

Study of Aluminum Matrix Metal Composite Reinforced with SiC Particles Fabricated by Powder Metallurgy Method

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Abstract

In this study, an aluminum matrix composite reinforced with silicon carbide (SiC) particles was fabricated via the powder metallurgy route, and the effects of three key parameters namely reinforcement content (0, 0.5, 1, 2, and 4 wt. %), compaction pressure (127, 140, 155, and 183 MPa), and sintering temperature (470, 500, 550, and 600 °C) on the microstructure and tensile strength were systematically evaluated. The experimental design was established using the Taguchi method. The results revealed that increasing the SiC content up to an optimum level (approximately 1wt. %) enhanced strength and reduced porosity; however, excessive SiC content (especially 4 wt. %) led to particle agglomeration and stress concentration, which promoted pore growth and significantly deteriorated the mechanical properties. Moreover, raising the sintering temperature within the studied range (from 470 to 600 °C) decreased the number of pores but increased their size, resulting in a higher overall porosity. The optimal combination of processing parameters (1wt.% SiC, 155MPa compaction pressure, and 600°C sintering temperature) yielded the best mechanical performance, exhibiting higher tensile strength (approximately 77MPa) while maintaining acceptable ductility compared with other samples. Microstructural analyses confirmed that precise control of reinforcement fraction, compaction pressure, and sintering temperature is crucial for achieving high densification and a uniform microstructure.

Keywords: Powder Metallurgy, Metal Matrix Composite, Aluminum, SiC.

1. Introduction

Powder metallurgy (PM) is a manufacturing process involving powder production, mixing, compaction, and sintering to produce metallic or composite components with desired properties. This process offers several advantages, including uniform distribution of reinforcement phases, precise control of chemical composition and microstructure, material and energy savings, particularly for alloys that are difficult or expensive to machine, and the capability to produce near-net-shape components with complex geometries without extensive casting or machining operations. These advantages make PM an attractive route for fabricating aluminum matrix composites (AMCs). Owing to its low density, high strength to weight ratio, and favorable thermal conductivity, aluminum is widely used in aerospace, automotive, and electronic applications. The addition of ceramic reinforcements such as silicon carbide (SiC) significantly improves hardness, wear resistance, and thermal stability while adding little weight, making Al-SiC composites suitable for structural and tribological applications. Nevertheless, the fabrication of Al-SiC composites by PM is

associated with several challenges, including poor wettability between SiC and aluminum during sintering, the presence of a native oxide layer (Al_2O_3) on aluminum particles that hinders metallurgical bonding, and the possible formation of brittle interfacial phases such as Al_4C_3 at elevated temperatures. These factors highlight the importance of careful control of processing parameters.

Extensive research has been conducted on PM fabricated aluminum matrix composites. Dilshad et al. [1] demonstrated that sintering temperature, sintering time, compaction pressure, and powder composition play important roles in determining the density, hardness, and wear resistance of aluminum matrix composites. Vani et al. [2] reported that reinforcement fraction, particle size, milling conditions, and sintering parameters significantly influence particle distribution and the resulting mechanical properties. Sadehi et al. [3] showed that improved densification through optimized sintering enhances hardness, wear resistance, and corrosion performance. Furthermore, comprehensive review studies by Singh [4] and Kumar et al. [5] emphasized that processing parameters, particularly compaction

pressure and sintering conditions, are critical factors governing densification, porosity, and the final properties of *Al–SiC* composites.

Although previous studies have mainly focused on the effects of reinforcement type and content, PM processing parameters, and microstructure on mechanical and tribological properties, comprehensive investigations into the simultaneous effects of reinforcement fraction, compaction pressure, and sintering temperature remain limited. In particular, the combined influence of these parameters on quantitative porosity characteristics, including pore count, average pore size, and pore density, together with tensile properties, has received relatively little attention. Therefore, the present study aims to evaluate the simultaneous effects of *SiC* weight fraction (0–4 wt.%), compaction pressure (127–183 MPa), and sintering temperature (470–600 °C) on the microstructure and mechanical properties of *Al–SiC* composites using the Taguchi design of experiments and analysis of variance (ANOVA) to determine the relative contribution of each processing parameter and identify the optimum processing conditions.

