

THE ANALYSIS OF SURFACE MODIFICATION OF SiCp AND INTERFACE OF SiCp/A390 COMPOSITES

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ABSTRACT

SiC particles were washed by clear water and then heated at high temperature of 1000 °C. Powder mixture of A390 Al and heated SiC particles and non-heated SiC particles were prepared into 20% (mass fraction) SiCp/Al composites, consolidating by high-energy ball milling and powder metallurgy method. The microstructure of SiC particles before and after pretreatment and interface of SiCp/Al composites were observed by using transmission electron microscopy (TEM). The chemical compositions of surface substance of SiC particles and SiCp/Al composites were studied through X-ray photoelectron spectroscopy (XPS). The results show that: the surface of SiC particles after washing by water was proven to relatively obvious edges and corners, presenting a small amount of the adsorbed C or free C, free O and very few of the SiO on the surface without SiO₂. The surface of heated SiC particles has obvious characteristics of amorphous material, testing for very small amount of carbon adsorption or free C, free O, most amount of SiO₂ and a little of SiO. The interface microstructure of SiC and Al of non-heated SiCp reinforced Al composite was clean interface, appearing a little Al₂O₃, no harmful phase Al₄C₃. The interface microstructure of SiCp and Al of heated SiCp/Al composite was a distinct interface type named reaction interface, producing obvious chemical reaction between the interface of SiCp and Al, improved the tensile strength and elongation of the composites. In addition, the mechanism of oxidation behavior and calculation of film thickness of SiC particles were discussed.

1 INTRODUCTION

SiC particle is the most widely used ceramic reinforcement in Al-matrix composites due to its excellent physical and chemical properties, such as high temperature, high pressure, high vacuum, strong corrosion and irradiation, etc [1, 2]. In the preparation of the SiCp reinforced Al-matrix composites, including the powder metallurgy, the wettability and interfacial chemical products play a crucial role in determination of the ease of processing and the final properties of the composites; just as important for the liquid phase preparation method, such as stirring casting and melt infiltration and so on [3, 4]. The expansion coefficients changing controllably with the volume fraction of SiC, the material density of SiC particles reinforced aluminum alloys composite only about 1/6 of traditional W-Cu material, good thermal conductivity, high specific strength, and many other advantages; as a new type of composite material, it is one of the research hot points in today's Metal Matrix Composites [5]. A variety of SiC particles pretreatment methods appear, in order to improve the comprehensive properties of SiCp/Al composites, but conclusions of the impact of each kinds pretreatment methods on the properties of the composite materials are different [6, 7]. Although the wettability of SiC by molten Al has been investigated by many researchers, the recent survey on this issue reveals that conclusions and the interface reactions are not unified. The reactant (Al₂O₃) at the molten Al drop surface, the substance (Al₄C₃) could be inhibited easily [8]. The interface between metal matrix and ceramic reinforcement particles and particle surface characterization play an irreplaceable role in improving properties of the metal matrix composites. A large amount of research work have been invested above liquid and semisolid preparation methods for SiCp/Al composite materials; but for the powder metallurgy method of the composite interface reactions are less [9]. The extent of the interface reaction and products of SiC and Al deeply influence the bonding interface and the performance of the

composite materials. Interface bonding strength of SiC/Al and mechanical properties of the composite materials can be improved by the moderate interface reaction. Therefore, the particle surface state is particularly important for reinforcement of SiC. In this article, the SiC particles were washed by water and heated at high temperature of 1000 °C after water washing, and then aluminum matrix composites reinforced by SiC particle were prepared through high-energy ball milling and powder metallurgy method. The changes of morphology and compositions of SiC particles after two kinds of pretreatment were studied through transmission electron microscopy (TEM) and X-ray photoelectron spectroscopy (XPS). The oxidation kinetics and calculation of film thickness of SiC particles were discussed. The interface morphology chemical reaction between SiC and Al of SiCp/Al composites were also researched.

2 EXPERIMENTAL METHODS

SiC particles used in this study are β -SiC having an average particle size of 5 μm . A390 Al alloy powder having an average particulate size of 10.5 μm was chosen as raw matrix. The main chemical compositions are 19.3% Si, 1.2% Cu, 0.8% Mg, 0.5% Ni. In order to having a better understanding about morphology and chemical state of the particle surface, SiC particles were washed in distilled water first; heated in high temperature oxidation furnace, heating-up by 10 °C/min to 1000 °C, the time for oxidation process was 6 h, supplemented oxygen to ensure sufficient oxidation reaction during oxidation process every half hour. Transmission electron microscopy samples were prepared by copper grid. The morphology of SiC particles were observed by transmission electron microscopy (TEM) and compositions were studied by X-ray photoelectron spectroscopy (XPS).

