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MAGNETIC PULSED COMPACTION AND PRESSURELESS SINTERING OF ALUMINUM MATRIX COMPOSITE REINFORCED BY TiC PARTICLES

This study investigated the effects of magnetic pulsed compaction pressure and pressureless sintering conditions on the microstructure and mechanical properties of aluminum matrix composites. Al-10 vol.% TiC composites were fabricated using magnetic pulsed compaction under two different pressures (1.5 GPa and 3 GPa), followed by pressureless sintering under three conditions: 500°C for 2 h, 600°C for 1 h, and 600°C for 2 h. Phase analysis, density, microstructural characterization, and hardness measurements were conducted to evaluate and compare the properties of the fabricated specimens. The results showed that no new phases were formed during the sintering process in any of the specimens, and no significant differences in microstructure were observed. Specimens compacted at 3 GPa exhibited higher green density than those compacted at 1.5 GPa, and the relative density increased with higher sintering temperature and longer holding time. The hardness of the specimens showed a trend similar to that of density, with the specimen compacted at 3 GPa and sintered at 600°C for 2 h exhibiting the highest density and hardness.

Keywords: Aluminum Matrix Composite; Titanium carbide; Magnetic Pulsed Compaction; Pressureless Sintering

1. Introduction

Metal matrix composites (MMCs) consist of various metals or alloys as the matrix combined with ceramic reinforcements such as oxides, carbides, and nitrides, resulting in superior strength, stiffness, and fracture toughness compared to monolithic metals. Aluminum (Al), in particular, is widely used as a lightweight structural material due to its low density, high ductility, excellent corrosion resistance, and superior thermal and electrical conductivity. Aluminum matrix composites (AMCs) reinforced with ceramic particles exhibit significantly improved strength and creep resistance compared to pure Al. Among various reinforcements, carbide particles such as NbC, WC, and TiC are especially effective in enhancing wear resistance and thermal stability [1-3].

In previous studies, carbides have been incorporated into Al matrix using fabrication routes such as stir casting. However, these approaches often suffer from inherent limitations, including non-uniform reinforcement distribution, particle clustering, and porosity formation. To overcome these issues, powder metallurgy (PM) processes have been adopted, offering advantages in microstructural control and uniform dispersion of reinforcements. Conventional PM compaction techniques, such as extrusion and cold isostatic pressing, rely on static compaction. Nevertheless, these methods frequently result in non-uniform stress transmission between powder particles, leading to crack initiation or fracture during compaction and limiting the achievable green density [4].

To address these challenges, the present study employs magnetic pulsed compaction (MPC), a high-velocity compaction technique, for the fabrication of AMCs. MPC utilizes an intense, transient electromagnetic field to generate magnetic forces that compact powders at ultra-high speeds. The compaction process occurs within microsecond to millisecond timescales, during which high-velocity impact loads are imparted to the powder compact. The large initial pressure generates stress waves at the surface of the compact, which propagate through the powder bed and induce particle rearrangement, thereby promoting densification and microstructural homogenization. In addition, the extremely short contact time between the die and the compact reduces die wear, while the penetration of shock waves into the particle interior minimizes internal defects. Owing to

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its high ductility, the Al matrix is particularly well suited for high-velocity impact compaction, as it can undergo plastic deformation without crack formation, facilitating the formation of a homogeneous microstructure [5,6].

In this study, Al matrix composites reinforced with 10 vol.% TiC were fabricated using MPC. The green compacts were subsequently sintered under an argon (Ar) atmosphere. The effects of compaction pressure and sintering conditions on the microstructure, density, and hardness of the composites were systematically investigated.

2. Materials and methods

2.1. Powder preparation

Al powder (99.9% purity, average particle size of 5 μm, Avention) and TiC powder (99.5% purity, average particle size of 2 μm, Avention) were used as the starting materials for the fabrication of Al-TiC composites. The Al and TiC powders were weighed to obtain a composition of Al-10 vol.% TiC and then loaded into a 3D shaker mixer (NeoNFL). The powders were mixed at a rotational speed of 70 rpm for 10 h to produce a homogeneous powder mixture.

