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# Preparation and properties of Al-$Al_2O_3$ metal ceramics via powder metallurgy methods

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**Metal ceramics are outstanding new engineering materials that offer the advantages of both ceramics and metals. In this study, Al-$Al_2O_3$ metal ceramics were prepared through powder metallurgy methods, and the densification and properties of the prepared metal ceramics were investigated to gain insights into the preparation of high-performance cermet materials. Results revealed that as the forming pressure was increased, the relative density of the ceramics increased, whereas their electrical resistivity decreased. The relative density increased with increasing sintering temperature up to 700 °C and decreased beyond 700 °C, whereas the electrical resistivity exhibited an opposite trend. The relative density increased with increasing Al content, whereas the electrical resistivity displayed an opposite trend. Under optimal technological parameters of 700 °C sintering temperature, < 20 MPa forming pressure, and 75 wt% Al content, Al-$Al_2O_3$ metal ceramics with a high relative density (97.52%) and a low electrical resistivity (101.34 Ω·m) were successfully prepared.**

**Key words: Metal ceramics, Powder metallurgy methods, Alumina, Aluminum.**

## Introduction

Metal ceramics have received considerable attention for many industrial applications in the aerospace, defense, and automobile industries [1-3]. These materials are utilized in automobile brake rotors and various components of internal combustion engines because of their high strength-to-weight ratio. The emergence of aluminum metal matrix composites has led to the development of new advanced materials characterized by light weight, high strength, high specific modulus, low coefficient of thermal expansion, and good wear resistance properties. In addition, the high specific stiffness, superior high temperature, mechanical properties, and excellent oxidation resistance of $Al_2O_3$ have resulted in the fabrication of these advanced engineering materials [4-6].

The production methods of metal ceramics can be categorized into solid phase, liquid phase, and semi-solid fabrication processes. Liquid processes present several advantages, including high production rate, low cost, and the feasibility of producing complex parts. However, the challenge in producing these materials is obtaining the wetting of reinforcement by the liquid metal, which is extremely poor and favored by the strong chemistry bonding at the interface. The poor wetting is due to the presence of an oxide film on the aluminum surface. Wettability is a complex phenomenon determined by various factors, such as interface geometry, process temperature, and soaking time. Wettability regulates the bonding quality among the systems. Ultrasonic dispersion of nano-scaled ceramic particles in molten aluminum has been recently conducted to equably distribute reinforcement particles into the matrix. In addition, the wettability of $Al_2O_3$ particles in molten Al can be improved using various methods, such as utilizing alloying elements to the melt, wrapping the surface of particles through CVD or PVD, making mechanical toss in the melt, applying force on the melt, and controlling the atmosphere. Vortex mixing is another alternative strategy for improving the wettability of particles in contact with molten metal [7-10].

Several articles have investigated the role of different parameters, such as volume fraction and size distribution, during the production of Al-$Al_2O_3$ composites through vortex process [7, 9-10]. However, the effects of using $Al_2O_3$ as an ultra-fine reinforcement on the densification of metal ceramics have yet to be extensively investigated via a low-cost manufacturing technology. In this study, Al powders were coated with $Al_2O_3$ powders via milling, and $Al_2O_3$ powders were distributed into an Al matrix to examine their impacts on the densification and properties of this metal ceramics.

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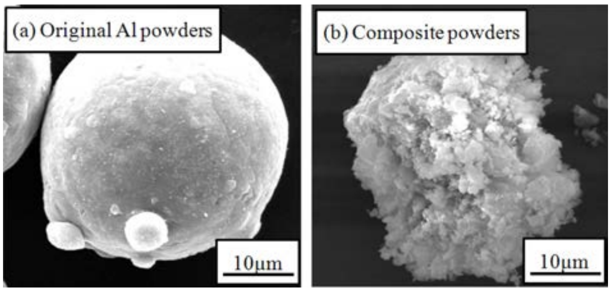


**Fig. 1.** Microstructure of raw materials.

## Experimental Procedure and Materials

The raw materials used in this study included Al (purity, > 99.9%; mean particle size, 40 μm) as the composite matrix and $Al_2O_3$ powder (purity, > 99.9%; mean particle size, 5 μm) as the reinforcement phase. First, $Al_2O_3$ and Al powders were milled with a roller ball mill for 30 h in an alumina jar and with alumina ceramic balls as the ball milling media. To coat Al with $Al_2O_3$, the rotation speed of the alumina jar was set to 200 rpm. The coated composite powders are shown in Fig. 1. The ceramic-balls-to-powder ratio was 5 : 1, and the balls with Ø5 mm were charged. In the forming step, the composite powders were filled into the die (Ø30 × 10 mm). The green body of the metal ceramics was formed through dry pressing. In the sintering step, the green body was sintered in a vacuum sintering furnace to obtain high-density Al-$Al_2O_3$ metal ceramics.

