

## OPTIMIZATION OF ELECTRICAL DISCHARGE MACHINING PARAMETERS OF SiSiC THROUGH RESPONSE SURFACE METHODOLOGY

Abdul Azeez Abdu Aliyu<sup>a,c</sup>, Jafri Mohd Rohani<sup>b</sup>, Ahmad Majdi Abdul Rani<sup>a\*</sup>, Hamidon Musa<sup>b</sup>

<sup>a</sup>Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia

<sup>b</sup>Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

<sup>c</sup>Faculty of Engineering, Department of Mechanical Engineering, P.M.B 3011, Bayero University, Kano (BUK), Nigeria

### Article history

Received

29 February 2016

Received in revised form

20 November 2016

Accepted

10 December 2016

\*Corresponding author

majdi@utp.edu.my

### Abstract

In recent years, researchers have demonstrated increases interest in studies involving silicon carbide (SiC) materials due to several industrial applications. Extreme hardness and high brittleness properties of SiC make the machining of such material very difficult, time consuming and costly. Electrical discharge machining (EDM) has been regarded as the most viable method for the machining of SiC. The mechanism of EDM process is complex. Researchers have acknowledged a challenge in generating a model that accurately describes the correlation between the input parameters and the responses. This paper reports the study on parametric optimization of siliconized silicon carbide (SiSiC) for the following quality responses; material removal rate (MRR), tool wear ratio (TWR) and surface roughness (Ra). The experiments were planned using Face centered central composite design. The models which related MRR, TWR and Ra with the most significant factors such as discharge current ( $I_p$ ), pulse-on time ( $T_{on}$ ), and servo voltage ( $S_v$ ) were developed. In order to develop, improve and optimize the models response surface methodology (RSM) was used. Non-linear models were proposed for MRR and Ra while linear model was proposed for TWR. The margin of error between predicted and experimental values of MRR, TWR and Ra are found within 6.7, 5.6 and 2.5% respectively. Thus, the excellent reproducibility of this experimental study is confirmed, and the models developed for MRR, TWR and Ra are justified to be valid by the confirmation tests.

Keywords: EDM, SiSiC, modeling, RSM, Optimization, MRR, TWR, Ra

### Abstrak

Sejak kebelakangan ini, ramai penyelidik berminat untuk mengkaji bahan *silicon carbide* untuk diaplikasikan dalam bidang perindustrian. Bahan ini mempunyai sifat kekarasan dan kerapuhan yang tinggi menyebabkan pemesinannya sukar, mengambil masa dan kos yang tinggi. Kaedah yang sesuai untuk memesis bahan ini melalui teknik yang dipanggil *Electrical Discharge Machining*. Mekanisma pemesinan melalui kaedah ini sangat kompleks. Ramai penyelidik mengakui menghadapi cabaran besar untuk membentuk model yang mempunyai korelasi diantara parameter input dan respon. Kajian ini melaporkan pengoptimuman *parameter siliconized silicon carbide (SiSiC)* untuk tiga respon berikut: kadar pemidahan bahan (MRR), kadar kehausan matalat (TWR) dan kemasam permukaan (Ra). Ujikaji menggunakan kaedah rekabentuk *face centered composite*. Model telah dibentuk untuk mengenal pasti faktor *parameter input* yang signifikan: *Discharge current ( $I_p$ )*, *Pulse on time ( $T_{on}$ )* dan *servo voltage ( $S_v$ )* terhadap tiga respon tersebut. Pengoptimuman *parameter input* terhadap tiga respon menggunakan kaedah *response surface methodology*. Model *non-linear* telah dicadangkan untuk hubungan diantara *parameter input* melawan MRR dan Ra, sementara model *linear* untuk TWR. Margin kesilapan diantara nilai ramalan dan eksperimen ke atas MRR, TWR dan Ra masing-masing adalah 6.7, 5.6 dan 2.5%. Oleh itu, hasil kajian ini diyakini dengan ketepatan yang tinggi, dan model yang dibangunkan untuk MRR, TWR dan Ra disahkan oleh ujian pengesahan.

© 2017 Penerbit UTM Press. All rights reserved

## 1.0 INTRODUCTION

Electrical discharge machining (EDM) remains among the most widely used non-conventional machining method in the industry. EDM is the most economical technique which remains a viable metal removal process in producing highly complex shapes with high accuracy irrespective of the mechanical properties of the work material especially hardness and brittleness. In EDM the tool does not physically contact the workpiece as such effect of vibration, chatter and mechanical stress during the machining process are highly controlled [1, 2, 3]. The EDM concept has also been applied in finishing parts of the aerospace, surgical and automobiles components [4, 5]. The EDM technique is a thermal process which utilizes high frequency discharge between the tool and the workpiece. This generates spark energy at the electric discharge gap which removes the material from the workpiece through melting and vaporization. During sparking, the work material is heated to a very high temperature sufficiently enough to raise the temperature of a small portion of the workpiece beyond its melting point.

Siliconized silicon carbide (SiSiC) also called reaction bonded silicon carbide (RBSiC) was first manufactured in 1975 by Hilling. The production SiSiC is achieved by infiltrating liquid silicon (Si) into a porous SiC-C green product. At temperature of about 1600°C, the Si melts and fills the porous structure of SiC-C. At this instance, the Si will react with carbon, producing a different form of SiSiC is produced. The infiltrated free Si provides increases significantly the electrical conductivity of the SiSiC and also limits its bending strength to about 250Mpa. The produced SiSiC maintains the mechanical properties of SiC such as excellent wear resistance, good chemical resistance, excellent temperature strength, low specific gravity and high hardness. SiSiC has been applied in several areas such as seal rings, gas turbines, pump components, shot blasting nozzles, burner nozzles, bearings and high temperature heat exchangers [2,6].

Several types of EDM dielectric fluid have been identified. These include mineral oils, kerosene oils, mineral seal, transformer oils, EDM oils, synthetic oils, deionized water and silicon based oils. Kerosene was one of the first popular dielectric oils. EDM oils are currently the most commonly used type in sinking EDM [7]. A new innovation in use of dielectric fluid is achieved by adding fine powder such chromium, aluminum and Si powders. This was found to improve the performance capabilities of the EDM process. It is thought that the powder helps to enhance the breaking down of the dielectric fluid as well as reducing the insulating strength thereby increasing the inter-electrode gap. The enlarged spark gap was found to increase the rate of material removal and improve surface finish due to proper gap flushing and stability of the process. Investigation involving use of such powder on different work material researches

have been reported for a different combination of materials and powders [3, 8].

