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Modeling the Machining Parameters in End Electric Discharge Milling of Silicon Carbide Ceramic

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Abstract: Silicon carbide (SiC) ceramic has been widely used in modern industry. However, the manufacture of SiC ceramic is difficult and expensive. This paper presents a new process of machining SiC ceramic using end electric discharge (ED) milling. It is able to effectively machine a large surface area on SiC ceramic. The effects of machining parameters such as open voltage, discharge current, pulse duration and pulse interval on the machining characteristics in terms of material removal rate, electrode wear ratio, and surface roughness have been investigated with Taguchi experimental design method. Analysis of variance and *F*-test are used to indicate the significant machining parameters affecting the machining characteristics. Furthermore, mathematical models relating to the machining characteristics are established with the stepwise regression method. *Copyright © 2012 IFSA.*

Keywords: Silicon carbide ceramic, End electric discharge milling, Analysis of variance, Taguchi method.

1. Introduction

The demand for advanced materials with high strength, high toughness and high hardness is now urgent. Therefore, the new species of advanced materials have been developed for diverse industrial applications. Silicon carbide (SiC) is regarded as one of the most promising engineering ceramics because of its combination of excellent physical and mechanical properties such as high strength at elevated temperature, high stiffness, low density, low coefficient of thermal expansion and superior creep resistance. The combination of the properties makes SiC ceramic attractive in many engineering applications [1]. However, the manufacture of SiC ceramic is difficult and expensive with conventional

diamond grinding and turning [2]. To overcome technical difficulties in machining of this material, non-traditional machining processes, such as water jet machining, laser beam machining, ultrasonic machining and electrical discharge machining (EDM), are employed, among which EDM has been the most suitable because there is no contact between the tool and workpiece during the EDM process [3-6]. However, low machining efficiency is one of the main EDM disadvantages. The topic of how to reduce machining time and to maintain reasonable accuracy has always been of research interest. Recently, some researches have been made to improve the efficiency with EDM milling. The results show that the material removal rate can be improved proportionally, but it still can't meet the demand of modern industrial applications, and the machined surface is poor [7, 8].

A novel high speed end electric discharge (ED) milling method using a turntable with several small cylindrical rods as the tool electrode has been developed in this paper. The process employs the pulse generator used in EDM, and uses a water-based emulsion as the machining fluid. It is able to effectively machine a large surface area on SiC ceramic. In this work, a L_{25} orthogonal array based on Taguchi method is adopted, and the experimental data are statistically evaluated by analysis of variance (ANOVA) to investigate the effects of open voltage, discharge current, pulse duration and pulse interval on the machining characteristics in terms of material removal rate (MRR), electrode wear ratio (EWR) and surface roughness (SR Ra). The optimal combination levels of machining parameters that optimized each machining characteristic are determined. Moreover, a series of mathematical models associated with MRR, EWR and SR are obtained by using the stepwise regression method.

2. Principle for End ED Milling of SiC Ceramic

Fig. 1 shows the schematic illustration for end ED milling of SiC ceramic. The tool and the workpiece are connected to the negative and positive poles of the pulse generator, respectively. The tool is a turntable with several small cylindrical rods rotating rapidly around its axis. The tool is mounted onto a rotary spindle, driven by an A. C. motor. The workpiece is SiC ceramic blank and is mounted onto a numerically controlled (NC) table. The machining fluid is a water-based emulsion.

