

## EXPERIMENTAL PREPARATION OF SHORT-CARBON-FIBER-REINFORCED Al-5Cu MATRIX COMPOSITES USING VACUUM SUCTION CASTING

### EKSPERIMENTALNA IZDELAVA S KRATKIMI OGLJIKOVIMI VLAKNI OJAČANEGA KOMPOZITA S KOVINSKO MATRICO Z UPORABO LIVARSKE TEHNIKE VAKUUMSKEGA ČRPANJA TALINE

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Carbon-fiber-reinforced aluminum matrix composites have been widely used in many industrial fields. The carbon-fiber content and elements content of Mg and Si has a significant influence on the performance of composites. It is vital to study the effects of the carbon-fiber content and elements content of Mg and Si on mechanical and electrical properties of composites. Short-carbon-fiber-reinforced Al-5Cu alloy composites (Cf/Al-5Cu) were prepared by vacuum suction casting (VSC) in this work. The mechanical and electrical properties of Cf/Al-5Cu were measured by testing machines, and the microstructures were observed and analyzed using a scanning electron microscope (SEM). Experimental results show that the mechanical and electrical properties of the Cf/Al-5Cu composites increase with the increase of the carbon-fiber content. The tensile strength of Cf/Al-5Cu composites with 2 wt% carbon-fiber content reached 258.7 MPa. Its microhardness reached 112.6 HV, and the resistivity was 26.5  $\mu\Omega$ /mm. The mechanical properties of the Cf/Al-5Cu composites can be improved by adding the elements Mg and Si. When the Mg content is 0.3%, the tensile strength of Cf/Al-5Cu composites reached 294.7 MPa, the microhardness reached 128.3 HV, and the resistivity was 18.4  $\mu\Omega$ /mm. Adding Mg was more effective for the electrical properties than Si.

Keywords: vacuum suction casting, carbon fiber, aluminum matrix composite, microstructure observation, properties test

Z ogljikovimi vlakni ojačani kompoziti z matrico iz Al zlitin se veliko uporabljajo na različnih področjih. Vsebnost ogljikovih vlaken in legirnih elementov, kot sta: Mg in Si, imajo pomemben vpliv na lastnosti kompozitov. Zato je pomembno študirati njihov vpliv na mehanske in električne lastnosti. Avtorji v raziskavi opisujejo izdelavo in lastnosti Al-5Cu kompozita, ojačanega s kratkimi ogljikovimi vlakni (Cf/Al-5Cu). Kompozit so izdelovali z livarsko tehniko vakumskega črpanja taline (VSC; angl.: vacuum suction casting). Določili so njegove mehanske in električne lastnosti ter opazovali in analizirali njegovo mikrostrukturo s pomočjo vrstičnega elektronskega mikroskopa (SEM). Eksperimentalni rezultati so pokazali, da se mehanske in električne lastnosti Cf/Al-5Cu kompozita povečujejo s povečevanjem deleža kratkih ogljikovih vlaken. Natezna trdnost Cf/Al-5Cu kompozita z 2 mas.% ogljikovih vlaken, je 258,7 MPa. Njegova mikrotvrdota je bila 112,6 HV in električna upornost je bila 26,5  $\mu\Omega$ /mm. Mehanske lastnosti Cf/Al-5Cu so izboljšali z dodatkom Mg in Si. Pri vsebnosti Mg je 0,3 mas.% je bila natezna trdnost kompozita 294,7MPa, mikrotvrdota 128,3 HV in električna upornost 18,4  $\mu\Omega$ /mm. Vpliv dodatka Mg na električne lastnosti je ugodnejši kot dodatek Si.

