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Finite element simulation of powder compaction via shock consolidation using gas-gun system

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Abstract

Shock consolidation is a promising method for consolidation of nanocrystalline metallic powders since it can prevent grain growth of nanopowders during the process due to very short processing time. However, internal cracks often occurs in powder compacts during the shock consolidation process. In this paper, finite element simulations showed that reflected tensile wave causes spall phenomena resulting internal crack of powder compaction during shock compaction process. To reduce spall phenomena, FEM simulation with changing compaction die's geometry was performed to find out relationship between shape and tensile wave intensity. Based on FEM results, new compaction die was designed and bulk nanocrystalline Cu are obtained using new compaction die.

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Keywords:Finite element method (FEM); Shock consolidation; Nanocrystalline; Spall

1. Introduction

Bulk ultrafine grained and nanostructured metallic materials are currently attracting great deal of attention from the materials research community due to their unique mechanical and physical properties. Among many methods for manufacturing bulk nanostructured metallic materials, shock consolidation recently draws attention in the

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community since shock wave rapidly solidifies metallic powders without destroying nanostructures of nanocrystalline metallic powders (Gourdin, 1986)

A gas-gun system is one of major methods of shock consolidation. Compared to an explosive method for shock consolidation, the gas-gun system allows the precise control of shock pressure and the observations of the consolidation process. However, internal cracks due to a reflected wave during the shock consolidation process severely damage mechanical properties of metallic bulk workpiece. In order to prevent the internal crack, many researchers, such as Gourdin (1984), Graham et al. (1983), and Korth et al. (1985), suggested optimized designs of compaction dies for the explosive shock consolidation. For the gas-gun shock consolidation process, however, only a few attempts exist. Counihan et al. (1999) suggested 'air gap' for homogeneous shock propagation, but still various designs of the compaction die are used without considering an optimization approach.

In this study, the finite element method (FEM) simulation were performed in order to numerically investigate the relationship between the designs of compaction die and shock propagation behavior. The optimized design of the shock compaction die was suggested based on the FEM results, and various shock compacts of nanocrystalline copper powders using each compaction die were compared for verifying the suggested design.

2. FEM simulation for optimizing shock compaction die

2.1. Background

Two primary factors were considered during the design optimization process. Firstly, shock pressure at the powder surface (incident wave) for complete consolidation was considered. As Meyers (1994) indicated, sufficient incident wave as per powder materials should be provided for complete consolidation. Therefore, it is important to check whether the compaction die produces sufficient incident wave for consolidation or not.

Secondly, reflected wave pressure (reflected wave) in the powders was considered. In general, the shock compaction process is assumed that powders were compacted by '1-dimensional planar shock wave'. However, Thadhani (1993) indicated that actually 2-dimensional shock behavior dominates the shock compaction when a heavy containment was used for safe recovering the powder compacts. Fig. 1 well shows 2-dimensional behavior of shock wave. At 2.4μs (Fig. 1a), the shock wave travels faster in the compaction die than in the powders since shock impedance of the powder is much lower than that of the compaction die. This difference of velocity make shock wave in compaction die surrounds the powder region. At a later instance, shock wave in the powder reaches the rear of the powder and interacts with the surrounded wave (Fig. 1b). This interaction leads to the generation of strong reflected wave (circled region in Fig. 1c) along the lower center of the powder. This reflected wave indicates that the pressure state of powder during shock consolidation is inhomogeneously distributed, which can result in the internal crack. Therefore, the objective for the design optimization should be focused on providing sufficient incident wave and suppressing reflected wave.

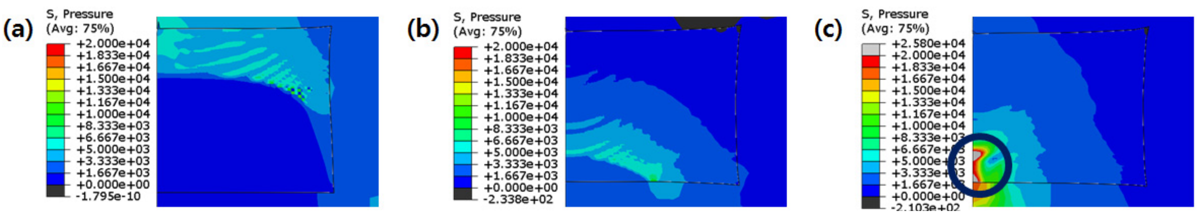

Fig. 1. Pressure distributions during shock compaction after (a) 2.4 μs, (b) 4.1 μs and (c) 4.6 μs.

