Jurnal Mekanikal
June 2014, No 37, 81-100

ELECTRICAL DISCHARGE MACHINING OF SILICONIZED SILICON CARBIDE USING GRAPHITE ELECTRODE

Muhammad Hafiz Adnan[1], Hamidon Musa[2]

[1]Production Technology Department,
German Malaysian Institute,
43000 Kajang, Selangor

[2]Faculty of Mechanical Engineering,
Universiti Teknologi Malaysia,
81200 Skudai, Johor Bahru

ABSTRACT

Siliconized silicon carbide (SiSiC) is an advanced engineering ceramic, and it has excellent properties such as high hardness, high strength, high wear resistance and good chemical inertness at elevated temperature. Thus it has been used in cutting tools, seal rings, valve seats, bearing parts, and a variety of engine parts. The purpose of this study to determine suitable parameters setting on SiSiC by electrical discharge machining (EDM) using graphite electrode. In this work, a study on the influence of the most relevant EDM factors over surface roughness (R_a), material removal rate (MRR) and electrode wear ratio (TWR) has been carried out. Design of Experiment (DOE) with full factorial design experiments was employed as experimental design procedure to investigate the significant effects of each design factors. In order to test for curvature and measuring stability of process, four centre points will be added into the experiments. The mathematical model then was proposed based from the substantial result that would give impact to the SiSiC EDM performance. The design factors selected in this case were: peak current (IP), pulse on time (ONN), voltage (V) and pulse off time (OFF). Those parameters was widely used and interest by the machinists or researchers to control the EDM machine generator precisely to obtain desire machining output whether finishing, roughing or minimizing tool wear. Besides, prediction equation was proposed in order to obtain multiple desires machining output when machining SiSiC using graphite electrode.

Keywords: *EDM, SiSiC, R_a, MRR, graphite*

1.0 Introduction

EDM is the most important and cost-effective of non-traditional methods of machining extremely hard and brittle material such as ceramic. In EDM, material removal processes based on thermal energy, removed the conducting surfaces of workpiece by means of rapid, repeated spark or electrical discharges from electric pulse generators with the help of dielectric fluid flushing between the electrode and workpiece [1].

In recent years, there has been an enormous increase of significance use in advance ceramic material. As a result of this interest, important advances in their development and its application have been used widely. Silicon carbide (SiC) is an advanced engineering ceramic, and it has excellent properties such as high hardness, high strength, high wear resistance and good chemical inertness at elevated temperature [2]. Thus it has been used in cutting tools, seal rings, valve seats, bearing parts, and a variety of engine parts [3].

However, due to its brittleness and high hardness, the traditional methods of machining silicon carbide ceramic mostly using diamond grinding or diamond turning which are time consuming and high cost of diamond tools, hence also can cause degradation of strength due to the formation of finish surface and subsurface cracks or other defects [4,5]. EDM enables to machine extremely hard materials and complex shapes that can be produced with high precision. Therefore, EDM is a potential and attractive technology for the machining of ceramics, providing that these materials have a sufficiently high electrical conductivity [6].

EDM is one of non-conventional machining methods which are applying the thermal energy consumption. Commonly it is used for machining conductive material no matter how hard it is or when the time would be impractically to be machined with conventional techniques. It is also extensively used especially in mould, die, automotive, surgical and aerospace industries for cutting complicated contours in order to obtain fine surface finish of parts that would be hard to produce with conventional machining methods or other machine tools. The benefits using EDM are free of residual stress, vibration and chatter problems during machining. By the way, critical limitation when using EDM is only working with electrically conductive material with presence of a dielectric fluid [7,8].

Manufacturing silicon carbide is critical due to high cost of material. Lack of machining suitable conditions and improper planning will lead to time consuming, redundant job, waste of material and increase manufacturing lead time. In case of this situation, it shows that how important research implementation on this field of study needs to be carried out.