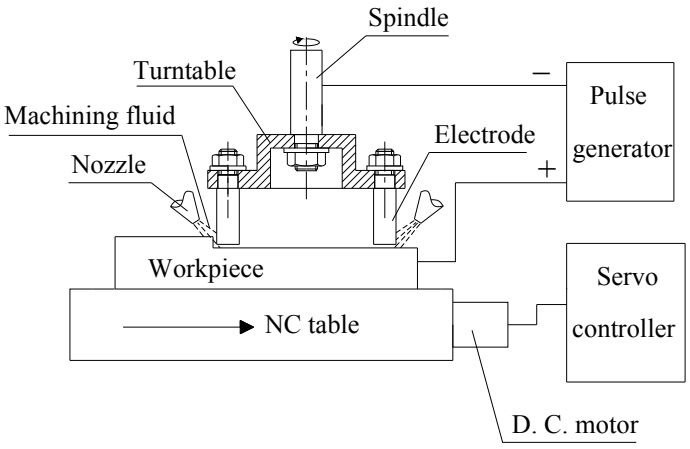


Fig. 1. Schematic illustration for end ED milling of SiC ceramic.

During machining, the tool rotates at a high speed, the SiC ceramic workpiece is fed towards the tool driven by a D.C. motor. The machining fluid is flushed to the electrode and discharge gap with several nozzles. As the workpiece approaches the tool and the distance between the workpiece and the electrode reaches the discharge gap, electrical discharges occur from the edge and the bottom of the cylindrical electrodes. The high instantaneous temperature and plasma pressure cause SiC ceramic to be removed

by electric discharge milling. As short circuits or arcs are generated in end ED milling, the workpiece is fed back by the D.C. motor. After short circuits or arcs are cleared up, the workpiece is fed on again. A large diameter turntable with several cylindrical copper rods is used as the tool, so the process is able to effectively machine a large surface area on SiC ceramic with low cost. The tool rotates to ensure that the cylindrical electrodes are worn homogeneously. In addition, a water-based emulsion is used as the machining fluid, so harmful gas is not generated during machining, and the equipment is not corroded.

3. Experimental Procedures

In the following experiments, the workpiece material was SiC ceramic, the tool was a turntable with eight uniform-distributed cylindrical copper electrodes in the circumference, the tool polarity was negative. The diameter of the cylindrical copper electrode was 10 mm, the diameter of the turntable was 90 mm, the rotational speed of the spindle was 3000 rpm. The machining fluid was a water-based emulsion composed of 8 mass% emulsified oil and 92 mass% distilled water. The flux of the machining fluid was 200 mL/s. The MRR and EWR were obtained through measuring the dimensions of the workpiece and the electrode before and after machining with a dial indicator and a vernier caliper. The SR was measured by a surface roughness tester. The experimental design employed a L_{25} orthogonal array based on the Taguchi method. In this investigation, four machining parameters such as open voltage (U), discharge current (I), pulse duration (t_i) and pulse interval (t_o) were chosen to explore their impacts on the machining characteristics in terms of MRR, EWR and SR. Table 1 presented the machining parameters and their levels used in this investigation. The relative importance of the machining parameters with respect to the MRR, EWR and SR was investigated to determine more accurately the optimum combinations of the machining parameters by using ANOVA. Statistically, F-test provides a decision at some confidence level as to whether these estimates are significantly different. When the F-value of the machining parameter is bigger than $F_{\alpha,n1,n2}$-value of the confidence table, where α is risk, n_1 and n_2 are degrees of freedom associated with numerator and denominator, the contribution of the machining parameter is defined as significant. During this investigation, there were three categories of significant machining parameters: (i) more significant machining parameters (α was 0.001); (ii) significant machining parameters (α was 0.01); (iii) less significant machining parameters (α was 0.1). $F_{\alpha,n1,n2}$ was quoted from the "Tables for Statisticians" [9]. To obtain applicable and practical predictive quantitative relationships, a series of mathematical models were obtained by using the stepwise regression method.

Table 1. Machining parameters and their levels.

Factors	Levels				
	1	2	3	4	5
U (V)	90	110	130	150	170
I (A)	15	30	45	60	75
t_i (μs)	400	120	90	50	40
t_o (μs)	300	600	1200	1800	2500

4. Experimental Results and Discussion

Table 2 presents the design matrix from the L_{25} orthogonal array based on the Taguchi method, as well as the experimental data of MRR, EWR and SR correlated with each experimental measurement.