A390 alloy matrix-20 wt. % SiC particles reinforced composites were prepared by high-energy ball milling and powder metallurgy method. The SiC particles after pretreatment and Al alloy were mixed well-distributed by the QM - BP type planetary ball milling and the process parameters were as following: the ratio of steel balls and materials for 2:1, the speed of ball-milling machine for 250 r/min, the time of ball milling for 4 h, adding 1% sodium stearate as dispersant. The mixtures (about 100 g) were pressed through TTD 32 four-column hydraulic, having pressure of 200 MPa for 50 min, unloading for 20 min. The compared semifinished products were sintered by the nitrogen protection sintering furnace, 2 °C/min up to 600 °C, staying heat for 3 h, cooling to room temperature along with the furnace. The sintered lumps were extruded by XJ-500 metal profile extrusion machine, extrusion ratio for 15:1, extrusion temperature for 500 °C, extrusion speed for 1 mm/s, to accomplish the preparation of SiCp/Al composite materials.

The SiCp/Al composite materials were dealt with heat treatment, having solid solution at 500 °C for 4 hours, aging at 200 °C for 6 hours.

The morphology and chemical valence states of SiCp and composite materials were observed by Transmission electron microscopy (TEM) and X-ray photoelectron spectroscopy (XPS). Analysis on the surface of SiC particles and interface of the composites was carried out, scanning all elements in the samples firstly, then separately analyzing separate elements to understand the related to element's states and chemical reactions of interface of composite materials.

The tensile strength of the composite was determined by SHIMADZU AG-I250KN precision universal testing machine at room temperature, and then the total amount of the sample after fracture was measured, and the elongation at break was calculated.

3 THE TEST RESULTS AND ANALYSIS

3.1 The microstructure of SiCp surface before and after the pretreatment

The characterization of nanoscale particle's surface has the certain difficulty by SEM photos. The microstructure surface of SiC particles after water washing and after high temperature heating by Transmission electron microscopy (TEM) were shown in Fig.1. The surface of SiC particles after the high temperature pretreatment generated a dense layer of amorphous SiO₂ layer, which was mentioned in literature [4]. The wetting of reinforced SiC particles and Al matrix was improved; the formation of harmful interface reactant Al₄C₃ was reduced by the dense layer of amorphous SiO₂ layer. But the

amorphous materials on the surface were not characterized, were identified to SiO₂ only by energy spectrum analysis of SiC particles and the related literature. The surface of SiC particles after washing by water was confirmed to "clean", having relatively obvious edges and corners at high magnification, which was shown in Fig.1 (a). TEM of SiC particles after washing by water be observed for obvious diffraction contrast, being the typical crystal structure, and the diffraction pattern was calibrated for the cubic system β -SiC, space group F - 43 m (216), the lattice constant of $a = 4.359 \text{ \AA}$. The microstructure of the SiC particles after the high temperature pretreatment seemed to be more rounded, smoother (Fig.1 b); having clearly about 50 nm material on the particle's surface, its diffraction spot to be dizzy ring, being obvious characteristics of amorphous material.

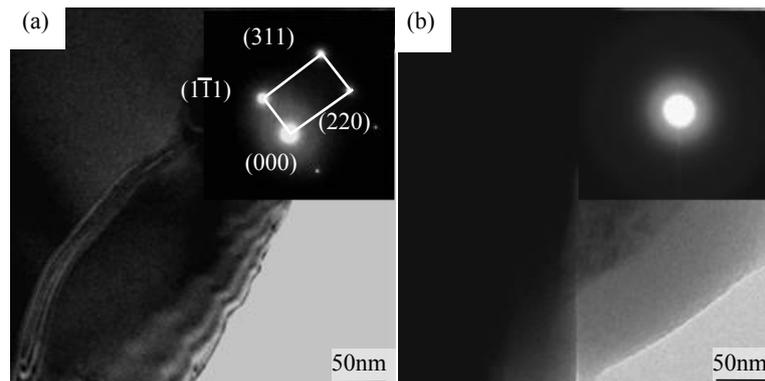


Fig.1 TEM of and diffraction pattern of SiC particles: (a) TEM original state SiC particles; (b) TEM and diffraction pattern of oxidized SiC particles.

3.2 The chemical state analysis of the surface of SiCp before and after the pretreatment

The material compositions of SiCp were studied by using XPS special testing for compositions of material surface. Firstly, fully compositional analysis on the two kinds of particles was carried out respectively, and then the elements of C, Si and O were scanned accurately one by one. The data were dealt with by using Multipak peak software, employing a standard free C of the binding energy 284.6 eV to correct data, and each element separately was splited, fitted peak, as shown in Fig.2. Fig.2 (b) showed the XPS survey spectrum of non-heated SiC particulates in the C1s region. The four peaks were appeared in the full spectrum, peak 284.6 eV and 282.4 eV, peak 286.3 eV and 288.8 eV after data fitting. According NIST XPS Database, standard binding energy of C in SiC is 282.4 eV; C-O and C-OO are 288.8 eV and 286.3 eV, respectively. The testing principle of XPS is that X-ray irradiates samples and launches the photoelectron, obtaining photoelectron intensity and energy by collecting the photoelectron, so it is very sensitive to C element. Fig.2 (b) showed that C element of the non-heated SiC were existed as most of the SiC, a small amount of the adsorption C or free C in the air, combining with photoelectron intensity. Instead, from the heated SiC particulates in the C1s region, peak of SiC did not seen, unless C-O and C-OO at 288.8 eV and 286.3 eV, as shown in Fig. 2 (e). Fig. 2(c) showed the XPS survey spectrum of non-heated SiC particulates in the Si 2p region. It was observed that the surface exhibited two significant levels of Si 2p core level from fitting peak. The binding energies of peaks were located at 100.2 eV and 101.3 eV, which corresponded to standard binding energy of SiC and SiO for 100.1 eV and 101.3 eV. Instead, two core levels of Si 2p were observed on the surface of heated particulates by fitting peak, as shown in Fig.2 (f). The binding energy at 101.3 eV and 103.4 eV were fixed for SiO and SiO₂. The volume ratio of SiO₂ to SiO could be estimated by calculating the area ratio of the deconvolution of the spectra as about 96:4. This meant that the oxidization thickness of heated SiC particulates was greater than 5nm, and most of the oxidization was proved to be SiO₂. Therefore, we got the conclusion that: a small amount of the adsorption C or free C, free O and very few of the SiO were presented on the surface of the non-heated SiC, no SiO₂; the surface of the heated treatment SiCp also had very small amounts of carbon adsorption or free C, free O, most amount of SiO₂ and a little of SiO. Accordingly, the heating treatment for the reinforcement is necessary.

