, subsonic impacts which introduce quasi-isentropic compression wave seemed helpful.

For producing quasi-isentropic plane compression wave normal to the axis of a cylinder in which specimen is enclosed, the following condition should be satisfied;

$$U_s > D \quad (1)$$

where U_s and D are the velocity of the shock wave generated by the impact in the specimen and the detonation velocity of the explosive; (see the arrangement in fig. 1).

For Eq. (1) to be obeyed, it is necessary to give sufficient energy to the specimen which should satisfy the condition expressed by the following equations;

$$E_t > E_j + E_p \quad (2)$$

$$E_j = m_d V_p^4 / (4D^2 + V_p^2) \quad (3)$$

or

$$E_j = m_d V_p^4 / (8D^2 + 2V_p^2) \quad (4)$$

where E_t is the total energy given to the system, E_j is the energy dissipated by jetting caused by a collision of driver tube and specimen tube, E_p is the energy given to the specimen. The mass of the driver tube is m_d , V_p is velocity of the driver tube normal to the axis of specimen tube, and D is the detonation velocity. Equation (3) is used when motions of both driver and specimen tubes

are subsonic and (4) is valid for one of the tubes when it moves at supersonic speed for the other at subsonic speed. Naturally, when the shock was loaded directly by the explosive without a driver tube, E_j is zero.

On the other hand, when the plane wave is loaded normal to the tube axis, the internal energy E_p of the shocked state is expressed by the following equation,

$$E_p = (V_o^* - V)(P + P_o)/2. \quad (5)$$

Where V_o^* represents the initial specific volume of the porous specimen, V expresses the specific volume of the specimen under shocked state, P the pressure attained and P_o is initial pressure before shock loading. Strictly speaking, this equation should be used for shock loaded by jump and not for quasi-isentropic loading, but for the porous specimens, the error is small and there is no problem from using this equation.

The Hugoniot for the porous material is obtained from its crystal density Hugoniot using Eq. (6).

$$P = P_H [1 - (\gamma/V)(V_o - V)/2] / [1 - (\gamma/V)(V_o^* - V)/2] \quad (6)$$

Here, P_H is the pressure on the crystal density material Hugoniot at the volume V , γ is the Grüneisen ratio treated by Eq. (7) and V_o^* is the initial specific volume of the porous material.

$$\gamma_o/V_o = \gamma/V \quad (7)$$

For the case when the shock was loaded indirectly as shown in Fig. 1 by using the driver tube, the speed of the tube normal to the axis will be given by Eq. (8) and (9).

$$V_{pm} = (2E_g)^{1/2} \{ [(1 + 2m_d/m_x)^3 + 1] / \{ 6(1 + m_d/m_x) + m_d/m_x \} \}^{-1/2} \quad (8)$$

$$Y_{px} / (m_d V_{pm}^2) = -\ln(1 - V_p/V_{pm}) - V_p/V_{pm} \quad (9)$$

Here, V_{pm} is the maximum speed of the driven tube, E_g is the Gurney energy which is 0.6 times the explosive energy, m_d is the mass of the driven tube per unit area, m_x is the mass of the explosive per unit area, Y is the

distance of the tube flight from the initial position, P_x is the pressure of the detonation of the explosive, and V_p is the speed of the tube at the distance Y .

By obtaining the speed of the driver tube at the point of collision with the specimen tube, the energy of the impact E_i can easily be calculated by using well-known Law of the conservation of energy.

Assuming the shock velocity U_s is the same as detonation velocity D , it is possible to calculate the energy E_p of the shock with the plane wave geometry normal to the axis by using Eq. (5), (6) and (10).

$$U_s = V_o * [(P + P_o) / (V_o * - V)]^{1/2} \quad (10)$$

When E_i satisfies the condition (2), the shock induced in the specimen can be considered as a quasi-isentropic compression wave with the plane wave geometry normal to the axis.

