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Research on Silicon Carbide Dispersion-Reinforced Hypereutectic Aluminum-Silicon Electronic Packaging Materials

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Abstract: The objective of this study is to improve the mechanical properties and machining performance of high thermal conductivity and low expansion silicon carbide dispersion-strengthened hypereutectic aluminum-silicon electronic packaging materials to meet the needs of aviation, aerospace, and electronic packaging fields. We used the powder metallurgy method and high-temperature hot pressing technology to prepare SiC/Al-Si composite materials with different SiC contents (5vol%, 10vol%, 15vol%, and 20vol%). The results showed that as the SiC content increased, the tensile strength of the composite material first increased and then decreased. The tensile strength was the highest when the SiC content was 15%; the sintering temperature significantly affected the composite material's structural density and mechanical properties. Findings indicated 700 ℃ was the optimal sintering and the optimal SiC content of SiC/Al-Si composite materials was between 10% and 15%. Besides, the sintering temperature should be strictly controlled to improve the material's structural density and mechanical properties.

Keywords: Silicon carbide; Electronic packaging materials; Powder metallurgy; Mechanical properties; Composite materials

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1. Introduction

Hypereutectic Al-Si alloy (Al 20 wt%; Si 80 wt%) and silicon carbide have become popular materials under research in aviation, aerospace, and electronic packaging industries due to their low expansion rate and high thermal conductivity. Common methods for preparing SiC-reinforced Al-Si-based composites include stir casting, squeeze casting, vacuum pressure impregnation, and powder metallurgy.

The melting casting method involves mixing particle reinforcements and liquid or semi-solid alloys and casting the mixture into ingots. The process and equipment of the stirring method are relatively simple. Still, during the high-speed stirring process, gas and inclusions will inevitably be mixed in, which can easily cause segregation and accumulation, thus affecting the performance of the composite material [1]. The squeeze casting method is preferred in industrial production. The squeeze casting method is used to prepare SiC/Al-Si-based

composite materials. This process requires only simple equipment and is able to produce dense, pore-less, and stable products. However, the high temperature of the molten metal causes the formation of interface reactants Al_4C_3, and this method requires a strong prefabricated body. Therefore, it is not suitable for making thin-walled parts. The vacuum pressure impregnation method begins with pre-shaping the reinforcement. Molten metal is then poured, and gas pressure is applied to ensure the molten metal penetrates the gaps in the prefabricated parts. Subsequently, the mixture solidifies to yield the blank. However, this technology demands high-pressure equipment and tightly sealed, high-pressure-resistant molds, rendering it relatively costly with high production expenses [2]. This method poses limitations in producing parts with complex shapes, especially small, thin-walled electronic packaging components.

Powder metallurgy has become an important method for producing parts that have high strength and plasticity. Powder metallurgy is also one of the first methods used to prepare SiC/Al-Si composite materials. The basic steps involve mixing the solid metal powder and reinforced particles mechanically and pressing and sintering them under a certain temperature and pressure. The content of reinforced particles can be adjusted arbitrarily, and the distribution of reinforced phase particles is more uniform. A very important process parameter in powder metallurgy is the temperature of sintering. Sintering temperature can be chosen within the solid-liquid two-phase region, a process known as liquid phase sintering. However, in many instances, the sintering temperature is set below the solidus line of the base alloy. This approach minimizes unnecessary interface reactions and mitigates the formation of harmful interface compounds. Hypereutectic aluminum-silicon alloy (Si-wt.% $\geq$ 12.6%) has become a new type of electronic packaging material because of its low thermal expansion coefficient, high thermal conductivity, and low density, which can meet the needs of different fields, especially for those with high-density requirements like aerospace equipment. The most significant advantage of hypereutectic aluminum-silicon alloy is that the material's thermal properties, such as the thermal expansion coefficient (CTE) and thermal conductivity (TC) can be modified by adjusting the Si content.

However, research shows that as Si content in the aluminum-silicon alloy gradually increases, the Si phase will aggregate and grow in the aluminum matrix, resulting in a gradual increase in the brittleness and the deterioration in weldability and machining performance, especially when the Si content exceeds 40 wt.%, the preparation and machining performance of the material is relatively poor, and the cost increases sharply. This is one of the key factors that is preventing the marketization of hypereutectic aluminum-silicon alloys.