Table 2. Orthogonal array L_{25} and experimental data.

No.	*U* (V)	*I* (A)	t_i (μs)	t_o (μs)	MRR (mm^3/min)	EWR (%)	SR Ra (μm)
1.	90	15	400	300	14.879	9.620	7.011
2.	110	30	400	600	36.484	39.907	8.329
3.	130	45	400	1200	40.783	45.293	8.729
4.	150	60	400	1800	49.784	77.688	8.771
5.	170	75	400	2500	54.341	95.775	9.514
6.	130	30	120	300	40.611	49.631	8.101
7.	150	45	120	600	38.637	60.911	8.214
8.	170	60	120	1200	64.600	71.928	8.171
9.	90	75	120	1800	25.126	47.375	6.429
10.	110	15	120	2500	6.639	40.313	5.014
11.	170	45	90	300	70.929	109.919	8.114
12.	90	60	90	600	25.200	54.758	6.043
13.	110	75	90	1200	25.033	80.916	6.457
14.	130	15	90	1800	18.272	38.351	4.514
15.	150	30	90	2500	15.687	87.230	6.057
16.	110	60	50	300	26.450	58.284	6.143
17.	130	75	50	600	52.139	84.690	6.214
18.	150	15	50	1200	25.231	67.080	4.814
19.	170	30	50	1800	30.164	103.470	6.729
20.	90	45	50	2500	12.351	62.292	4.400
21.	150	75	40	300	57.253	89.916	6.371
22.	170	15	40	600	21.681	77.731	5.614
23.	90	30	40	1200	6.404	60.911	4.201
24.	110	45	40	1800	15.300	77.852	4.910
25.	130	60	40	2500	21.741	97.830	5.529

4.1. Analysis of MRR

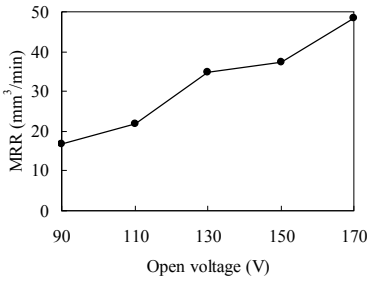
The results of ANOVA and *F*-test values for the MRR are presented in Table 3. It can be seen from Table 3 that open voltage (*U*) is the significant parameter on the MRR, whereas discharge current (*I*) is the less significant parameter on the MRR. The average MRR for each factor level is displayed graphically in Fig. 2. It can be observed from Fig. 2 that the optimal combination levels of machining parameters that maximized MRR are as follows: 170 V open voltage, 75 A discharge current, 400 μs pulse duration, and 300 μs pulse interval.

Table 3. ANOVA and *F*-test of MRR.

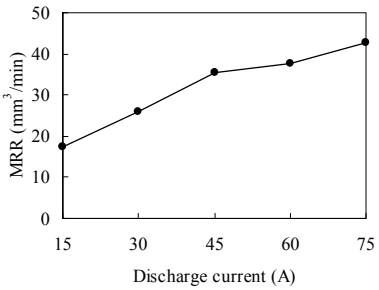
Parameter	Sum of squares	Degree	Mean square	*F*
U	3170.179	4	792.5448	7.85**
I	2062.213	4	515.5531	5.11*
t_i	636.037	4	159.0093	1.57
t_o	1119.664	4	279.9161	2.77
$Error_e$	807.731	8	100.9664	
Total	7795.824	24		

** Significant parameter

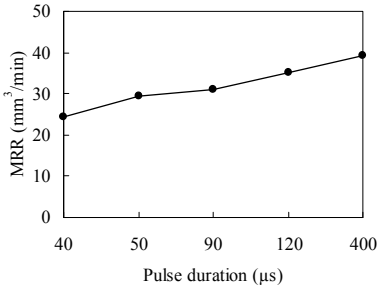
* Less significant parameter



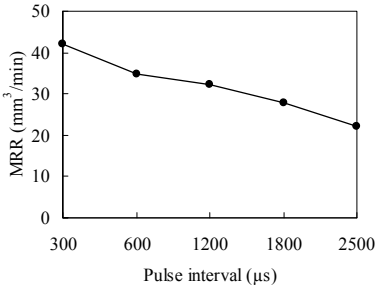
(a) Effect of open voltage on average MRR.



