MANUFACTURING TECHNOLOGY OF CERAMIC MATRIX COMPOSITES USING UNDERWATER SHOCK COMPACTION

Youngkook Kim¹*, Yeonwon Lee²
¹ Shockwave & Condensed Matter Research Center, Kumamoto University, Kumamoto 860-8555, Japan
² Department of Mechanical and Automotive Engineering, Pukyong National University, Busan 608-739, Korea
* Corresponding author (kim@shock.smrc.kumamoto-u.ac.jp)

Abstract

As a fabrication method for ceramics, we introduce an underwater shock compaction technique using a high performance explosive. This technique uses an underwater shock wave generated by detonation of the explosive with a peak shock pressure of about 6 GPa. The underwater shock compaction is very effective to obtain denser ceramics and ceramic matrix composites, and it has unique characteristics such as no grain growth or no phase transition; strong surface bonding between powder particles; and high grain boundary resistivity and lattice defects.

Keywords: Underwater shock compaction, Explosive, Ceramics

1 Introduction

Many sintering methods for ceramics and ceramic matrix composites exist such as conventional hot sintering [1], spark plasma sintering [2], two-step sintering [3] and micro-wave sintering [4]. Underwater shock compaction [5-7] is another fabrication method for ceramics and ceramic matrix composites. This technique is advantageous to obtain fully dense ceramics without grain growth because of the very fast consolidation process within microsecond time scale and high shock pressure, which is generated by detonation of an explosive. Furthermore, this technique can retain the structural characteristics of starting powders and avoid prolonged heating treatments.

In this work, we introduce the underwater shock compaction technique and manufacturing processes of shock-consolidated ceramic bulks using an numerical analysis and real experiments.

2 Experimental set up

An underwater shock compaction device typically consists of an electrical detonator, explosive container, water container, powder container and powder capsule as shown in Fig. 1. A high performance explosive (detonation velocity: 6970 m/s) of about 50 g is charged in the explosive container. The water container is filled with water to create an underwater shock wave, which can be controlled by the height of the water container. First, ceramic powders are filled and pressed in the powder capsule using a uniaxial press machine at 50 Mpa; next, copper (Cu) powders are filled and pressed over the ceramic powders to delay the rapid cooling process and assist in strong surface bonding between powder particles [8]. The green densities of the compressed ceramic powders and Cu powders are about 50 ~ 60 % of each theoretical density. The powder capsule is set in the powder container followed by the water container and finally the explosive container on top. The electric detonator is installed to the top of the high performance explosive.

In this work, a peak shock pressure is tested using a piezofilm stress gauge (PVF2-11,-125-EK, Dyansen, Inc., USA). The stress gauge is set below the water
container and recorded by an oscilloscope measuring device.

To understand the generation and propagation processes of underwater shock wave, a numerical calculation is carried utilizing the LS-DYNA 3D commercial program based on the explicit finite element code.

To understand the generation and propagation processes of underwater shock wave, a numerical calculation is carried utilizing the LS-DYNA 3D commercial program based on the explicit finite element code.

3 Results and discussion

3.1 Numerical simulation

The propagation process of a detonation wave and underwater shock wave is clearly shown in Fig. 2. When the electric detonator is ignited, the detonation wave is generated in the high performance explosive and propagated into the water, where it changes to an underwater shock wave, inducing a rapid and intense deformation of powder particles passing through the powders.

In particular, a reflected wave is simultaneously generated with the underwater shock wave converging at the central position of water container. The converging effect of the reflected wave can induce further high shock pressure [9].

3.2 Shock pressure

In the present compaction system, if the height of the water container is 10 mm, a peak shock pressure of about 6.23 GPa is usually generated, as shown in Fig. 3. The peak shock pressure can be varied by the height of the water container; however, accurately design of water container height is required to obtain a planar shock wave acting on the powders. For numerical calculation, two peak shock pressures at different times are shown. The first peak is the underwater shock wave; the second is the converged reflected wave. Unfortunately, the second peak shock pressure cannot be measured during actual experimentation because the stress gauge is demaged upon compaction.

3.3 Consolidation and characteristics

Figure 4 shows various shock-consolidated ceramics fabricated by this underwater shock compaction technique. The diameters of each material are approximately 15 mm ~ 30 mm with densities of about 96 ~ 99 %. Visible cracks are not apparent on the bulk surface. In fact, cracking is generally a serious problem in shock compaction. Because large-sized cracks are easily generated by
shock energy or tensile stresses [8, 10], proper design of the charging layer of compressed powders in the powder capsule is important. For example, the anatase-structured TiO$_2$ shown in Fig. 4(b) is well-known as a difficult material to sinter at high temperature because of its low-phase transition temperature. However, underwater shock compaction facilitates obtaining anatase-structured TiO$_2$ bulk because of the extremely fast consolidation process by shock energy. Moreover, a sandwich-type materials, such as the ceramic matrix composites and metals shown in Fig. 4(d), are also possible. Figure 4(d) shows sandwich-type YBa$_2$Cu$_3$O$_{7-x}$ bulk and Cu bulk which were completely combined with each other. Thus, underwater shock compaction facilitates ease of obtaining a sandwich-type combined ceramic and metal bulk if the same element is included in each material, ceramic and metal.

One of the main characteristics of shock-consolidated ceramics and ceramic matrix composites is the suppression of grain growth. As mentioned above, the extremely rapid consolidation by shock energy leads to surface bonding between powder particles without grain growth [8], while lattice defects are easily generated in the compacts. Figure 5 shows X-ray diffraction of starting powder and shock-consolidated ZnO bulk with the mixture ratio of 99:0.5:0.5. It is shown that all diffraction peaks of shock-consolidated ZnO bulk are broadened. Also, we can expect that the crystalline size was deformed. Indeed, we confirmed the decreased crystalline size in our previous work [8].

Another feature is that shock-consolidated ceramic bulk has high electric resistivity. This is caused by an increase in grain boundary area. By shock energy, grains are easily broken into smaller-sized grains, so
the grain boundary area naturally increases. Figure 6 shows a Nyquist plot of shock-consolidated ZnOGa₂O₃ bulk with the mixture ratio of 98 : 2. The linear parts are derived from resistivity of electrode, and the semicircles are derived from grain boundary barriers and grain barriers. The quite high grain boundary resistivity of about several hundred MΩ is shown in the plot. Indeed, the shock-consolidated ZnOGa₂O₃ bulk displayed far higher electric resistivity than commercial ZnOGa₂O₃ with almost the same characteristics with as insulating material.

4 Summaries
The underwater shock compaction technique uses an extremely fast and high shock energy generated by an high performance explosive. Therefore, this technique is very effective to fabricate ceramics and inhibit grain growth. Although the cracking problem and lattice defects still exist in the shock-consolidated ceramics, this underwater shock compaction has demonstrated to be a promising method as a new functional ceramic fabrication method.

Acknowledgments
This work was supported in part by the Research Funds of Innovative Collaboration Organization of Kumamoto University in Japan.

References