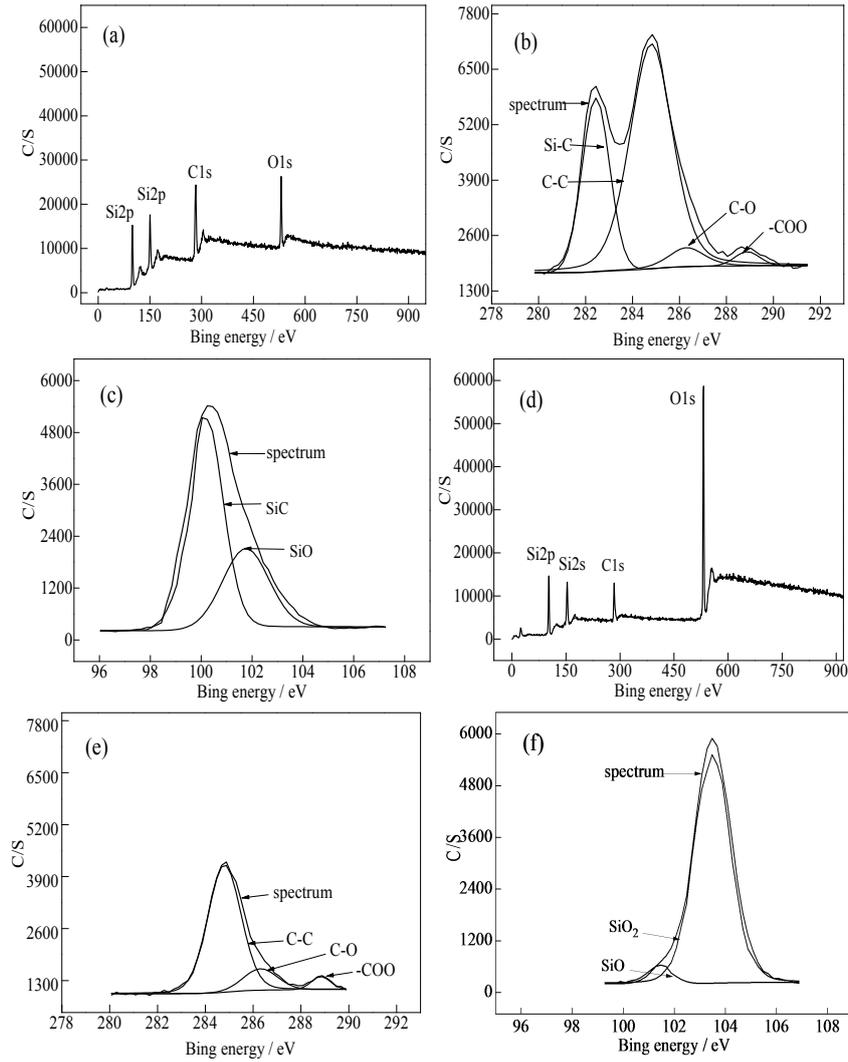


Fig.2 XPS of SiC particles: (a) the whole spectrum diagram of unheated SiC particles; (b) and (c) the peak fitting spectra of C1s and Si2p of non-heated SiC particles; (d) the whole spectrum diagram of heated SiC particles; (e) and (f) the peak fitting spectra of C1s and Si 2p of heated SiC particles.

3.3 The calculation of oxidized layer thickness of SiCp

The oxidation reaction steps of SiCp according to the principle of gas-solid reaction kinetics [10] were that: 1) O_2 molecules diffused to the surface of SiC particles; 2) the interface reaction happened on the particle's surface ($O_2 + SiC \rightarrow SiO + SiO_2 + CO + CO_2$); 3) O_2 molecules diffused inwards through surface oxidation after further reaction; 4) gas reaction products such as CO or CO_2 etc., spread outward through the surface of the oxidation.