2.0 Experimental Detail

The experiment was done by EDM process on SiSiC. Response values such as material removal rate and electrode wear ratio was determined. Meanwhile, surface roughness was measured using surface roughness tester. After obtaining all valuable data, DOE software was employed in order to proceed with analysis of variance (ANOVA). The purpose of this ANOVA is to determine the significant parameters which might affect on the responses studied. The curvature test will determine whether the response model requires second order model or not. The predicted mathematical model for optimization of all responses will be gained. Finally, the conformation run in will be conducted in order to validate the model obtained.

3.0 Dependent Variables

Dependent variables refer to the performance of EDM characteristic. Three dependent variables are selected to be examined for these studies which are R_a, MRR and TWR. In order to achieve the optimum parameter settings for EDM process, all the dependent variables mentioned must be justified. It would be tremendous contribution for industrial manufacturing sector which is fabricate a product using SiSiC material by EDM process.

Basically, R_a is referring to arithmetic mean average in µm. In addition, Surfcom 1800D Ra tester was employed for this study. The average of R_a values inside the cavity surface finish was measured with the three different spots with maximum distance is 10 mm.

MRR is the amount of material removed per unit time. MRR is expressed as the ratio of the workpiece volumetric removed divide by machining time [9,10].

$$MRR = \frac{\text{Volume of material removed from workpiece} \quad (mm^3)}{\text{Machining time} \quad (min)} \tag{1}$$

Higher value of MRR is favourable condition when EDM initial or roughing process to fast stock removal before finishing allowance.

TWR is expressed as the ratio of volume removed from electrode to volume removed from workpiece during the EDM process. This volumetric removal can be end wear or corner wear, and it is measured linearly or volumetrically but is most often expressed as per cent, measured linearly [9,10].

$$TWR = \frac{\text{Volume removed from electrode } (mm^3)}{\text{Volume removed from workpiece } (mm^3)} \times 100 \quad (2)$$

Various number of machining performances has been studied by the previous researchers on EDM characteristics. For this study, four proficient independent variables influence in EDM performance has been chosen for the experimentation.

i. Peak Current (IP)
ii. Pulse On Time (ON)
iii. Voltage (V)
iv. Pulse OFF Time (OFF)

Table 1 shows the complete experimental design for parameters used with the specific range of values. Meanwhile, Table 2 shows the full factorial design.

Table 3.1: The parameter design values

Parameters	Unit	Level		Centre point
		Low (-)	High (+)	
IP	Amperes	6	12	9
ON	µs	25	100	62.5
V	Volts	80	120	160
OFF	µs	25	100	62.5

Table 3.2: Full factorial design

Run	IP Amperes	ON µs	V Volts	OFF µs
1	6	25	80	25
2	12	25	80	25
3	6	100	80	25
4	12	100	80	25
5	6	25	160	25
6	12	25	160	25
7	6	100	160	25
8	12	100	160	25
9	6	25	80	100
10	12	25	80	100
11	6	100	80	100
12	12	100	80	100
13	6	25	160	100
14	12	25	160	100
15	6	100	160	100
16	12	100	160	100
17	9	62.5	120	62.5
18	9	62.5	120	62.5
19	9	62.5	120	62.5

20	9	62.5	120	62.5

4.0 Experimental Results

All the results obtained after the machining process, such as machining time, weight of electrode removed before and after, weight of workpiece removed before and after machining was calculated. Hence, changing unit weight from gram to unit volume mm^3. After that, employed equations (1) and (2) to find MRR and TWR. Finally, data was transferred into the Design Expert software for further analysis.

4.1 DOE Analysis

All the measured data was analyzed using Design Expert software in order to validate and evaluate experiment results before come up with mathematical modelling for responses selected.

4.2 Analysis on Surface Roughness, Ra

The half-normal probability graph as shown in Figure 4.1 indicates significant effects which are suitable to fit in the model. Normally, main effects located at upper right or on the right side of line. While chosen the main effects it will result the line shifted away and re-fitted on the line with remaining non-selected effect points. Factor A and B are chosen as significant effects which are positive effects behaviour.