The relative density of the Al-$Al_2O_3$ metal ceramics was determined with a density balance (Model: Sattorius YDK01-C, Germany). The microstructure of the Al-$Al_2O_3$ metal ceramics was observed through scanning electron microscopy (SEM; model: TESCAN VEGA II, Japan). The electrical resistivity of the Al-$Al_2O_3$ metal ceramics was obtained with a DC resistance tester (Model: CHT3540, China).

## Results and Discussion

### Effect of forming pressure on properties of Al-$Al_2O_3$ metal ceramics

Fig. 2 shows the effect of forming pressure on the properties of Al-$Al_2O_3$ metal ceramic composites sintered at 700 °C for 1 hr. The relative density increased and the electrical resistivity decreased with increasing forming pressure. When the forming pressure was less than 20 MPa, the variation tendencies of the relative density and electrical resistivity displayed a wide band and showed a crosscurrent, the relative density was high, the binding degree among the raw material particles was high [11-12], and the conductive network in the structure of the metal ceramics was great; thus, the electrical resistivity decreased with increasing relative density.

Fig. 3 shows the surface of the prepared metal

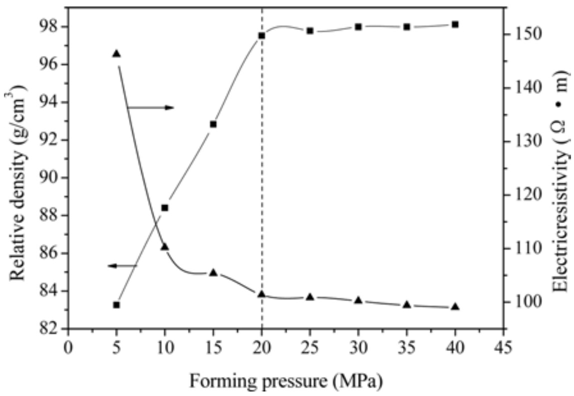


**Fig. 2.** Effect of forming pressure on the properties of Al-$Al_2O_3$ metal ceramics.

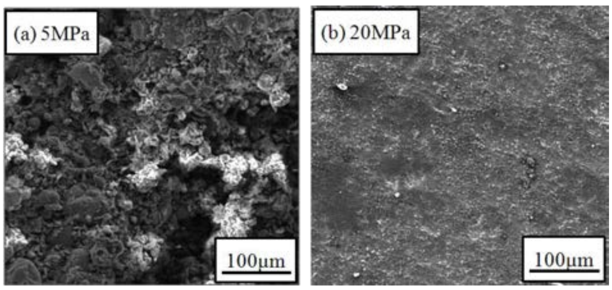


**Fig. 3.** Effect of forming pressure on the surface topography of Al-$Al_2O_3$ metal ceramics.

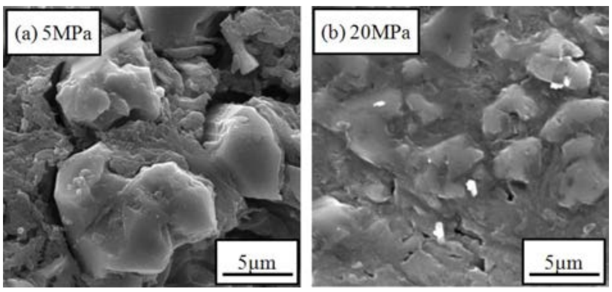


**Fig. 4.** Effect of forming pressure on the microstructure of Al-$Al_2O_3$ metal ceramics.

ceramic composites under different forming pressures, indicating that the surface of the prepared metal ceramics under 5 MPa exhibited a scraggy condition, and the relative density was low. When the forming pressure was 20 MPa, the surface showed a smooth condition, and the relative density was high. At a high forming pressure, the slide distance of the raw material particles was great, and the relative density was high. The relative density was sufficiently high, and the action of the forming pressure for increasing the relative density was weak.

