Electrical Discharge Machining of Al2024-65 vol% SiC Composites

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Abstract In the present work, the wire electrical discharge machining (WEDM) process of the 65 vol% SiCp/2024Al composite prepared by pressure infiltration methods has been investigated. The microstructure of the machined composite was characterized by scanning electron microscope, the average surface roughness (Ra), X-ray diffraction, X-ray photoelectron spectroscopy and transmission electron microscopy (TEM) techniques. Three zones from the surface to the interior (melting zone, heat affected zone and un-affected zone) were found in the machined composites, while the face of SiC particles on the surface toward the outside was “cut” to be flat. Increase in Al and Si but decrease in C and O were observed in the core areas of the removed particles. Si phase, which was generated due to the decomposition of SiC, was detected after the WEDM process. The irregular and spherical particles were further observed by TEM. Based on the microstructure observation, it is suggested that the machining mechanism of 65 vol% SiCp/2024Al composite was the combination of the melting of Al matrix and the decomposition of SiC particles.

KEY WORDS: Metal matrix composites; SiCp/Al composite; Metal infiltration; Wire electrical discharge machining (WEDM); SiC decomposition; Machining mechanism

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1 Introduction

Al matrix composites [1] have been paid great attention due to their high specific stiffness and strength, good corrosion resistance, low coefficient of thermal expansion and high dimensional stability. Compared with other ceramic particles (such as Al₂O₃, TiB₂, B₄C, TiC and Si₃N₄), SiC particles have the comprehensive advantage of low cost, low density, high elastic modulus, high thermal conductivity and good bonding with Al matrix [2]. Therefore, SiC particles reinforced Al matrix composites have been extensively explored and are widely used in aerospace industry [3] and brake systems for automobile [4].

After several decades of research, the main problems for preparing high quality and industrial quantity SiCp/Al composites have recently been overcome. Several methods, such as powder metallurgy [5–8], stir casting technique [9–12], spraying process [13, 14], friction stir welding [15, 16] and pressure infiltration method [17, 18] have been

used to prepare SiCp/Al composites. Powder metallurgy is a very effective method to prepare Al matrix composites with low content reinforcements [5–8]. The stir casting has the advantage of being low cost [9–11]. However, the limitations of stir casting are poor distribution, wettability, porosity, interfacial reaction and moderate volume fraction [12]. Generally, pressure infiltration method is an effective technique to fabricate poor-wetting system through forcing infiltration of molten metal alloy into the preform under high pressure, and the main advantages of pressure infiltration method include simplicity in preparation process, high quality (especially high relative density) in composites and no restrictions on the composition of the matrix alloys [19–21].

Machining the SiCp/Al composites to components is another issue that still limits their application. Several methods, such as cutting [22], grinding [23], laser-cutting [24] and wire electrical discharge machining (WEDM) [25], have been used to machine SiCp/Al composites. Cutting methods and tools have been widely investigated. It has been evidenced that polycrystalline diamond (PCD) cutting tools are more suitable for machine precision SiCp/Al components rather than the traditional cemented carbide cutting tools [26, 27]. However, the cost of the PCD tools is very high. Compared with the cost of the PCD cutting tools, the machining cost of the WEDM is much lower. Therefore, for components with less dimensional accuracy, such as the blank pieces, the WEDM has been considered as the most suitable machining method for SiCp/Al composites.

The WEDM machining processes of Al matrix composites have recently been investigated. Ramulu and Taya [28] found that the material removal rates of 15 and 25 vol% SiCw/Al composites were increased with the power of electrode. Moreover, surface softening and micro-damage on the surface/subsurface area were found in the low and high cutting speed, respectively [28]. De Silva and Rankine [29] observed that the Al matrix surrounding the SiC particles was melted, and the SiC particles were then dislodged from the matrix and flushed away by the dielectric fluid. Ramulu *et al.* [30] further found that the surface integrity effects of 15 vol% SiCp/A336 composite after machining included surface roughness caused by deposition of recast layer, pitting of surface, surface micro-cracks and slight material softening below recast layer [30]. They also observed that the material softening was taken place up to depth of approximately 200 μm below recast layer [30]. Mohan *et al.* [31] investigated the machining process of 20 and 25 vol% SiCp/Al composites and concluded that the materials removing rate (MRR) was increased with the current. Moreover, the MRR was decreased while the surface roughness was increased with increasing SiC amount [31].