Ključne besede: vakuumsko črpalno litje, ogljikova vlakna, kompozit s kovinsko matrico iz Al zlitine, opazovanje mikrostrukture, testi lastnosti

## 1 INTRODUCTION

Carbon-fiber-reinforced aluminum matrix composites have broad applications in many fields, such as aerospace, automotive and mechanical engineering,<sup>1</sup> due to their high strength with light weight, high fracture toughness and good electrical and thermal conductivity.<sup>2,3</sup> Traditional preparation methods for carbon-fiber-reinforced aluminum matrix composites were subdivided into two categories: the liquid-state method and the solid-state method.<sup>4</sup> The typical liquid-state methods include: agitating casting,<sup>5</sup> extrusion casting,<sup>6</sup> vacuum pressure infiltration,<sup>7</sup> liquid-solid extrusion following

vacuum infiltration,<sup>8</sup> and so on.<sup>9,10</sup> VSC has a similar forming principle to the agitating casting method, which can be applied to prepare a carbon-fiber-reinforced aluminum matrix composite. Although VSC can make sure of the rapid filling and strong plasticity, the interfacial bond strength between the carbon fiber and the matrix need to be focused on. Some material defects such as fiber pull-out and holes can emerge at the interface of the carbon fiber and the matrix.

Many researchers stated that these defects could be effectively reduced by selecting the appropriate process parameters and adding Si and Mg to the aluminum alloy matrix. Z. G. Liu et al.<sup>11</sup> prepared Cf/Al materials by extrusion casting. The results show that the carbon fibers changed the solidification structure of the Al-Cu matrix

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alloys. S. R. Bakshi, et al.<sup>12</sup> analyzed the influence of the addition of Si and Mg on the interfacial reaction of the aluminum-based alloy matrix by TEM observation. C. Wang et al.<sup>13</sup> studied the effect of Mg content on the Cf/Al interface prepared using the pressure-infiltration method. Few publications can be found about the preparation of carbon-fiber-reinforced aluminum matrix composites using VSC, and the effect of carbon fiber content and Mg and Si on the composites was seldom reported.

The aim of this work is to prepare the Cf/Al-5Cu using the VSC method. Firstly, experiments were conducted to prepare composites with different carbon-fiber contents and different Mg and Si contents using the VSC technique. Secondly, the effects of carbon-fiber content and Mg and Si content on the microstructure, mechanical and electrical properties of aluminum alloy were studied. The reinforcing effect of carbon fiber on aluminum-based composites under different conditions was analyzed. Finally, good performance was obtained by optimizing the parameters of the carbon-fiber content and the Mg and Si content.

## 2. EXPERIMENTAL MATERIALS AND METHODS

### 2.1 Experimental procedure

Al-5Cu was selected as the matrix of the composite material. The T-1000 short carbon fiber (Cf) was selected as the reinforcing term. In order to study the effects of carbon-fiber content and elements content of Mg and Si on the material properties, the chemical compositions of the composite materials were listed in **Table 1**. Nine different specimens were prepared in this section.

**Table 1:** The chemical composition of the composite materials (in mass fractions (w/%))

Number	Carbon fiber	Mg	Si	Al-5Cu
1	0	0	0	Bal.
2	1	0	0	Bal.
3	2	0	0	Bal.
4	1	0.1	0	Bal.
5	1	0.2	0	Bal.
6	1	0.3	0	Bal.
7	1	0	0.1	Bal.
8	1	0	0.2	Bal.
9	1	0	0.3	Bal.

Short-carbon-fiber-reinforced aluminum matrix composites (Cf/Al-5Cu) were prepared by VSC. VSC is a precision casting process, which was completed by the coupling of gravity and suction under a high differential pressure.<sup>14,15</sup> This method has three advantages. First, the entire casting process was carried out under high vacuum, effectively avoiding the problem of alloy oxidation and impurity doping. Secondly, non-contact magnetic stirring can avoid the metal pollution caused by mechanical stirring. Finally, the use of suction coupled with

gravity increases the speed and success rate of traditional gravity casting. This method can be well applied to the preparation of composite materials. The process parameters of VSC are shown in **Table 2**.