2.2. Compaction and sintering

The mixed powders were compacted using magnetic pulsed compaction (MPC; Nano Technology Inc., NTI-10M) in a cylindrical die with an inner diameter of 10 mm. For each specimen, 1.148 g of powder was loaded to produce cylindrical green compacts. The compaction pressure was varied between 1.5 GPa and 3 GPa. The fabricated green compacts were subsequently pressurelessly sintered under an argon (Ar) atmosphere at 500°C for 2 h, 600°C for 1 h, and 600°C for 2 h.

TABLE 1

Sample identification of fabrication process

Specimens	Compaction pressure	Sintering
S1	1.5 GPa	500°C for 2 h
S2	3 GPa	500°C for 2 h
S3	3 GPa	600°C for 1 h
S4	3 GPa	600°C for 2 h

2.3. Analysis

The density of the green compacts was calculated from their measured mass and volume, while the density of the sintered specimens was determined using the Archimedes method, and the reported values represent the average of multiple measurements. Phase analysis of the sintered specimens was carried out using an X-ray diffractometer (XRD; MiniFlex 600, Rigaku) equipped with a Cu target over a 2θ range of 10-90°.

Surface morphology and microstructural observations were performed using a scanning electron microscope (SEM; EVO 10, Carl Zeiss) and a field emission scanning electron microscope (FE-SEM; IT-800SHL, JEOL Ltd.). Hardness measurements were conducted using a micro-Vickers hardness tester (FM-700, Future-Tech) with an applied load of 500 gf and a dwell time of 10 s. For each specimen, hardness was measured ten times, and the average value was reported.

3. Results and discussion

Fig. 1 shows the XRD patterns of the pressureless sintered specimens. The results confirm that no secondary phases were formed during the sintering process. Previous studies have reported that reaction products in the Al-TiC system are typically formed when samples are held at temperatures above approximately 650°C for tens to hundreds of hours [7-11]. Therefore, the absence of secondary phases in the present study can be attributed to the fact that the applied sintering conditions did not reach such reaction regimes. Fig. 2 presents the surface microstructures of the sintered specimens observed using Back Scattered Electron (BSE) mode in SEM. To examine the effect of compaction pressure on the microstructure, specimens sintered at 500°C for 2 h were compared. The specimen compacted at 1.5 GPa exhibited relatively larger residual pores compared to the specimen compacted at 3 GPa. This behavior can be explained by the increased plastic deformation at particle contact points in ductile metal powders such as Al under higher compaction pressure, which leads to a reduction in porosity. Furthermore, microstructural analysis of specimens compacted at 3 GPa and sintered under different conditions revealed that the pore size gradually decreased with increasing sintering temperature and holding time, resulting in a more densely packed microstructure. This densification behavior is attributed to the enhanced diffusion activity of the Al matrix at elevated temperatures and extended sintering durations. Fig. 2(e) shows a high-magnification (12 k×) FE-SEM BSE image of the interface between the TiC particles