The current research is mainly focused on the influence of process parameters on the performance of low volume content SiCp/Al composites (<25 vol%). However, research on high volume content SiCp/Al composites (higher than 35 vol%) has been rarely reported. Moreover, it is usually considered that the machining mechanism of the WEDM process in SiCp/Al composites (<25 vol%) is the molten of Al matrix, while SiC particles would be then dislodged from the matrix and flushed away by the dielectric fluid [29]. However, at high volume content SiCp/Al composites (higher than 35 vol%), the effect of SiC particles on the machining process could not be neglected, and the corresponding mechanism has not been investigated. Patel *et al.* [32] investigated the WEDM removal mechanism of SiC whisker reinforced Al_2O_3 composite and found that the mechanism was predominately dissociation, melting and evaporation, and to some extent, oxidization and decomposition at lower current range. It is indicated that the SiC could be affected during the WEDM process.

The present work is mainly focused on the WEDM process of high volume content SiCp/Al composite, which has been rarely explored. 65 vol% SiCp/2024Al composite was prepared by pressure infiltration methods and was subsequently machined by the WEDM. Microstructure of SiCp/2024Al composite after the WEDM process was investigated. Moreover, the removed products of the WEDM process were collected and characterized, and afterward the machining mechanism of the WEDM process for SiCp/Al composites was further discussed.

2 Experimental

In order to increase the amount of SiC particles to highlight their roles, 30 and 10 μm α -SiC particles with a ratio of 3:1 were used as reinforcement. The morphology of the raw SiC particles is shown in Fig. 1. The chemical composition of 2024Al matrix alloys has been listed in Table 1. The 65 vol% SiCp/2024Al composite was prepared by pressure infiltration method. The preform of 65 vol% SiC particles was first fabricated and preheated. The raw SiC particles with measured weight were put into a steel mold and eventually were pressed at about 5 MPa to the set height (65 vol%). The preheating temperatures for the preform and pressure infiltration dies were 500 and 770 $^{\circ}\text{C}$, respectively. The matrix alloy was melted under protection of argon (Ar) and poured into dies at 760–770 $^{\circ}\text{C}$ in the presence of Ar. During the infiltration process, a pressure of 5 MPa was applied and maintained for 10 min, followed by the solidification of the composites in air. Before the machining process, aging treatment was performed on the samples. The composite specimens were solution treated at

Fig. 1 Representative SEM morphologies of SiC particles. **a** Low magnification, **b** high magnification

Table 1 Chemical composition of 2024Al matrix alloy (mass fraction, %)

Cu	Mg	Mn	Fe	Si	Zn	Cr	Ti	Ni	Al
4.79	1.49	0.611	0.245	0.168	0.068	0.049	0.046	0.013	Balance

Table 2 Basic properties of the 65 vol% SiCp/2024Al composite

Density (g/cm ³)	Porosity (%)	Elastic modulus (GPa)	Hardness (HB)	Bending strength (MPa)	Electrical conductivity (IACS%)
2.99	1.6	167	265	622	18

470 °C in KNO₃ salt bath furnace for 1 h and water quenched to room temperature. After solution treatment, specimens were aged at 120 °C/24 h and cooled under air. The basic properties of 65 vol% SiCp/2024Al composite are listed in Table 2.

The WEDM was performed on a commercial machine (DK7752E, Suzhou Jingma Machinery & Electronics Co., Ltd, China). Mo wire (0.5 mm in diameter) was used in the present work for machining, and peak current, pulse width and pulse interval were fixed at 3.5 A, 9 and 4 μs, respectively. The feed rate of the Mo wire during machining was about 0.5 mm/min. The composites of cuboid bars (60 mm × 20 mm × 20 mm) have been used for investigation. Before machining, the WEDM equipment was carefully cleaned. During the WEDM process, fresh mixture of emulsified oil (Huarun, Jinan Suntory Tungsten and Molybdenum Metal, Ltd. China) and water was used. After 24 h WEDM, the emulsion with removed products was collected. After water washed, the collected products were then washed three times with ethanol to further remove the emulsion.

