The Preparation of High-Volume Fraction SiC/Al Composites with High Thermal Conductivity by Vacuum Pressure Infiltration

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Abstract: The high-volume fraction SiC/Al composite is the new type of electronic packaging material, which plays an important role in the field of high-power integrated circuits. In this study, SiC/Al composites with high-volume fraction of SiC particles were prepared by vacuum pressure infiltration. The influence of SiC particle size and NH4HCO3 on the pores in the preform was explored, aiming to accurately adjust the volume fraction of SiC to meet the thermal performance requirements in different fields. In addition, the preform was infiltrated with different Al alloys, and the relationship between the porosity and thermal conductivity of SiC/Al was studied. For the SiC preform, the volume fraction of SiC can be adjusted regularly when 12 µm and 100 µm SiC particles are mixed in different proportions, and the volume fraction reaches the maximum when the proportion of coarse particles is about 77%. NH4HCO3 is conducive to the connectivity of pores in the preform, and about 40 vol.% of NH4HCO3 can effectively increase the porosity of the preform. Thermal conductivity is sensitive to the porosity of composites, especially in the range of 2.5–4.5%. A simple application of the Hasselman–Johnson model and a new thermal conductivity model, \( \lambda_d \), established in this article, offer a good agreement with the experimental results.

Keywords: SiC/Al; volume fraction; infiltration; pore; thermal conductivity

1. Introduction

With the rapid development of electronic science and technology, the high integration of chips and the miniaturization of packaging put forward higher requirements for electronic packaging materials [1]. High-volume fraction SiC/Al composites (the volume fraction of SiC is more than 50 vol.%) have attracted much attention in the field of aerospace, rail transit, automobile, and other high-power integrated circuits, which need fast heat dissipation and matching expansion coefficient, due to their excellent thermal conductivity, low expansion coefficient, low density, and designability [2,3]. However, many previous works have focused on the preparation of SiC/Al composites with low volume fraction, and the preparation of high-volume fraction composites containing more than 50 vol.% SiC particles have not been fully studied. Moreover, with the introduction of a large number of SiC particles, the machining of SiC/Al composites becomes increasingly harsh. It is necessary to explore a near net forming technology for the composites [4,5]. Compared with powder metallurgy and the stirring casting method [6,7], the vacuum pressure infiltration method has characteristics including short infiltration time, near net shape, and...
low cost, which is why it is the most competitive method to prepare high-volume SiC/Al composites [8,9].

Vacuum pressure infiltration method mainly includes two processes, namely, the preparation of the SiC preform and the infiltration of liquid Al into the preform [3,10]. The porosity and pore characteristics (pore size and connectivity) of the preform determine the microstructure of the composite directly. For an ideal SiC preform, the volume fraction of SiC must be easily controlled, and the pores in the preform need to be connected [11]. SiC/Al composites with different volume fractions can be prepared by combining SiC particles with various sizes or adding pore forming agents [12–15]. These two ways also change the pore characteristics of the preform [15,16]. For the process of Al liquid infiltration, clarifying the properties of Al, such as its fluidity and wettability with SiC, are helpful to further improve the performance of SiC/Al [17]. The majority of current research focuses on the properties of liquid Al in pressureless infiltration [18–20]. There are few studies on the infiltration behavior of liquid Al under vacuum pressure infiltration. Lee et al. [21] successfully infiltrated liquid Al into the preform by changing vacuum pressure infiltration parameters. For SiC/Al composites, the porosity is an unavoidable phase, which is intrinsically related to the poor wetting characteristics of the interface [22]. For the two characteristics of interest in the field of electronic packaging, namely thermal expansion coefficient and thermal conductivity, it has been proven that for different systems, the former rarely, or does not at all, depend on the porosity of SiC/Al [23]. On the contrary, the porosity may greatly reduce the thermal conductivity of SiC/Al. Therefore, it is necessary to study the relationship between porosity and thermal conductivity [22,24]. With the development of the research on SiC/Al composites, researchers have gradually realized the influence of interface, phase composition, particle size, and other factors on the thermal conductivity [15,25,26]. They have established different models to predict the thermal conductivity of composites which deepen the researchers’ understanding of SiC/Al and reduce the test cost [27].