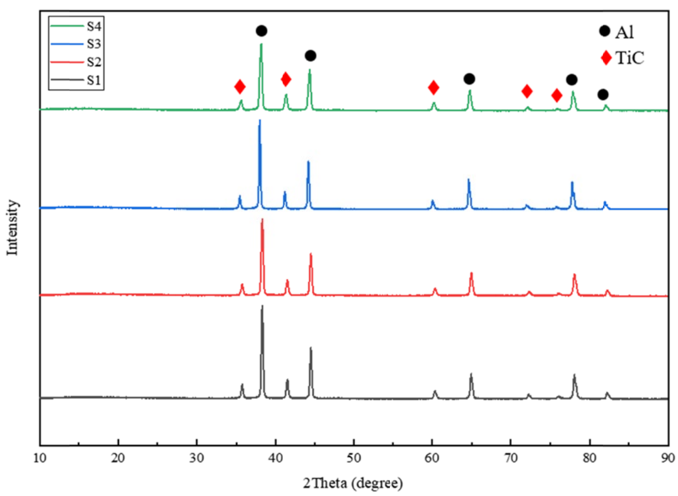

Fig. 1. XRD patterns of S1-S4 specimens

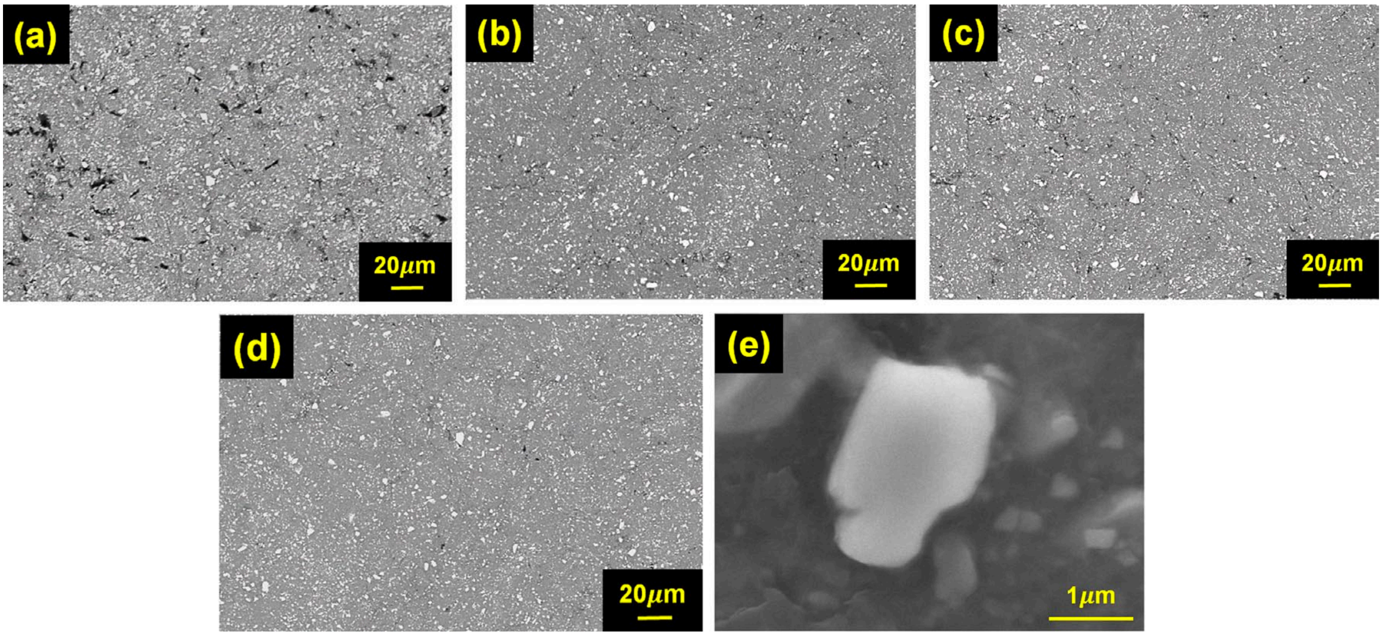

Fig. 2. SEM images (BSE mode) of (a) S1, (b) S2, (c) S3, and (d) S4, illustrating the reduction in pore size and porosity. (e) High-magnification (12 k×) FE-SEM BSE image of the interface between the TiC particles and the Al matrix

and the Al matrix. It can be observed that the interfacial bonding between the Al matrix and the TiC particles is well established, and no secondary phases are detected at the interface.

