Material Removal Rate and Surface Roughness of SiC/Al Matrix Composites Machined by Wire Electrical Discharge Machining: Experimental Method

Qi Lijun
School of Mechatronic Engineering,
Shaanxi Key Laboratory of Non-Traditional Machining
Xi'an Technological University
Xi'an, China
E-mail: gyzxqlj@163.com

Ma Baoji
School of Mechatronic Engineering,
Shaanxi Key Laboratory of Non-Traditional Machining
Xi'an Technological University
Xi'an, China
E-mail: mabaoji@xatu.edu.com

Abstract*—In the present study, the experiments have been made to investigate the effect of wire electrical discharge machining (WEDM) parameters such as pulse duration, pulse off time, discharge current , working voltage on the material removal rate and the surface roughness (Ra) during WEDM of particulate silicon carbide aluminum (SiC/Al) metal matrix composites. It was found that the material removal rate and the surface roughness of the SiC/Al matrix composites with the SiC content of wt.10% SiC/Al is higher than the SiC content of wt.5%. The removal rate increases with the increase of discharge current; and first increases with the pulse duration, when the pulse duration reaches 11µs, the removal rate shows a slow downward trend. The material removal rate decreases with the values increase of pulse off time and working voltage. The surface roughness of the work piece increase with the increases of pulse duration and discharge current, while the effect by pulse off time and working voltage is not significant. The surface morphology was observed by SEM, found that the surface of SiC/Al matrix composites by WEDM is mainly composed of molten recasting layer, little ball of different diameters, pits, holes and a few micro fissure.

Keywords-Sic; Al Matrix Composite; WEDM; Parameters; Material Removal Rate; Surface Roughness

I. INTRODUCTION

Metal matrix composite material is alloy, which is prepared by adding certain reinforcement to aluminum. It has good physical and chemical properties[1-3], such as low density, high specific strength, high specific stiffness, excellent high temperature properties, high wear resistance, excellent dimensional stability, fatigue properties, and high resistance to atmospheric corrosion. Because of these properties, it has been widely used in mechanical, aerospace, automobile industries.

Particle reinforced aluminum matrix composite is a kind of hard-to-cut material. The main problems existing in traditional cutting are low processing efficiency, severe tool wear[4-6], and there are various defects on the machined surface[7, 8] and so on. With the increase of particles volume fraction and the size, its processing becomes more difficult, which has become the bottleneck of its further wide application.

TABLE I. COMPOSITION OF 5% SICP/AL MATRIX COMPOSITES

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	SiC	Al
Content (wt%)	0.4~0.8	0.7	0.15~0.4	0.15	0.8-1.2	0.25	0.15	5	others

TABLE II. COMPOSITION TABLE OF 10% SIC/AL MATRIX COMPOSITES

Element	Si	Mg	SiC	Al
Content (wt%)	7	0.3	10	others

In view of the problems in cutting, researchers have carried out a lot of research on the non-traditional manufacturing process of particle reinforced aluminum matrix composites. Kumar[9] studied the effects of pulse duration, pulse off time, working voltage, peak current, line tension and line feed rate on the response variables such as cutting speed, surface roughness (Ra) and spark gap. M. Kathiresan[10], researched the EDM in the process of aluminum matrix composites and found that the material removal rate and surface roughness increased with the increase of current. The effects of discharge current, pulse duration and the content of reinforced particles on the material removal rate and surface roughness of WEDM of aluminum matrix composites were studied by A Srivastava[11], he found that the surface roughness increases with the increase of discharge current, pulse duration and particle content.

However, there are many factors and methods effect on the material removal rate and surface roughness, the current study has not produced a consistent conclusion. In order to solve the problem of low machining efficiency and poor surface quality, it is necessary to make further study. In order to investigate the influence of machining parameters: pulse duration, pulse off time, discharge current and working voltage toward the material removal rate that characterizes machining efficiency, and the surface roughness that characterizes the quality of machining surfaces, single factor experiments have been carried out on the SiC content of wt.5% and wt.10% SiC/Al matrix composites material, and the machining surface was characterized by SEM.

II. EXPERIMENT

A. Experimental Material

The materials used in the experiment is SiC/Al matrix composites, and the size of SiC particles contained in the SiC/Al composites are 10μm. The specific composition of wt.5% SiC/Al matrix composites is shown in Table Ⅰ, and the composition of wt.10% is shown in Table Ⅱ.

