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OPTIMIZATION OF ELECTRICAL DISCHARGE MACHINING PARAMETERS OF SISIC THROUGH RESPONSE SURFACE METHODOLOGY

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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 (Ip), pulse-on time (Ton), and servo voltage (Sv) 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 memesin bahan ini melalui teknik yang dipanggil *Electrical Discharge Machining*. Meknisma pemesinan melalui kaedah ini sangat komplek. 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 kemasan permukaaan (Ra). Ujikaji menggunakan kaedah rekabentuk *face centered composite*. Model telah dibentuk untuk mengenal pasti faktor *parameter input* yang signifikan: *Discharge current (Ip), Pulse on time (Ton)* dan *servo voltage (Sv)* 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.

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 reacts 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 arching 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, it's 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 cupper 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 augumented 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:

$$MRR = \frac{(W_2 - W_1)x1000}{\rho_w T} \qquad (1)$$

where W_1 = workpiece weight after machining (g)
W_2 = workpiece weight before machining (g)
ρ_w = workpiece material density (g/cm3)
T = machining time (minutes).

$$TWR = \frac{(W_4 - W_3)x100}{W_2 - W_1} \qquad (2)$$

where W_3 = electrode weight after machining (g)
W_3 = electrode weight after machining (g)

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

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 sythen 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

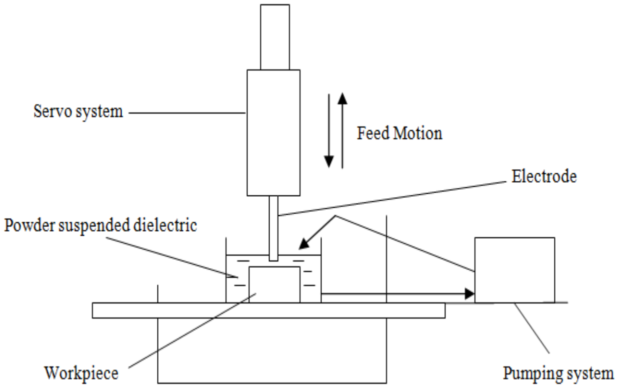


Figure 1 Experimental set-up

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 (Ip, Ton, Sv, pulse off time, and supply voltage)was carried out. This gives a total of 16 experiments. The main and intraction effects obtained, revealed that Ip, Ton, and Sv are the most significant parameters on the selected responses (MRR, TWR and Ra) [20]. However, FCCD was adopted to investigate the significance of the curvature. The previous factorial design was agumented 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, centaral 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 electronde on the EDM maching table and the servo fixture respectively
(d) Write suitable programe 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) Repaeat the above procedures for the next sample

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 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.

$$Y = f(I, T, V) \qquad (4)$$

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

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 (mm3/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

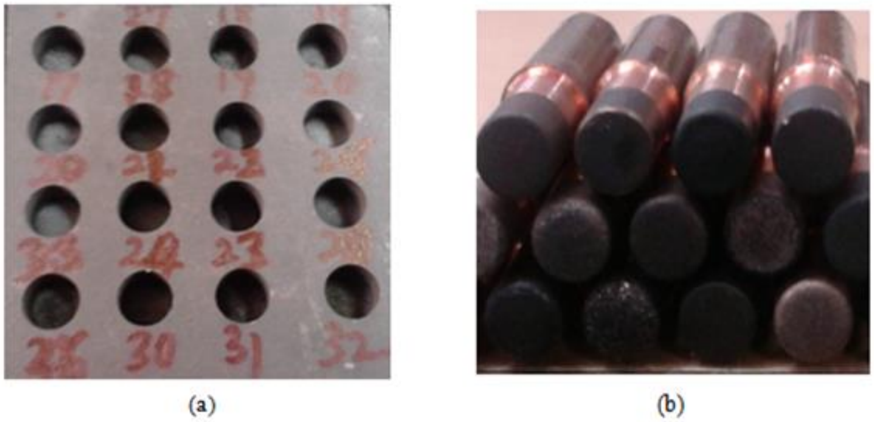


Figure 2 (a) EDMed holes (b) Electrodes used

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 Ip and Ton are the main significant process parameters. Interaction AB (Ip-Ton) 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 Ra values were obtained directly from the surface roughness tester. Table 6 displays the ANOVA for curvature test for Ra. It can be examined that the curvature for Ra has "F value" of 239.37 which indicates its significance. Thus, second order equation is required for Ra 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 Ra 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.