Structural integrity of the copper electrode gives it ability to produce very fine surface finish even without polishing. Moreover, it is highly resistant to DC arcing when poor flushing is involved. The distinct advantage of copper over graphite electrode is that, copper electrode can be sized automatically using sizing plate during unsupervised CNC cutting which gives it ability to be re-used for finishing cut or production of another component. Among most significant drawbacks of copper electrode include its softness and gummy to machine or grind, burn only half as fast as graphite and difficult to de-burr than to manufacture [9].

There are many processes that influence the outcome in die-sinking EDM operation. Selection of optimum design parameter combinations that will enhance the selected machining performance measures such as material removal rate (MRR), surface roughness (Ra) and tool wear ratio (TWR) in sinking EDM of SiSiC is still not fully understood. Moreover, generating a model that can precisely describe and predict the machining performance is still challenging task. This is due to the complexity and non-deterministic thermal nature of EDM process [10].

Several works have been reported on different aspects of EDM for machining difficult-to-machine materials such as; tungsten carbide, boron carbide, ceramic composite, tool steel, stainless steel, high speed steel and medium carbon steel, using different design parameter combinations and techniques [11-16]. Owing to the high hardness and brittleness of SiSiC, its shaping using conventional methods such as diamond grinding and lapping is time consuming, costly, and can also cause strength degradation due to the formation some defects like cracks in the machined surface [17, 18, 19]. This paper proposed the use of EDM for machining SiSiC using copper electrode. In addition, DOE was adopted in this study to properly design the experiment and to achieve the desired mathematical models. Fractional factorial design was applied on the process parameters to select the most influential parameters on the selected responses. However, to investigate the significance of the curvature on the responses centre and axial points were augmented to the previous design. The model coefficients of the selected factors were determined using face centered central composite design (FCCD). Response surface methodology (RSM) was applied to generate the mathematical models. Optimum responses were achieved through optimum setting of process parameters including peak current, servo voltage, and pulse-on time. Analysis of variance (ANOVA) was used to investigate the experimental data. The models developed were validated by running confirmation tests.

### Sinking EDM Process Parameters and Responses

Several design parameters that affect the machining performance of sinking EDM have been identified [20].

These process parameters were generally classified into two; electrical and non electrical machining process parameters. The present study focuses mainly on the electrical process parameters defined as follows:

**Pulse-on time (Ton):** determines the duration of an electric discharge and electric discharge pulse control system

**Discharge peak current (Ip):** determines the peak current for electrical discharge machining

**Servo voltage (Sv):** specifies a reference voltage for servo motions to maintain constant gap voltage

**Polarity (PL):** determines the electrical polarity of the workpiece and the tool. Negative (normal) tool polarity is the most stable and therefore recommended for sinking EDM of silicon carbide [21].

The selected responses are defined by the following equations:

$$MRR = \frac{(W_2 - W_1) \times 1000}{\rho_w T} \quad (1)$$

where  $W_1$  = workpiece weight after machining (g)  
 $W_2$  = workpiece weight before machining (g)  
 $\rho_w$  = workpiece material density (g/cm<sup>3</sup>)  
 $T$  = machining time (minutes).

$$TWR = \frac{(W_4 - W_3) \times 100}{W_2 - W_1} \quad (2)$$

where  $W_3$  = electrode weight after machining (g)  
 $W_4$  = electrode weight before machining (g)

$$R_a = \frac{1}{L} \int_0^L |Y(X)| dX \quad (3)$$

where  $Y(x)$  = roughness profile value,  
 $L$  = evaluation length [11,21,22].

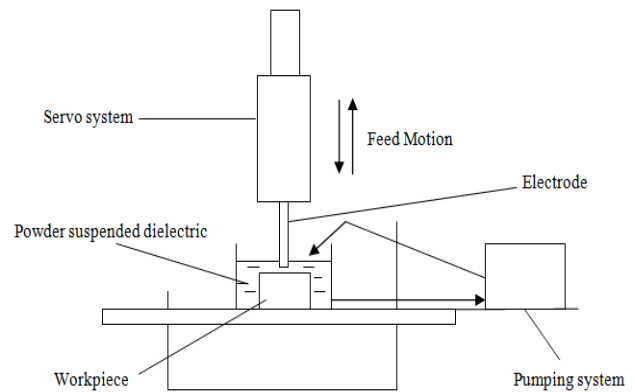
## 2.0 METHODOLOGY

The experimental set-up was developed to run the experiments with powder suspended dielectric fluid as shown in Figure 1. The workpiece was completely immersed into the dielectric fluid, and a gap of 0.5 mm was maintained by a servo system, which allows efficient cleaning and prevents powder particles sedimentation. In the present study, the experiments were conducted using sodik-AG40L die-sinking EDM machine. A solid block of siliconized silicon carbide (SiSiC) 12mm x 50mm x 50mm was selected as the workpiece sample. Copper electrode with 50 x φ6mm was used as tool material. PGM white 3 aluminum

powder was added to synthen SEM 212 dielectric fluid. The surface quality of the machined SiSiC surface was measured using Mitutoyo formtracer CS-5000 machine. The selected process parameters and their levels were depicted in Table 1.

**Table 1** Process parameters and levels selected

Factors	level	
	low (-)	high (+)
Discharge peak current (A)	4.4	13.2
Pulse-on time (μs)	10	30
Servo voltage (V)	40	80



**Figure 1** Experimental set-up

## Experimental Design

Design of experiment (DOE) remained a powerful means which is applied to model and analyzes the influence and relationship between the various design parameter levels and responses. RSM was used as a tool to develop the mathematical models. Owing to the presence of large number of EDM parameters, a two level  $2^{5-1}$  factorial design using 5 factors ( $I_p$ ,  $T_{on}$ ,  $S_v$ , pulse off time, and supply voltage) was carried out. This gives a total of 16 experiments. The main and interaction effects obtained, revealed that  $I_p$ ,  $T_{on}$ , and  $S_v$  are the most significant parameters on the selected responses (MRR, TWR and  $R_a$ ) [20]. However, FCCD was adopted to investigate the significance of the curvature. The previous factorial design was augmented by additional 8 center and 6 axial points experiments, using the selected parameters. Thus, a total of 30 experimental runs was achieved. The FCCD is an efficient experimental design for fitting a quadratic model. Unlike Box-Behnken design, central composite design can include runs from a factorial experiment [23].