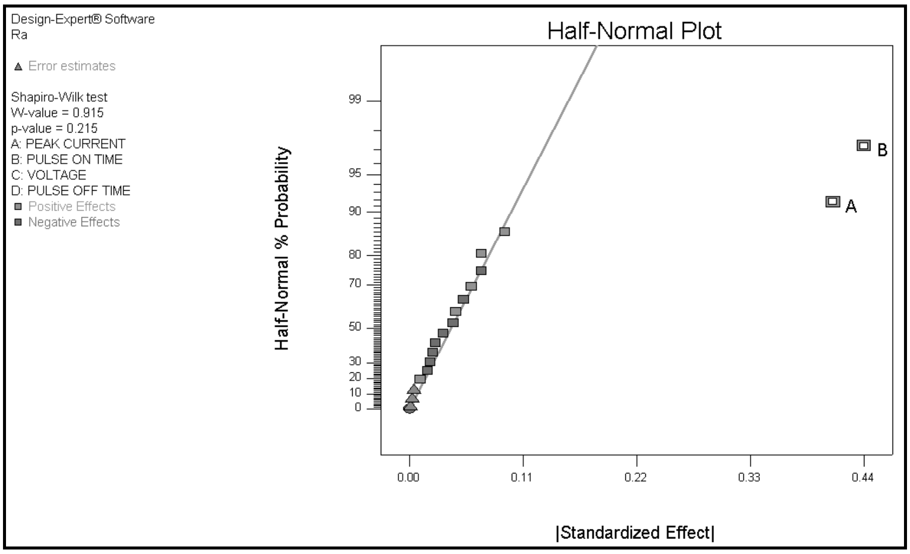


Figure 4.1: Half-Normal Probability Graph (Ra)

From the ANOVA Report (R_a) as depicted in Figure 4.2, the most important term need to verify is P-value. P-value represent as a probability for the model. By default, Design Expert considers values of 0.05 or less to be significant effects. If bigger than that, the factor is considered as not significant to model. This analysis shows that the significant effects are factor A and B and also known as main effects. No interaction between the factors was found in the model. The model shows significant effect. Besides, the curvature is the term used in comparing the average response of the factorial points to the average response of the centre points to test for non-linearity between the factorial points in three-dimensional response surface. The ‘not significant’ curvature shows in the ANOVA Report (R_a) indicates that the three-dimensional response surface for the model is a flat surface to fits the model responses. Therefore, only the first order model is involved. The model fits the data well as the lack of fit is not significant. No need to add axial-points for further analysis.

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	
Model	1.46	2	0.73	88.08	< 0.0001	significant
A-PEAK CURRENT	*0.68*	*1*	*0.68*	*81.91*	*< 0.0001*	
B-PULSE ON TIME	*0.78*	*1*	*0.78*	*94.26*	*< 0.0001*	
Curvature	7.200E-004	1	7.200E-004	0.087	0.7723	not significant
Residual	0.13	16	8.309E-003			
Lack of Fit	*0.13*	*13*	*9.704E-003*	*4.28*	*0.1286*	*not significant*
Pure Error	*6.800E-003*	*3*	*2.267E-003*			
Cor Total	1.60	19				

Figure 4.2: ANOVA Report (R_a)

Std. Dev.	0.089	R-Squared	0.9163
Mean	2.17	Adj R-Squared	0.9065
C.V. %	4.09	Pred R-Square	0.8787
PRESS	0.19	Adeq Precisior	24.896

Figure 4.3: Determination of R-Squared (R_a)

Since the R-Squared as shown in Figure 4.3 is 0.9163, it indicates that all the sources of variation during investigation are under controlled in order to obtain optimum parameters setting within the particular range of investigation selected. In addition, Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 24.896 obtained indicates an adequate signal which means no further investigation is needed.