**Table 2:** Process parameters to prepare Cf/Al-5Cu composites by VSC

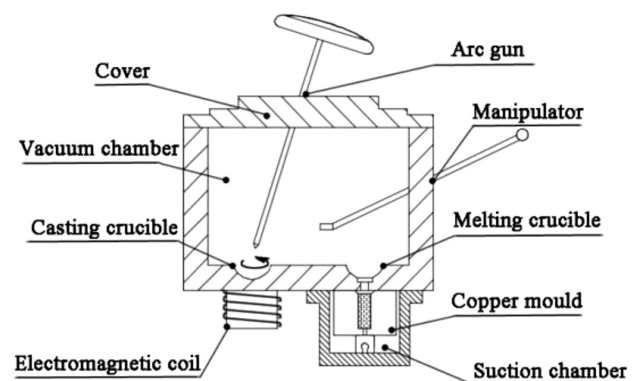
Vacuum degree (Pa)	Melting temperature (°C)	Smelting current (A)	Suction-hole diameter (mm)	Casting pressure (MPa)
$8 \times 10^{-4}$	$750 \approx 800$	0.15	3.5	0.65

Experiments were carried out on a VSC machine. A schematic diagram of the equipment is shown in **Figure 1**. The experimental steps were as follows:

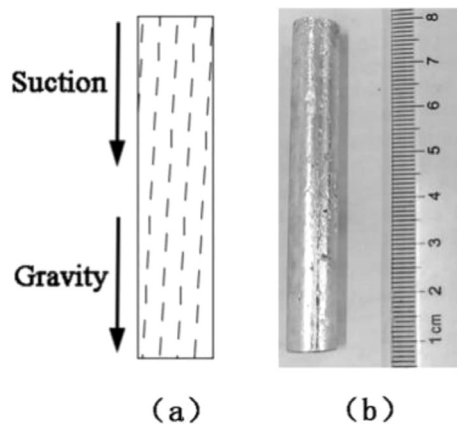
1) The aluminum alloy of Al-5Cu and short carbon fibers were placed in the melting crucible of the VSC equipment. Then, the cover was closed, and the vacuum chamber and the suction chamber were evacuated, and filled with a certain pressure of argon gas to make sure of the stability.

2) The arc gun was used to heat the aluminum alloy of Al-5Cu and short carbon fibers in the melting crucible. After the aluminum matrix material became a molten state, the electromagnetic stirring device was used to stir molten material with a rotating electromagnetic field until the short carbon fibers were uniformly distributed in the aluminum alloy matrix. It is experimentally observed that carbon fibers can be uniformly incorporated into metal liquids under the action of a magnetic stirring force, instead of floating on metal surfaces.

3) The carbon-fiber-reinforced aluminum matrix composite of the well-mixed molten state was transformed into the casting crucible by the manipulator. Opening the suction casting valve, a negative pressure difference was created between the vacuum chamber and the suction chamber. The well-mixed molten state composite passed through the graphite suction hole between the two chambers. It quickly filled into a copper mould under the effect of gravity and negative pressure difference. In order to improve the microstructure of the specimens, radial pressurization was conducted. A pressure of



**Figure 1:** Schematic diagram of VSC equipment



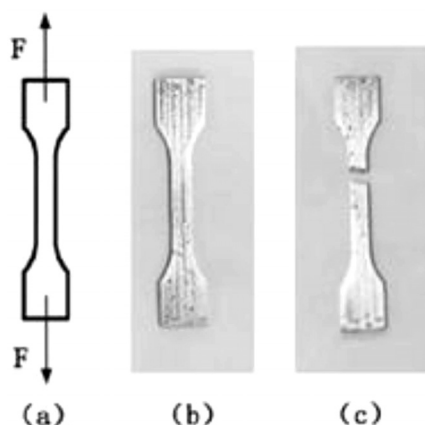
**Figure 2:** a) Schematic diagram of Cf/Al-5Cu composites and b) the specimen of the Cf/Al-5Cu composites

4 MPa was applied and held for 1 min. The pressure was applied repeatedly 6 times. The well-mixed molten state composite was solidified due to cooling of the copper mould, and the carbon fibers were evenly arranged along the axial direction of the casting, shown in **Figure 2a**.