The effects of forming pressure on the microstructure of the Al-$Al_2O_3$ metal ceramics is shown in Fig. 4, indicating that the boundary surface between $Al_2O_3$ and Al formed under 5 MPa showed several large crackles. When the forming pressure was 20 MPa, the boundary surface between $Al_2O_3$ and Al showed a high binding degree. At a low forming pressure, the relative density of the green body of the metal ceramics was low, the green body was sintered in the vacuum sintering furnace, and the spillover effect of the Al phase occurred, which decreased the Al content on the surface of the $Al_2O_3$ particles. The boundary surface bonding force between $Al_2O_3$ and Al decreased; thus, the boundary surface between $Al_2O_3$ and Al formed under 5 MPa showed several large crackles. The Al content in the composites was increased with increasing forming pressure. The boundary surface bonding force between $Al_2O_3$ and Al increased with increasing forming pressure, and the relative density increased.

## Effect of sintering temperature on properties of Al-$Al_2O_3$ metal ceramics

Fig. 5 shows the effects of sintering temperature on the properties of Al-$Al_2O_3$ metal ceramics when the green body of the Al-$Al_2O_3$ metal ceramic composites formed at 20 MPa were sintered at different temperatures for 1 hr. The relative density increased with increasing sintering temperature up to 700 ºC and decreased beyond that, whereas the electrical resistivity displayed an opposite trend. Given that the melting point of the Al phase was 660.4 ºC, the composites sintered at 700 ºC had a high relative density. When the sintering temperature reached the melting point, the inside of the composites showed increased liquid content, which filled into the pores and cracks [13-15]. As the liquid came in contact with the raw material particles (Fig. 6(a)), the electrical resistivity decreased. When the composites were sintered at 800 ºC, the inside of the composites showed increased liquid phase. The liquid Al phase overflowed to the outside surface of the composites (Fig. 7(b)). The content inside the Al phase was insufficient to fill the pores and cracks (Fig. 6(b)). As such, the composites achieved a low relative density.

## Effect of Al content on properties of Al-$Al_2O_3$ metal ceramics

The effects of Al content on the properties of the Al-$Al_2O_3$ metal ceramics is shown in Fig. 8. As shown, the relative density increased with increasing Al content, whereas the electrical resistivity showed an opposite trend. The liquid phase was greater in the sintering process because the Al content was higher. As such, the Al phase easily formed a continuous grain boundary phase on the surface of $Al_2O_3$ as the reinforced phase (Fig. 9(a)). The relative density was very high, and the electrical resistivity of the Al phase was $2.94 \times 10^{-8}$ $\Omega \cdot m$, which consequently decreased the electrical resistivity of the composites. The Al content decreased, the liquid phase was scattered, and the composite was difficult to sinter for densification. The effects of Al content on the microstructure of the composites is shown in Fig. 9.