In this work, the vacuum pressure infiltration method for preparing high-volume fraction SiC/Al composites was studied. The adjustment of pores in the SiC preform and the influence of the Al alloy element are emphasized in this article. The relationship between porosity and thermal conductivity of composites is also discussed, and based on the Hasselman–Johnson model, a new prediction model of thermal conductivity for composites with 2–8% porosity is established.

2. Materials and Methods

2.1. Materials

Green α-SiC powders with mean particle sizes of 12 and 100 μm were used as reinforcements in this study, the theoretical density was 3.2 g/cm³. Al-7Si-Mg and Al-12Si-Mg were selected as matrix alloys, in which the content of Mg was only about 0.3 wt.%. Ammonium bicarbonate with the molecular formula of NH₄HCO₃ (analytical purity), the theoretical density of 1.58 g/cm³ (Tianjin Bailunsi Biotechnology Co., Ltd.), was used as pore forming agent [28]. Ammonium dihydrogen phosphate was used as binder with the molecular formula of NH₄H₂PO₄ (analytical purity) and the theoretical density of 1.803 g/cm³ (Tianjin Fuchen chemical reagents factory) [29]. Anhydrous ethanol was used for surface cleaning of SiC particles with molecular formula of CH₃CH₂OH (analytical purity) (Beijing Chemical Works).

2.2. Experiments

The experiment of preparing SiC/Al composites by vacuum pressure infiltration method includes two predominant processes: the preparation of SiC preforms and the infiltration of liquid Al alloy into the pores of the preforms. Figure 1 shows the method.
Figure 1. Illustration of the preparation of high-volume fraction SiC/Al by the liquid infiltration method.

The preparation process of the SiC preform is as follows: firstly, the SiC particles are cleaned by ultrasonic wave with ethanol to remove the surface impurities. According to the designed proportion, the cleaned SiC particles, NH$_4$H$_2$PO$_4$ and NH$_4$HCO$_3$, are stirred and mixed evenly. We filled the mold with these mixed materials, and the mixture was shaped with mechanical pressure (40 Mpa). Then, the pressed SiC preform blank was slowly heated to 700 °C, so that the pore former can be fully volatilized to leave pores (it can be completed at about 145 °C), and the binder was thermally degreased to ensure the high temperature strength of the SiC preform [29]. In this work, the influences of the ratio of 2 kinds of SiC particles and the content of pore forming agent NH$_4$HCO$_3$ on the volume fraction and internal pore characteristics of the SiC preform were investigated. The specific experimental parameters are shown in Tables 1 and 2.

Table 1. Experimental scheme of 2 kinds of SiC particles with different proportions.

| Content Ratio of 100 µm and 12 µm SiC Particles | NH$_4$H$_2$PO$_4$ Content/vol.% | NH$_4$HCO$_3$ Content/vol.% | SiC Content/vol.% |
|-----------------------------------------------|-------------------------------|----------------------------|------------------|
| 0:1                                          | 5                             | 25                         | 70               |
| 1:2                                          | 5                             | 25                         | 70               |
| 1:1                                          | 5                             | 25                         | 70               |
| 2:1                                          | 5                             | 25                         | 70               |
| 3:1                                          | 5                             | 25                         | 70               |
| 4:1                                          | 5                             | 25                         | 70               |
| 5:1                                          | 5                             | 25                         | 70               |
| 7:1                                          | 5                             | 25                         | 70               |
| 10:1                                         | 5                             | 25                         | 70               |
| 1:0                                          | 5                             | 25                         | 70               |

Table 2. Experimental scheme of the different content of NH$_4$HCO$_3$.

| NH$_4$HCO$_3$ Content/vol.% | SiC Content/vol.% | Content Ratio of 100 µm and 12 µm SiC Particles |
|-----------------------------|-------------------|-----------------------------------------------|
| 0                           | 100               | 10:1                                         |
| 10                          | 90                | 10:1                                         |
| 20                          | 80                | 10:1                                         |
| 30                          | 70                | 10:1                                         |

The process of liquid Al infiltration is as follows: firstly, we put the prepared preform into a crucible, and the Al alloy was placed above the preform. After loading the crucible into the furnace, we vacuumed the whole device. When a certain vacuum degree was reached, the crucible was heated to the designed temperature to melt the Al alloy. Then, the device was filled with nitrogen to infiltrate the Al liquid into the preform under a certain
pressure. After holding the pressure for a period of time, we took out the infiltrated sample. The technological parameters of liquid Al infiltration from this experiment are shown in Table 3.