The experimental materials used in this paper were prepared by small whirlpool liquid stirring method. The aluminum matrix composites with SiC wt.5% reinforced phase were extruded, with cross section size of 17mm by 8.5 mm. The strip material with rectangular cross section can be directly used for WEDM experiment. Where the material with the content of SiC wt.10% is casted ingots, and the cross section size of 21.5mm by 10 mm is obtained by sawing and milling with the same parameters to make sure the initial condition consistency.

The material was cut into cuboid of length 15mm by WEDM machine using given parameters, and used as the experimental work piece.

B. Experimental Equipment

The schematic of WEDM is shown in Figure 1.The work piece was machined by FW-1 WEDM machine tool

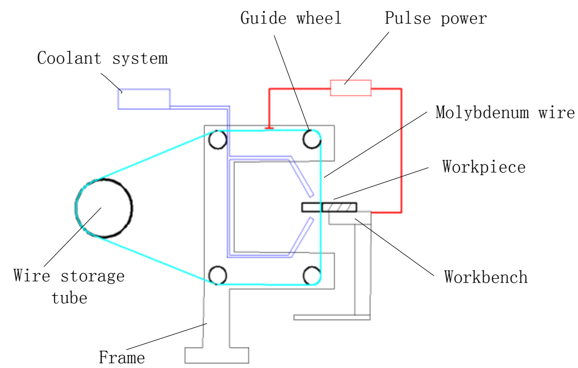

Figure 1. Schematic diagram of WEDM

(a) WEDM machine tool (b) Machining

Figure 2. WEDM machine tool and maching

Figure 3. Roughness meter

Figure 4. Scanning electron microscope

TABLE III. THE VALUE OF EACH PARAMETER

Parameters	Test serial number of each parameter						
	1	2	3	4	5	6	7
Pulse duration (μs)	3	7	11	15	19	23	27
	(Others: 5 μs, 30A, 60V)						
Pulse off time (μs)	10	15	20	25	35	55	75
	(Others: 11 μs, 30A, 60V)						
Discharge current (A)	5	10	15	20	25	30	40
	(Others: 11 μs, 5 μs, 60V)						
Working voltage (V)	20	40	60	80	100	120	140
	(Others: 11 μs, 5 μs, 30A)						

(Figure 2), which is produced by Beijing Archie Chamfer Industrial Electronics Co., Ltd. Surface roughness measured by SRT-1(F) portable roughness meter (Figure 3). The surface morphology was characterized by VEGA3-SBH scanning electron microscopy (Figure 4).

C. Experimental procedure

1) *Work piece preparation:* Adjust the processing parameters to the experiment designed. Then the WEDM experiment is carried out to obtain the work piece. The experiment data, such as the machining parameters, processing time, processing speed and so on are recorded.
2) *Remove oil pollution:* Wipe the surface of work piece with defatted cotton dipped in acetone to remove the grease.
3) *Removal of impurities:* Cleaned the work piece with deionized water for 5 minutes using the ultrasonic cleaning machine, in order to remove the impurities, and then drying.
4) *Measuring surface roughness:* The surface roughness of the work piece was measured 3 times by the roughness meter, and the average value was recorded.
5) *Surface characterization:* Typical machining characteristic specimens were characterized by SEM.

D. Experimental Parameters

The main machining parameters of WEDM are pulse duration, pulse off time, working voltage, discharge current. Firstly, a series of exploratory experiments has been conducted to identify the parameter range based on the WEDM SiC/Al matrix composite. The value of each parameter is shown in Table Ⅲ.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Effect of WEDM parameters on material removal rate and surface roughness

Table Ⅳ represents the results of the 28 experiments carried out as per parameter of WEDM. The surface roughness is directly measured and the material removed rate is calculated as follows:

$$MRR = \frac{\text{the area of cross section}}{\text{proccesing time}} \tag{1}$$

TABLE IV. TEST RESULTS OF WEDM EXPERIMENT

parameters		material removal rate （mm2/min）		surface roughness (Ra μm)	
		Wt.5%	Wt.10%	Wt.5%	Wt.10%
Pulse duration (μs)	3	69.36	96.6	3.9	5.91
	7	110.92	134.2	3.2	7.42
	11	131.07	185.7	4.69	8.24
	15	134.64	114.3	5.31	6.97
	19	107.61	128.1	5.37	7.04
	23	112.96	136.2	5.95	6.76
	27	95.88	115.5	5.88	7.6
Pulse off time (μs)	10	82.88	173	4.69	8.91
	15	69.62	119.4	3.58	5.76
	20	66.81	141	4.12	7.43
	25	56.61	82.8	4.5	6.59
	35	30.6	111	3.78	7.72
	55	29.07	36.9	4.32	5.22
	75	24.74	6.6	3.8	5.32
Discharge current (A)	5	34.36	40.2	3.37	4.67
	10	61.71	88	3.43	4.17
	15	77.52	102.6	3.51	5.78
	20	103.53	125.7	4.64	5.65
	25	118.62	134.4	4.66	7.68
	30	130.05	142.5	4.69	7.57
	40	149.17	170.4	6.12	8.16
Working voltage (V)	20	96.64	211.5	4.05	8.44
	40	132.85	174	4.69	7.54
	60	130.05	156.9	4.69	8.38
	80	112.96	152.4	5.01	6.63
	100	106.59	127.8	4.38	7.75
	120	95.62	120.3	5.28	8.37
	140	90.27	111	4.5	6.15