## Experimental Procedure

- (a) Cut the electrode and the workpiece to required shape and size

- (b) Measure the weight of both the workpiece and the electrode
- (c) Mount the workpiece and the electrode on the EDM machining table and the servo fixture respectively
- (d) Write suitable program on the EDM CNC computer
- (e) Input the selected design parameters
- (f) Start the machining and monitor the stability of the EDM machine
- (g) When the machining completed EDM will stop automatically
- (h) Wash, clean and dry both the tool and the workpiece
- (i) Measure the final weight of the tool and the workpiece
- (j) Repeat the above procedures for the next sample

purpose of RSM is to optimize the responses [25, 26]. The first stage of RSM is to determine the applicable approximation for response surface and then the model is validated using the experimental data [10]. In the present study, the experiments were carried out in order to generate the empirical models for MRR, TWR and Ra in terms of the selected design factors. Equation 4 shows the mathematical relationship between the responses and the desired process parameters is given in equation 4.

$$Y = f(I, T, V) \tag{4}$$

where Y = response variable  
 f = function of the response  
 I = discharge peak current  
 T = Pulse-on time  
 V = servo voltage

**Response Surface Methodology**

RSM is a compilation of statistical and mathematical technique that plays a significant role in modeling and analysis of problems, whereby responses are influenced by several design parameters. The main

Table 2 shows the DOE matrix and the machining performance measures. The machined workpiece sample and the electrodes used were depicted in Figure 2.

**Table 2** DOE matrix and machining performance measure

Std order	Run order	Block	Type	Ip (A)	Ton (µs)	Sv (V)	MRR (mm <sup>3</sup> /min)	TWR (%)	Ra (µm)
1	9	Block 1	Fact	4.4	10	40	0.5538	18.94	1.544
2	28	Block 1	Fact	4.4	10	40	0.5728	18.66	1.594
3	14	Block 1	Fact	13.2	10	40	1.4403	41.81	1.941
4	12	Block 1	Fact	13.2	10	40	1.4747	42.14	1.969
5	29	Block 1	Fact	4.4	30	40	0.7857	17.71	2.296
6	1	Block 1	Fact	4.4	30	40	0.7923	17.76	2.245
7	13	Block 1	Fact	13.2	30	40	1.6485	41.98	2.747
8	6	Block 1	Fact	13.2	30	40	1.6554	41.98	2.766
9	5	Block 1	Fact	4.4	10	80	0.2393	19.81	1.445
10	19	Block 1	Fact	4.4	10	80	0.2305	19.75	1.368
11	3	Block 1	Fact	13.2	10	80	1.1583	40.62	1.845
12	26	Block 1	Fact	13.2	10	80	1.1575	40.99	1.821
13	2	Block 1	Fact	4.4	30	80	0.4794	17.4	2.355
14	16	Block 1	Fact	4.4	30	80	0.4864	17.11	2.309
15	22	Block 1	Fact	13.2	30	80	1.3438	42.71	2.821
16	33	Block 1	Fact	13.2	30	80	1.3548	42.14	2.858
17	31	Block 1	center	8.8	20	60	1.3013	29.44	2.509
18	8	Block 1	center	8.8	20	60	1.2901	29.22	2.53
19	36	Block 1	center	8.8	20	60	1.2899	29.43	2.433
20	4	Block 1	center	8.8	20	60	1.2905	30.1	2.668
21	10	Block 1	center	8.8	20	60	1.304	29.89	2.459
22	11	Block 1	center	8.8	20	60	1.3075	30.23	2.614
23	30	Block 1	center	8.8	20	60	1.2854	29.44	2.452
24	18	Block 1	center	8.8	20	60	1.313	29.22	2.639
25	20	Block 2	Axial	4.4	20	60	0.6423		2.045
26	35	Block 2	Axial	13.2	20	60	1.5021		2.621
27	34	Block 2	Axial	8.8	10	60	1.1431		1.634
28	7	Block 2	Axial	8.8	30	60	1.3767		2.721
29	23	Block 2	Axial	8.8	20	40	1.3432		2.512
30	25	Block 2	Axial	8.8	20	80	1.0212		2.456

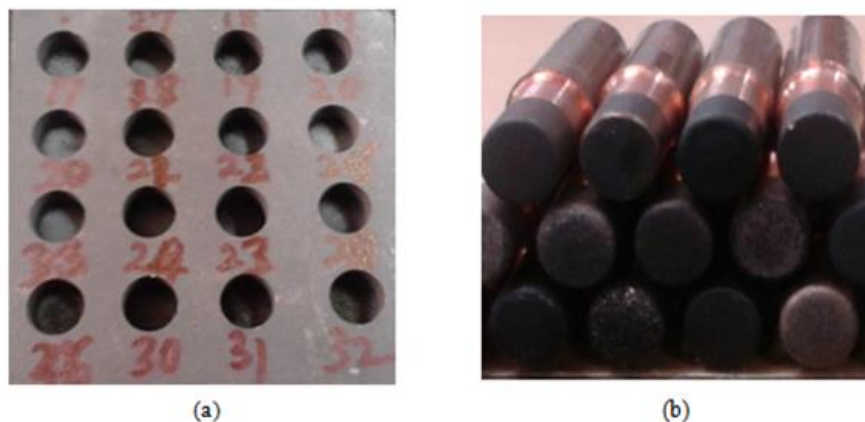


Figure 2 (a) EDMed holes (b) Electrodes used

### 3.0 RESULTS AND DISCUSSION

The results were analyzed using design expert 7.0 software. The experimental results in terms of ANOVA are presented. The ANOVA table provides the summary of the regression model, process parameters, interactions, curvature and lack of fit experimental tests. The model terms with p-value less than 0.05 are considered significant. Terms with p-value above 0.1 is taken to be insignificant. If the p-values lie between 0.05 and 0.1, they may be taken into consideration for supporting the hierarchy [25].