Metal matrix composite materials use metal as the matrix and particles or fibers as the reinforcing phase. They can combine the properties of metal and reinforcing particles simultaneously. Al_2O_3 is one of the most widely used reinforcing phases in electronic packaging materials. Its thermal expansion coefficient matches that of semiconductor chip materials such as Si and GaAs, and it has strong thermal resistance and is an excellent electrical insulator. However, the low thermal conductivity makes it unsuitable for large-scale integrated circuits [3]. Although the thermal expansion coefficient of Kovar (Fe-Ni-Co) and Invar (Fe-Ni) alloy is close to that of Si chips, their thermal conductivities are low, so they will heat up during the operation of the electronic equipment. AlN ceramics offer many advantages as an electronic packaging material. Its thermal expansion coefficient is low, it is not prone to thermal mismatch, and it has high thermal conductivity. However, its manufacturing process is complicated and expensive, so it is not suitable for large-scale production [4].

SiC ceramic particles have high strength, small expansion coefficient, low density, and large elastic modulus, making them ideal for particle reinforcements. SiC is a potential reinforcement for aluminum-based composite materials for several reasons. Its low thermal expansion provides the dimensional stability of Al-Si alloys used in packaging materials. Secondly, its high modulus allows the maximization of the load-bearing function of the reinforcement. Thirdly, its high chemical stability can ensure the long-term effectiveness of

composite materials during the manufacturing and application processes. Lastly, its hardness improves the wear resistance of Al-Si alloys for pistons. In short, SiC is an effective and commonly used reinforcement for aluminum-based composite materials. SiC particle-reinforced aluminum-based composite materials have been used to manufacture rotor systems, opto-mechanical structures, remote control pilots, and electronic technology measurement arrays [5,6].

In this study, we prepared electronic packaging materials with low expansion and high thermal conductivity using SiC reinforcement phase. While ensuring the thermophysical properties of the material, it also improved the material's mechanical properties and machining performance. The thermal properties were discussed, and the effects of matrix element content and various preparation process parameters of the pressure sintering method on the structure, physical properties, and mechanical properties of the composite materials were comprehensively analyzed and tested.

2. Experimental materials and methods

2.1. Material preparation

We used Al-Si alloy powder with an average particle size of 200 mesh as the matrix powder and SiC powder with an average particle size of 200 mesh as the reinforcement.

The Al-Si and SiC powders of were mixed with different ratios (i.e., 5vol%, 10vol%, 15vol%, and 20vol%) using a mechanical mixing method to prepare four composite powders. Next, the powders were placed into the mold. SiC/AlSi composite materials were then prepared through high-temperature hot pressing in a Φ30×3mm thick aluminum mold. During hot pressing, the temperature was elevated to 650°C, 700°C, 750°C, or 800°C for 0.5 hours, followed by removal from the furnace after cooling. Using the above method, SiC/Al-Si composite materials with SiC contents of 5vol%, 10vol%, 15vol%, and 20vol% were prepared. Unreinforced Al-Si samples were prepared using the same process, which would be used as a control for this experiment.

2.2. Tests

In the experiment, scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) were used to characterize the chemical composition of the composite materials. The distribution and interface reaction of SiC particles on the AlSi matrix were analyzed using SEM.

2.2.1. Density

The sintered density of the production samples (unreinforced Al-Si and SiC/Al-Si composites) was evaluated using the Archimedean displacement method. The theoretical density of the powder mixture (SiC/Al-Si) was calculated [7,8].

2.2.2. Hardness

The microhardness of the sintered samples (unreinforced Al-Si alloy and SiC/Al-Si composite) was measured using the Vickers test.

A laser thermal conductivity meter was used to measure the thermal diffusivity of the composite material at normal temperature. Then, the thermal conductivity of the composite material was obtained based on the thermal diffusion coefficient, density, and constant pressure-specific heat capacity.

2.2.3. Thermal expansion coefficient

The linear thermal expansion coefficient of the composite material was determined using a thermal analyzer.

The range of temperature was 50–500°C, the temperature was increased at a rate of 5°C/min, and argon gas was used to create an inert environment for the test.

2.2.4. Mechanical properties

The tensile strength, yield strength, and elongation of a specimen with a known size and diameter were tested [9].