(b) Effect of discharge current on average MRR.



(c) Effect of pulse duration on average MRR.



(d) Effect of pulse interval on average MRR.

Fig. 2. Effects of machining parameters on average MRR.

The capability of the stepwise model to represent the experimental data is assessed through the analysis of variance. The results of the analysis of variance for the stepwise model of MRR are shown in Table 4. As in this case F is far greater than $F_{0.001,5,19}$, it is accepted that the mathematical model of MRR by using stepwise regression analysis method is appropriate for a significance level, α, of 0.001. The equation for the mathematical model is as follows:

$$MRR = 18.87338 + 9.7728\times10^{-4} t_i U - 1.8\times10^{-6} t_i^2 U - 2.51237\times10^{-8} t_o^2 U - 1.978\times10^{-5} I^2 U + 3.605\times10^{-5} I U^2, \quad (1)$$

Table 4. ANOVA table for the stepwise regression model of MRR.

Source	DF	Sum of Squares	Mean Square	*F* Value	$F_{0.001,5,19}$
Model	5	7047.6149	1409.5230	35.19	6.62
Error	19	748.2098	39.3795		
Corrected Total	24	7795.8247			

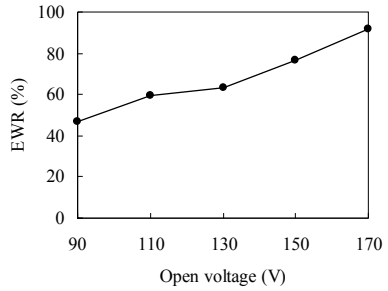
4.2. Analysis of EWR

The results of ANOVA and *F*-test values for the EWR are presented in Table 5. It can be seen from Table 5 that open voltage (U) and pulse duration (t_i) are the significant parameters on the EWR, whereas discharge current (I) is the less significant parameter on the EWR. Fig. 3 shows the average EWR for each factor level. It can be seen from Fig. 3 that the optimal combination levels of machining parameters that minimized EWR are as follows: 90 V open voltage, 15 A discharge current, 400 μs pulse duration, and 300 μs pulse interval.

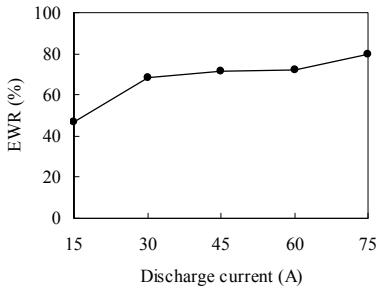
Table 5. ANOVA and *F*-test of EWR.

Parameter	Sum of Squares	Degree	Mean Square	*F*
U	5883.969	4	1470.992	12.80**
I	3106.099	4	776.5248	6.76*
t_i	3280.544	4	820.1361	7.14**
t_o	615.190	4	153.7976	1.34
$Error_e$	919.138	8	114.8923	
Total	13804.940	24		

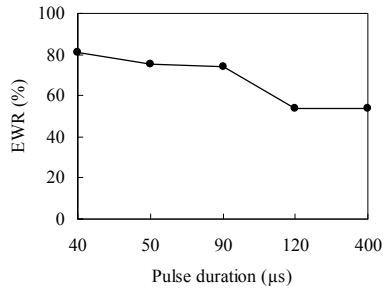
** Significant parameter
* Less significant parameter



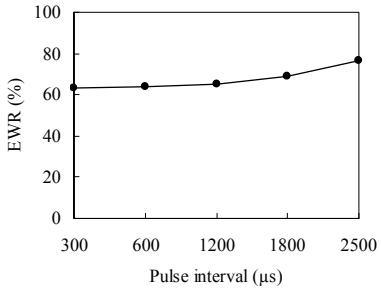
(a) Effect of open voltage on average EWR.