For the calculation of the temperature, the method explained by McQueen et al. [3] or Kondo and Ahrens [4] could be employed.

2. Experiment

Fig. 1 is a cross sectional view of the shock loading geometry employed. The conditions are shown in Table 1. The pressures and the temperatures were calculated by using the methods explained above.

Fig. 1. Cross sectional view of setup.

Table 1. Experimental Conditions.

	Experiment 1	Experiment 2
Specimen	WC	WC
Mean Grain Size	3.5 μ m	3.5 μ m
Packing Density	40 % to theo.	60 % to theo.
Detonation Velocity	4,300 m/s	4,300 m/s
Loaded Pressure	70 GPa	60 GPa
Calculated Temp.	10,000 K	6,000 K
Collision speed*	2,000 m/s	1,300 m/s

* Normal to the tube axis.

3. Results

Nearly all of the specimen was recovered after shock loading for experiment 2, although for experiment 1 which employed higher pressure and temperature, the recovered specimen was very few. They were cut and examined by SEM, X-ray diffraction, diamond pyramid hardness, pycnometric density, etc. Fig. 2 is a SEM photograph of one of the samples recovered from the lower temperature experiment. It is evident that the surface of the particles was melted to bond to the neighboring particles. For the higher-temperature specimen, as shown in Fig. 3, newly formed triangular particles were found. X-ray diffraction analysis concluded that the phase of the triangular particles is hexagonal.

Fig. 2. SEM photograph of low temperature specimen's polished surface.

Fig. 3. SEM photograph of high temperature specimen.

In spite of the success of the formation of the plane shock wave geometry normal to the detonation axis by the calculation, many fine cracks over the cross section and a hole along the tube axis at the center on the low-

temperature experiment were observed as shown in Fig. 4. This clearly indicates that the shock induced in a specimen was oblique, and the hole was formed by a formation of the Mach axis. For the high temperature experiment, the tube and the specimen were recovered as fragments and could not find that the shock was plane or oblique. In Table 2, the recovery rate of the specimen, pycnometric density and maximum diamond pyramid hardness are shown.

Fig. 4. Cross-sectional view of recovered low-temperature experiment specimen.

Table 2. Experimental results by experiment 1 and 2.

	Experiment 1	Experiment 2
Recovery Rate %	Few	80
Pycnometric Density (% Crystal Density)*	—	14,970 kg/m ³ (98)
Max. DPHN	—	20.89 GPa

* 15,600 kg/m³ as 100%.

4. Discussion

The melting observed at the lower temperature specimen's grain boundary could be explained by the skin model⁴ which indicates the thermal gradients occur along the grain boundaries under the shocked state. For the higher-temperature specimen, formation of the new triangular particles could have occurred through evaporation. This type of formation of new particles was reported by Tobisawa and Yamada [5]. From these results, it may be concluded that the temperature calculation could be used for the rough estimation of the temperatures under the shocked

states for the boiling temperature of tungsten carbide is known as 6,000°C. However, the evidence of the Mach axis proves that the plane wave was not formed, although the condition estimated by the calculation is sufficient for the formation of the plane wave.

This may depend upon because of the error of the flying tube speed calculation. Similarly, the fracture of the tube and specimen of the high-temperature experiment suggests that the formation of the plane wave is also doubtful. But for this case, the formation of triangular crystal could have occurred after the shock pressure was removed and evaporation and recrystallization occurred because of residual temperature and cooling by the burst of the tube. For successful compaction of refractory materials, smooth shock loading should be essentially different from the synthesis of the new materials [6].

From Figure 2, it is evident that the grains are bonded through the melts, although the pores are observed between grain boundaries. For improving the nature of the recovered specimens as a compacted material, the fine adjustment of the loading condition would be necessary for the smooth pressure rise and fall to eliminate cracks and pores through experiments.

Although the experimental focus was compaction, the result suggest possible evaporation, making it conceivable that new materials could be synthesized by chemical reactions through gaseous reactions or coating of surfaces.

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