4) The T5 heat treatment was carried out for prepared specimens.<sup>16,17</sup> It was held at 515 °C for 6 h using a box-type resistance furnace and then quenched with water at 50 °C. Thereafter, solution treatment was carried out, and the mixture was kept at 175 °C for 5 h, and then cooled and molded at room temperature. The specimens of Cf/Al-5Cu composites were obtained shown in **Figure 2b**.

## 2.2 Property tests and microstructure observation

Property tests include measuring the microhardness, measuring tensile strength and measuring electrical performance. The tensile strength of the composite material was measured using the JVJ-50s microcomputer-controlled electronic universal testing machine. The microhardness of the specimen was measured using an MHVD-1000IS image analysis multi-function digital microhardness tester. In the electrical performance tests,



**Figure 3:** The tensile specimen

the resistivity of the material was measured using a FT300 resistivity tester. The standard test samples were machined using a wire cutting machine. And then, the test pieces were grinded with a abrasive paper to remove the stress concentration generated by the wire-cutting process. **Figure 3** shows a tensile specimen. The tensile specimens were stretched to failure.

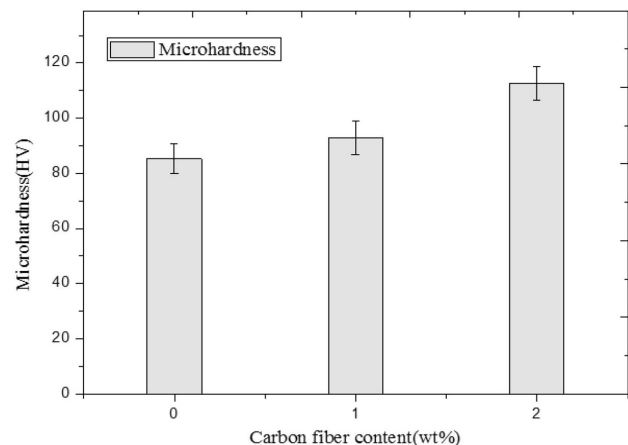
Before the microstructure observation, the specimens were sectioned, grinded by 800#, 1000#, 2000# waterproof abrasive paper and polished on a polishing machine. The polished surface was etched using an acidic solution (2 mL HF + 3 mL HCl + 5 mL HNO<sub>3</sub> + 190 mL H<sub>2</sub>O). Then, the polished surface was cleaned using alcohol and dried with a hair drier. The microstructures of the Cf/Al-5Cu composites were observed using a SM-6700F SEM.

## 3 EXPERIMENTAL RESULTS AND DISCUSSION

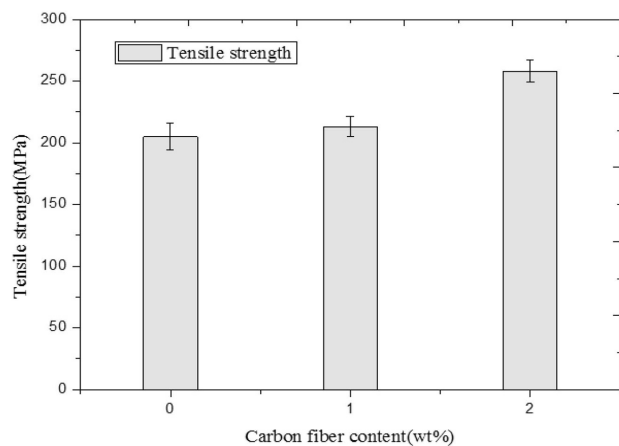
### 3.1 Effect of carbon-fiber content on the mechanical and electrical properties

**Figure 4** shows the microhardness of the Cf/Al-5Cu composites under different carbon fiber contents. It can be seen that the microhardness of the Cf/Al-5Cu composites increases with the increase of the carbon fiber content. The microhardness of the Cf/Al-5Cu composites was 112.6 HV under a carbon fiber of 2 wt%. Compared with the original alloy without carbon fiber, the microhardness increased by 26.1 % under carbon fiber of 2 wt%.