Table 3. Technological parameters of liquid Al infiltration process.

| Al Alloy    | Infiltration Pressure (Mpa) | Infiltration Temperature (°C) | Infiltration Time (min) | Vacuum Degree (Pa) |
|-------------|-----------------------------|------------------------------|-------------------------|--------------------|
| Al-7Si-Mg   | 1.1                         | 800                          | 10                      | 100                |
| Al-12Si-Mg  | 2.3                         | 900                          | 15                      | 150                |

2.3. Characterization

A field emission scanning electron microscope (SEM), JSM-7610F, was used to observe the microstructure and pores of the SiC preform and the microstructure and morphology of SiC/Al composite. The phase identification, micro element type, and composition of the SiC preform and composite were carried out by smartlab X-ray diffraction (XRD) and energy dispersive X-ray spectrometer (EDS). The actual density of the SiC preform was measured by the mass volume method, and the volume fraction of SiC particles and the porosity of the SiC preform were calculated. The Archimedes drainage method was used to measure the actual density of SiC/Al composites. The specific steps refer to the national standard GB/T 3850-2015. The density and porosity of SiC/Al composites were obtained by calculating the ratio of actual density to theoretical density. According to the national standard GB/T 22588-2008, the thermal conductivity of SiC/Al composites was measured by Netzsch LFA467 thermal conductivity tester. The number of test samples for porosity and thermal conductivity is 3, and the average value is taken after measurement.

3. Results and Discussion

3.1. Volume Fraction and Pore Characteristics of SiC Preforms

3.1.1. SiC Preform with a Bimodal Size Distribution (12 and 100 µm)

High-volume fraction SiC preforms were made by mixing SiC particles with mean diameters of 12 and 100 µm, as shown in Table 1. It is considered that the apparent volume of the preform after sintering is the volume formed by SiC particles and pores, that is, SiC volume fraction = 1-porosity. Figure 2 shows the experimental results for the SiC volume fraction of the preform versus the proportion of coarse particles (100 µm) in the mixture. Undoubtedly, the volume fraction of SiC in the preform is about 56% using only the fine particles (12 µm), and 62% using only the coarse particles. The volume fraction of SiC can be adjusted from 56% to 68% when SiC particles with bimodal size are mixed in different proportions. With the increase in coarse particles, the volume fraction of SiC increases first and then decreases. From the fitting curve in Figure 2, the preform with 77% of coarse particles shows the maximum volume fraction (68%), which is 21% higher than that using only fine particles. It is worth noting that the extreme point is larger than that of most research in the bimodal size system [15]. Their results show that when the content of coarse particles is about 67%, the volume fraction of SiC particles in the preform shows the maximum. The reasons for the differences are as follows: (1) in this work, additional pore forming agent was added. When under a molding pressure, the NH₄HCO₃ was further crushed, which changed the stacking mode of mixed particles, resulting in the maximum SiC volume fraction being obtained in different coarse proportions. It should be emphasized that the trends between the two results are consistent. In other words, with the increase in coarse particle proportion, the volume fraction of the preform increases first and then decreases. The role of the pore forming agent will also be mentioned in Section 3.1.2. The shape of particles and the difference of particle size ratio also caused some differences [13,30,31].
3.1.2. The shape of particles and the difference of particle size ratio also caused some differences [13,30,31].

In order to describe the pore characteristics of the preform with different proportions of coarse particles, the micro morphology of the SiC preform and the corresponding SiC/Al composite was observed, as shown in Figure 3. It can be seen from Figure 3a that the irregular shape of 100 µm coarse particles were randomly stacked to create loose pores, most of which were 20–30 µm in diameter. When coarse and fine particles exist at the same time, as shown in Figure 3c, there are two stacking modes of the fine SiC particles: (1) squeezing between the coarse SiC particles causes the volume of the SiC preform to increase; (2) filling in the loose pores stacked by coarse particles, which does not cause the volume fraction of the preform to change. Therefore, in the first stage of Figure 2, with the increase in coarse particles, the number of pores stacked by coarse particles in the preform increases, and the fine particles will fill these pores, thus increasing the volume fraction of SiC. When the proportion of coarse particles is greater than the critical value (77% as mentioned above), the increase in coarse particles leads to a decrease in SiC volume fraction. Fewer fine particles fill into the loose pores which coarse particles stacked, and the volume fraction of SiC decreases until coarse particles are 100%, that is the second stage of Figure 2. Therefore, the volume fraction of SiC can be adjusted accurately and effectively to satisfy different thermal performance requirements by the trend analyzed above.