3. Experimental results and analysis

3.1. Effect of SiC content on the microstructure and mechanical properties of SiC/Al-Si composites

3.1.1. X-Ray diffraction analysis (XRD)

Figure 1 shows the XRD pattern of the aluminum alloy matrix and composite materials containing SiC particles with volume fractions of 5%, 10%, 15%, and 20%. As the volume fraction of SiC particles increased, the intensity of the SiC peaks increased without the formation of other reactants.

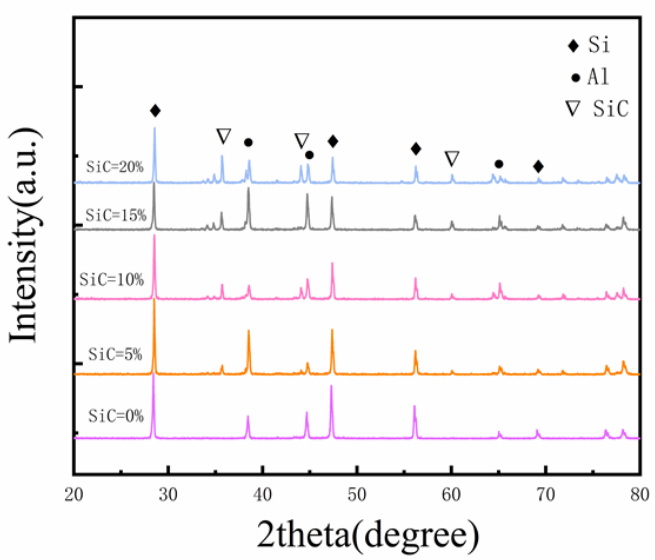

Figure 1. X-ray patterns of the composites with different volume fractions of SiCp particles

3.1.2. SEM

Figure 1 shows the tensile fracture morphology of samples with different SiC contents. **Figures 2(a) & (c)** illustrate the macroscopic fractures of samples with different SiC contents, showing relatively flat surfaces without any obvious necking phenomenon. This observation further confirms that the fracture is consistent with a typical brittle fracture. Comparing **Figures 2(d) & (f)**, the fracture shape changed as the SiC content increased from 10% to 20%. Locally on the fracture, holes composed of SiCp and some smooth surfaces could be observed. This phenomenon was magnified locally on the fracture, as shown in **Figures 2 (h) & (i)**. It was observed that during the stretching process, SiC easily peeled off from the aluminum matrix, leaving vacancies. This suggested a physical connection between SiC and the Al-Si matrix [10]. Additionally, the fracture surface revealed that the material contained certain pores and inclusions, with the 20% SiC sample showing not only inclusions and voids but also numerous secondary cracks, as depicted in **Figure 2(c)**. Furthermore, **Figures 2(g) & (i)** display the formation of tearing edges during the stretching process. Dimples were still visible on the tearing edge, indicating ductile fracture of the material matrix structure during the fracturing process. Despite a certain level of plastic deformation, the abundance of SiC in the material facilitated the formation of

microcracks at the interface between SiC and the matrix due to their physical connection. These microcracks then expanded into secondary microcracks under continued external stress, resulting from the concentration of interface stress. Moreover, the presence of pores and inclusions further promoted crack expansion, leading to brittle fracture of the material [11,12]. After the dispersion of SiC in the Al matrix reached 15%, its content began to increase, and SiC agglomeration started to rise, leading to a sharp decrease in SiC dispersion. The 10% SiC sample exhibited less agglomeration and was generally evenly distributed. In the fracture of the 15% SiC sample, there was a small amount of small-sized agglomeration, while large-sized SiC agglomerations appeared in the fracture of the 20% SiC sample, impacting the material's tensile strength and elongation performance. This effect was associated with the presence of pores and inclusions, as well as the large-size agglomeration of SiC in the material. Microcracks were prone to initiating at the interface between large-sized SiC clusters and the matrix, serving as crack nucleation sites or pathways for crack expansion, which significantly reduced the material's tensile strength.