The microstructure of the SiCp/2024Al composite and the removed products were observed under an FEI Sirion

Quanta 200 scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). The average surface roughness (Ra) was measured by using a contact-based surface roughness tester (SV-3000S4, Mitutoyo, Tokyo, Japan). X-ray diffraction (XRD) analysis was carried out under a Rigaku D/max-rB diffractometer. The specimens were subjected to CuKα radiation (0.15418 nm) with a scanning speed set at 2°/min. 2θ scans were performed between 15° and 90°. X-ray photoelectron spectroscopy (XPS) studies were performed on a PHI 5700 ESCA XPS with a hemispherical analyzer and an AlKα radiation source (1486.6 eV). The microstructure of the removed products was further observed by high-resolution transmission electron microscopy (HRTEM, JEM-2010F).

3 Results and Discussion

3.1 Microstructure of SiCp/2024Al Composite

As shown in Table 2, the density of the 65 vol% SiCp/2024Al composite was about 2.99 g/cm³, while its calculated relative density was about 98.4%, indicating the

dense microstructure of the composites with the advantage of the pressure infiltration methods. The microstructure of 65 vol% SiCp/2024Al composite after polishing is shown in Fig. 2a, and very few pores could be found. Moreover, it is clear that the SiC particles were uniformly distributed within the composite (Fig. 2a). However, after the WEDM process, some pores were observed on the surface of the SiCp/2024Al composite (Fig. 2b).

The material removal rate (MRR) of 65 vol% SiCp/2024Al composite machined by WEDM, which is the product of feed rate multiplicities thickness of the composite specimens, was about $15 \text{ mm}^2/\text{min}$, slightly lower than the conventional metal materials [33]. The WEDM process involves the movement of the Mo wires, and the MRR is significantly affected by the machining mechanism and the electrical conductivity of the materials. If the material is very hard with high melting point or the electrical conductivity is very low, the movement of the wires could be inhibited. For 65 vol% SiCp/2024Al composite with high hardness, high melting point (for SiC particles) and low electrical conductivity (Table 2), it is suggested to choose a relatively low MRR in trade of efficiency. Otherwise, the Mo wires will be easily damaged.

Moreover, the representative roughness profiles of the 65 vol% SiCp/2024Al composite after the WEDM process are shown in Fig. 3. The average roughness of 65 vol% SiCp/2024Al composite after the WEDM process was about $2.8 \text{ }\mu\text{m}$ while the maximum roughness was about $9.7 \text{ }\mu\text{m}$, respectively. The WEDM process demonstrated relative good machining quality. However, it is proposed that the large size of SiC particles (about $30 \text{ }\mu\text{m}$) has a significant effect on the surface roughness of the composite.

Cross-sectional microstructure of 65 vol% SiCp/2024Al composite after the WEDM process was further observed, as shown in Fig. 4a. It is obvious that 65 vol% SiCp/

Fig. 3 Representative roughness profiles of the 65 vol% SiCp/2024Al composite after the WEDM process

2024Al composite after the WEDM process was composed of three zones from the surface to the interior (Fig. 4a, b): melting zone (or recasting zone), heat affected zone and un-affected zone. This result is similar to that of Ramulu and Taya [28] and Ramulu et al. [30] in low content SiCp/Al composite. The melting zone was not dense, with some pores (Fig. 4a), which was similar to the microstructure on the surface. The formation of the porous melting zone should be due to the rapid molten/solidification process of Al matrix during the WEDM process [29]. The heat affected zone was rather dense with a few pores, and the amount of SiC particles in the heat affected zone, especially the larger SiC particles, was slightly higher than that in the un-affected zones (Fig. 4a). Compared with SiC particles, molten Al was easier to be washed away by the emulsion, leading to the re-arrangement of SiC particles and increase in the reinforcement amount in this zone. Although microstructure of the SiCp/2024Al composite after the WEDM process was divided into the three zones, it should be noted that there was not distinct boundaries between the adjacent zones.