![Figure 2](image-url)  
Figure 2. The relationship between the volume fraction of SiC and the proportion of coarse SiC particles (100 µm).

![Figure 3](image-url)  
Figure 3. Representative SEM images showing the micromorphology of the SiC preforms and the corresponding SiC/Al composites with coarse to fine particle ratios of (a,b) 1:0 and (c,d) 5:1.
The internal pore characteristics of the preform are an important parameter, such as pore size and pore connectivity [32]. According to the expression of prediction model [33]:

\[ \Delta P = -\frac{2D_f}{r} \]  

(1)

In Equation (1), \( r \) represents the radius of the smallest pore that will be penetrated by the liquid, \( D_f \) is the driving force for wetting. According to the equation, the driving force (\( \Delta P \)) required for penetration is inversely proportional to the size of the pore in the preform. Therefore, under the same infiltration pressure, molten Al tends to penetrate the large pore channel preferentially. As shown in Figure 3c, the introduction of fine particles fills up the space between coarse particles, resulting in the pore size (10–20 \( \mu m \)) significantly smaller than the loose pores (20–30 \( \mu m \)) in Figure 3a. In addition, the pores formed by the fine particles are even smaller (<5 \( \mu m \)), as shown by the circle in Figure 3c. Figure 3b,d is the SiC/Al composite material infiltrated from the preform shown in Figure 3a,c under same infiltration pressure. As shown in Figure 3b, the SiC/Al composite material with 100% 100 \( \mu m \) SiC preform is well infiltrated, which has uniform structure distribution and excellent interface bonding. On the contrary, the composite material in Figure 3d has many pores and poor interface bonding. Pores are more likely to exist between small particles (such as the circle in Figure 3d). From the Equation (1), the small-sized pores formed between small particles are more difficult to be infiltrated under the same impregnation pressure. Therefore, the pore characteristics of the preform determine the infiltration results directly. When fine SiC particles are introduced to increase the volume fraction of the preform, the infiltration pressure should be increased accordingly.

3.1.2. SiC Preform with Different Contents of Pore Forming Agent (NH\(_4\)HCO\(_3\))

The role of the pore forming agent is to adjust the porosity and pore characteristics of the SiC preform. In order to better understand how NH\(_4\)HCO\(_3\) acts, different contents of NH\(_4\)HCO\(_3\) were added to prepare the SiC preform (as shown in Table 2). The relationship between the porosity of the SiC preform and the content of NH\(_4\)HCO\(_3\) is shown in Figure 4. It can be seen that the addition of NH\(_4\)HCO\(_3\) effectively increases the porosity of the SiC preform. According to the pyrolysis characteristics of NH\(_4\)HCO\(_3\), it will decompose and release gas during the heating process, which forms pores in the preform. In addition, there is a remarkable linear relationship between the porosity of the SiC preform and the NH\(_4\)HCO\(_3\) content. By fitting the data in Figure 4, the model of Equation (2) is established:

\[ Y = 26.9 + 0.4X \]  

(2)

where \( Y \) is the porosity of the SiC preform, and \( X \) represents NH\(_4\)HCO\(_3\) content. Undoubtedly, the fitted curve offers a good agreement with the experimental results. In other words, when no NH\(_4\)HCO\(_3\) is added, the original porosity of the preform is 26.9%, and the increase in the porosity of the preform is about 40 vol.% of that of the added NH\(_4\)HCO\(_3\). Equation (2) provides a good calculation model and the volume fraction of the SiC preform can be controlled more accurately through it.