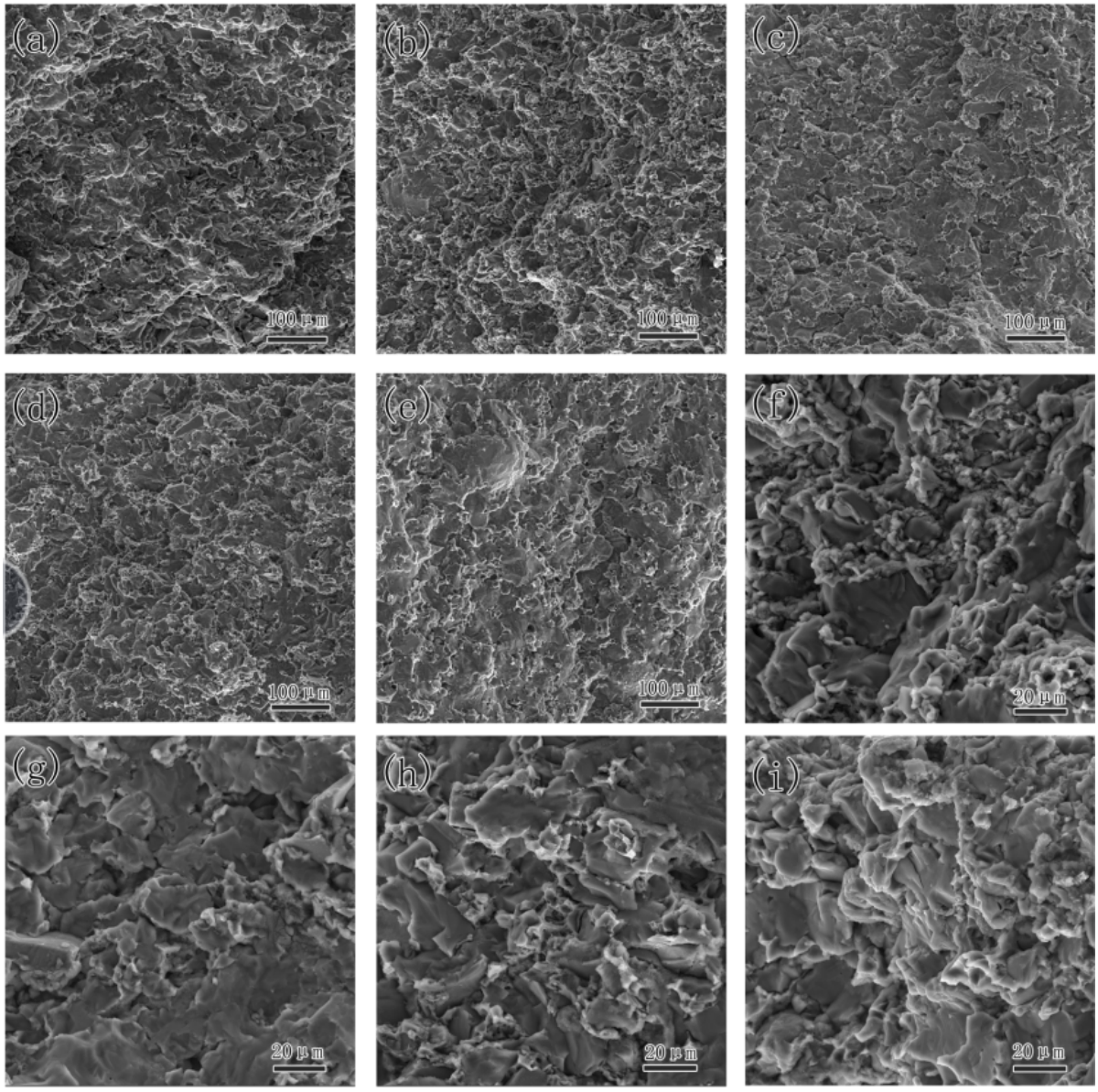

Figure 1. Fracture morphology of the tensile samples with different SiC contents (a)–(d); (e) macro fractography of 0%, 5%, 10%, 15%, and 20% SiCp samples; (f)–(i) micro fractography of 5%, 10%, 15%, and 20% SiC samples

3.1.3. Mechanical properties

Table 1 shows the tensile test results of SiC/Al-Si composites with different SiC contents. It can be seen from Table 1 that as the SiC content continues to increase, the tensile strength of the SiC/Al-Si composite material first increases and then decreases. When the SiC content is 15%, the tensile strength of the SiC/Al-Si composite material is the highest, far exceeding that of the matrix material; when the SiC content increases to 20%, the tensile strength of the composite material is significantly lower than that of the matrix material [13]. It can also be seen from **Table 1** that the post-fracture elongation of composite materials with different SiC contents is small and has little difference, indicating that SiC has a small impact on the post-fracture elongation of composite materials and the composite material exhibits brittle fracture. Therefore, from the perspective of ensuring mechanical properties, the additional amount of SiC is best controlled between 10% and 15%.