In order to understand the effect of SiC particles during the WEDM process, the microstructure of the residual SiC particles on the surface was observed, as shown in Fig. 5a,

Fig. 2 Representative surface morphologies of 65 vol% SiCp/2024Al composite after **a** polishing, **b** the WEDM process

Fig. 4 Cross-sectional microstructure of 65 vol% SiCp/2024Al composite after the WEDM process: **a** SEM observation result, **b** corresponding schematic diagram

Fig. 5 Microstructure of the residual SiC particles on the surface after the WEDM process: **a** SEM observation, **b** magnification of red box area in **a**, **c** corresponding schematic diagram of **b**

b. The surface of the 65 vol% SiCp/2024Al composite after the WEDM process was not flat but in wave shape. Moreover, it is obvious that no outcrop SiC particle was observed, while the face of SiC particles on the surface toward the outside was “cut” to be flat. Since the melting/decomposition temperature of SiC particles is very high (2730 °C) [14], it is usually considered that the SiC is slightly affected by the WEDM process [29]. However, according to this theory, the SiC particles on the surface point should be outcrop and have the morphology shown in Fig. 5c with the striped parts, which is not consistent with the SEM observation results (Fig. 5a, b). Therefore, SiC particles should also be affected and machined during the WEDM process, but the corresponding mechanism could not be obtained through the microstructure observation of the SiCp/2024Al composite.

3.2 Characterization of the Removed Products

3.2.1 Morphology of the Removed Products

In order to understand the machining mechanism of the SiCp/2024Al composite, particularly the “cutting”

mechanism of SiC particles, the removed products were collected and characterized. Representative morphology of the removed products is shown in Fig. 6a, b, respectively. Three kinds of the removed products were observed: small irregular particles (marked by red box in Fig. 6a), small spherical particles (marked by blue box in Fig. 6a) and large irregular particles (marked by green box in Fig. 6b). EDS analysis results (Fig. 6c) indicate that the Al amount in the small irregular particles (marked by red box in Fig. 6a) could be neglected. However, very high amount of Al (Fig. 6d) was found in the small spherical particles (marked by blue box in Fig. 6a). The morphology and size of the large irregular particles (marked by green box in Fig. 6b) were very similar to those of the raw SiC particles, and the amount of Si element was higher than that in the previous small particles. Therefore, the large irregular particles should be the SiC particles that dislodged during the WEDM process. However, since the raw reinforcement was composed of 30 and 10-μm irregular SiC particles (Fig. 1), it is difficult to distinguish the “dislodged” and the “cut” SiC particles by their morphologies.

The removed products were then embedded in resin. After polishing (Fig. 7a), their internal composition was analyzed,

Fig. 6 Representative morphology of the removed products of SiCp/2024Al composite after the WEDM process: **a, b** morphologies of different products, **c–e** corresponding EDS analysis of the red, blue box area in **a** and of the green box area in **b**, respectively

as shown in Fig. 7b, c. It is difficult to find the large particles shown in Fig. 7b. However, small irregular and spherical particles were observed. Compared with the surface composition (Fig. 6c, d), higher Al and Si but lower C and O amount were detected in the core areas of the removed particles (Fig. 7b, c), implying that the removed particles were coated by carbon/carbides and oxides.

3.2.2 Phase Composition of the Removed Products

Comparison of the XRD patterns of SiCp/2024Al composite and removed products is shown in Fig. 8. The main phases in the SiCp/2024Al composite were Al and SiC. However, after the WEDM process, high intensity peak of Si phase was detected beside Al and SiC, indicating that some SiC particles were decomposed during the WEDM process. It implies that the local point temperature near the cutting wire might be higher than 2730 °C [34].

The phase composition of the removed products was further identified by XPS analysis, as shown in Fig. 9. Peaks of O 1s, C 1s, Si 2s, Si 2p (Fig. 9a) and Al

2p (Fig. 9b) were detected, indicating the presence of SiO, SiO₂, SiC and Al₂O₃ in the removed products.

3.2.3 Microstructure of the Removed Products

The microstructure of the removed products was further observed by TEM and HRTEM. Similar to the morphology observation results (Fig. 6a), irregular and spherical products were found, as shown in Fig. 10a, b, respectively. The internal microstructure of the products could not be observed because their thickness did not meet the requirement for the transmission electrons. Therefore, advanced methods should be applied to reveal the internal microstructure of the removed products. The microstructure of the surface area of the removed products was characterized by HRTEM, as shown in Fig. 10c, e. The irregular particles were mainly coated by an amorphous layer with an average thickness of about 13 nm (Fig. 10c, d), and the main composition of the amorphous layer was Si and O elements. Meanwhile, a graphite layer with an average thickness of about 30 nm was found on the

Fig. 7 Polished microstructure of the removed products of SiCp/2024Al composite after the WEDM process: **a** morphology, **b**, **c** corresponding EDS analysis of the red and blue box area in Fig. 2a, respectively

Fig. 8 Comparison of the XRD patterns of SiCp/2024Al composite and removed products after the WEDM process

external surface of the spherical products. It should be noted that the graphite layer was composed of nano-crystalline graphite since its diffraction patterns were polycrystalline rings (Fig. 10f).