The tensile strength of the Cf/Al-5Cu composites under different carbon fiber content is shown in **Figure 5**. It can be seen that the tensile strength of the Cf/Al-5Cu composites increases with the increase of the carbon fiber content. The Cf/Al-5Cu composites with 2 wt% carbon fiber content had a tensile strength of 258.7 MPa, which is higher than that of the original aluminum alloy of about 26.1 %. As the carbon-fiber content increases, the number of carbon fibers contained in the matrix in-



**Figure 4:** Microhardness of Cf/Al-5Cu composites with different carbon-fiber contents

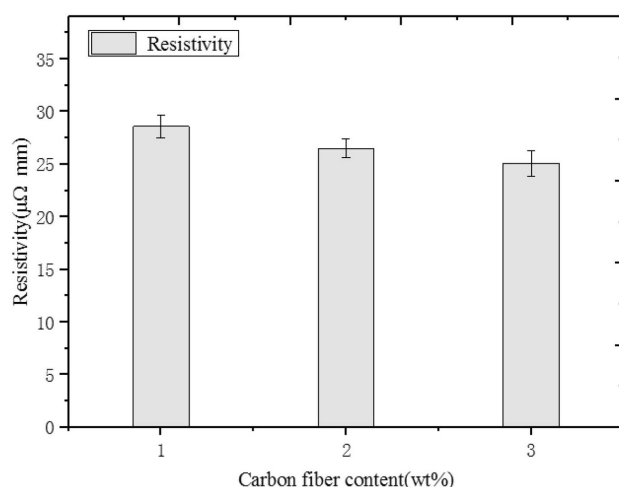


**Figure 5:** Tensile strength of Cf/Al-5Cu composites with different carbon-fiber contents

creases. The more the number of carbon fibers, the more obvious the increase of the bearing capacity. So, the mechanical properties of the Cf/Al-5Cu composites are improved. However, due to the difference in the elastic modulus between the carbon fiber and the base aluminum alloy, the interface bonding between the matrix alloy and the carbon fiber was restrained. This limited the reinforcing effect of the carbon fiber.

The resistivity of the Cf/Al-5Cu composites is shown in **Figure 6**. It can be seen that the resistivity of the Cf/Al-5Cu composites decreases with the increase of the carbon fiber content. When the carbon fiber content is 1 w%, the average volume resistivity of the composites is 28.6  $\mu\Omega/\text{mm}$ . This resistivity increases by 31.2 % compared to the original matrix of 21.8  $\mu\Omega/\text{mm}$ . When the carbon fiber content is 2 w%, the resistivity of the composite is 26.5  $\mu\Omega/\text{mm}$ . The resistivity of the material is reduced by 6.8  $\mu\Omega/\text{mm}$  compared to the 1 w% Cf/Al-5Cu composites.

This is because the higher the fiber content, the easier the fibers overlap each other. It is more conducive to the