#### Material Removal Rate

The MRR was determined using equation 1. The weight of the workpiece was measured before and after each experiment. The ANOVA table for curvature test of MRR is depicted in Table 3. The p-value of 0.0001 indicates that the curvature is significant. Thus, the model is quadratic. Therefore, additional 6 axial point experiments are further required to be conducted to account for non-linearity present in the model.

After augmenting the design with 6 axial points (Table 2, block 2) and eliminating the insignificant terms the ANOVA table for MRR is displays in Table 4. The model "F-value" of 4277.21 indicates the significance of the model. Thus, there is only 0.0001 chance that a "model F-value" this large could occur as a result of noise. The results obtained indicate that the discharge peak current (A), pulse-on time (B), servo voltage (C), AB interaction and pure quadratic (A2, B2 and C2) are the significant terms of MRR model. The "Lack of fit F-value" of 2.49 justified it is insignificant. Thus, there is 6.51% chance that "Lack of fit value" this large could occur as a result of noise. Insignificant lack of fit is favorable for the selected model to fit the data. The "Pred R-squared" value of 0.9984 agreed reasonably with the "Adj R-Squared" value of 0.9990. The signal to noise ratio value of 214.763 justified the adequate signal for this model. The R-square value is very important term to be considered. It determines the sources of variations left. A high value of R-square (close to 100%) indicates that

the variation in the process is controlled. Thus, the values of R-square and adjusted R-square of 99.93% and 99.90% respectively justified that the model gives a good explanation of the relation between design parameters and the response (MRR). A mirror-like finishing which do not require any secondary process was achieved. However, the material removal is much higher with less tool wear when compared with conventional process.

#### Tool Wear Ratio

Equation 2 was used to determine the TWR. The electrode weight before and after the experiment was measured. Table 5 shows the ANOVA table linear model of TWR. It can be observed that the  $I_p$  and  $T_{on}$  are the main significant process parameters. Interaction AB ( $I_p$ - $T_{on}$ ) is also significant on TWR. There is insignificant 'Lack of fit' with the value of 0.67. Therefore, the model can fit the data as required. Moreover, the curvature is not significant. Thus, only linear or 2-factor interaction (2FI) model need to be generated and no further axial point experiments are required. The "Pred R-squared" value of 0.9951 agreed reasonably with the "Adj R-Squared" value of 0.9967. The signal to noise ratio more than 4 is usually required. The "Adeq precision" ratio is 95.246 which indicate sufficient signal.

#### Surface Roughness

The  $R_a$  values were obtained directly from the surface roughness tester. Table 6 displays the ANOVA for curvature test for  $R_a$ . It can be examined that the curvature for  $R_a$  has "F value" of 239.37 which indicates its significance. Thus, second order equation is required for  $R_a$  and the model is non-linear. Therefore, there is a need to augment the previous design with additional 6 axial point experimental runs (Table 2, block 2). The ANOVA for the quadratic model for  $R_a$  is displays in Table 7. The "Lack of fit" is not significant which is preferable for the model to fit the response. The parameters A, B, BC interaction, A2, and B2 are significant terms of the model. The "Pred R-

squared" with value 0.962346 is similar with "Adj R-squared" of 0.971941 as required.

**Normal, Residuals and Surface Plots**

Figure 3 shows the residuals versus predicted plots for MRR, TWR and Ra. It can be seen that most of the data lie along a straight line. This signifies that the errors are distributed normally, and the terms stated in the model are the only significant parameters [22, 23, 24].

Internally studentized residuals were plotted against the run for the model of MRR, TWR and Ra as displayed in Figure 4. From the plots, it can be deduced that the models developed can be applied in predicting the machining characteristics, since all the studentized residuals for regression models of MRR, TWR and Ra lie within the limits ( $\pm 3$  sigma) without any outliers.

Figure 5 displays the surface plots for MRR, TWR and Ra. A curved plane is observed on the plots for MRR and Ra due to the significant curvature on the said responses, while flat surface is observed in the TWR plot due to insignificant curvature. Considerable increase in MRR with an increase in Ip and Ton was noticed from plot. This is due to the demonstrative control over the input energy. The plot also shows that the maximum MRR is achieved at the higher level of the Ip, 13.2A and Ton, 30 $\mu$ s (Figure 5(a)). As Ip increases TWR increases considerably and decreases marginally with increase in Ton. The increase in TWR with high Ip is due to an increase in heat energy rate. High Ton leads to low TWR due to decrease in the current density of the discharge channel [13]. Low TWR occurs at low Ip, 4.4A and high Ton, 30 $\mu$ s (Figure 5(b)). Figure 5(c) shows that the low Sv and low Ton provide good surface quality.

**Table 3** ANOVA for curvature test f or MRR

ANOVA for selected factorial model Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Remark
Model	3.71	4	0.93	7737.86	<0.0001	Significant
A-Ip	3.14	1	3.14	26208.74	<0.0001	
B-Ton	0.18	1	0.18	1539.49	<0.0001	
C-Sv	0.38	1	0.38	3187.12	<0.0001	
AB	1.929E-0030.61	1	1.929E-	16.08	0.0008	
Curvature	2.160E-003	1	0030.61	5044.45	<0.0001	Significant
Residual	5.133E-004	18	1.200E-004			
Lack of Fit	1.646E-003	3	1.711E-004	1.56	0.2407	Not significant
Pure Error	4.32	15	1.098E-004			
Cor Total		23				

**Table 4** ANOVA for quadratic model of MRR – After augmenting the design

ANOVA for selected factorial model Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Remark
Model	4.85		0.69	4277.21	<0.0001	Significant
A-Ip	3.51	7	3.51	21700.41	<0.0001	
B-Ton	0.21	1	0.21	1308.24	<0.0001	
C-Sv	0.43	1	0.43	2681.24	<0.0001	
AB	1.929E-003	1	1.929E-003	11.92	0.0023	
A2	0.13	1	0.13	774.97	<0.0001	
B2	1.444E-003	1	1.444E-003	8.92	0.0068	
C2	0.029	1	0.029	176.19	<0.0001	
Residual	3.562E-003	1	1.619E-004			
Lack of Fit	1.916E-003	22	2.737E-004	2.49	0.0651	Not significant
Pure Error	1.646E-003	7	1.098E-004			
Cor Total	4.85	15				
		29				
Std.Dev.	0.012725		R-Squared	0.999266		
Mean	1.092793		Adj R-Squared	0.999032		
C.V. %	1.164441		Pred R-Squared	0.998426		
PRESS	0.007635		Adeq Precision	214.7628		