(b) Effect of discharge current on average EWR.



(c) Effect of pulse duration on average EWR.



(d) Effect of pulse interval on average EWR.

Fig. 3. Effects of machining parameters on average EWR.

The results of the analysis of variance for the stepwise model of EWR are shown in Table 6. As in this case F is far greater than $F_{0.001,7,17}$, it is accepted that the mathematical model of EWR by using stepwise regression analysis method is appropriate for a significance level, α, of 0.001. The mathematical relation between EWR and machining parameters is as follows:

$$EWR = 35.84721 - 1.2215\times10^{-1}t_i - 1.646\times10^{-5}t_i^2U + 1.4255\times10^{-4}IU^2 + 4.266302\times10^{-8}t_i^3U + 6.61759\times10^{-12}t_o^3U + 1.32\times10^{-6}I^3U - 2.05\times10^{-6}I^2U^2 , \quad (2)$$

Table 6. ANOVA table for the stepwise regression model of EWR.

Source	DF	Sum of Squares	Mean Square	*F* Value	$F_{0.001,7,17}$
Model	7	12645.0748	1806.4308	26.48	6.22
Error	17	1159.9252	68.2309		
Corrected Total	24	13805			

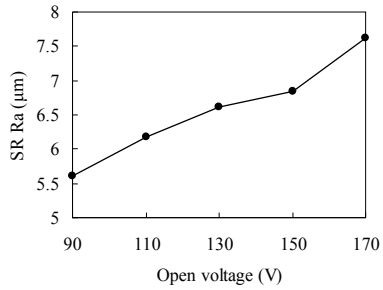
4.3. Analysis of SR

The results of ANOVA and *F*-test values for the SR are presented in Table 7. It can be seen from Table 7 that pulse duration (t_i), open voltage (U) and discharge current (I) are the more significant parameters on the SR, whereas pulse interval (t_o) is the significant parameter on the SR. The average SR for each factor level is displayed graphically in Fig. 4. It can be observed from Fig. 4 that the optimal combination levels of machining parameters that minimized SR are as follows: 90 V open voltage, 15 A discharge current, 40 μs pulse duration, and 2500 μs pulse interval.

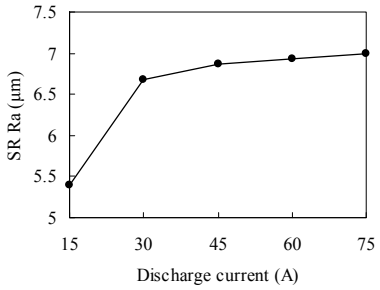
Table 7. ANOVA and *F*-test of SR.

Parameter	Sum of Squares	Degree	Mean Square	*F*
U	11.366	4	2.8415	31.86***
I	9.028	4	2.2570	25.30***
t_i	32.389	4	8.0973	90.78***
t_o	3.737	4	0.9343	10.48**
$Error_e$	0.714	8	0.0892	
$Total$	57.234	24		

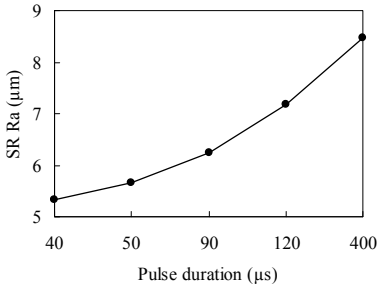
*** More significant parameter
** Significant parameter



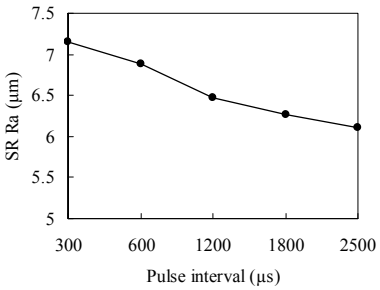
(a) Effect of open voltage on average SR.