**Figure 6:** Resistivity of Cf/Al-5Cu composites with different carbon-fiber contents

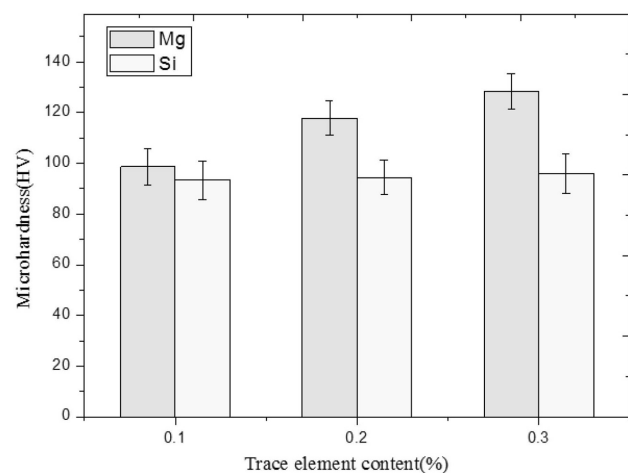
formation of conductive paths. Thereby, it can reduce the volume resistivity of the conductive composite. Within a certain range, a higher conductive carbon composite can be obtained by adding a higher carbon-fiber content.

### 3.2 Effect of elements content on mechanical and electrical properties

Since the surface energy of Si and Mg is lower than that of Al, the addition of Si and Mg can reduce the surface tension of the aluminum alloy matrix. Mg and Si can improve the wettability between the carbon fiber and the aluminum alloy matrix,<sup>18</sup> and improve the interfacial bonding. In the study, different contents of Mg and Si were added into the Cf/Al-5Cu alloy with 1 w% carbon fiber. And the mechanical and electrical properties of the composites were measured.

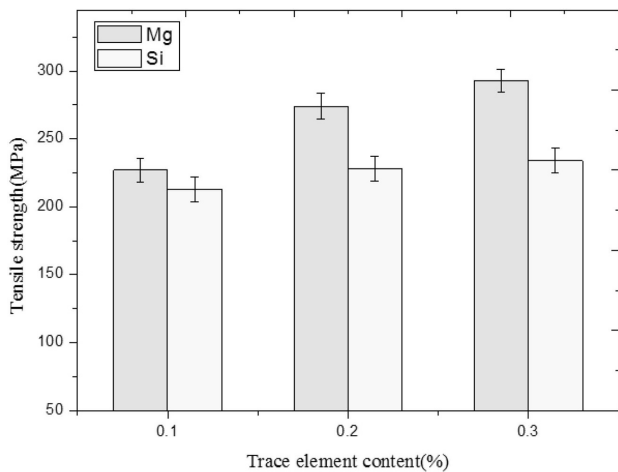
The microhardness of the composites with different Mg and Si contents is shown in **Figure 7**. It can be seen that both Mg and Si can improve the microhardness of the Cf/Al-5Cu composites. The effect of Mg on material properties is more obvious than that of Si. The microhardness increases with the increase of the element content. The microhardness of the Cf/Al-5Cu composites after adding 0.3 % Si element was 96.1 HV. With the addition of the same amount of Mg, the hardness was increased to 128.3 HV, which was higher than that of the same amount of Si-added material by about 33.5 %.

The tensile strength of the composites with different Mg and Si contents is shown in **Figure 8**. It can be seen that the addition of Si has no obvious effect on the tensile strength. The improvement effect of Mg is better than that of Si element. The addition of Mg element can effectively improve the tensile strength of the composites. When 0.3 % Mg is added, the tensile strength of the composites is increased to 294.7 MPa. The composite material obtained by adding the same amount of Si is 213.3 MPa, while the tensile strength was reduced by 38.2 %.