In combination with the chemical oxidation reactions of SiCp, 1 mol SiC changed into 1 mol SiO_2 , having increment of 20 g in theory. Namely, 2 m g SiC generated 3 m g SiO_2 after oxidation reaction, increasing m g in weight. Assuming that the SiCp were the same rules for globule and equal grain size, the original radius of SiCp was r_1 , internal residual radius of SiCp for r_2 , the radius after oxidation for r_3 , the increased mass fraction of SiCp after oxidation reaction for w , the film thickness of SiO_2 oxidation reaction for $r_3 - r_2$. The present work reveals that the densities of amorphous SiO_2 and SiC are 2.196 g/cm^3 and 3.16 g/cm^3 . If the volume of SiCp before oxidation was v_{SiC} , weight of SiCp was $\rho_{SiC}v_{SiC}$, weight of SiCp after oxidation reaction was $(1 + w) \rho_{SiC}v_{SiC}$. The equations will be as follows:

$$\frac{4}{3} \pi (r_1^3 - r_2^3) \rho_{SiC} / \frac{4}{3} \pi (r_3^3 - r_2^3) \rho_{SiO_2} = \frac{2}{3} \quad (1)$$

$$\frac{4}{3}\pi r_2^3 \rho_{SiC} + \frac{4}{3}\pi (r_3^3 - r_2^3) \rho_{SiO_2} = (1+w) \frac{4}{3}\pi r_1^3 \rho_{SiC} \quad (2)$$

According to the equation (1) and (2), we could get the relations:

$$r_2 = (1+w)^{\frac{1}{3}} r_1 \quad (3)$$

$$r_3 = \left(\frac{3w\rho_{SiC}}{\rho_{SiO_2}} + 1 - 2w \right)^{\frac{1}{3}} r_1 \quad (4)$$

The film thickness (x) of SiO₂ after oxidation reaction was:

$$x = r_3 - r_2 = \left[\left(\frac{3w\rho_{SiC}}{\rho_{SiO_2}} + 1 - 2w \right)^{\frac{1}{3}} - (1-2w)^{\frac{1}{3}} \right] r_1 \quad (5)$$

In the formulas:

ρ_{SiC}, ρ_{SiO_2} — the densities of SiC and SiO₂, kg/m³;

w — the increased mass fraction of SiCp after oxidation reaction, %.

On the conditions that the original weight of the SiCp was m , specific surface area of original SiCp was s , the increased weight of SiCp was Δm , increment for oxidation of n particles, and d was the thickness of the SiCp oxidized. The thickness of generated SiO₂ was Nd , if the number of the oxidized SiC was N . The molar mass of SiC and SiO₂ were m_{SiC} and m_{SiO_2} respectively. The relations [11] between them are as the following:

$$n = \frac{m_{SiO_2}}{\rho_{SiO_2}} \cdot \frac{\rho_{SiC}}{m_{SiC}} \quad (6)$$

$$\frac{\Delta m}{s \cdot n} = \frac{nd \cdot s \cdot \rho_{SiO_2} - d \cdot s \cdot \rho_{SiC}}{s} \quad (7)$$

The thickness of the generated SiO₂ was x' :

$$x' = Nd = \frac{N}{N\rho_{SiO_2} - \rho_{SiC}} \cdot \frac{\Delta m}{s \cdot n} = \frac{N}{N\rho_{SiO_2} - \rho_{SiC}} \cdot \frac{\Delta m \cdot r_1 \cdot \rho_{SiC}}{3 \cdot m} \quad (8)$$

If SiCp oxidation weight percentage and the radius of the values were known, the formula (8) for calculating the thickness of the oxide generated SiO₂ is more simple and quick than formula (5). The two calculation methods are the basis of SiCp ball for ideal circular. In fact, the size and shap of SiCp was complex, so the method can only estimate the thickness of the oxide of SiCp quickly. The average weight gain of SiCp in different oxidation temperature and time and known data respectively were calculated into thickness by formulas (5) and (8). The theoretical thickness value of SiCp at different time and temperature were shown in Fig.3. The data showed that the calculation results were not big, and the formula (8) was relatively simple. The surface morphology of SiCp was observed at high magnification, heated at 1000 °C for 6 h, using transmission electron microscopy, as shown in Fig.1(b). We can clearly see that the surface oxidation film thickness of SiCp was about 50 nm. While the Fig.3 (a) shows that the calculated average thickness of SiO₂ was 87 nm.

In experiment, SiCp was not rules, and the throughout surface oxidation degree was different; but the result of the experiment was consistent with theory fact, The SiO₂ thickness calculation formula can be used. HuoYuzhu[12] studied the thermal oxidation of SiC chip, the oxide film thickness was

about 75 nm after 1200 °C, for 60 min. The average 87 nm in article is consistent with the value.