Where MRR is the material removal rate.

1) *The effect of WEDM parameters on material removal rate*

WEDM is a process in which electrical energy is converted into thermal energy, where the material is melted and etched due to the action of thermal energy. In practical processing, the spark maintenance voltage is a constant for the electrode pair material and coolant liquid have been determined. The amount of electrode erosion is proportional to the amplitude of its pulse current and pulse duration, which can be expressed as follows [12]:

$$W_M = (25 \sim 30) i_e t_e \qquad (2)$$

Where i_e is pulse current amplitude and t_e is pulse duration.

The effects of different WEDM process parameters on the removal rate of two materials were compared, as shown in Figure 5. It can be found that material removal rate the SiC/Al matrix composites with SiC content of wt.10% is higher than the content of wt.5%.

This is because the melting point of aluminum is lower than SiC, so the aluminum base is removed first by WEDM in processing. While the thermal conductivity of aluminum （217W/mk） which is higher than that of the SiC （120-180W/mk）, because the processing energy is identical using the same processing parameters, and the aluminum content in the wt.10% SiC/Al matrix composite is higher than the wt.5% SiC/Al matrix composite, the quantity of thermal generated by the spark discharge was transferred rapidly to the surrounding material, which results the reduction of the effective processing energy. And according to the equation (2), along if the effective processing energy is reduced, the machining efficiency is also reduced, which leads to the material removal rate is lower.

Figure 5(a) shows that for the two kinds of metal matrix composites, the material removal rate increases with the increase of pulse duration. When the value of pulse duration is 11μs, the value of material removal rate almost reaches to the peak, and then it goes down at a slower rate than it went up. This is because with the increase of pulse duration, the single pulse energy increases, so the discharge erosion quantities also will increase. However, when the pulse duration reaches a certain extent, less energy is applied to material removal, as a result, the removal rate shows a slow downward trend.

It can be seen from Figure 5(b) that the material removal rate decreases with the increase of pulse off time. This is due to the decrease of effective processing energy and the decrease of material removal rate with the increase of pulse off time.

Figure 5(c) demonstrates that the material removal rate increased with the increase of discharge current, which is consistent with the results in reference [11]. As can be seen from formula (2), that the discharge current is proportional to the processing energy, the removal rate increases with the increase of processing energy.

From Figure 5(d) it can be visualized that the material removal rate decreases with the increase of working voltage. This is because the larger the voltage, the larger the discharge gap, in addition, the faster the dispersion of heat, lead to the smaller the effective energy.

2) The effect of WEDM parameters on surface roughness

The relationship between surface roughness and energy can be expressed by the following experimental formulas [12]:

$$R_{\max} = K_R i_e^{0.4} t_e^{0.3} \qquad (3)$$

Where R_{max} is the measured value, K_R is a constant, i_e is pulse current amplitude and t_e is pulse duration.

Surface roughness effected by the machining parameters is shown in Figure 6. The corresponding surface roughness of the SiC/Al matrix composites with SiC content of wt.10% is higher than the SiC content of wt.5% is. This is due to the different surface structures.

It can be seen clearly that the surface roughness of the work piece increase with the increases of pulse duration and discharge current from Figure 6(a) and (c). This is because the surface roughness is closely related to the individual pulse energy, according to equation (3), the surface roughness is linear correlation with the individual pulse duration and the peak current. While Figure 6(b) and (d) show the effect of pulse off time and working voltage on the surface roughness is not significant