Table 1. Mechanical properties of SiC/Al-Si composites with different SiC contents

Properties \ SiC content (%)	0	5	10	15	20
Tensile strength (MPa)	78	88.2	111.5	114.6	77.3
Percentage elongation (%)	2.11	2.00	2.10	2.12	2.11

3.2. Effect of sintering temperature on the microstructure and mechanical properties of the composite materials

3.2.1. Mechanical properties

Table 2 shows the tensile test results of the composite material at different temperatures. As the hot-pressing temperature continued to increase, the tensile strength of the composite material first increased and then decreased, mainly because increasing the sintering temperature can reduce the number of pores in the composite material and improve the bonding strength of the interface [14]. The composite material demonstrated the highest tensile strength at 700°C, far exceeding that of the matrix material. However, when the temperature increased to 800°C, the tensile strength of the composite material decreased sharply, even lower than the matrix material. It should also be noted that the elongation of composite materials first increased and then decreased. Still, the overall fluctuation of the post-break elongation of composite materials at different temperatures is smaller, indicating that temperature has less impact on the post-break elongation of composite materials. The composite material showed brittle fracture. Therefore, 700°C was the optimum temperature for the production of the composite material.

Table 2. Mechanical properties of SiC/Al-Si composite materials at different temperatures

Properties \ Temperatures (°C)	650	700	750	800
Tensile strength (MPa)	100.1	114.6	109.8	99.9
Percentage elongation (%)	2.0	2.12	1.96	2.0

3.2.2. XRD

Figure 3 shows the composite material's XRD pattern at different sintering temperatures. It can be seen from the figure that at different sintering temperatures, there are only peaks of Al and SiC in the composite material, indicating that the sintering temperature selected in the experiment did not cause serious interface reactions in the material.

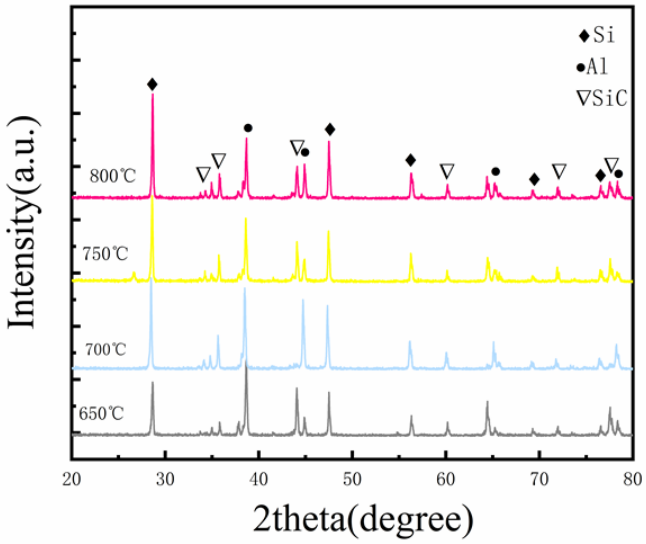

Figure 3. X-ray patterns of the composites sintered at different temperatures

3.2.3. SEM

Figure 4 shows the tensile fracture morphology of samples at different sintering temperatures. Composite materials were prepared at different sintering temperatures using the hot-press sintering method. When the sintering temperature was low, more holes were observed in the structure of the material, and the composite material structure was less dense. When the sintering temperature was increased, there were fewer holes in the structure, and the density increased. This is mainly because as the sintering temperature increases, the fluidity of the alloy powder increases significantly, which promotes the densification of the material [15,16]. Initially exhibiting a brittle fracture, dimples were observed on the fracture surface of the aluminum alloy matrix as the temperature increased. This indicates a transition to a ductile fracture mode for the aluminum alloy matrix.