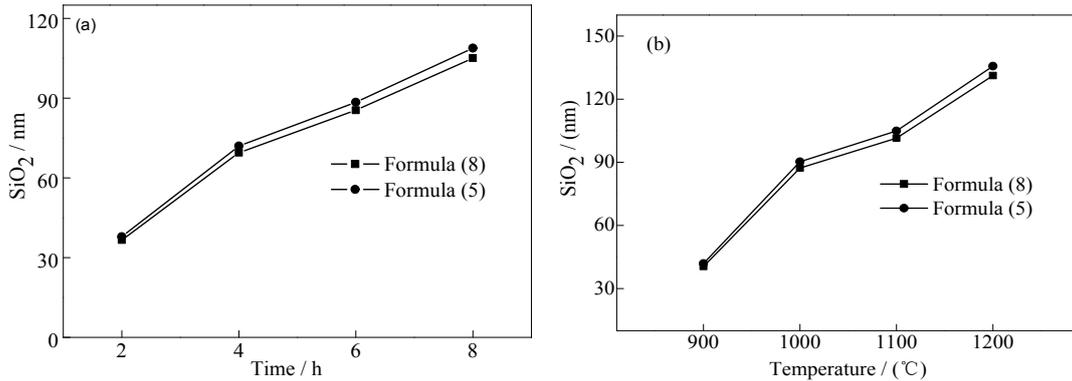


Fig.3 Thickness of SiO₂ under different time and temperature: (a) at 1000 °C for different time; (b) for 6h at different temperature.

3.4 The interface microstructure of SiCp/A390 composite

The microstructure and interface between metal matrix and ceramic reinforcement of a composite play an important role in improving its properties [13]. It has been proposed that Al element interface of composite was diffused, the diffusion interface between SiC particles and Al matrix can be infiltrated well, which made a good interface combination of composite[14]. Therefore, the interface microstructure of SiC and Al of SiCp/Al composite materials was observed by TEM, as shown in Fig.4. Fig.4 (a) showed the interface microstructure of non-heated SiCp reinforced Al composite, an interface type of SiC and Al named clean interface. The distinct interface of SiCp and Al and smooth border of interface could be observed exactly and obviously. There are no obvious interface chemical reaction and particle dissolution phenomena as well as cavity defects. Which showed that particle's surface had no obvious change, having compact structure, organize uniform in non-heated SiCp reinforced Al composite. The interface microstructure of SiCp and Al of heated SiCp reinforced Al composite was shown in Fig.4 (b). The plenty data show that composite materials still exists interface reactions in preparation by powder metallurgy, even low temperature in the preparation compared with the liquid phase methods relatively[15-17]. In Fig.4 (b), about 50 nm interface layer between SiCp and Al, completely different from the clean interface non-heated SiCp reinforced Al composite (Fig.4a), known as reaction interface. There was no doubt that some chemical reactions were produced between the surface of SiCp and Al. On basis of the analysis of the wettability, the reactive interface can improve the wettability of SiC and Al, to realize delivery of the load from the matrix to reinforcement effectively [18].

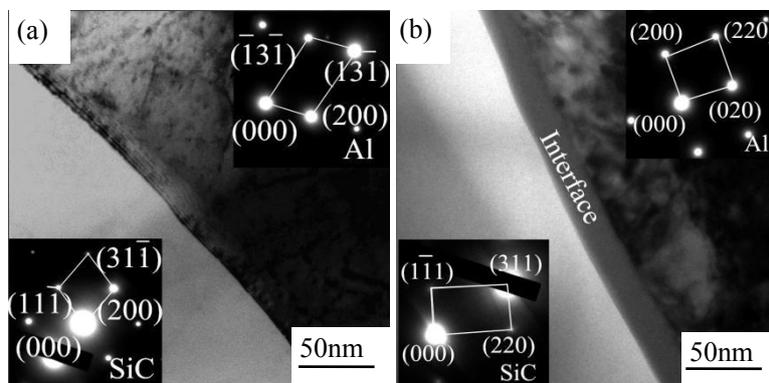


Fig.4: TEM of SiC and Al of SiCp/A390 composites: (a) original; (b) oxidation.

3.5 The chemical analysis of interface material of SiCp/A390 composites

In the previous investigation, at temperatures lower than 627 °C no reaction can occur between Al

and SiC, even during the prolonged period of heat treatment, no harmful phase Al_4C_3 identified at the interface of Al/SiC composites after the prolonged period of heat treatment at 575 °C for 48 h [19]. The temperature at which SiCp/Al composites were fabricated via ordinary PM method is always around the melting point of Al, and during the PM process it was difficult to inhibit the chemical reaction (9) at the interface between Al and SiC [15].



The interfacial phase Al_4C_3 forming in this reaction is a kind of brittle compound which can weaken the bonding strength of SiC/Al interface [20]. In this study, the severe hydro-static pressure during the extruding process may support the driving power of the harmful interaction which is equal to the thermal power during processing by PM.