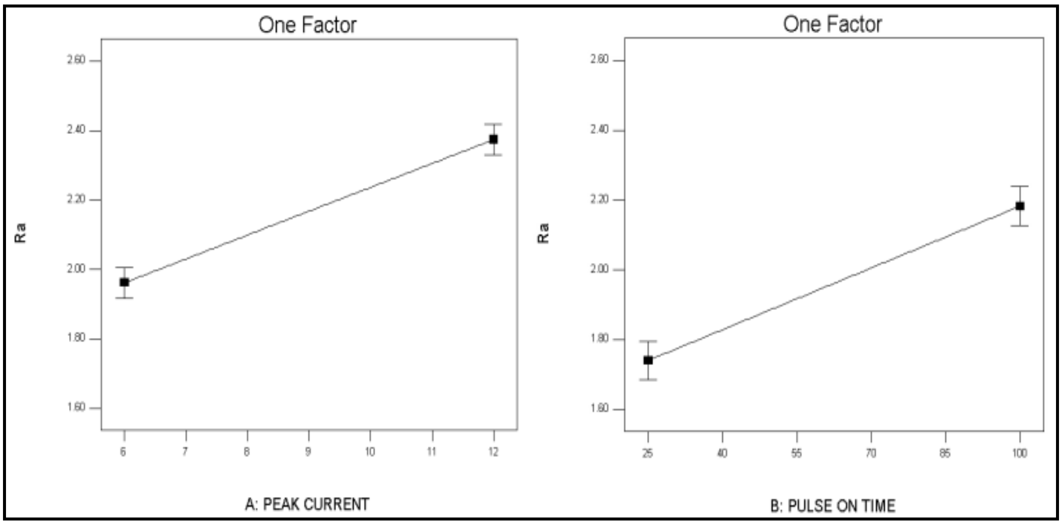


Figure 4.4: Main Effects Graph (R_a)

From the main effects graph shows in Figure 4.4, when factors A and B at low level, it will provides low value of Ra, 1.74 µm. All factors of main effects are positive effects for R_a.

4.3 Analysis on Material Removal Rate

The half-normal probability graph as shown in Figure 4.5 indicates significant effects which are suitable to fit in the model. As chosen the main effects it will result the line shifted away and re-fitted on the line with remaining non-selected effect points. Factors A, B, C, D and BC are chosen as significant effects. The positive effects are factors A, B, C and BC meanwhile the negative effect is only factor D.

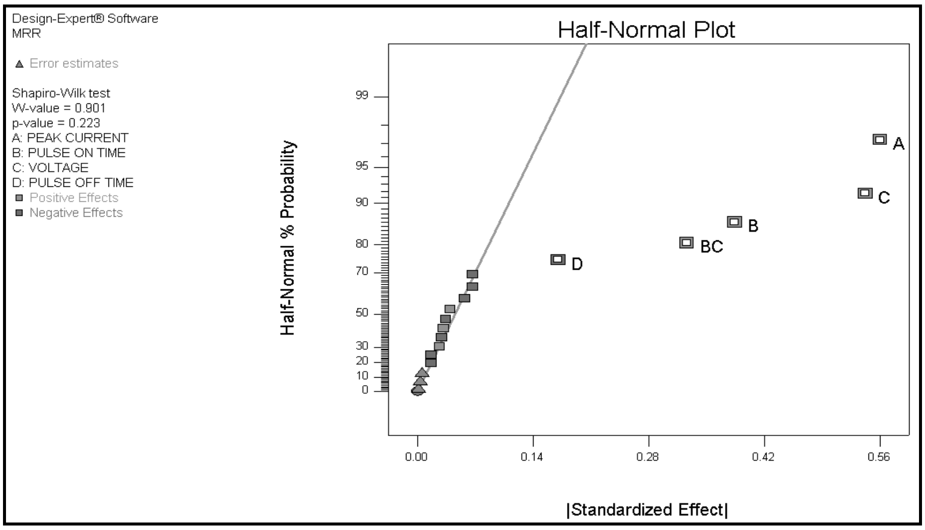


Figure 4.5: Half-Normal Probability Graph (MRR)

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3.51	5	0.70	115.50	< 0.0001	significant
A-PEAK CURRENT	*1.24*	*1*	*1.24*	*203.44*	*< 0.0001*	
B-PULSE ON TIME	*0.58*	*1*	*0.58*	*95.57*	*< 0.0001*	
C-VOLTAGE	*1.16*	*1*	*1.16*	*190.84*	*< 0.0001*	
D-PULSE OFF TIME	*0.11*	*1*	*0.11*	*18.72*	*0.0008*	
BC	*0.42*	*1*	*0.42*	*68.92*	*< 0.0001*	
Curvature	1.013E-004	1	1.013E-004	0.017	0.8993	not significant
Residual	0.079	13	6.084E-003			
Lack of Fit	*0.070*	*10*	*7.041E-003*	*2.44*	*0.2511*	*not significant*
Pure Error	*8.675E-003*	*3*	*2.892E-003*			
Cor Total	3.59	19				