Table 5 ANOVA for linear model OF TWR

ANOVA for selected factorial model Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Remark
<b>Model</b>	2130.96	3	710.32	2204.92	<0.0001	Significant
A-Ip	2118.30	1	2118.30	6575.47	<0.0001	
B-Ton	2118.30	1	1.60	4.97	0.0381	
AB	1.60	1	11.06	34.32	<0.0001	
Curvature	11.06	1	0.95	2.96	0.1019	Not significant
Residual	0.95	1	0.32			
<i>Lack of Fit</i>	6.12	19	0.23	0.67	0.6218	Not significant
Pure Error	0.93	4	0.35			
Cor Total	5.19	15				
	2138.03	23				
Std. Dev.	0.567584		R-Squared	0.997136		
Mean	30.00792		Adj R-Squared	0.996684		
C.V. %	1.891449		Pred R-Squared	0.995148		
PRESS	10.37286		Adeq Precision	95.24614		

Table 6 ANOVA for curvature test for Ra

ANOVA for selected factorial model Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	P-value Prob > F	Remark
<b>Model</b>	3.69	5	0.74	195.43	<0.0001	Significant
A-Ip	0.77	1	0.77	204.32	<0.0001	
B-Ton	2.86	1	2.86	759.26	<0.0001	
C-Sv	2.025E-003	1	2.025E-003	0.54	0.4738	
AB	0.013	1	0.013	3.54	0.0773	Significant
BC	0.036	1	0.036	9.52	0.0067	
Curvature	0.90	1	0.90	239.37	<0.0001	Significant
Residual	0.064	17	3.773E-003			
<i>Lack of Fit</i>	2.762E-004	2	1.381E-004	0.032	0.9681	Not significant
Pure Error	0.064	15	4.257E-003			
Cor Total	4.65	23				

Table 7 ANOVA for quadratic model for Ra – after augmenting the design

ANOVA for selected factorial model Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Remark
<b>Model</b>	5.57	6	0.93	168.42	<0.0001	Significant
A-Ip	0.97	6	0.97	176.69	<0.0001	
B-Ton	3.52	1	3.52	637.81	<0.0001	
C-Sv	6.272E-003	1	6.272E-003	1.14	0.2973	
BC	0.046	1	0.046	8.34	0.0083	Significant
A2	0.053	1	0.053	9.53	0.0052	
B2	0.27	1	0.27	48.62	<0.0001	Not significant
Residual	0.13	1	5.515E-003			
<i>Lack of Fit</i>	0.060	23	7.535E-003	1.70	0.1794	Not significant
Pure Error	0.067	8	4.437E-003			
Cor Total	5.70	15				
		29				
Std.Dev.	0.074262		R-Squared	0.977746		
Mean	2.2739		Adj R-Squared	0.971941		
C.V. %	3.265855		Pred R-Squared	0.962346		
PRESS	0.214616		Adeq Precision	40.60802		