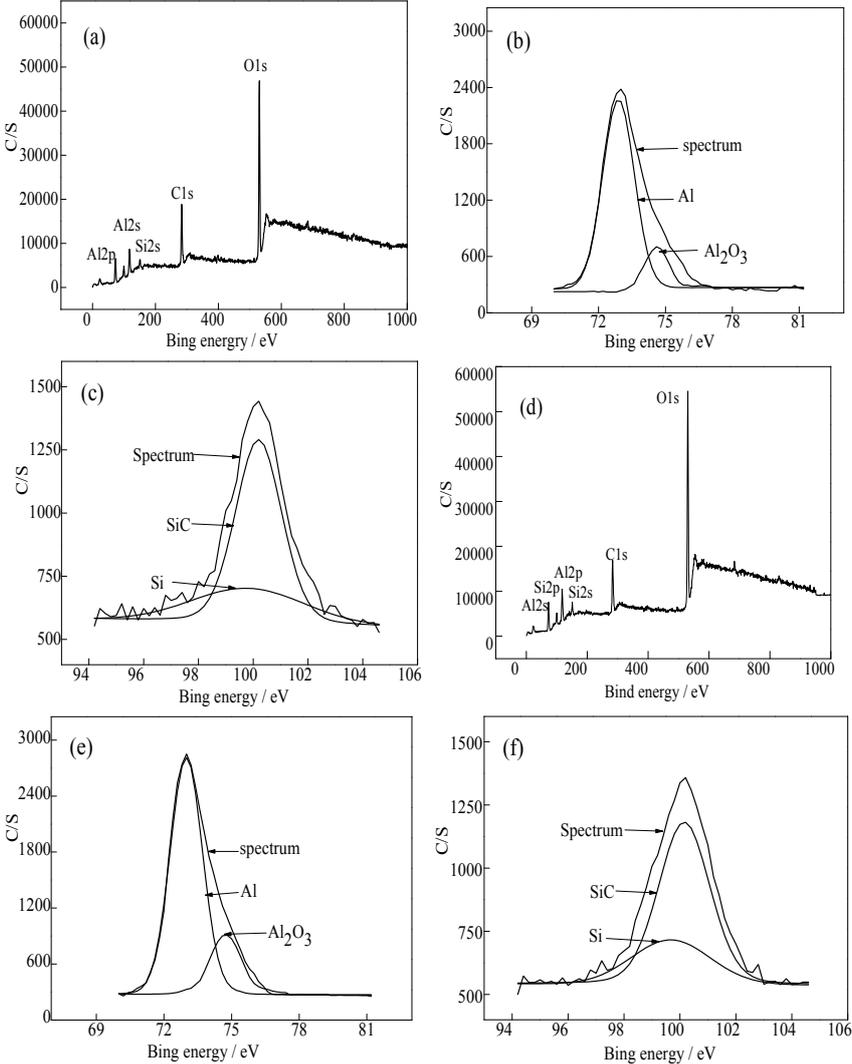


Fig.5 XPS of SiCp/Al composites: (a) the whole spectrum diagram of non-heated SiCp reinforced; (b) and (c) the peaks fitting spectra of C1s and Si 2p of non-heated SiCp reinforced; (d) the whole spectrum diagram of heated SiCp reinforced; (e) and (f) the peaks fitting spectra of C1s and Si2p of heated SiCp reinforced

The interface materials of two kinds of SiCp/Al composites were detected by XPS testing. Firstly, fully all compositional analysis was carried out on the two kinds of composites respectively, then spectra of the elements of Al, C, Si, O were accurately scanned using Multipak peak software to deal with the data, in a standard of the binding energy of free C located at 284.6 eV to revise the data, to

peak and fit the main elements of Al, Si and C and O independently, as shown in Fig.5. Fig.5 (b) showed the XPS survey spectrum of non-heated SiCp reinforced Al composite in the Al 2p region. It was observed that the XPS survey spectrum exhibited two significant level of Al 2p core level after fitting. The intensity peaks were located at 72.9 eV and 74.4 eV, which corresponded to Al and Al₂O₃ according NIST XPS Database, standard binding energy of Al in Al₂O₃ and elemental Al at 75.4 eV and 74.4eV. Meanwhile, no intensity peak appeared at 73.6 eV, which meant that the harmful phase Al₄C₃ was inhibited to generate. The same study was observed in Fig.5 (e), but Al peak strength namely quantitative analysis in Fig.5 (b,e) were the very different in composite materials. The materials can be analyzed in qualitative, content for semi-quantitative analysis by XPS testing, so the volume ratio of Al₂O₃ to Al on non-heated SiCp reinforced Al composite can be estimated by calculating the area of the two peaks as about 32.7:67.3, but which was about 39.6:60.4 on heated SiCp reinforced Al composite. Therefore, we could know the volume of Al₂O₃ on interface in heated SiCp reinforced Al composite increased significantly. Similarly, two core levels of Si 2p were observed in Fig.5(c,f). According to the binding energy of the spectra, we fixed the binding energy at 99.8 eV and 100.1eV for Si simple substance and SiC. The area ratio of peak Si to peak SiC were calculated as about 23.2:76.8 (Fig.5c) and 26.5:73.5 (Fig.5f) from the fitting curve. By the way, the volume of Si simple substance on interface in heated SiCp reinforced Al composite increased not obviously. Which still meant that the amount of reaction product Si rose up, an unavoidable for Si to solid solution in matrix Al when heating treatment.

The above analysis of chemical analysis of SiCp/Al composites favored the following reaction:



3.6 Effect of SiCp pretreatment on tensile properties of composites

The Fig. 6 was the tensile performance analysis chart of SiCp/A390 composites. The tensile strength of the original state SiCp/A390 composite was 223 MPa, which was seen from Fig.6 (a). And the tensile strength of high temperature oxidation state SiCp/A390 composite had reached to 310 MPa; increased 39% compared to the original state 223 MPa. The elongation of high temperature oxidation SiCp/A390 composite increased to 1.950% from 1.524% of the original state, increased by 0.426%, from Fig.6 (b) of elongation data. The strengthening mechanism shows that, strengthening of composite is mainly decided by microstructure and interfacial combination of composite, namely the morphology and size of SiCp, the distribution of SiCp in the composite and the interface between SiCp and Al. SiCp was oxidized and grain boundaries became more rounded and dispersed more evenly in the mixing and hot extrusion process of the preparation. The obvious phase interface (Fig. 4(b)) between SiC and Al improved the bonding strength of the interface, improved transfer capacity of the load between the particle matrix, and ultimately improved the tensile strength and elongation of the composite. Then the overall properties of the composites were improved.