2. Experimental Procedure

The matrix material was pure aluminum powder (99.5% purity, mean particle size 45 μm , spherical morphology). *SiC* reinforcing particles (99% purity, mean size 20 μm) were added at the specified weight fractions. To improve wettability and disrupt the surface oxide film on the aluminum particles, magnesium powder (*Mg*, 99% purity, mean size 50 μm) was added at a constant level of 1wt.% to all samples. Magnesium acts as a reducing agent, breaking the Al_2O_3 layer and forming intermediate phases (such as MgAl_2O_4 and MgO) that provide a clean interface for metallurgical bonding; it also reduces the contact angle between molten aluminum and *SiC* during liquid-phase sintering, thereby enhancing interfacial adhesion and load transfer. In the preliminary stage, samples fabricated at sintering temperatures below and above the eutectic point, with *SiC* contents exceeding 4wt.%, and compaction pressures below 127MPa exhibited unacceptable quality due to excessive porosity and insufficient strength. These observations served as the basis for defining the optimal parameter ranges for the main experiments, and images of several substandard samples from these initial trials are presented in Fig. 1.

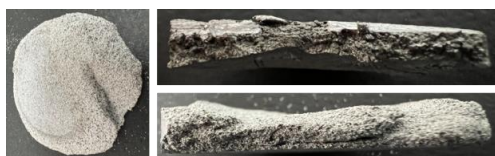


Figure 1. Images of the initially fabricated specimens with unacceptable quality.

For the main experiments, the powders were milled and blended for 60 min in a ball mill at 200 rpm with a ball to powder weight ratio of 10:1 to achieve homogeneous dispersion of *SiC* particles within the aluminum matrix and to prevent agglomeration. The homogenized powder mixtures were then uniaxial cold pressed in a hardened steel die using a hydraulic press (capacity up to 215MPa) at the designated compaction pressures. The loading rate and dwell time at maximum pressure (30 s) were kept constant for all specimens. The green compacts were sintered in an electric tube furnace under a continuous flow of high-purity argon (99.99%, flow rate 1L/min) with a controlled thermal cycle: heating from room temperature to the set temperature (470, 500, 550, or 600 °C) at 10°C/min, holding for 60min at the sintering temperature, and then controlled cooling at 5°C/min to 150°C, followed by furnace cooling to ambient temperature under argon atmosphere.

Cylindrical specimens with a diameter of 10mm and thickness of 8mm were produced; tensile test mini-specimens were prepared by wire electrical discharge machining according to ASTM E8 standard, and metallographic examination was performed per ASTM E7. The experimental design followed a modified L16 orthogonal array (with 17 runs; sample specifications are given in Table 1). The measured responses were ultimate tensile strength and elongation to failure. Data analysis was carried out using Minitab software and analysis of variance (ANOVA).

Table 1. Fabrication parameters of the prepared specimens.

Sample No.	Sintering Temperature (°C)	<i>SiC</i> (%wt)	Compaction Pressure (MPa)
1	470	0	127
2	470	2	170
3	500	0	127
4	500	0.5	140
5	500	1	155
6	500	2	170
7	500	4	183
8	550	0	127
9	550	0.5	140
10	550	1	155
11	550	2	170
12	550	4	13
13	600	0	183
14	600	0.5	140
15	600	1	155
16	600	2	170
17	600	4	183

3. Results and Discussion

The tensile test results for all fabricated samples are shown in Fig. 2, while the ultimate tensile strength and elongation values are presented in Figs. 3(a) and 3(b), respectively. The best mechanical performance was obtained for Sample No. 15, which had 1wt.% *SiC*, a compaction pressure of 155MPa, and a sintering temperature of 600°C; this sample exhibited an ultimate tensile strength of approximately 77.4MPa. ANOVA results based on the Taguchi

method (Table 2) indicate that SiC weight fraction is the most influential parameter affecting tensile strength, with an F- value of 24.15 and a P- value<0.001, contributing 43.2% to the variation in strength. Sintering temperature also showed a highly significant effect (F- value=28.41, P- value<0.001), with a contribution of 38.5%. In contrast, compaction pressure had the smallest effect (F- value=3.86, P- value=0.0395), contributing only 6.8% to the tensile strength variation.

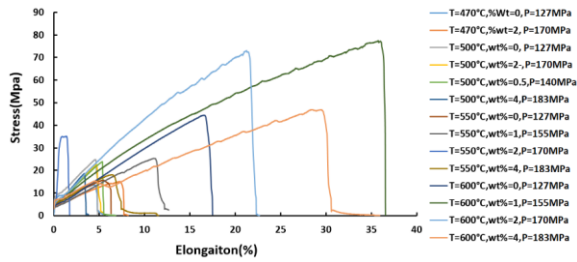


Figure 2. Tensile test results of the fabricated specimens.

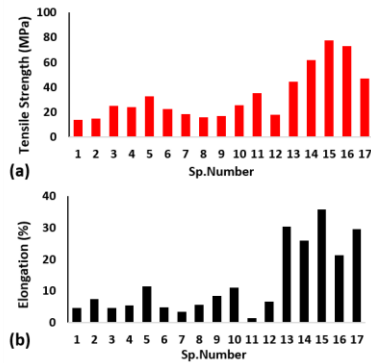


Figure 3. Tensile test results: (a) tensile strength and (b) elongation at fracture of the specimens.