3.3 Machining Mechanism of the WEDM Process in the SiCp/2024Al Composite

The formation of Si, which was generated due to the decomposition of SiC particles, was evidenced by the XRD analysis (Fig. 8), implying that the local point temperature near the cutting wire might be higher than the decomposition temperature of SiC (2730 °C) [34]. Moreover, the

Fig. 9 XPS analysis of the removed products of SiCp/2024Al composite after the WEDM process: **a** full spectrum, **b** narrow spectrum

formation of SiO₂, SiO and Al₂O₃ was detected (Fig. 9). Therefore, the following reactions (1) to (4) might have been occurred.

Fig. 10 TEM and HRTEM observations of the removed products of SiCp/2024Al composite after the WEDM process: **a** irregular and **b** sphere products, **c** surface of irregular products, **d** corresponding SAED pattern of Si–O amorphous layer in **c**, **e** surface of sphere products, **f** corresponding SAED pattern of graphite layer in **e**

The EDS results (Fig. 7c) suggested that the spherical particles were Al alloy containing a few Si and/or SiC particles. The sphere morphology was generated due to the rapid melting and solidification during the WEDM process. Meanwhile, the irregular particles were produced mainly due to the decomposition of SiC since their Si amount was more than 65 at.% in the core area of the particles. Afterward, the external of the Si phase might be oxidized

to form the SiO and SiO₂ at high temperature and eventually formed the amorphous layer in the external area of the irregular particles. Since emulsified oil was used in the present work, it is suggested that the nano-crystalline graphite was produced due to the decomposition of the emulsified oil. Since the particles were coated by a graphite layer, high amount of C was detected in the external area while low amount of C was found in the core area of the removed products.

In literature [29, 35], it has been speculated that the machining mechanism of the SiCp/Al composite should be due to the melting of the Al matrix. Al matrix surrounding the SiC particles would be melted firstly, and then, the SiC particles would only be dislodged from the matrix and be

flushed away by the dielectric fluid [29]. However, the behavior of 65 vol% SiCp/Al composite was very similar to that of ceramic materials [32], and decomposition of SiC particles was observed in the present work, which is the complementary to the previous speculation. The present observation results indicate that machining mechanism of high content SiCp/Al composite might be combination of the melting of the Al matrix and decomposition of SiC particles. Therefore, the alloys with high melting point are suitable for cutting wires to machine high content SiCp/Al composite.

4 Conclusion

The 65 vol% SiCp/2024Al composite prepared by pressure infiltration method was machined by the WEDM. Some pores were observed on the surface of the SiCp/2024Al composite after the WEDM process, and three zones from the surface to the interior (melting zone, heat affected zone and un-affected zone) have been found. The melting zone was not dense with some pores, and the heat affected zone was rather dense with a few pores but characterized by higher amount of SiC particles (especially larger SiC particles). No outcrop SiC particles were observed, while the face of SiC particles on the surface toward the outside was “cut” to be flat, indicating that SiC particles were “cut” during the WEDM process. Higher Al and Si but negligible C and O elements were observed in the core areas of the removed particles. Si phase, which was generated due to the decomposition of SiC, was detected by XRD after the WEDM process, and the presence of SiO, SiO₂, SiC and Al₂O₃ in the removed products was also found by the XPS measurement. Moreover, it has been found that the irregular and spherical particles were mainly coated by a Si–O amorphous layer with an average thickness of about 13 nm and a graphite layer with an average thickness of about 30 nm, respectively. It is suggested that the machining mechanism of the 65 vol% SiCp/2024Al composite was combination of the melting of Al matrix and the decomposition of SiC particles. Therefore, the alloys with high melting point (higher than 2730 °C) are suitable for cutting wire to machine high content SiCp/Al composite.

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