2.2. Simulation setting

Abaqus/Explicit ver. 6.9 was used for the FEM simulations of the optimizing process. Axisymmetric simulations were performed since the compaction die and projectile have cylindrical shapes. Fig. 2 represents the initial compaction die considering the geometric factors. Table 1 shows the Mie-Grüneisen equation of state parameter of the material used in the FEM simulation. Pre-compacted Cu powders have 10 mm in diameter and 5 mm in height. Initial distances of the top part were 5 mm, side part 35 mm, and bottom part 30 mm in thickness. The method of optimization was performed employing the FEM simulations with varying one of the above distances while two other distances are fixed. For generating the shock wave, a 26 mm diameter and 12.7 mm thickness steel projectile for FEM simulations was the same as the real experimental one. Based on Brown et al. (1989)'s calculation, velocity of a projectile at a lunching pressure of 1300 psi of N_2 gas was 376 m/s.

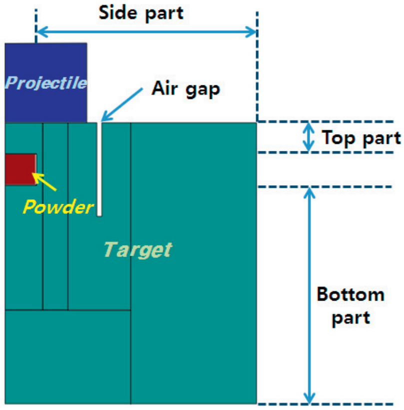

Fig. 2. Initial die shape and considered geometric factor in optimization process.

Table 1. Equation of state parameter used in FEM simulation.

Equation of state parameter	Copper	Steel
Sound speed	4700 m/s	4570 m/s
s	1.49	1.49
Gamma0	2	2.2

2.3. Simulation results

Fig. 3a shows the relation between the thickness of top part and incident wave. Since the shock wave initially propagates though the top part, thickness of the top part is highly related with the total shock energy delivered to powders. Therefore, the intensity of incident wave rises as the top part becomes thinner. However, the thin top part delivers also more shock energy to the surrounding part, which results in a dramatic increase of reflected wave. The thick top part, on the other hand, reduces reflected wave, but incident wave also decreased, which means the top part absorbed excessive shock energy. In this case, danger of incomplete consolidation exists due to the insufficient incident wave. Therefore, maintaining proper thickness of the top part is important. If not, high reflected wave or insufficient incident wave may disturb the shock compaction process.

On the other hand, the FEM results demonstrate that varying the thickness of the bottom part (Fig. 3b) is an efficient way for optimization. When the thickness of the bottom part decreased, the intensity of reflected wave reduces and little reduction of incident wave happens. From the information that the reflected wave occurred by the interaction between surrounding wave and shock wave in powders, it can be concluded that the thin bottom part bothers the interaction by limiting the amount of surrounding wave. This result indicates that preventing the propagation of surrounding wave is important for optimizing the compaction die design.

Fig. 4a well proves the effect of the suppressing surrounding wave. Carving the air-gap on the front surface suppresses most of the reflected wave with a little drop of the incident wave. Both air-gap and thin bottom part decrease the reflected wave in a similar way, but air-gap is more effective since air-gap directly limits the amount of initial surrounding wave. This limitation of the initial surrounding wave also induces shock wave to propagate 1-dimensionally rather than 2-dimensionally. Therefore, the air-gap should be considered in top priority for the optimization process of design not only to reduce reflected wave but also to make the 1-dimensional wave state. It should be noted that 1-dimensional planar wave is the first aim of this research.

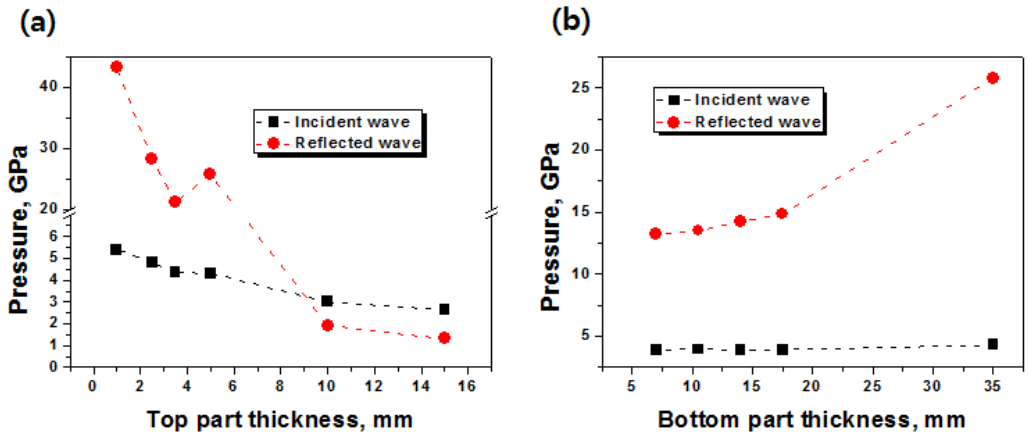

Fig. 3. Shock pressures as a function of (a) top part thickness and (b) bottom part thickness.