Figure 4.6: ANOVA Report (MRR)

From the ANOVA Report (R_a) as depicted in Figure 4.6, the most important term need to verify is P-value. This analysis shows that the significant effects need to consider is factor A, B, C and D which are known as main effects. The interaction between the factors BC was found in the model. The model shows significant effect. The 'not significant' curvature shows in the ANOVA Report (R_a) indicates that the three-dimensional response surface for the model is a flat surface to fits the model responses. Therefore, only the first order model is involved. The model fits the data well as the lack of fit is not significant. No need to add axial-points for further analysis.

Std. Dev.	0.075	R-Squared	0.9780
Mean	1.07	Adj R-Squared	0.9701
C.V. %	7.05	Pred R-Square	0.9491
PRESS	0.18	Adeq Precisior	39.934

Figure 4.7: Determination of R-Squared (MRR)

The R-Squared as shown in Figure 4.7 is 0.9780. It indicates that all the sources of variation during investigation are under controlled in order to obtain optimum parameters setting within the particular range of investigation selected. In addition, Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 39.934 obtained indicates an adequate signal which means no further investigation is needed.

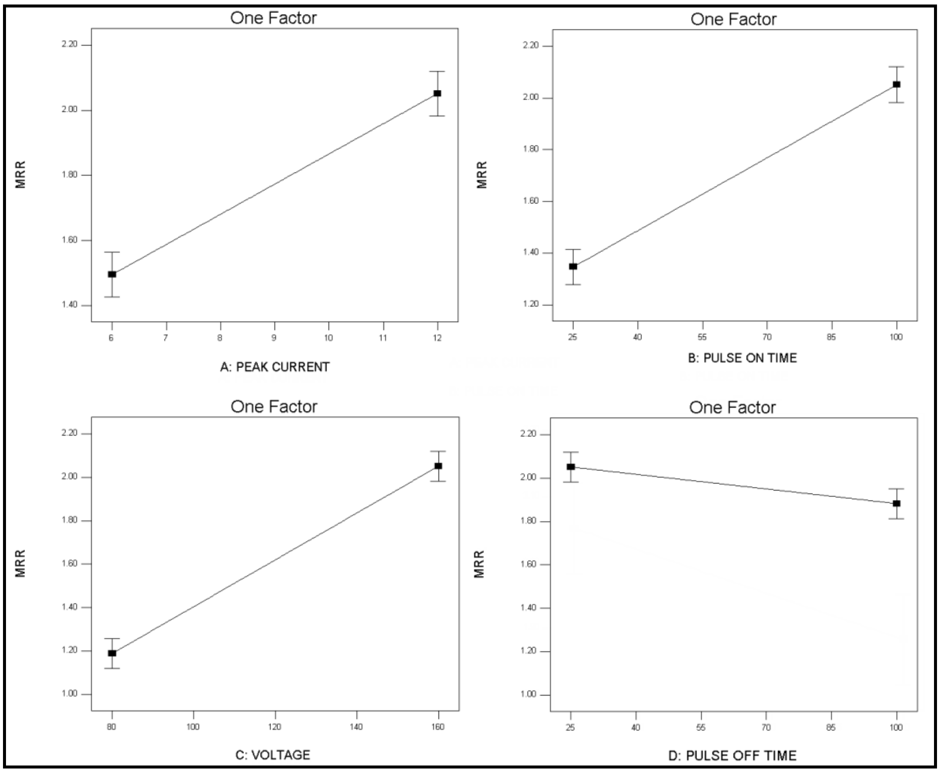


Figure 4.8: Main Effects Graph (MRR)

From the main effects graph shows in Figure 4.8, when factors A, B, C at high level, it will provides greater value of MRR, 2.05 mm^3/min. All factors of main effects are positive effects for except factor D.