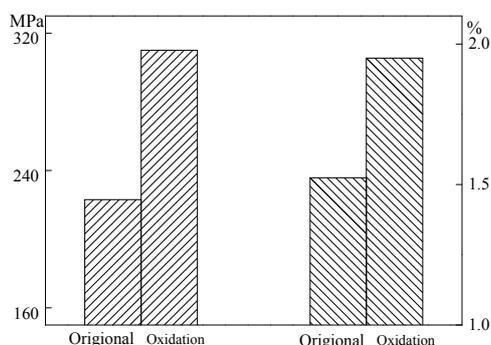


Fig.6 Tensile strength and elongation data of composites: (a) tensile strength; (b) elongation

3.7 Effect of SiCp pretreatment on the fracture morphology of composites

During tensile deformation, the difference of elastic and plastic deformation properties of Al

alloy matrix and SiCp is very big, which lead to stress concentration between SiCp and Al at the interface, and form the source of crack, then break. From Fig.7 (a), the fracture morphology of original SiCp/A390, fracture toughness was irregular. From it, the kind of nest was caused by partial matrix tear due to SiCp particle reunion. It showed that the SiCp particles fall off from the matrix and matrix crack. According to poor plasticity and low elongation, the fracture form belonged to brittle fracture. From Fig.7 (b), the fracture morphology of oxidized SiCp/A390, the nest was shape the rules, and the size was relatively consistent, tear face narrow, which showed that plastic slightly was better than original SiCp/A390, and belonged to brittle ductile fracture. High temperature oxidation treatment improved the SiCp morphology, and reduced the stress concentration on the matrix of reinforcing particles, then reduced the tendency of the interface crack. The increased interface between SiCp and Al could transfer the load to SiCp from Al matrix, then little toughening dimple into “big dimple”. In the end, the overall performance of oxidized SiCp/A390 is improved than the original SiCp/A390 composite.

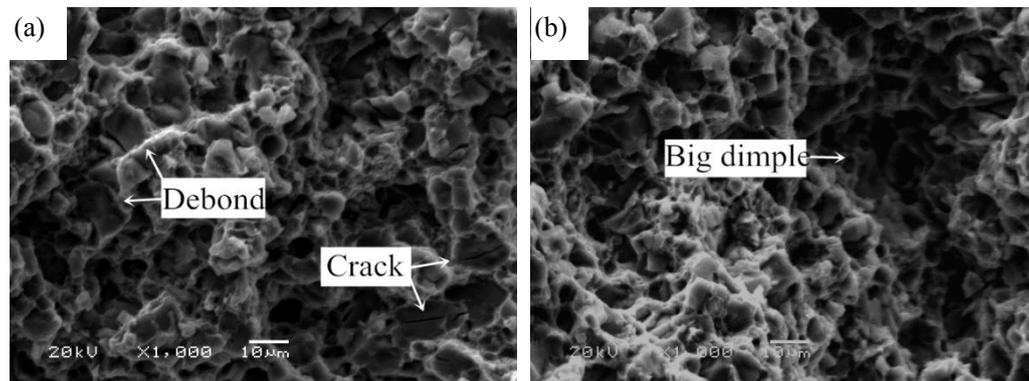


Fig.7 fracture morphology of SiCp/A390 composites: (a) original; (b) oxidation

4 CONCLUSIONS

The surface of SiC particles after washing by water was proven to "clean", having relatively obvious edges and corners at high magnification observed by TEM; presenting a small amount of the adsorption C or free C, free O and very few of the SiO on the surface, no SiO₂, though analysis of XPS tests.

The surface of heated SiC particles having clearly about 50 nm material on the particle's surface, being obvious characteristics of amorphous material though TEM photos, had very small amounts of carbon adsorption or free C, free O, most amount of SiO₂ and a little of SiO, measured via XPS survey spectrum.

The interface microstructure of SiC and Al of non-heated SiCp reinforced Al composite was clean interface, appearing Al₂O₃ and elemental Al on the interface surface from the XPS survey spectrum, no harmful phase Al₄C₃.

The interface microstructure of SiCp and Al of heated SiCp/Al composite was a distinct interface type named reaction interface, about 50 nm interface layer, no doubt that some chemical reactions were produced between the interface of SiCp and Al. The tensile strength and elongation of the oxidized composite had been obviously improved.