A similar effect can also be expected by changing the thickness of the side part. As shown in Fig. 4b, reduced side thickness also reduces the reflected wave by limiting the propagation material. The thick side part also shows decreasing the reflected pressure. In this case, surrounding wave spreads into the thick side parts, resulting in the suppressing of the reflected wave. In conclusion, changing the thickness of the side part can affect the reflected wave, and the air-gap reduces reflected wave efficiently. To sum up, the optimized geometry will provide sufficient shock energy from the proper thickness of top part. It should also be noted that the reflected wave can be minimized by introducing the air-gap and thin bottom part.

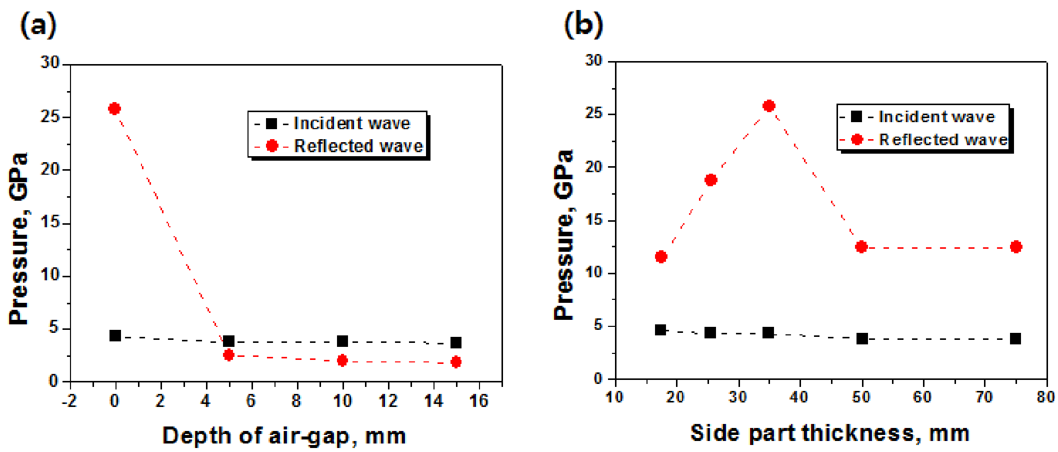

Fig. 4. Shock pressures as a function of (a) air-gap and (b) side part thickness.

3. Test for verifying

3.1. Shock compaction test with new compaction die

The FEM results indicate that suppressing the surrounding shock wave eventually reduces the reflected wave during the shock compaction process. Hence, following the FEM result, a newly designed compaction die was manufactured, see Fig. 5. Compared with the initial compaction die (Fig. 5a), the new compaction die (Fig. 5d) has a thin bottom part and air-gap. Nanocrystalline copper powders were used for verifying the performance of the new die system. Since the oxide surface layer of the copper nanoparticles severely disturbs a bonding between nanoparticles, the nanocrystalline copper powders were hydrogen treated, i.e. reducing surface oxides at 350 °C for 20 minute. After the oxide reduction process, the powders were pre-compacted into a 10 mm diameter and 5 mm height pellet shape. Initial density of the copper powder pellet was 6.251g/cm^3, which is 70% of theoretical maximum density.

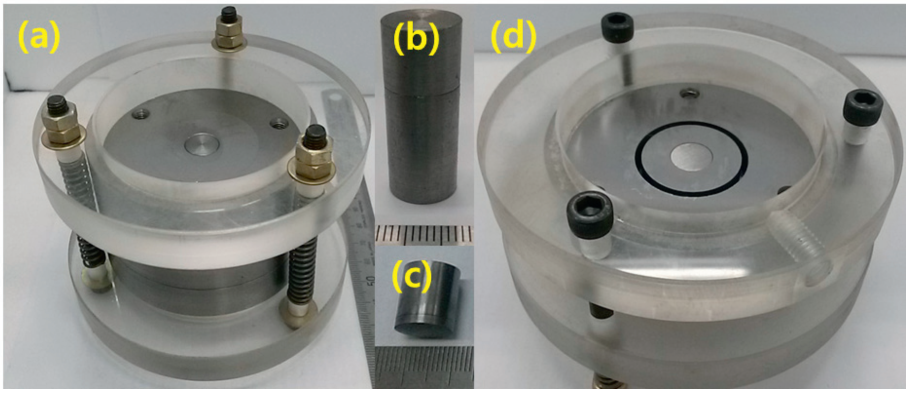

Fig. 4. (a) initial compaction die (b) powder capsule for initial die (c) powder capsule for new compaction die (d) new compaction die.