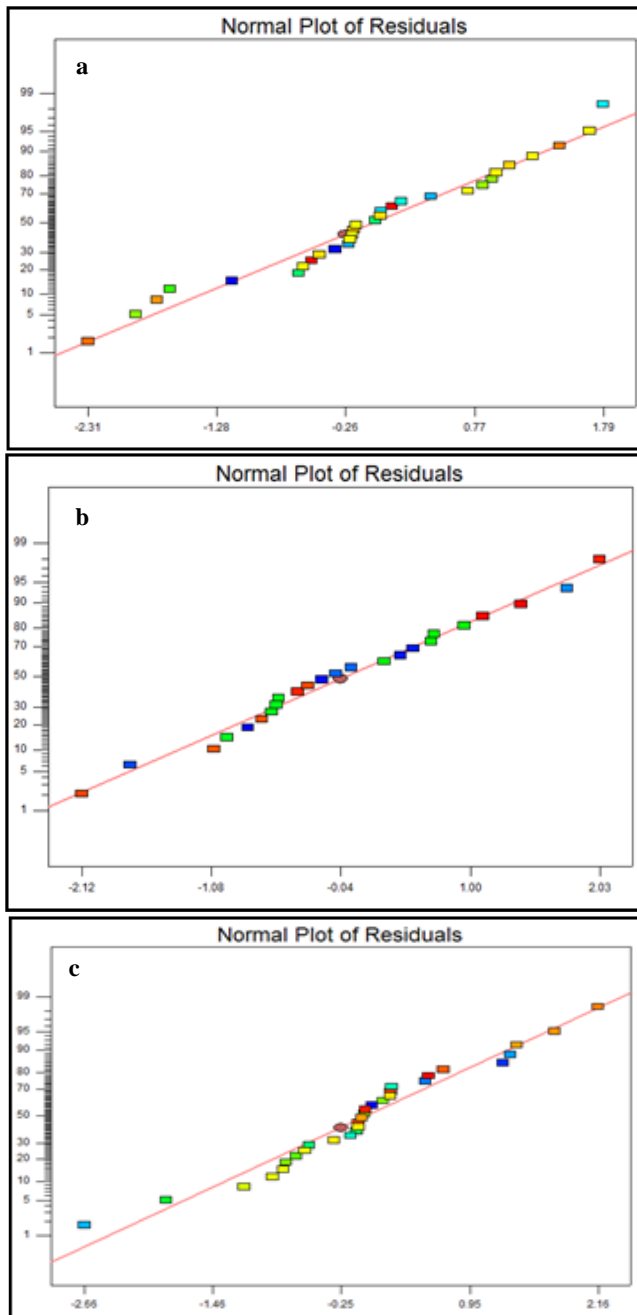


Figure 3 Residuals versus predicted for (a) MRR (b) TWR (c) Ra

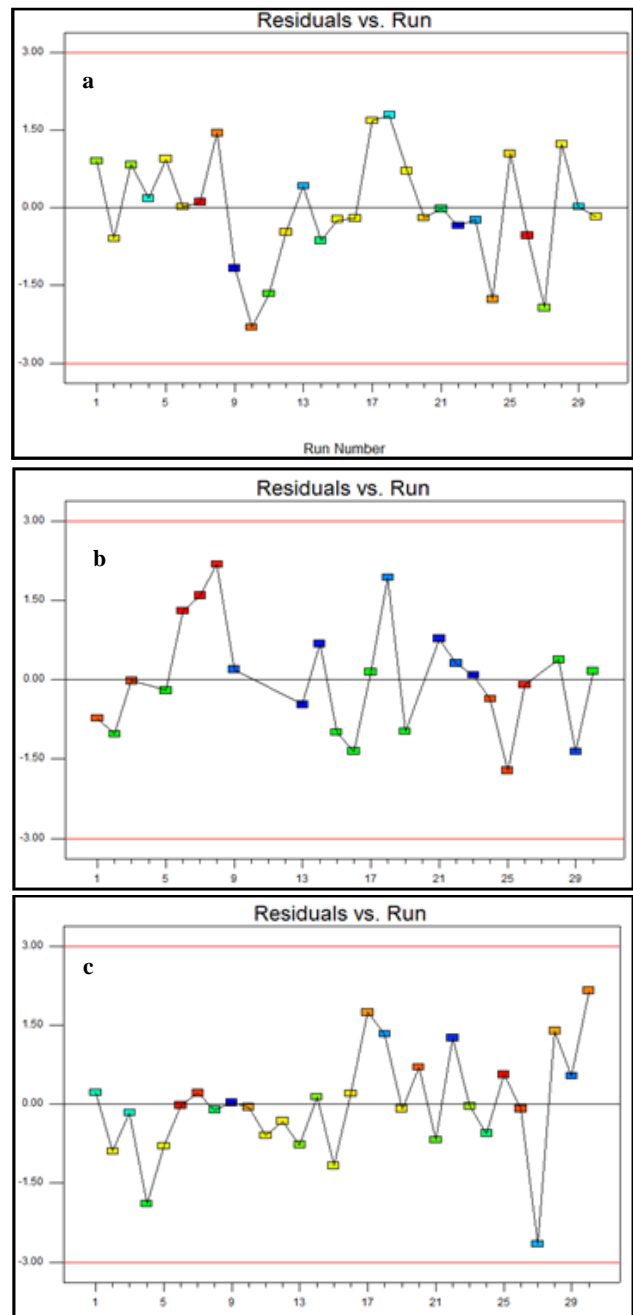


Figure 4 Residuals versus run for (a) MRR (b) TWR (c) Ra



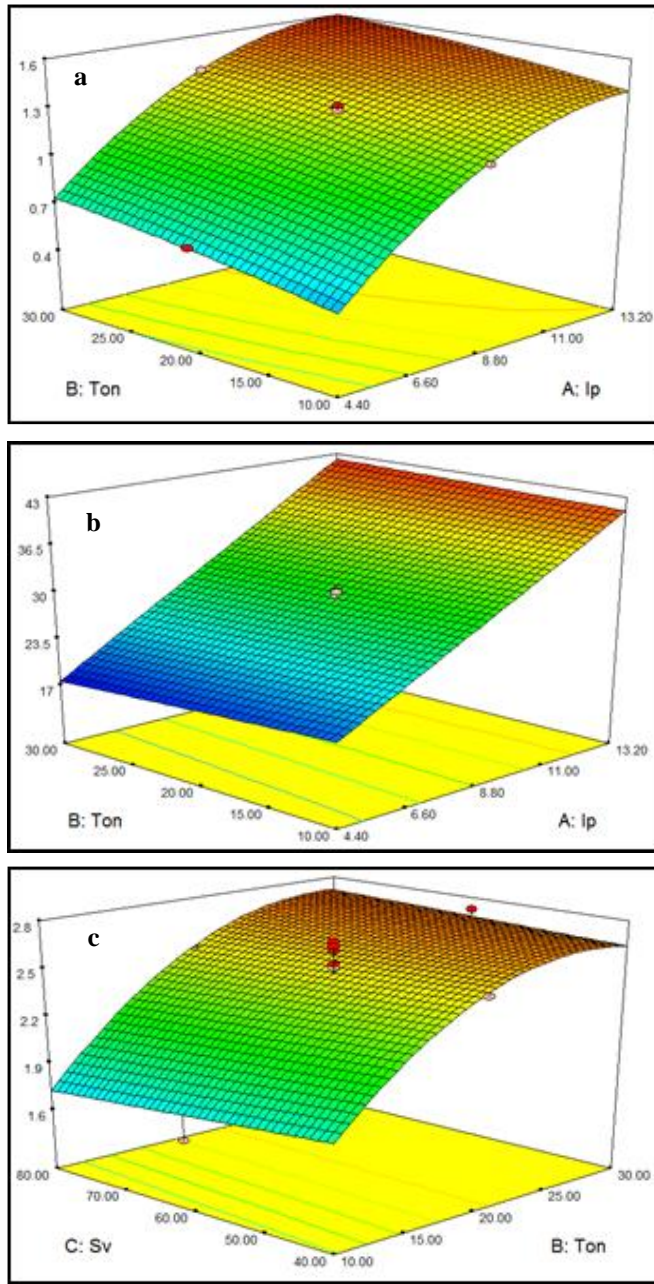


Figure 5 3D surface plots for (a) MRR (b) TWR (c) Ra

### FESEM Observation of EDMED SiSiC Surface

The machined surface of SiSiC was observed using field emission scanning electron microscopy (FESEM). Figure 6 displays the micrographs of the EDMed surfaces of SiSiC at variable machining parameter settings. All the micrographs were observed under 500x magnifications. Presence of many spark-induced craters, droplets, micropores, and microcracks indicates that SiSiC is melted and evaporated by thermal energy. Electric spark is produced at the inter-electrode gaps which depend on the amount of Ip and Ton. A very high temperature is produced at the point of spark by the

discharge energy, which melts and overheats some part of the workpiece. The melted workpiece will be washed away by the flowing dielectric fluids thereby forming craters on the machined surface of the SiSiC workpiece. Minute part of the molten material will remain on the machined workpiece surface which is subsequently cooled by the dielectric fluid and formed droplets. Micropores are produced due to ejection of gases during machining. High thermal stresses which normally exceed fracture strength and plastic deformation lead to the formation of Microcracks [6]. Renjie et al., [23] reported that negative tool polarity produces larger and deeper craters while positive tool polarity produces smaller and shallow craters when sets at the same machining parameter settings. Few and shallow microcracks were observed at lower value of Ip and Ton settings (Figure 6(a)) while deeper and pronounced microcracks were obtained at higher Ip and Ton parameter settings (Figure 6 (b)). This is probably due to increase in energy at the machining gap which leads to the heating and cooling effect and subsequent increase in the temperature gradient and stresses during machining.