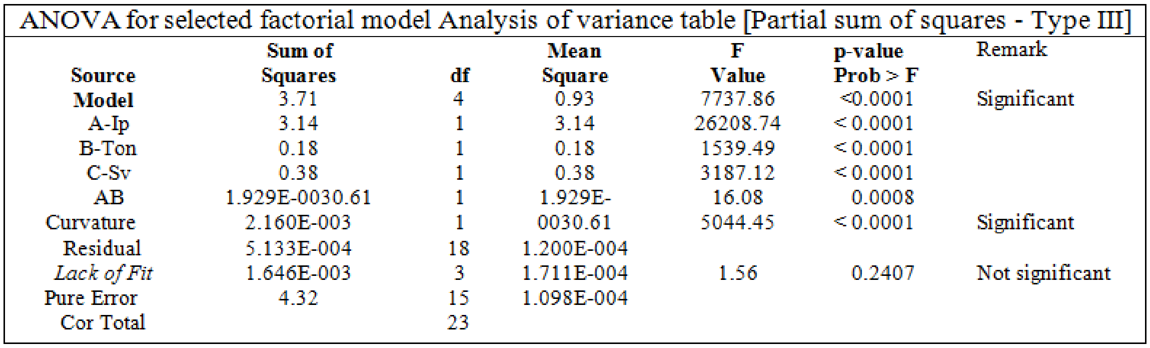
Normal, Residuals and Surface Plots

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 (± 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, 30μs (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, 30μs (Figure 5(b)). Figure 5(c) shows that the low Sv and low Ton provide good surface quality.

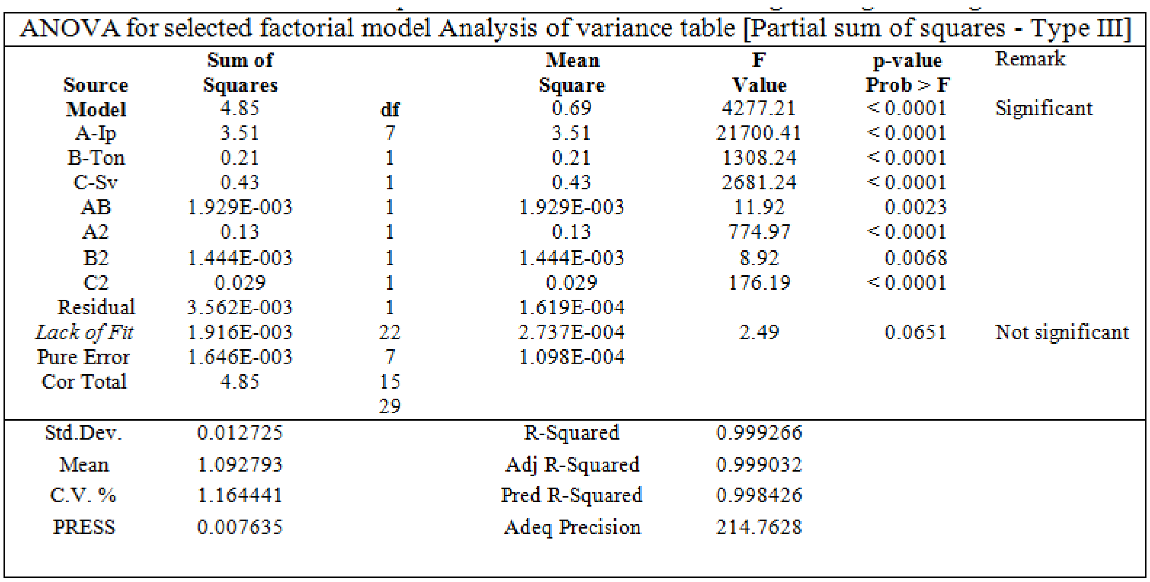
Table 3 ANOVA for curvature test f or MRR