After pre-compaction, a pellet was placed into a powder capsule (Fig. 5c), and the capsule was inserted into the center of the compaction die. With this fully assembled compaction die, shock consolidation experiment was conducted. Projectile used in this experiment was a 26 mm diameter steel projectile with 40 mm sabot, lunched by high-pressure (1300 psi) N_2 gas. The calculated velocity of projectile was 376 m/s. After shock compaction, the powder compact was recovered from compaction die by cutting the die. Density of recovered sample was measured using the Archimedes method, and hardness of the top surface was measured. After the density and hardness measurements, the results of copper compaction from the new die system (new copper bulk) was compared to that of the copper compaction from the initial die (initial Cu bulk) system, which was compacted at the same condition.

3.2. Test results

Most components of the new compaction die were disintegrated by impact. The recovered powders were split into two pieces by horizontal crack in the middle of the compact, as can be seen in Fig. 6a. This crack shape is different from the 'bowl shape crack' in previous studies, which suggests a possibility of cracking due to the external effect.

Although the recovered compact part was split into two pieces, the density measurement and hardness result shows good compaction behavior of this compaction process. Density of the upper piece was 96.5% of theoretical maximum density and that of the lower piece was 94% of theoretical maximum density, which is a similar result to the compacted initial copper bulk (95.9% of theoretical maximum density). Compared with the initial copper bulk, the hardness of the new copper bulk shows lower hardness than that from the initial die; also shows homogeneous distribution and small error ranges of hardness (Fig. 6b). It seems that the copper powders in the new die were well-compacted by shock wave. However, the new die was made of much less amount of material than that in the initial die system. Therefore, the new die system could not stand the whole impact and was disintegrated. As a result, the copper compact was exposed to external impact, which resulted in the horizontal crack and damaged the powder compact. This explains the high density of the powder compact after the shock and at the same time low hardness and horizontal crack, which is different from the previous results.

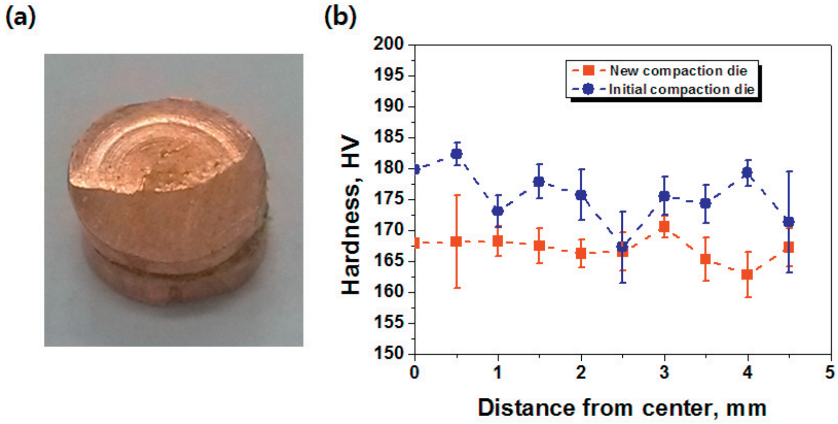

Fig. 5. (a) Recovered New Cu bulk (b) Hardness result compare of Initial Cu bulk and New Cu bulk.

4. Conclusions

In this study, optimization of the shock compaction die via the FEM simulations was performed and verified through experiment. The FEM results shows that suppressing surrounding wave is crucial for reducing reflected wave and generate the 1-dimensional compaction condition. A newly designed compaction die based on the FEM simulation resulted in well compacted nanocrystalline copper powders. Density of the copper powder compact represents little difference with the initial copper bulk. Compared to the initial copper bulk, hardness of the new copper bulk was a little lower but showed homogenous density distribution. Since the new die system could not protect the powder from external impact, horizontal crack divided the new copper bulk into two pieces. In order to prevent this crack, additional shock absorbing system should place into the existing gas-gun system. Considering the properties of the new copper bulk, the newly designed compaction die has a possibility of enhancing material properties of powder compacts and reduces internal crack if a proper shock absorbing system is provided.

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