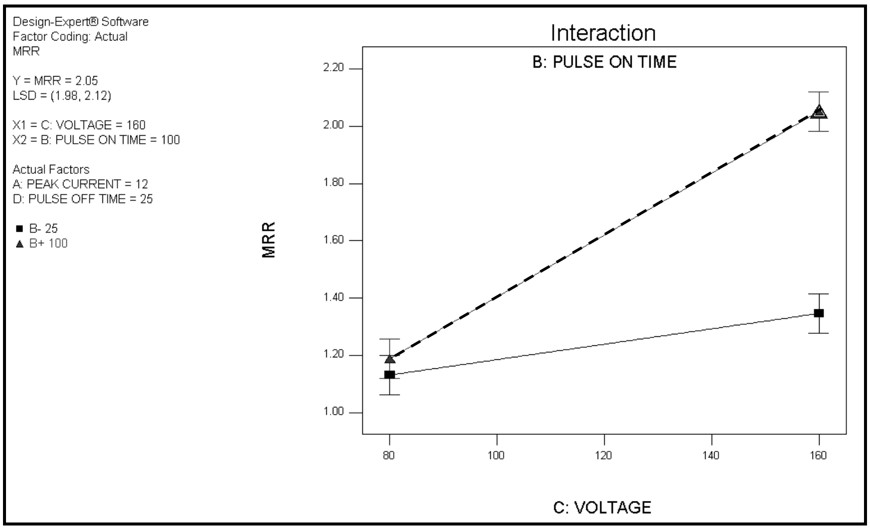


Figure 4.9: Interaction Graph (MRR)

Interaction graph is obtained for interpretation of two factor interactions. Since the two-factor interaction BC is not significant, two curves with no tendency for intersection are obtained as shown in Figure 4.9. The maximum MRR can be obtained by choosing factor B dashed curve at high level (100µs).

4.4 Analysis on Tool Wear Ratio

The half-normal probability graph of TWR as shown in Figure 4.10 indicates significant effects which are suitable to fit in the model. As chosen the main effects it will result the line shifted away and re-fitted on the line with remaining non-selected effect points. Factors A, B, D and AB are chosen as significant effects. The positive effects are factors A and D meanwhile the negative effect are factor B and AB.

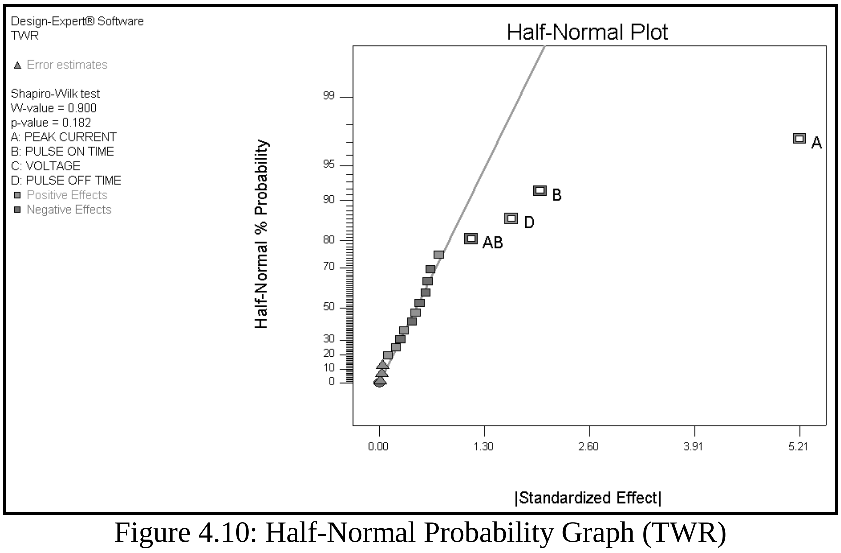


Figure 4.10: Half-Normal Probability Graph (TWR)

From the ANOVA Report (TWR) as depicted in Figure 4.11, the most important term need to verify is P-value. This analysis shows that the significant effects need to consider is factor A, B and D which are known as main effects. The model shows significant effect. The interaction between the factors AB was found in the model. The ‘not significant’ curvature shows in the ANOVA Report (TWR) indicates that the three-dimensional response surface for the model is a flat surface to fits the model responses.