The results further revealed a nonlinear influence of SiC content on mechanical properties: increasing the SiC fraction up to the optimal level (approximately 1wt.%) enhanced strength and reduced porosity, whereas further addition (especially to 4wt.%) led to particle agglomeration, stress concentration, and pore growth, resulting in a sharp deterioration of mechanical properties. On average, increasing SiC from 1 to 4wt.% reduced the tensile strength by 39%. Regarding thermal effects, raising the sintering temperature from 470 to 550°C decreased the number of pores by about 45%; however, a further increase to 600°C increased the average pore size (by roughly 93%) and consequently raised the total porosity from 3.1% to 8.2%. Increasing the compaction pressure from 127 to 183MPa reduced the total porosity by 27%, but this effect became less pronounced at higher temperatures (600°C) owing to matrix softening and pore coarsening.

For quantitative microstructural evaluation, metallographic images were analyzed to extract porosity parameters, including pore count, total pore area, average pore size (calculated using Eq. (1)), and pore density (calculated using Eq. (2)). The results of

these quantitative measurements are presented in Fig. 4.

$$\text{Average pore size} = \frac{\text{Total pore area}}{\text{Number of pores}} \quad (1)$$

$$\text{Pore density} = \frac{\text{Number of pores}}{\text{Total image area}} \quad (2)$$

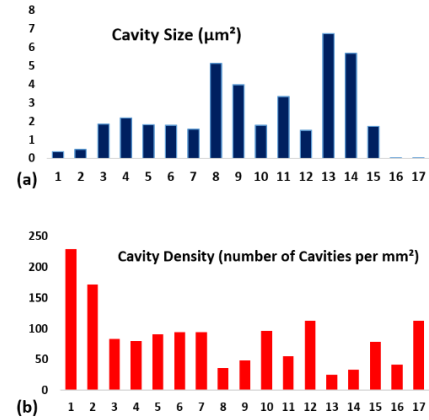


Figure 4. Metallographic analysis results: (a) average pore size and (b) pore density.

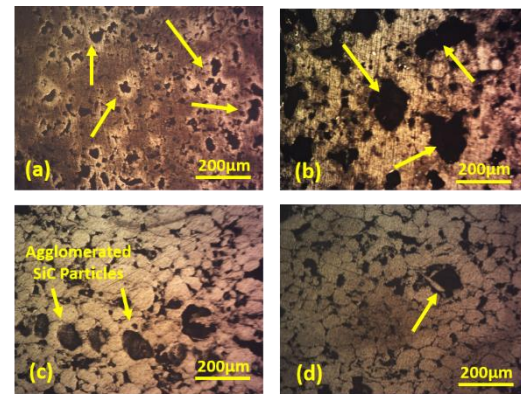


Figure 5. Microstructures of the fabricated specimens, showing the pores formed during fabrication (highlighted in the images): (a) 470°C–170MPa–2%wt, (b) 600°C–155MPa–1%wt, (c) 550°C–183MPa–4%wt, and (d) 550°C–155MPa–1%wt

Statistical analysis confirmed that sintering temperature is the dominant factor controlling porosity characteristics, accounting for over 60% of the variation in pore count, average pore size, and pore density. Correlation analysis between porosity features and tensile strength revealed that pore density exhibits a stronger negative correlation with strength than average pore size. Specifically, when pore density decreased from 229 to 25 pores/mm², the tensile strength increased from 13.6 to 44.5MPa. The optimal sample (with a strength of 77.4MPa) had pore density of 79 pores/mm² and an average pore size of 1.73μm². These findings confirm that achieving a microstructure with fewer pores is the key and most effective strategy for improving mechanical performance. Fig. 5 displays the microstructures of two representative samples (panels a, b, c, and d),

clearly highlighting the differences in pore distribution, size, and density between specimens with desirable and undesirable quality.

4. Conclusions

In this study, Al–SiC composites were successfully fabricated via powder metallurgy, and the simultaneous effects of SiC weight fraction, compaction pressure, and sintering temperature on mechanical properties and microstructure were systematically evaluated using Taguchi design and ANOVA. The results demonstrate that SiC weight fraction is by far the most dominant parameter affecting tensile strength, followed by sintering temperature and compaction pressure. The optimal processing conditions to achieve maximum strength and minimum porosity were identified as 1wt.% SiC, 155MPa compaction pressure, and 600°C sintering temperature. Microstructural analyses confirmed that precise and concurrent control of reinforcement content, compaction pressure, and sintering temperature is crucial for attaining high densification and a uniform microstructure, ultimately leading to enhanced mechanical performance. These findings provide practical guidelines for the design and fabrication of high-performance aluminum-matrix composites for industrial applications.

References

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