(b) Effect of discharge current on average SR.



(c) Effect of pulse duration on average SR.



(d) Effect of pulse interval on average SR.

Fig. 4. Effects of machining parameters on average SR.

The results of the analysis of variance for the stepwise model of SR are shown in Table 8. As in this case F is far greater than $F_{0.001,6,18}$, it is accepted that the mathematical model of SR by using stepwise regression analysis method is appropriate for a significance level, α, of 0.001. The equation for the mathematical model is as follows:

$$SR = 3.84691 - 1.09\times10^{-3} t_o + 4.544\times10^{-2} I - 2.63404\times10^{-8} t_i^2 t_o + 2.306377\times10^{-9} t_o^2 U + 1.34\times10^{-6} t_i U^2 - 1.53678\times10^{-8} I^2 U^2, \quad (3)$$

Table 8. ANOVA table for the stepwise regression model of SR.

Source	DF	Sum of Squares	Mean Square	*F* Value	$F_{0.001,6,18}$
Model	6	53.8852	8.9809	48.27	6.35
Error	18	3.3488	0.1861		
Corrected Total	24	57.2340			

5. Conclusions

1) Using a large turntable with several small cylindrical copper rods as the tool electrode, the SiC ceramic can be easily machined by end ED milling. The process shows high MRR. In addition, end ED milling employs a water-based emulsion as the machining fluid, and it shows a good working environmental practice.

2) ANOVA and *F*-test of experimental data related to the essential machining parameters of end ED milling reveal that open voltage is the significant parameter on the MRR, whereas discharge current is the less significant parameter on the MRR. Open voltage and pulse duration are the significant parameters on the EWR, whereas discharge current is the less significant parameter on the EWR. Pulse duration, open voltage and discharge current are the more significant parameters on the SR, whereas pulse interval is the significant parameter on the SR.

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Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

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- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
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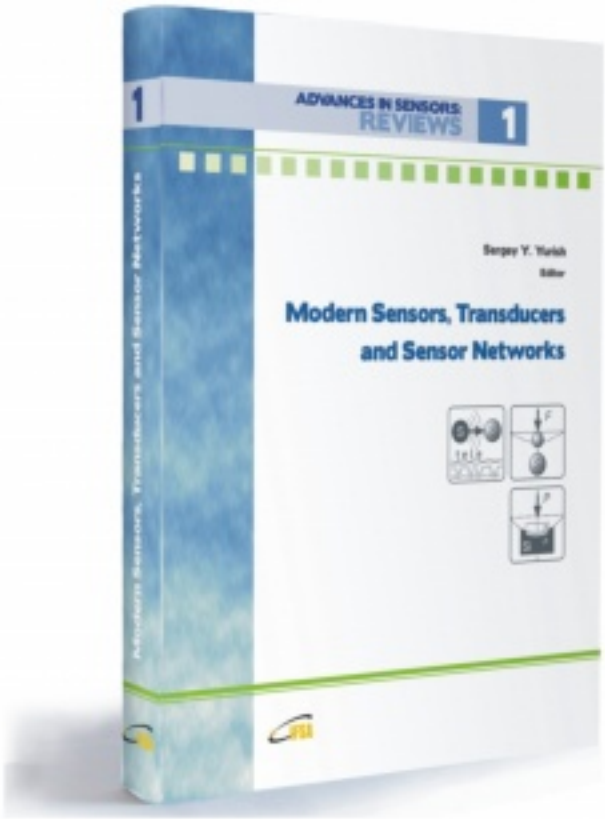

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