To further study the characteristics of the pores in the preform, the micromorphology of SiC/Al composite with different content of NH\(_4\)HCO\(_3\) was observed, as shown in Figure 5. It can be seen from Figure 5a,b that there are many closed pores in the composite with 10% NH\(_4\)HCO\(_3\) in the experiment. In contrast, the infiltration result of the composite with 30% NH\(_4\)HCO\(_3\) is better, in which there is no obvious pore. It is considered that NH\(_4\)HCO\(_3\) can increase the connectivity of pores. The action mechanism of the pore forming agent is analyzed as follows: the particle size of NH\(_4\)HCO\(_3\) used in this experiment is less than 230 \( \mu m \). During the molding process, NH\(_4\)HCO\(_3\) is subjected to a certain pressure and further broken to smaller particles. As shown in Figure 6, pore forming agents of different sizes randomly adhere to the surface of SiC particles and occupy part of the space. After decomposition at high temperature, all the generated gases escape,
and the corresponding positions become pores. The pore forming agent, which occupies the channel of Al liquid flowing through, decomposes to form pores, and then connects with other pores. Therefore, the increase in NH$_4$HCO$_3$ is conducive to the connection of preformed pores, so as to achieve a better infiltration result. In this case, the pore forming agent NH$_4$HCO$_3$ acts as a bridge to connect more pores.

![Figure 4.](image)

**Figure 4.** The relationship between the porosity of the SiC preform and the content of NH$_4$HCO$_3$.

![Figure 5.](image)

**Figure 5.** Representative SEM images showing the micromorphology of SiC/Al composites with (a,b) 10%; (c,d) 30% NH$_4$HCO$_3$ added.
3.2. Infiltration of SiC Preform with Al

Al-7Si-Mg and Al-12Si-Mg (with less Mg content, about 0.3 wt.%) were used to infiltrate the preforms with a different SiC volume fraction. Figure 7 shows the thermal conductivity of the composites infiltrated with Al-7Si-Mg and Al-12Si-Mg. It is clear that, using the alloy Al-12Si-Mg with high Si content for infiltration, the thermal conductivity of the composite material is always greater than that of the alloy Al-7Si-Mg with low Si content. Generally, the increase in Si content will lead to the decrease in thermal conductivity of the matrix Al. In this work, although the thermal conductivity of the Al-12Si-Mg matrix is relatively low, the thermal conductivity of the composite material did not decrease. Figure 8 shows the microstructure of SiC/Al-7Si-Mg and SiC/Al-12Si-Mg composites. Comparing Figure 8a,c and Figure 8b,d, it can be observed that under the same conditions, the composite with Al-12Si-Mg is more completely infiltrated than the composite with Al-7Si-Mg. SiC/Al-12Si-Mg have fewer pores and better interface bonding. It can be considered that Al-12Si-Mg is more conducive to infiltration.
Al4C3. Figure 9 shows the line scan analysis of SiC/Al-7Si-Mg and SiC/Al-12Si-Mg. It has been found that the Al-12Si-Mg alloy with high Si content has a low tendency to form and better fluidity in 800 °C, which makes it easier to fill the pores of the preform. The Mg (near eutectic composition point, when little Mg is ignored) has a lower melting point than 12Si-Mg (when the Mg content is negligible). At the same infiltration temperature, the better fluidity of Al-12Si-Mg, the easier it is to fill the preform. Adequate impregnation improves the density of the composite material which is beneficial to the thermal conductivity. (2) From interface reaction between SiC and Al, it can be seen from the Al-Si binary phase diagram that the melting point of Al-12Si-Mg is lower than that of Al-7Si-Mg (when the Mg content is negligible). At the same infiltration temperature, the better the fluidity of Al-12Si-Mg, the easier it is to fill the preform. Adequate impregnation improves the density of the composite material which is beneficial to the thermal conductivity. (3) From what is mentioned above, the higher thermal conductivity of SiC/Al-12Si-Mg composites are mainly attributed to the following: (1) From the Al liquid infiltration behavior, it can be seen from the Al-Si binary phase diagram that the melting point of Al-12Si-Mg is lower than that of Al-7Si-Mg (when the Mg content is negligible). At the same infiltration temperature, the better the fluidity of Al-12Si-Mg, the easier it is to fill the preform. Adequate impregnation improves the density of the composite material which is beneficial to the thermal conductivity. (2) From interface reaction between SiC and Al, it is considered that the Al-12Si-Mg alloy with higher Si content has a lower tendency to form Al4C3 with poor thermal performance, which is beneficial to the thermal conductivity of the composite. The XRD analysis of SiC/Al-12Si-Mg in Figure 10 also confirmed this view. The diffraction peaks of the composite are mainly composed of the SiC phase and Al phase; a small amount of Si phase is also found.

\[
4\text{Al} + 3\text{SiC} = 3\text{Si} + \text{Al}_4\text{C}_3 \tag{3}
\]

Figure 8. Representative SEM images showing the micromorphology of: (a) SiC/Al-12Si-Mg (62% SiC); (b) SiC/Al-7Si-Mg (62% SiC); (c) SiC/Al-12Si-Mg (56% SiC); (d) SiC/Al-7Si-Mg (56% SiC).
Figure 9. EDS patterns of SiC/Al Composites: (a) SiC/Al-7Si-Mg; (b) SiC/Al-12Si-Mg.