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

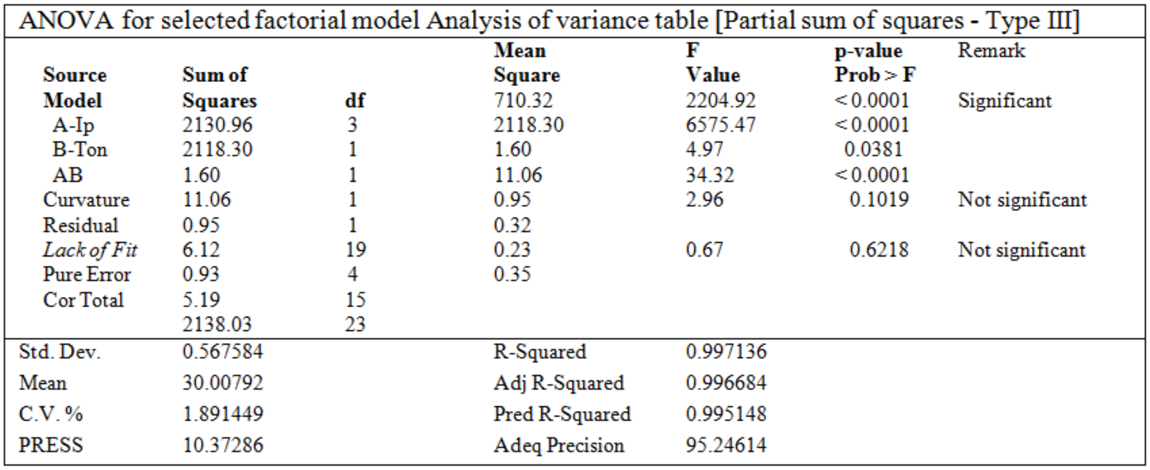


ANOVA for selected factorial model Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares		Mean Square	F Value	p-value Prob > F	Remark
Model	4.85	**df**	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

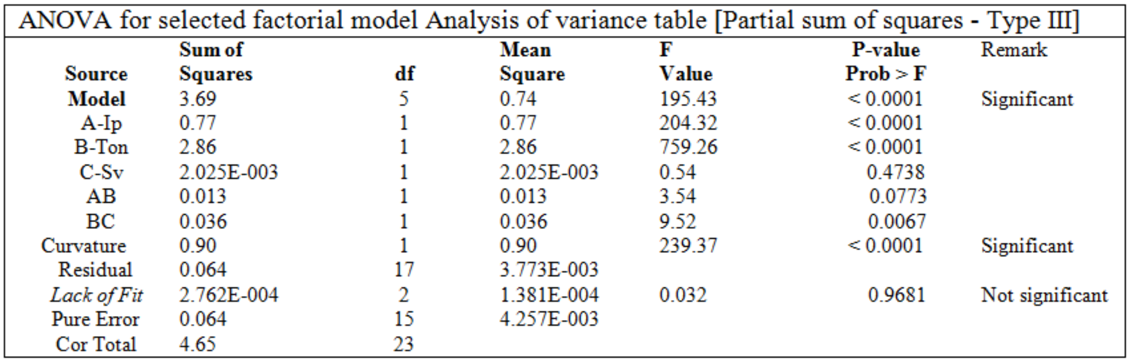
Table 5 ANOVA for linear model OF TWR



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
Model			710.32	2204.92	< 0.0001	Significant
A-Ip	2130.96	3	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			
Lack of Fit	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		