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REFERENCES

- [1] LIU Pei, WANG Ai-qin, HAO Shi-ming, XIE Jing-pe, Microstructure Evolution of SiCp /2024Al Composite During Heat Treatment, *Transactions of Materials and Heat Treatment*, **36**, 2015, pp. 8-14

- [2] SHI Zhong-liang, LIU Jun-you, GU Ming-yuan et al., Interfacial Characteristics of SiC Particles Reinforced Aluminum Matrix Composites, *Journal of Chinese Electron Microscopy Society*, **21**, 2002, pp. 52-55
- [3] LIU Jun-you, LIU Ying-cai, LIU Guo-quan, Oxidation Behavior of Silicon Carbide Particles and Their Interfacial Characterization in Aluminum Matrix Composites, *The Chinese Journal of Nonferrous Metals*, **12**, 2002, pp. 961-966
- [4] GUO Jian, LIU Xiu-bo. Effect of Pre-heating Processing of SiC Particles on Porosity of SiCp/Al Composites, *Transactions of Materials and Heat Treatment*, **27**, 2006, pp. 20-22
- [5] WANG Chuan-ting, Ma Li-qun, YIN Ming-yong, LIU Zhen-yun, DING Yi, ZHANG Hua, CHEN Yu-gui. Effects of SiC Particles Oxidation on the Wettability and Interfacial Bonding of SiC-p/Al Composites, *Special Casting & Nonferrous Alloys*, **30**, 2010, pp. 1062-1065
- [6] Chun-xue MA, Jia-kang, YU Chuen XUE, Zhi-qing ZHANG, Interfacial Reactions and Bending Strength of SiC/A356/FeNi50 Composite Fabricated by Gas Pressure Infiltration, *Transactions of Nonferrous Metals Society of China*, **8**, 2013, pp. 2229-2235
- [7] YAN Li-peng, WANG Ai-qin, XIE Jing-pei, WANG Hang, Interface Reaction Mechanism of SiC Reinforced Al-30Si alloy Composites, *Materials Science and Engineering of Powder Metallurgy*, **19**, 2014, pp. 191-196.
- [8] Ping Shen, Yi Wang, Li-hua Ren, Shi-xin Li, Yu-hua Liu, Qi-chuan Jiang, Influence of SiC Surface Polarity on the Wettability and Reactivity in an Al/SiC system, *Applied Surface Science*, **355**, 2015, pp. 930-938
- [9] LIU Xiao-fei, LIU Yan-qiang, FAN Jian-zhong, WEI Shao-hua, MA Zi-li, ZUO Tao, Microstructure and Properties of SiCp/Al-Cu Composites Fabricated by Hot Isostatic Pressing, *The Chinese Journal of Nonferrous Metals*, **22**, 2012, pp. 3059-3065
- [10] LI Yu-hai, HUANG Xiao-ying, WANG Cheng-zhi, LI Ying, High Temperature Oxidation Kinetics of SiC Particles, *Chinese Journal of Materials Research*, **23**, 2009, pp. 582-586.
- [11] GAO Ying. Oxidation Behavior of SiC/Si₃N₄-SiC in Middle-high Temperature, *Xian University of Architecture and Technology*, 2007, pp. 34-65
- [12] Huo Yuzhu, Shang Qingjie, Pan Hongshu, Study on High Temperature Oxidation in SiC Process, *Process Technique and Materials*, **35**, 2010, pp. 980-982
- [13] Guoju Li, Xu Zhang, Qunbo Fan, Process Technique and Materials Simulation of damage and Failure Processes of Interpenetrating SiC/Al Composites Subjected to Dynamic Compressive Loading, *Acta Materialia*, **78**, 2014, pp. 190-202
- [14] Y.Q. Wang, X.J. Wang, W.X. Gong, K. Wu, F.H. Wang, Effect of SiC Particles on Microarc Oxidation Process of Magnesium Matrix Composites, *Applied Surface Science*, **283**, 2013, pp. 906-913
- [15] Chen-hao QIAN, Ping LI, Ke-min XUE, Influence of Deformation Passes on Interface of SiCp/Al Composites Consolidated by Equal Channel Angular Pressing and Torsion, *Transactions of Nonferrous Metals Society of China*, **25**, 2015, pp. 1376-1382
- [16] FAN Jian-zhong, ZUO Tao, XU Jun, SHI Li-kai, Interface Structure of SiCp / Composites Fabricated by High-energy Ball Mill Conjunction with Powder Metallurgy, *Chinese Journal of Rare Metals*, **28**, 2004, pp. 648-651
- [17] PUROHIT R, SAGAR R, Fabrication and Testing of Al-SiCp Composite Poppet Valve Guides, *The International Journal of Advanced Manufacturing Technology*, **51**, 2010, pp. 685-698
- [18] Fan Tongxiang, Zhang D, Yang G, Shibayanagi T, Naka M, Sakata T, et al, Chemical Reaction of SiCp/Al Composites During Multiple Remelting, *Composites: part A*, **34**, 2003, pp. 291-299
- [19] Durbadal Mandal, Srinath Viswanathan, Effect of Heat Treatment on Microstructure and Interface of SiC Particle Reinforced 2124 Al Matrix Composite, *Materials Characterization*, **85**, 2013, pp. 73-81
- [20] A. Bahrami, M.I. Pech-Canul, C.A. Gutierrez, N. Soltani. Effect of Rice-husk ash on Properties of Laminated and Functionally Graded Al/SiC Composites by One-step Pressureless Infiltration, *Journal of Alloys and Compounds*, **644**, 2015, pp. 256-266