Figure 10. XRD analysis of SiC/Al-12Si-Mg.

3.3. Thermal Conductivity of Composites and Its Prediction Model

In this work, SiC/Al composites with different porosity were prepared to study the relationship between porosity and thermal conductivity, as Figure 11 shows. It is easy to find that the increase in porosity will lead to the decrease in thermal conductivity. The thermal conductivity of SiC/Al is particularly sensitive to the porosity, especially in the range of 2.5–4.5%. When the porosity is greater than 4.5%, the thermal conductivity decreases at a slower rate. The thermal conductivity of SiC/Al composites does not depend entirely on the porosity, it is also related to other factors, such as the thermal conductivity of raw materials, volume fraction of SiC and the interface combination. The influence of pores on thermal conductivity of SiC/Al is analyzed as follows: The thermal conductivity of pore is close to 0. If it is regarded as dispersed phase, the larger the porosity is, the smaller the thermal conductivity of the composite is. Pores cause strong scattering of phonons and electrons, which hinders heat conduction seriously. The heat flow has to bypass the pores, which undoubtedly increases the length of the heat conduction path, resulting in the decrease in thermal conductivity. In this work, when the porosity is in the range of 2.5–4.5%, it is considered that porosity damage plays the most significant role. The thermal conductivity of the composite decreases greatly with the increase in porosity.
in this range. When the porosity of SiC/Al composite is more than 4.5%, The damage of thermal conductivity reduces with the growing porosity.

![Thermal conductivity vs Porosity](image)

**Figure 11.** Thermal conductivity of composite materials with different porosity.

Inevitably, pores appear in SiC/Al composite materials, especially in SiC/Al with a high SiC volume fraction, for the poor wettability between SiC and Al. As mentioned above, the thermal conductivity of SiC/Al is sensitive to its porosity. With the further study of SiC/Al composites, various models have been established to predict the thermal conductivity of the composites. The H-J model considers the influence of interface thermal resistance and particle size on the thermal conductivity, which has been widely used in the field of particle reinforced composites and has achieved good results. In this work, The H-J model is simply applied to establish a new model to study the relationship between porosity and thermal conductivity of SiC/Al. The mathematical expression of the H-J model is as follows:

\[
K_{\text{eff}} = K_m \frac{2V_p \left( \frac{K_p}{K_m} - \frac{K}{\text{avg}} - 1 \right) + \frac{K_p}{K_m} + 2 + 2 \frac{K_p}{\text{avg}}}{V_p \left( 1 - \frac{K_p}{K_m} + \frac{K}{\text{avg}} \right) + \frac{K_p}{K_m} + 2 + 2 \frac{K_p}{\text{avg}}} \quad (4)
\]

where \(K_{\text{eff}}\) is the effective thermal conductivity of SiC/Al composite; \(K_m\) and \(K_P\) represent the thermal conductivity of Al alloy and SiC, respectively; \(V_p\) is the volume fraction of SiC; \(a\) is the particle radius of SiC; \(h_c\) is the interface thermal conductivity.

Suppose that in the first extreme case, there is no interfacial thermal resistance, i.e., when \(h_c \to \infty\), the H-J model is expressed as follows:

\[
K_\infty = K_m \frac{2V_p \left( \frac{K_p}{K_m} - 1 \right) + \frac{K_p}{K_m} + 2}{V_p \left( 1 - \frac{K_p}{K_m} \right) + \frac{K_p}{K_m} + 2} \quad (5)
\]