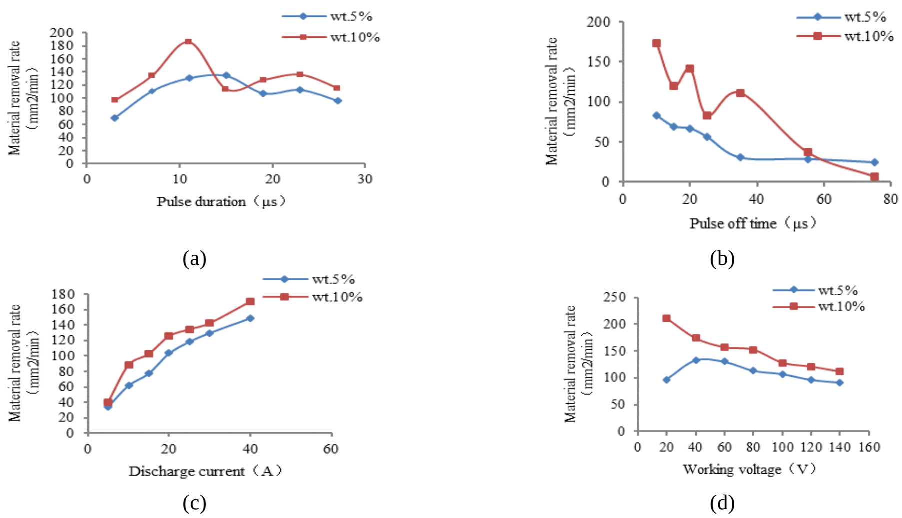

Figure 5. Material removal rate at different machining parameters

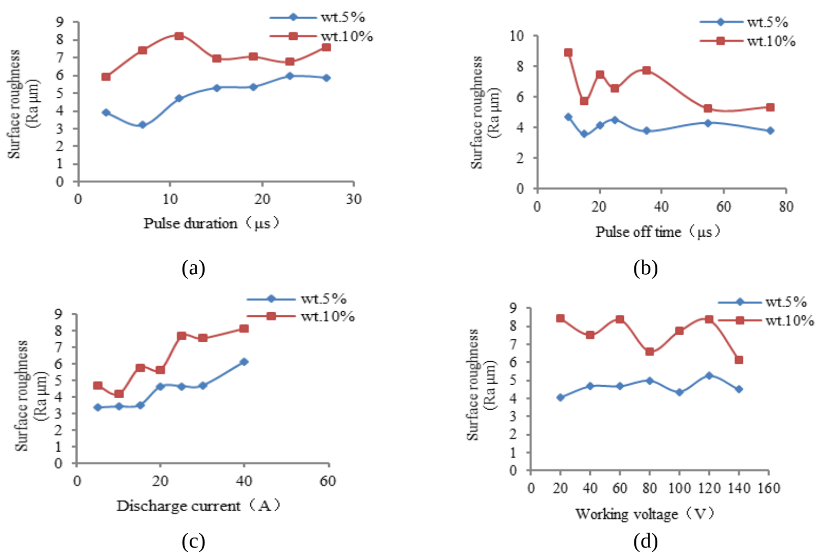

Figure 6. Surface roughness at different machining parameters

B. *Morphology of SiC/Al matrix composite surface by WEDM*

In order to study the surface morphology of the SiC particle-reinforced aluminum-based composite material, we observed a series of WEDM work piece surface by SEM. Figure 7 shows that the surface of SiC/Al matrix composite by WEDM, and the machining parameters are pulse duration: 27μs, pulse off time: 5μs, discharge current: 30A and working voltage: 60V. Figure 7 (a) is magnify 300 times, (b) is magnify 600 times, (c) is magnify 5000 times, and (d) is magnify 10000 times. The image shows the surface is mainly composed of molten recasting layer, little ball of different diameters, pits, holes and a few micro fissure.

From the (b), (c), and (d) in Figure 7, it can be seen that some balls correspond to a small hole or pit. It can be inferred that sparks cause the material here to melt, forming pellets due to surface tension, and forming pits or holes in the corresponding position. Some melts are sputter to the surface of the material, forms the ball after cooling. While the thickness of the recasting layer is different so the cooling rate is different, the thermal stress is produced, and the micro crack is formed under the action of the thermal stress.

IV. Conclusions

The material removal rate and the surface roughness of wt.10% SiC/Al matrix composites is higher than that of wt.5% SiC/Al matrix composites with the same processing parameters. All of them increased with the increase of discharge current. The material removal rate decreases with the increase of pulse off time and working voltage, however, the effect of pulse off time and working voltage on surface roughness is not obvious. With the increase of pulse duration, the material removal rate and surface roughness first increased to a peak and then tend to be stable.

The work piece surface of SiC/Al matrix composites by WEDM is mainly composed of molten recasting layer, little ball of different diameters, pits, holes and a few micro fissure. There are two ways in which spheres on the surface are formed, one is directly machined by discharge, and the other is, the most spheres, which are in the surface of the recasting layer, is formed due to the action of sputter.