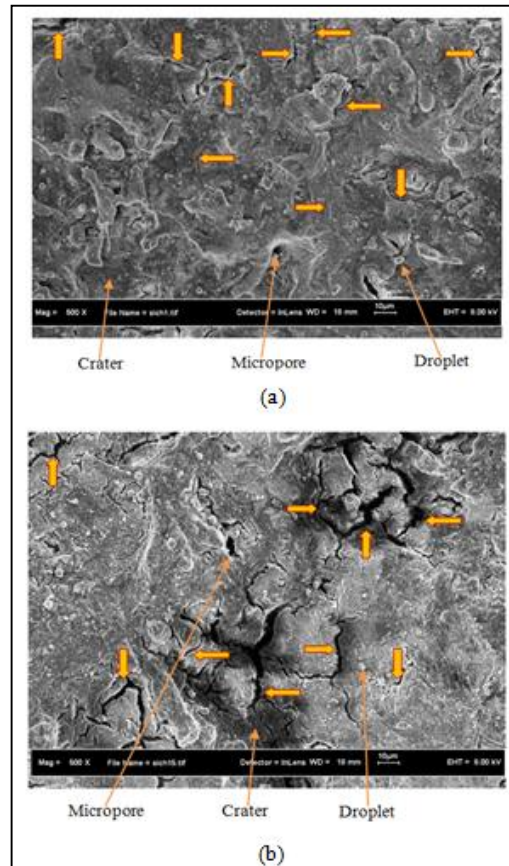


Figure 6 FESEM showing micrographs of EDMed SiSiC surfaces by sinking-EDM at (a) Ip = 4.4A, Ton = 10μs, Sv = 40V (b) Ip = 13.2A, Ton = 30μs, Sv = 40V, (arrows indicate the microcracks)

### Modeling Response Variables

The responses and the design parameters are related by the final equation which was obtained from ANOVA table and results. The prediction models for MRR, TWR, Ra, are presented in the following equations.

The Final equations in terms of coded factors are given in equations 5, 6 and 7.

$$\text{MRR} = +1.29+0.44*A+0.11*B-0.16*C-0.011*A*B-0.21*A^2-0.023*B^2-0.10*C^2 \quad (5)$$

$$\text{TWR} = +30.01+11.51 * A-0.32 * B+0.83*A * B \quad (6)$$

$$\text{Ra} =+2.52+0.23*A+0.44*B-0.019*C+0.054*B*C-0.12*A^2-0.28* B \quad (7)$$

### Confirmation Test

After the optimum levels of design parameter are selected, the next stage is to validate the models developed for MRR, TWR and Ra through confirmation tests. To validate the developed mathematical models confirmation tests were conducted using the optimum parameters developed by the design software. This will greatly help in verifying the adequacy of the mathematical models developed. The optimum parameter settings were suggested by the design software as shown in Table 8.

**Table 8** Parametric settings for quality characteristics

Optimum Parameters Setting			Percentage Errors (%)		
Ip (A)	Ton (µs)	Sv (V)	MRR (mm <sup>3</sup> /min)	TWR (%)	Ra (µm)
6.70	10	48.97	4.73	3.04	3.70
6.71	10	49.40	5.67	5.78	0.60
6.69	10	49.25	7.94	7.02	5.63
7.12	10	48.23	9.56	9.56	2.04
4.69	30	42.21	5.51	4.00	0.48
Average Predicted Errors (PE)			6.68	5.88	2.49

Percentage error for the responses below 10% are considered within the acceptable limit [8, 13, 21]. However, the excellent reproducibility of this experimental study is confirmed, and the models developed for MRR, TWR and Ra are justified to be valid. In addition, the results affirm the suitability of EDM process in shaping of SiC ceramic. A higher quality surface can be achieved through EDM process at low cost and reduced time when compared with traditional processes.

### 4.0 CONCLUSION

- Ip and Ton were found to be significant on all the responses. In addition to Ip and Ton, Sv is also significant on MRR.
- Ip-Ton interaction is significant on MRR and TWR while Ton-Sv interaction is significant on Ra.
- Quadratic models were developed for MRR and Ra, 2FI model was developed for TWR.
- The optimum MRR, TWR and Ra was achieved.
- Microcracks, micropores, craters and droplets were observed on machined SiSiC surface.
- The confirmation runs reveal that the margin of error between predicted and experimental values of MRR, TWR and Ra are found within 6.7, 5.6 and 2.5% respectively. Thus, the excellent reproducibility of this experimental study is confirmed, and the models developed for MRR, TWR and Ra are justified to be valid.

### Acknowledgement

The authors of this paper sincerely appreciate the giant effort of Kano state government, Nigeria and Universiti Teknologi Malaysia (Faculty of Mechanical Engineering) for their propound support towards the conduct and completion of this research. A special thanks to the Lab technicians especially Mr Roslin and Mr Khalid for their strong guidance during this study.