Under optimal preparation parameters of 700 ºC

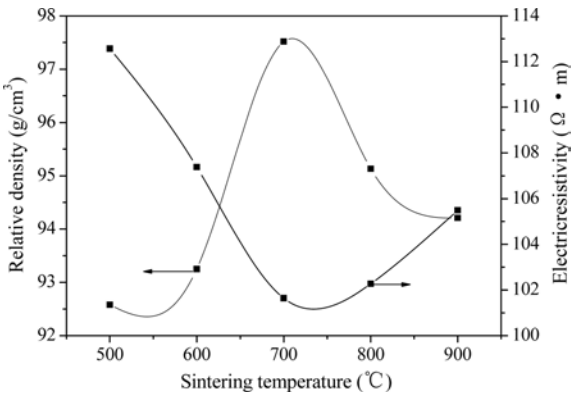


**Fig. 5.** Effect of sintering temperature on the properties of Al-$Al_2O_3$ metal ceramics

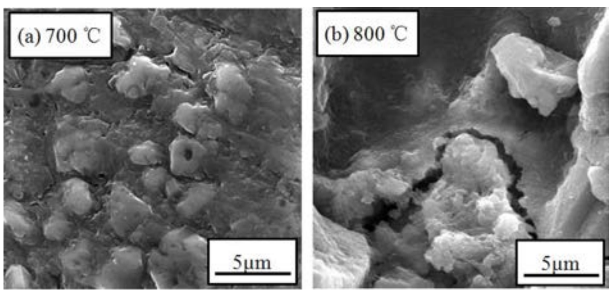


**Fig. 6.** Microstructure of Al-$Al_2O_3$ metal ceramics sintered at different temperatures.

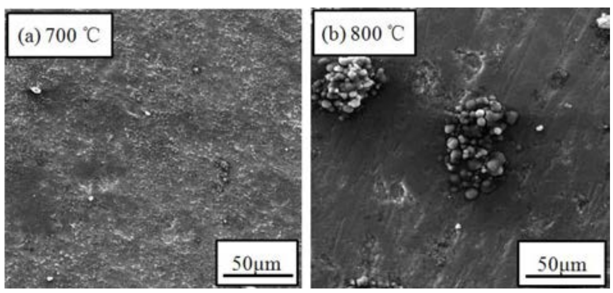


**Fig. 7.** Surface topography of Al-$Al_2O_3$ metal ceramics sintered at different temperatures.

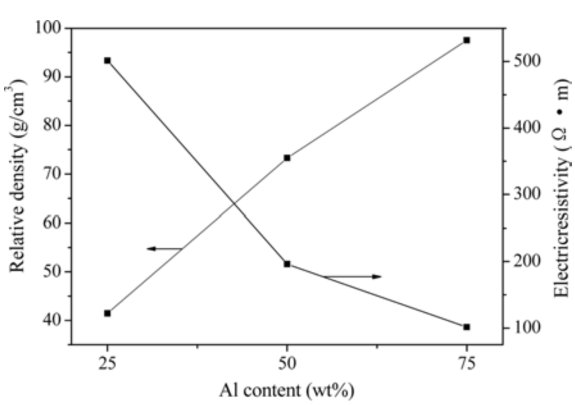


**Fig. 8.** Effect of Al content on the properties of Al-Al2O3 metal ceramics.

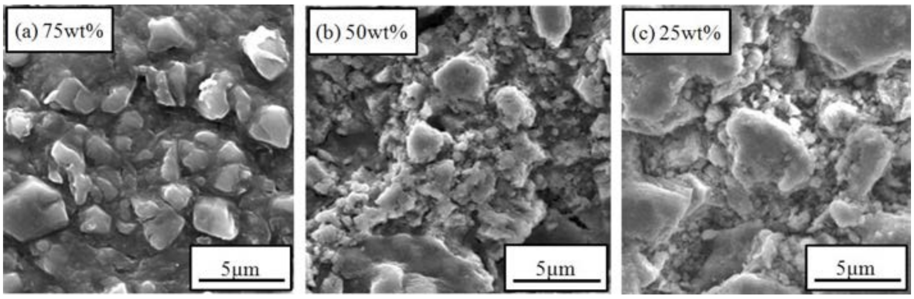


**Fig. 9.** Effect of Al content on the microstructure of $Al\text{-}Al_2O_3$ metal ceramics.

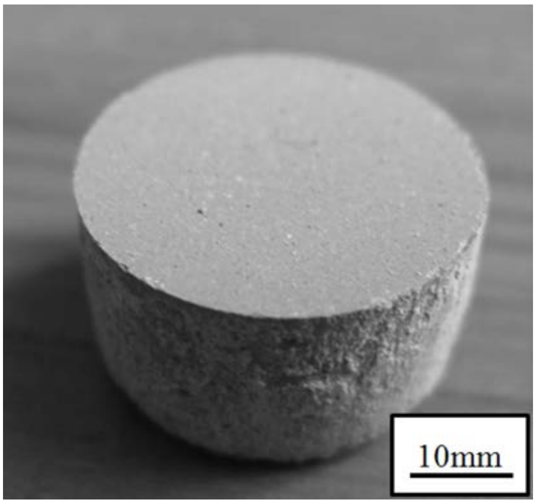


**Fig. 10.** Topography of the prepared $Al\text{-}Al_2O_3$ metal ceramics after design optimization.

sintering temperature, < 20 MPa forming pressure, and 75 wt% Al content, a composite with a high relative density and a low electrical resistivity was successfully prepared. The outside drawing is shown in Fig. 10. The relative density was 97.52%, and the electrical resistivity was 101.34 Ω·m.

## Conclusions

With increasing forming pressure, the relative density of the $Al\text{-}Al_2O_3$ metal ceramics increased, and the electrical resistivity decreased. The relative density increased with increasing sinterings temperature up to 700 ºC and decreased beyond 700 ºC, whereas the electrical resistivity exhibited an opposite trend. The relative density increased with increasing Al content, whereas the electrical resistivity displayed an opposite trend. Under optimal preparation parameters of 700 ºC sintering temperature, < 20 MPa forming pressure, and 75 wt% Al content, $Al\text{-}Al_2O_3$ metal ceramics with a high relative density (97.52%) and a low electrical resistivity (101.34 Ω·m) were successfully prepared.

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