Acknowledgment

The authors are grateful to Shaanxi Key Laboratory of Non-Traditional Machining. This work was financially supported by Open Research Fund Program of Shaanxi Key Laboratory of Non-Traditional Machining (No. 2017SXTZKFJG09), and Scientific Research Plan Projects of Shaanxi Education Department (No. 15JK1353).

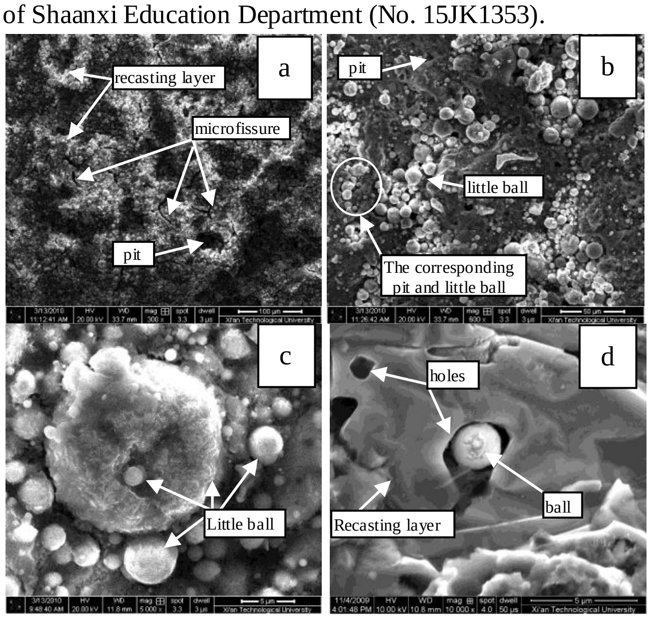

Figure 7. SiC/Al matrix composite surface morphology by WEDM

References

[1] Moreno M F, Oliver C J R G. Compression creep of PM aluminummatrix composites reinforced with SiC short fibres[J]. MaterialsScience and Engineering：A, 2006, 418 (1/2) :172.

[2] Sahin Y. Wear behaviour of aluminium alloy and its composites reinforced by SiC particles using statistical analysis [J]. Materialsand Design,2003, 24 (2) :95.

[3] CHINMAYA R DANDRKAR, Modeling of Machining of Composite Materials:A review[J].International Journal of Machine Tool &Manufacture.2012,57:102-121.

[4] WANG Jinfeng, FAN Xiaoliang, CAO Yuwei, Experimentation in vestigations of surface roughness in High-speed turning of SiCp/Al composites, CHINESE JOURNAL OF CONSTRUCTION MACHINERY, 2017, 15(1): 62-66.

[5] Liu Hanzhong, Research on precision turning technology and tool wear of SiCp/2024Al composites, Harbin Institute of Technology [D], 2017.

[6] Duan Chunzheng, Feng Zhan, Sun Wei, Research on Cutting Force and Tool Wear of SiCp/AI Composite with Different Al Matrix, Tool technology, 2018,52(1):40-44.

[7] Zhou, L., Cui, C., Zhang, P. F., & Ma, Z. Y. (2016). Finite element and experimental analysis of machinability during machining of high-volume fraction sicp/al composites. International Journal of Advanced Manufacturing Technology, 91(42863), 1-10.

[8] Han, J., Hao, X., Li, L., Wu, Q., & He, N. (2017). Milling of high volume fraction SiCp/Al composites using PCD tools with different structures of tool edges and grain sizes. The International Journal of Advanced Manufacturing Technology, 92(5-8), 1875–1882.

[9] Kumar, H., Manna, A., & Kumar, R. (2018). Modeling and desirability approach-based multi-response optimization of WEDM parameters in machining of aluminum metal matrix composite. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40(9).

[10] M.Kathiresan,T.Sornakumar,EDM Studies on Alloy-Silicon Carbide Composites Developed by Vortex Technique and Pressure Die Casting, Journal of Minerals and Materials Characterization and Engineering , 2010, vol.9,No.1:79-88 .

[11] A Srivastava , AR Dixit, Experimental Investigation of Wire EDM Process Parameters on Aluminium Metal Matrix Composite Al2024/SiC, International Journal of Advance Research and Innovation , Volume 2, Issue 2 (2014) 511-515.

[12] Zhao Wansheng, Liu Jinchun, Electrical Discharge Machining Technology[M], Harbin, Harbin Institute of Technology Press, 2000:17.