Fig. 3 shows the relative densities of the fabricated specimens and the hardness values of the fabricated green compacts and sintered specimens. The relative density of the green compacts increased with increasing compaction pressure: the specimen compacted at 1.5 GPa exhibited a relative density of approximately 87%, whereas the specimen compacted at 3 GPa showed a higher relative density of about 93%. This increase

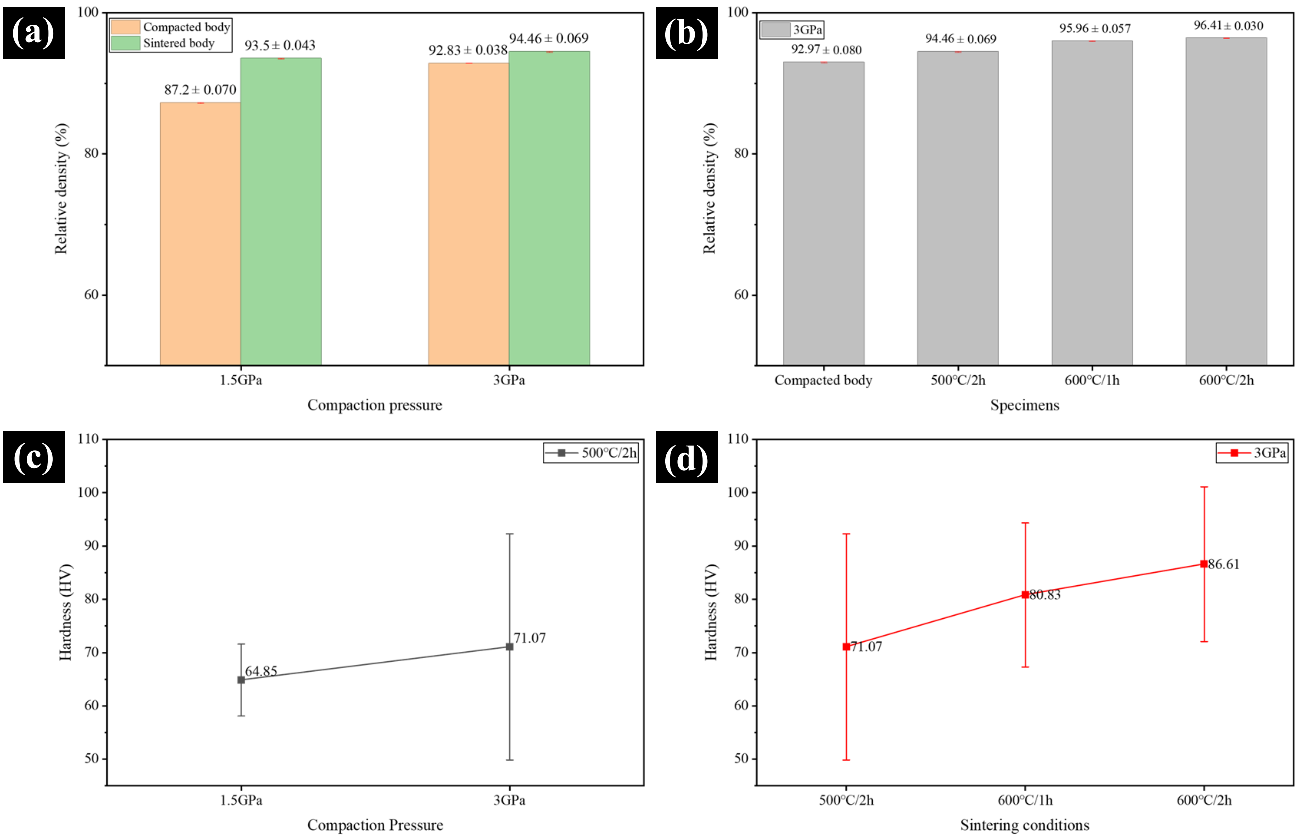

Fig. 3. Relative density of (a) the green compacts and sintered specimens, and (b) the green compacts and the sintered specimens fabricated under a compaction pressure of 3 GPa. Hardness comparison of sintered specimens: (c) S1 and S2 specimens with different compaction pressure, and (d) S2, S3, and S4 specimens with different sintering conditions

in density is attributed to the reduction of residual porosity with increasing compaction pressure. The green compacts were subsequently sintered at 500°C for 2 h under identical conditions to produce specimens S1 and S2. As a result, S1 and S2 exhibited relative densities of 93.51% and 94.46%, respectively, with S2 showing a higher density. This result indicates that the initial compaction pressure significantly influences the final densities of the sintered specimens. Additionally, comparison of specimens S2-S4, which were all compacted at 3 GPa, revealed that the densities of the sintered specimens increased with increasing sintering temperature and holding time. This trend suggests enhanced densification of the specimens under higher sintering temperatures and longer sintering durations.