In the second extreme case, the interfacial thermal resistance is infinite, i.e., \(h_c \to 0\), it is equivalent to the case that the particle in the metal matrix is a pore. The expression is as follows:

\[
K_0 = K_m \frac{1 - V_p}{1 + 0.5V_p} \quad (6)
\]
In this study, use $\lambda_d$ as the difference between the actual thermal conductivity of the composite material and the predicted value of the two extreme cases of the H-J model, namely:

$$\lambda_d = K_\infty + K_0 - K_a$$  \hspace{1cm} (7)

where $K_a$ is the experimental value of the thermal conductivity of SiC/Al. In this experiment, the thermal conductivity of SiC is 220 W/(m·K), $a = 50 \mu m$; the thermal conductivity of Al-7Si-Mg and Al-12Si-Mg calculated by JMatPro are 183.41 W/(m·K) and 180.66 W/(m·K), respectively. Using these data, $K_\infty$ and $K_0$ of SiC/Al, with different porosity, are calculated. After measuring the actual thermal conductivity of each SiC/Al, $\lambda_d$ can be obtained according to Equation (7).

The porosity of each composite and its corresponding $\lambda_d$ value are shown in Figure 12. The thermal conductivity $\lambda_d$ model offers a good agreement with the porosity of high-volume SiC/Al. Further, the original hypothesis of the theory makes the use of the H-J model limited, that is, the H-J theoretical model has better prediction results and applicability for low volume fraction of SiC. With the increase in the SiC volume fraction, the theoretical model deviates from the experimental results in application. From Figure 12, the curve of porosity agrees well with the thermal conductivity $\lambda_d$ model. It is considered that the introduction of porosity can reduce the limitation of the H-J model. Usually, high-volume SiC/Al composites are easier to form pores, due to the poor wettability between matrix and reinforcement phase. Therefore, difficult measurement of $h_c$ ignoring the volume fraction of pores (porosity) will limit the application of the H-J model which only considers the volume fraction of SiC and Al, especially in high-volume fraction SiC/Al composites. This also confirms what has been mentioned above, that is, for the high-volume fraction SiC/Al with porosity in the range of 2–8%, their thermal conductivity is highly sensitive to porosity. It is considered that porosity is the dominant factor affecting the thermal conductivity. In addition, the consistency of $\lambda_d$ and porosity allows us to calculate $\lambda_d$ from its corresponding porosity. Through Equation (7), we can further predict $K_a$ (the actual thermal conductivity). It is apparent that the good consistency between porosity and the $\lambda_d$ model indirectly reflects the consistency between the porosity and $K_a$. Therefore, through the $\lambda_d$ model, it is easy and precise to predict the actual thermal conductivity $K_a$ of SiC/Al by measuring the porosity but $h_c$. In this paper, the $\lambda_d$ model can be regarded as a bridge, which is more accurate to connect the thermal conductivity and porosity of high-volume fraction SiC/Al composites. It should be emphasized that this prediction prefers high-volume fraction SiC/Al composites with porosity in the range of 2–8%.

![Figure 12. The porosity of each composite and its corresponding $\lambda_d$ value.](image-url)
4. Conclusions

In this study, the preparation process and thermal conductivity of high-volume fraction SiC/Al composites by vacuum pressure infiltration were investigated, and the main conclusions are as follows:

- The volume fraction of SiC can be adjusted regularly by using 12 μm and 100 μm SiC particles with different proportions. When the proportion of 100 μm SiC particles is about 77%, the volume fraction of SiC reaches the maximum. The introduction of small particles easily causes the pore size of the SiC preform to shrink, which requires greater infiltration pressure to prepare SiC/Al composites.

- The porosity of the SiC preform can be adjusted stably by adding pore forming agent NH₄HCO₃, which satisfies the following mathematical model: Y = 26.9 + 0.4X. It is understood that NH₄HCO₃ acts as a bridge to connect more pores in the preform, which is conducive to the subsequent infiltration process.

- Compared with Al-7Si-Mg, Al-12Si-Mg shows better infiltration results. The main reasons are as follows: First, Al-12Si-Mg is infiltrated fully for the best fluidity and low infiltration resistance. In addition, it is considered that Al-12Si-Mg with high Si content has little tendency to form harmful phase Al₄C₃, which is beneficial to achieve good infiltration results.

- The thermal conductivity of high-volume fraction SiC/Al is sensitive to their porosity, especially when the porosity is in the range of 2.5–4.5%. Through the newly established λ₃ model and its connection with the porosity, the thermal conductivity of high-volume fraction SiC/Al with 2–8% porosity can be effectively predicted.

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