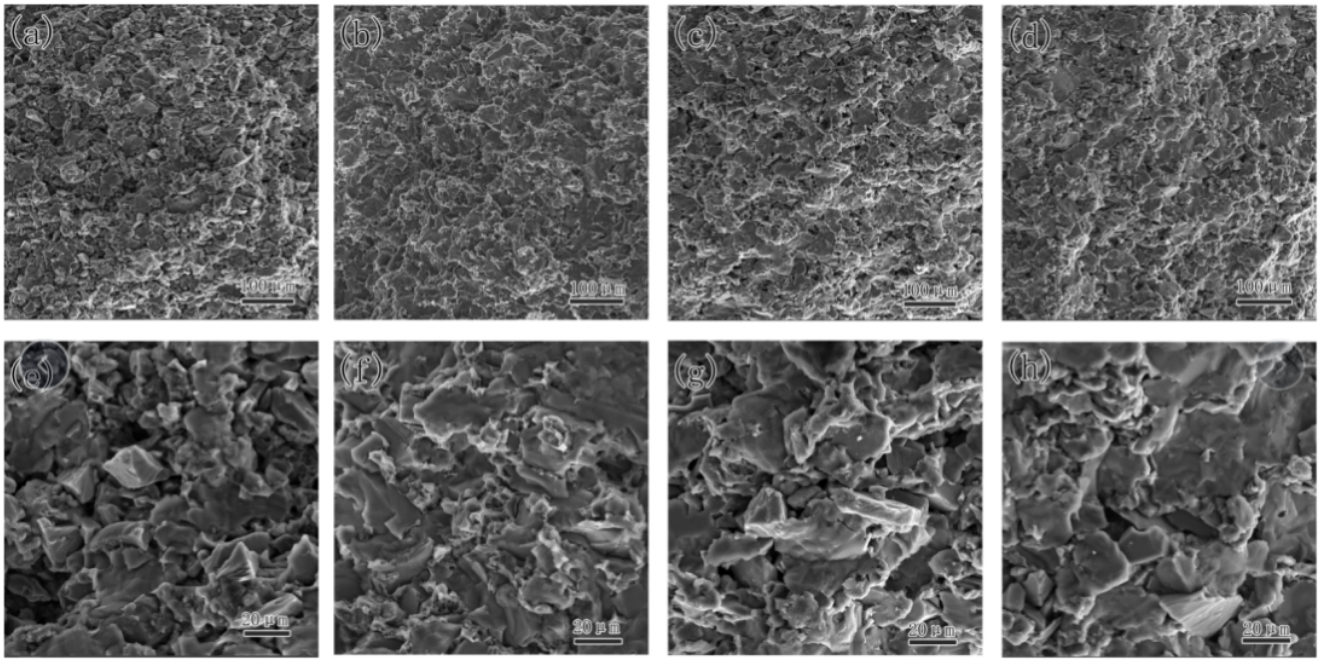

Figure 4. The fracture morphology at different sintering temperatures. (a), (b), (c), and (d) are macroscopic fractures of the specimens with different sintering temperatures at 650°C, 700°C, 750°C, and 800°C, respectively. (e), (f), (g), and (h) are microscopic fractures of specimens with sintering temperatures of 650°C, 700°C, 750°C and 800°C, respectively.

4. Conclusion

(1) Based on reaction thermodynamics, surface oxidation pretreatment was carried out on SiC particles. Subsequently, SiC/Al-Si composite materials were prepared using the powder metallurgy method with high-temperature hot pressing. The resulting SiC/Al-Si composite materials with SiC contents of 5vol%, 10vol%, 15vol%, and 20vol%. The preparation process parameters of the composite material were determined accordingly.

(2) The organizational morphology, phase composition, and microstructure of the matrix and reinforcement phases of SiC/Al-Si composite materials were investigated. Special attention was given to the effects of sintering temperature and holding time on the interface conditions of SiC/Al-Si composite materials. From the perspective of ensuring mechanical properties, a temperature of 700°C is preferred. With increasing sintering temperature, the fluidity of the alloy powder significantly improves, resulting in smaller pores in the composite material structure, thereby promoting densification during sintering.

(3) The mechanical properties, including hardness and tensile strength, and the fracture morphology of SiC/Al-Si composite materials, were investigated. The influence of various factors on the mechanical properties of composite materials and the fracture mechanism was discussed. From the perspective of ensuring mechanical properties, it was observed that as the SiC content increased, the tensile strength of SiC/Al-Si composite materials initially increased and then decreased. Therefore, it was concluded that the optimal SiC addition amount should be controlled between 10% and 15%.

Disclosure statement

The authors declare no conflict of interest.

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