**Figure 7:** Microhardness of Cf/Al-5Cu composites with different Mg and Si contents

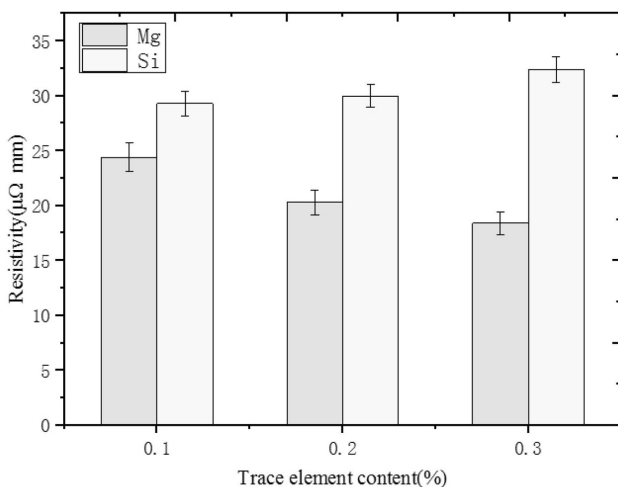




**Figure 8:** Tensile strength of Cf/Al-5Cu composites with different Mg and Si contents

This is mainly because the strengthening mechanism of Mg to the material is solid-solution strengthening. It is beneficial to improving the wettability between the carbon fiber and the alloy matrix, and reducing the harmful substances formed on the surface of the carbon fiber. Therefore, the addition of Mg can improve the mechanical properties of the material. However, Si belongs to the second phase in the composite material. Si does not work on the interface. Therefore, at low levels, the effect of Si on the performance of the composite is lower than that of the Mg on the mechanical properties.

The resistivity of the composites under 1 w/% carbon fiber with different Mg and Si contents is shown in **Figure 9**. The results show that with the increase of Mg, the resistivity of the 1 w/% Cf/Al-5Cu composites showed a downward trend. The resistivity of the composites added with 0.3 % Mg was 18.4  $\mu\Omega/\text{mm}$ . It is lower than that of the original material by 55 %. With the increase of Si, the resistivity of the composites exhibits an opposite upward trend. When the same mass fraction of Si was



**Figure 9:** Resistivity of Cf/Al-5Cu composites with different Mg and Si contents

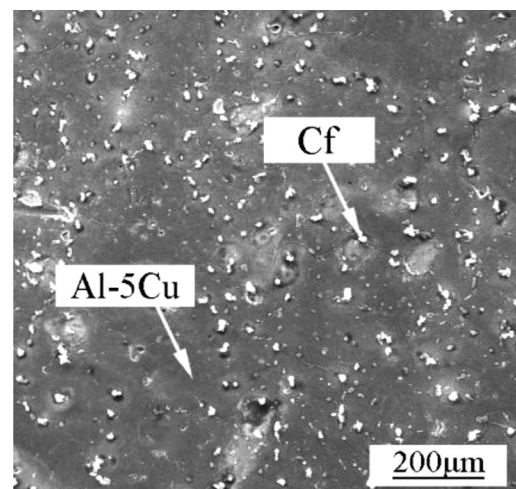
added, the resistivity of the composites was 32.4  $\mu\Omega/\text{mm}$ . It is higher than that of the original matrix by 13 %. This means that the conductivity of the material deteriorates.

This is because the Mg is distributed in the matrix with a dispersed form. This form increases the scattering of electrons in the propagation. Therefore, the addition of the Mg can significantly increase the electrical conductivity, thereby lowering the electrical resistivity. However, Si adversely affects the conductivity of the aluminum alloy conductor. In addition, Si also affects the casting properties and creates defects. Through the above analyses, the addition of Si leads to a decrease in the electrical conductivity, and the resistivity increases.

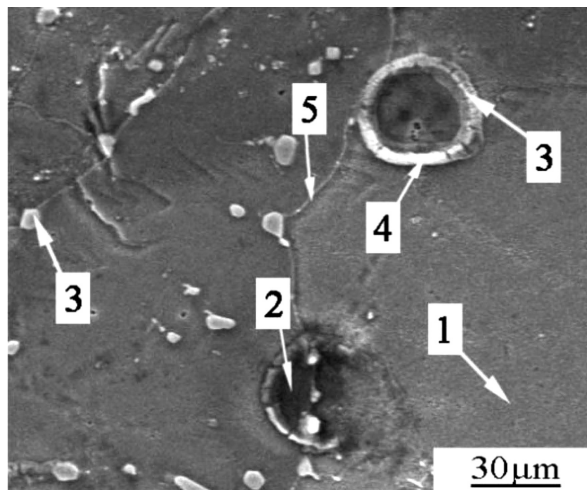
### 3.3 Microstructure observation and analysis