The hardness of each specimen exhibited a trend similar to that of the density. This indicates that the reduction of residual porosity due to densification contributed to the improvement in hardness. The micro-Vickers hardness of a pure Al specimen compacted at 500 MPa was measured to be 67.8 HV. However, after sintering, the hardness of pure Al tended to decrease, which is believed to be due to grain growth. Specifically, the hardness values were approximately 31 HV after sintering at 500°C for 75 min, 39 HV after sintering at 600°C for 1 h, and 26 HV after sintering at 600°C for 75 min [12].

In contrast, the Al matrix composites reinforced with 10 vol.% TiC exhibited more than twice the hardness of the pure Al specimens. This significant improvement in hardness can be attributed to the dispersion strengthening effect of uniformly distributed TiC particles and load transfer mechanisms. Furthermore, the mismatch in coefficients of thermal expansion (CTE) between the matrix and the reinforcement induces substantial thermal strain during cooling. This strain is relieved by the generation of a high density of dislocations at the interface, which effectively inhibits plastic deformation and leads to strengthening. When the composite is subjected to an external load, the non-deformable TiC particles, which possess a higher stiffness than the Al matrix, bear a considerable portion of the applied load through interfacial shear load transfer. This behavior implies strong interfacial bonding between the matrix and the reinforcement, thereby enhancing the load-bearing capacity and overall mechanical performance of the composite. In addition, plastic deformation in metallic materials occurs through the motion of dislocations, and finely dispersed TiC particles act as obstacles to dislocation movement. Consequently, uniformly distributed fine TiC particles induce the Orowan looping mechanism, which further impedes dislocation motion and contributes to strength enhancement. The coefficient of thermal expansion (CTE) of Al is approximately 23.6×10^{-6} K^{-1}, whereas that of TiC is about 7.6×10^{-6} K^{-1}. During cooling from the high-temperature sintering state, the CTE mismatch between the Al matrix and the TiC particles generates thermal mismatch strains near the interfaces. These strains lead to a significant increase in dislocation density in the interfacial regions, resulting in localized strain hardening, which ultimately enhances the overall strength and hardness of the composites.

4. Conclusion

Al-TiC composites were fabricated by magnetic pulsed compaction (MPC) under two different compaction pressures, followed by sintering under three different conditions. Specimens with different compaction pressures under identical sintering conditions, as well as specimens with different sintering conditions under the same compaction pressure, were prepared. Based on the evaluation of the microstructure and mechanical properties of the fabricated specimens, the following conclusions were drawn:

1. XRD pattern analysis and SEM observations revealed that TiC particles were uniformly distributed within the Al matrix in all specimens, and no secondary phases or interfacial reactions were detected. In contrast, differences in residual porosity were observed depending on the compaction pressure and sintering conditions. Specimens compacted at 1.5 GPa exhibited larger and more numerous residual pores compared to those compacted at 3 GPa. Among the specimens compacted at 3 GPa, an increase in sintering temperature and holding time resulted in smaller and fewer residual pores.
2. Comparison of the densities of the sintered specimens showed that, under identical sintering conditions of 500°C for 2 h, the specimen compacted at 3 GPa (S2) exhibited a higher density than that compacted at 1.5 GPa (S1). For specimens compacted at 3 GPa and sintered under different conditions, the density increased in the order of S2 < S3 < S4.
3. The hardness exhibited a trend similar to that of the density. Specimens with higher density showed higher hardness, and under the same compaction pressure, hardness increased with increasing sintering temperature and holding time.
4. The specimen compacted at 3 GPa and sintered at 600°C for 2 h exhibited the highest density and hardness among all fabricated specimens.

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