### References

- Newman, S. T., Ho. K. H. 2003. State Of The Art Electrical Discharge Machining (EDM). *International Journal of Machine Tools & Manufacture*. 43: 1287-1300.
- Sanchez, J. A, Cavanese, I., Lopez, L. N., Lamikiz, A. 2001. Development of Optimum Electrodischarge Machining Technology for Advanced Ceramics. *Int J Adv Manuf Technol*. 18: 897-905.
- Singh, S., Bhardwaj, A. 2011. Review to EDM by Using Water and Powder-Mixed Dielectric Fluid. *Journal of Minerals & Materials Characterization & Engineering*. 10(2): 199-230.
- Abbas, N. M., Solomon D. G., Bahari M. F. 2007. A Review On Current Research Trends In Electrical Discharge Machining (EDM). *International Journal of Machine Tools & Manufacture*. 47: 1214-1228.
- Paulo P., and Henriques E. 2008. Effect Of The Powder Concentration And Dielectric Flow In The Surface Morphology In Electrical Discharge Machining With Powder-Mixed Dielectric (PMD-EDM). *Int J Adv Manuf Technol*. 37(10): 1120-1132.
- Clijsters, S., Liu, K., Reynaerts, D., Lauyers, B. 2010. EDM Technology And Strategy Development For The Manufacturing Of Complex Parts In SiSiC. *Journal of Materials Processing Technology*. 210: 631-641.
- Kern, R. 2009. Sinker Dielectric Fundamentals. [Online] Available at [edmtodaymagazine.com/AAweb2\\_2010/.../Tech](http://edmtodaymagazine.com/AAweb2_2010/.../Tech) [Accessed 30 July 2013].
- Kansal, H. K., Singh, S., Kumar, P. 2005. Parametric Optimization Of Powder Mixed Electrical Discharge Machining By Response Surface Methodology. *Journal of Materials Processing Technology*. 169: 427-436.

- [9] Kern, R. 2008. Electrode Materials Properties that affect EDM. Available at: [www.edmtodaymagazine.com/AAweb2\\_2010/.../TechTipsM-J-8.pdf](http://www.edmtodaymagazine.com/AAweb2_2010/.../TechTipsM-J-8.pdf) [Accessed 25 July 2013].
- [10] Iqbal, A. K. M., and Khan, A. A. 2009. A Study of Electrode Shape Configuration on the Performance of die sinking EDM. *International Journal of Mechanical and Materials Engineering (IJMME)*. 4(1): 19-23.
- [11] Tomadi, S. H., Hassan, M. A. Hamedon, Z., Daud, R., Khalid, A. A. 2009. Analysis of the Influence of EDM Parameters on Surface Quality, Material Removal Rate and Electrode Wear of Tungsten Carbide. Hong Kong.
- [12] Iqbal, A. K. M., and Khan A. A. 2010. Modeling and Analysis of MRR, EWR and Surface Roughness in EDM Milling through Response Surface Methodology. *American J. of Engineering and Applied Sciences*. 3(4): 611-619.
- [13] Baraskar, S., Banwait, S. S., Laroia, S. C. 2011. Mathematical Modeling of Electrical Discharge Machining Process through Response Surface Methodology. *International Journal of Scientific & Engineering Research*. 2(11): 2229-5518.
- [14] Ramasawmy, H., Blunt L. 2004. Effect of EDM Process Parameters on 3D Surface Topography. *Journal of Materials Processing Technology*. 148: 155-164.
- [15] Puetas, I., Luis, C. J. 2007. A Study of Optimization of Machining Parameters for Electrical Discharge Machining of Boron Carbide. *Journal Of Materials And Manufacturing Processes*. 19: 1041-1070
- [16] Patel, K. M., Pulak M., Pandey, Venkateswara, R. 2009. Determination of an Optimum Parametric Combination Using a Surface Roughness Prediction Model for EDM of Al<sub>2</sub>O<sub>3</sub>/SiCw/TiC Ceramic Composite. *Journal Of Materials And Manufacturing Processes*. 24: 675-682.
- [17] Agarwal, S., Rao, P. V. 2010. Grinding Characteristics, Material Removal And Damage Formation Mechanisms In High Removal Rate Grinding Of Silicon Carbide. *International Journal of Machine Tools & Manufacture*. 50: 1077-1087.
- [18] Yan, J., Zhang, Z., and Kuriyagawa, T. 2009. Mechanism For Material Removal In Diamond Turning Of Reaction-Bonded Silicon Carbide. *International Journal of Machine Tools and Manufacture*. 45(5): 366-374
- [19] Yang, X. H., Zhang Y. M., and Han, J. C. 2007. High Speed Lapping Of SiC Ceramic Material With Fixed Abrasive. In *Proceedings Of Key Engineering Materials*. 336-338: 1458-1460.
- [20] A. A. Aliyu, H. Musa and J. M. Rohani. 2014. Parametric Study Of Powder Mixed Electrical Discharge Machining And Mathematical Modeling of SiSiC Using Copper Electrode. *Proceedings Of Advanced Materials Research*. 845: 878-882
- [21] Puertas, I., Luis, C. J., Villa, G. 2005. Spacing Roughness Parameters Study On The EDM Of Silicon Carbide. *Journal of Materials Processing Technology*. 164-165: 1590-1596.
- [22] Junaid, M., Sheikh, K., Singh, B., Malhotra, N. 2012. Modeling And Analysis Of Machining Parameters For Surface Roughness In Powder Mixed EDM Using RSM Approach. *International Journal of Engineering, Science and Technology*. 4: 45-52.
- [23] Zahraee, S. M., Hatami, M., Yusof, N. M., Rohani, J. M., and Ziaei, F. 2013. Combined Use Of Design Of Experiment And Computer Simulation For Resources Level Determination In Concrete Pouring Process. *Jurnal Teknologi*. 64(1).
- [24] Zahraee, S. M., Shariatmadari, S., Ahmadi, H. B., Hakimi, S., & Shahpanah, A. 2014. Application Of Design Of Experiment And Computer Simulation To Improve The Color Industry Productivity: Case Study. *Jurnal Teknologi*. 68(4).
- [25] Montgomery, D. C. 2013. *Design and Analysis of Experiments*. 8th ed. New York: John Wiley & sons, Inc.
- [26] Renjie, J., Liu, Y., Zhang Y., Wang, F. 2011. Machining Performance Of Silicon Carbide Ceramic In End Electric Discharge Milling. *Int. Journal of Refractory Metals and Hard Materials*. 29: 117-122.
- [27] Zahraee, S. M., Khademi, A., Khademi, S., Abdullah, A., & Ganjbakhsh, H. 2014. Application of Design Experiments to Evaluate the Effectiveness of Climate Factors on Energy Saving in Green Residential Buildings. *Jurnal Teknologi*. 69(5).