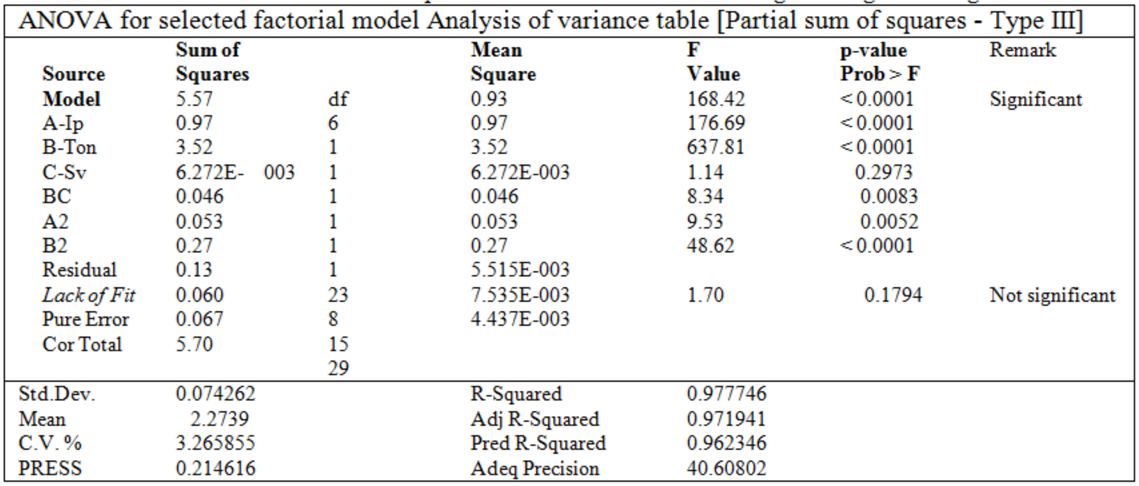
Table 6 ANOVA for curvature test for Ra



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
Model	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	
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			
Lack of Fit	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
Model	5.57	df	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	
A2	0.053	1	0.053	9.53	0.0052	
B2	0.27	1	0.27	48.62	< 0.0001	
Residual	0.13	1	5.515E-003			
Lack of Fit	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		