Above analyses show that the mechanical and electrical properties of the composite were the best by adding 0.3 % Mg element and 1 w/% carbon fiber. So, it is necessary to observe the microstructure of the composite with 0.3 % Mg and 1 w/% carbon fiber. As shown in **Figure 10**, it indicates that the fibers are arranged in the direction of suction. The Cf/Al-5Cu composites prepared by the VSC method have a uniform distribution. There are no obvious fiber agglomeration, breakage and drift phenomenon. The composite material has no defects such as shrinkage, cracks and voids. The carbon fibers were distributed in the axial section of the specimens.

As shown in **Figure 11**, the carbon fiber is mainly distributed in the grain boundary of the matrix alloy. Carbon fiber appears as a composite reinforcement in the material. The addition of carbon fibers makes the metal matrix undergo secondary phase strengthening, dislocation strengthening, and fine grain strengthening during the forming process. Therefore, the performance of the material is improved. However, the carbon fiber and the metal matrix produce an interfacial reaction during the casting process. Thereby,  $\text{Al}_4\text{C}_3$  phases were produced in



**Figure 10:** Microstructure morphology within the cross-section of the Cf/Al-5Cu composites with 1 w/% carbon fiber and 0.3 % Mg



**Figure 11:** Microstructure morphology within the cross-section of Cf / Al-5Cu composite with 1 w% carbon fiber and 0.3% Mg (1-Al-5Cu; 2-Cf; 3-Al<sub>4</sub>C<sub>3</sub>; 4-Mg; 5-Grain boundary)

the vicinity of the carbon fibers.<sup>19,20</sup> Part of the Al<sub>4</sub>C<sub>3</sub> phase is formed on the surface of the carbon fiber. Part of the Al<sub>4</sub>C<sub>3</sub> phase is distributed away from the carbon fibers in the composite matrix.

It can also be observed that the Mg is distributed on the surface of the carbon fiber.<sup>21</sup> This is because that the negative mixed enthalpy of Mg and C is the highest.<sup>22,23</sup> And Mg is easily bonded to the carbon fiber, so that Mg is found near the carbon fiber. The proper amount of Mg not only benefits the aluminum alloy matrix, but also improves the wettability of the carbon fiber and the aluminum. And it improves the combination of the carbon fiber and the aluminum. By adding Mg in the Cf/Al-5Cu composite, the interface strength between the carbon fiber and the aluminum alloy can be effectively improved.

#### 4 CONCLUSIONS

1) The VSC method can be applied to the preparation of Cf / Al-5Cu composites by selecting appropriate process parameters, including the melting temperature, the suction-hole diameter and the suction casting pressure.

2) The mechanical properties and electrical conductivity of the composite increase with increasing carbon fiber content. When the carbon fiber content is 2 %, the microhardness reaches 112.6 HV and the tensile strength of Cf/Al-5Cu reaches 258.7MPa. The resistivity is 26.5 μΩ/mm.

3) Both Mg and Si can improve the mechanical properties of the material. And Mg improved the mechanical properties of the material, which is better than that of Si. When the Mg content is 0.3 %, the tensile strength of Cf/Al-5Cu is the highest. The microhardness reaches 128.3 HV. And the tensile strength reaches 294.7 MPa, which is 38.2 % higher than that of Cf/Al-5Cu without addition. At the same time, Mg increases the electrical conductivity of the material. However, as the Si content increases, the resistivity of the material increases, and

the electrical conductivity of the composite material decreases accordingly.

4) The carbon fibers were arranged within the composite material along the direction of gravity and suction coupling after VSC. The carbon fibers were evenly distributed in the grain boundary of the composite material. By adding Mg to the Cf/Al-5Cu composite, the interface strength between the carbon fiber and the aluminum alloy can be effectively improved.

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