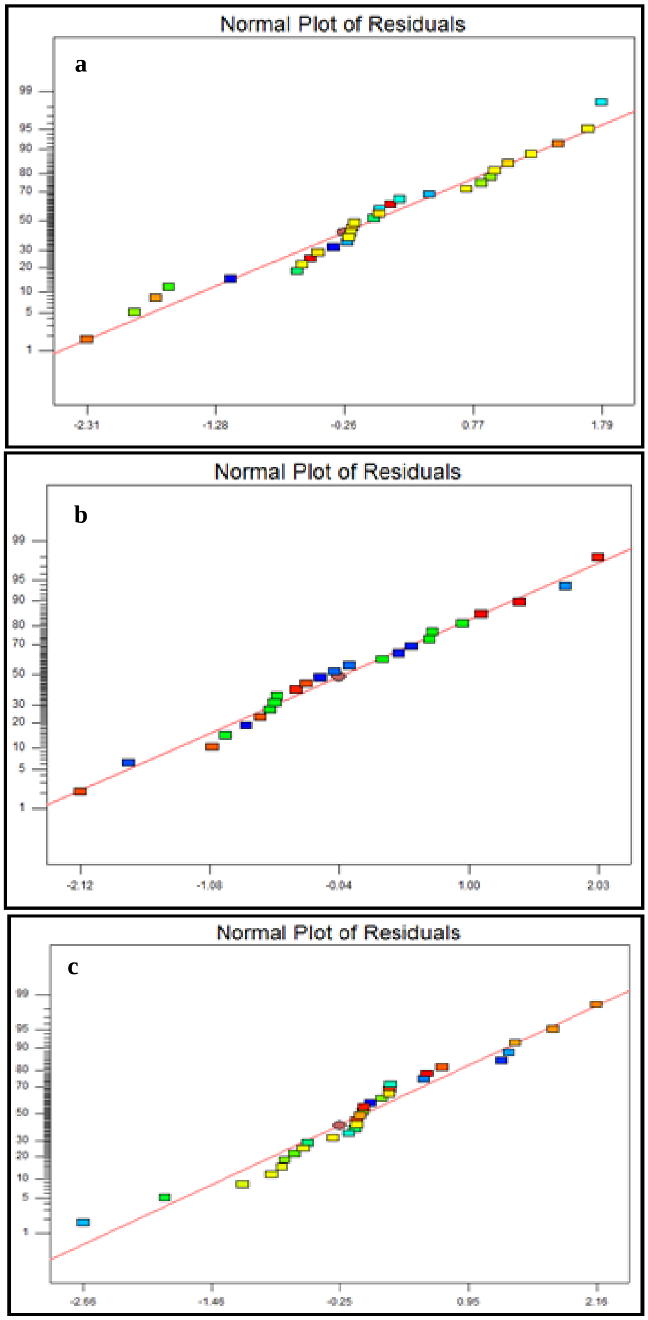


Figure 3 Residuals versus predicted for (a) MRR (b) TWR (c) Ra

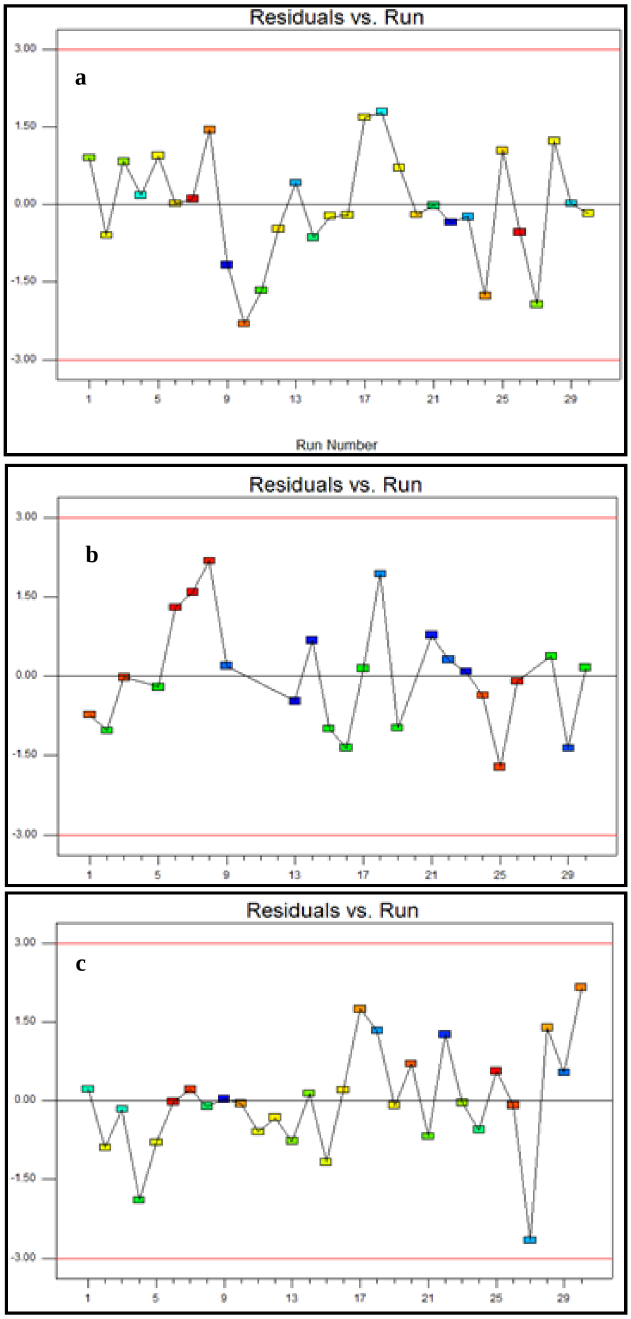


Figure 4 Residuals versus run for (a) MRR (b) TWR (c) Ra TWR

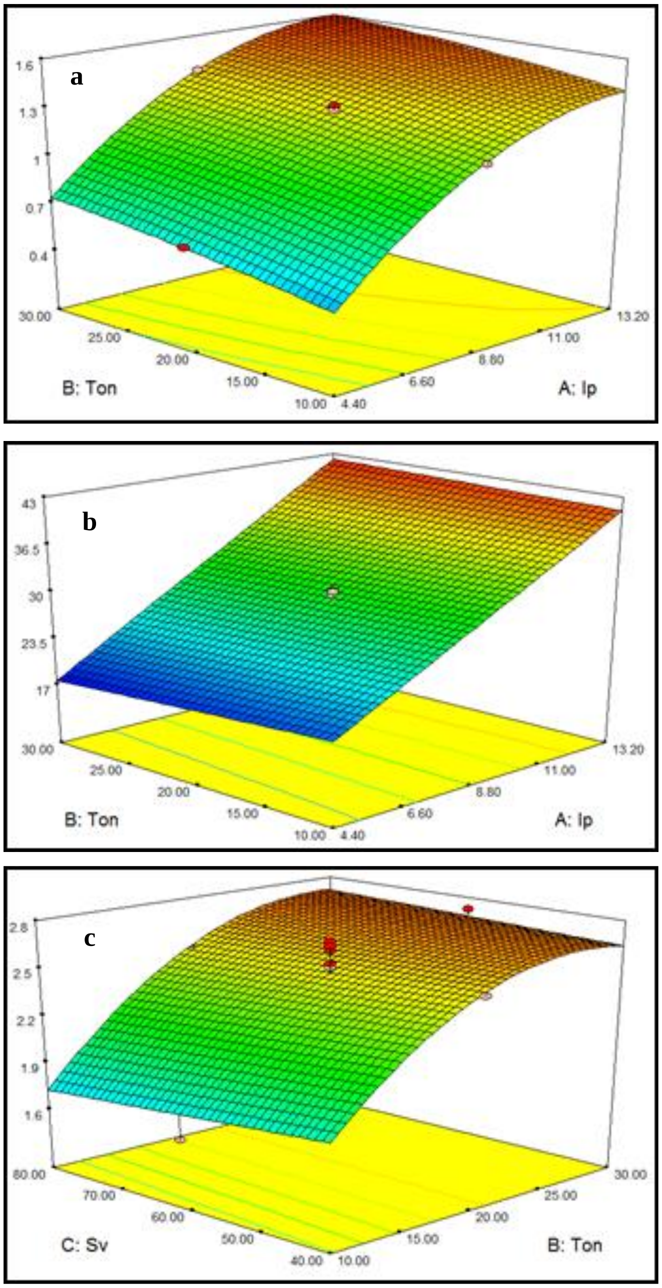


Figure 5 3D surface plots for (a) MRR (b) TWR (c) Ra

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.

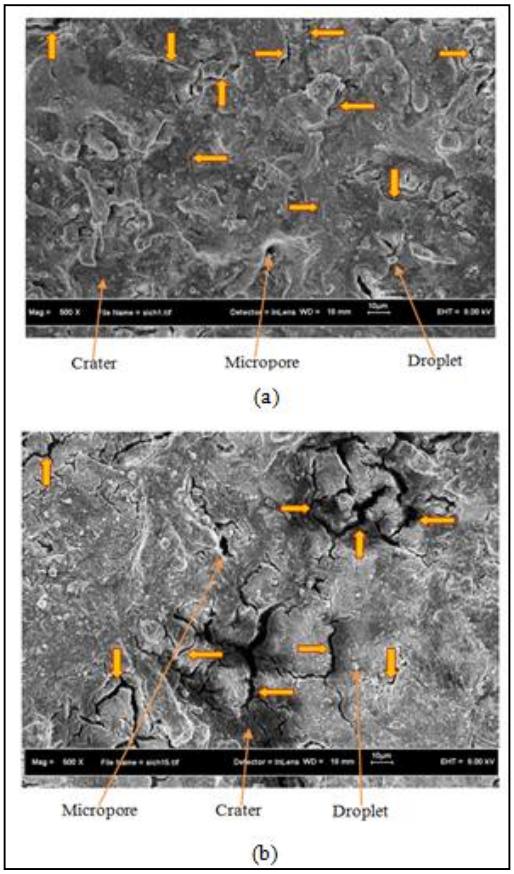


Figure 6 FESEM showing micrographs of EDMed SiSiC surfaces by sinking-EDM at (a) Ip = 4.4A, Ton = 10µs, Sv = 40V (b) Ip = 13.2A, Ton = 30µs, Sv = 40V, (arrows indicate the microcracks)

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.

MRR = +1.29+0.44*A+0.11*B-0.16*C-0.011*A*B-0.21*A2-0.023*B2 -0.10*C2 (5)

TWR = +30.01+11.51 * A-0.32 * B+0.83*A * B (6)

Ra =+2.52+0.23*A+0.44*B-0.019*C+0.054*B*C-0.12*A2-0.28* B (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 (mm3/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 achieve through EDM process at low cost and reduced time when compared with traditional processes.

4.0 CONCLUSION

(a) Ip and Ton were found to be significant on all the responses. In addition to Ip and Ton, Sv is also significant on MRR.
(b) Ip-Ton interaction is significant on MRR and TWR while Ton-Sv interaction is significant on Ra.
(c) Quadratic models were developed for MRR and Ra, 2FI model was developed for TWR.
(d) The optimum MRR, TWR and Ra was achieved.
(e) Microcracks, micropores, craters and droplets were observed on machined SiSiC surface.
(f) 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.

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