Only the first order model is involved. The model fits the data well as the lack of fit is not significant. No need to add axial-points for further analysis.

Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		**Mean**	**F**	**p-value**	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	140.34	4	35.08	47.24	< 0.0001	significant
A-PEAK CURRENT	*108.57*	*1*	*108.57*	*146.17*	*< 0.0001*	
B-PULSE ON TIME	*15.87*	*1*	*15.87*	*21.37*	*0.0004*	
D-PULSE OFF TIME	*10.72*	*1*	*10.72*	*14.43*	*0.0020*	
AB	*5.18*	*1*	*5.18*	*6.97*	*0.0194*	
Curvature	0.28	1	0.28	0.38	0.5488	not significant
Residual	10.40	14	0.74			
Lack of Fit	*9.81*	*11*	*0.89*	*4.57*	*0.1187*	*not significant*
Pure Error	*0.59*	*3*	*0.20*			
Cor Total	151.02	19				

Figure 4.11: ANOVA Report (TWR)

Std. Dev.	0.84	R-Squared	0.9293
Mean	7.45	Adj R-Squared	0.9104
C.V. %	11.32	Pred R-Square	0.8607
PRESS	21.04	Adeq Precisior	20.951

Figure 4.12: Determination of R-Squared (TWR)

The R-Squared as shown in Figure 4.12 is 0.9293. It indicates that all the sources of variation during investigation are under controlled in order to obtain optimum parameters setting within the particular range of investigation selected. In addition, Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 20.951 obtained indicates an adequate signal which means no further investigation is needed.

From the main effects graph shows in Figure 4.13, when factors A and D at low level, factor B at high level, it will provides lower value of TWR (3.60%). Factors A and D are positive effects but factor B is negative effect

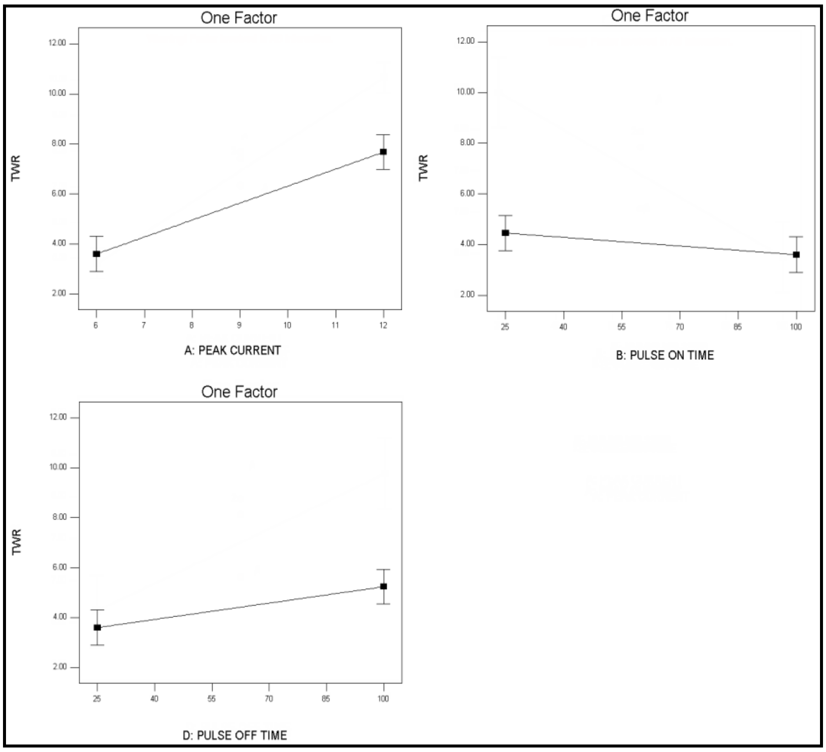


Figure 4.13 Main Effects Graph (TWR)

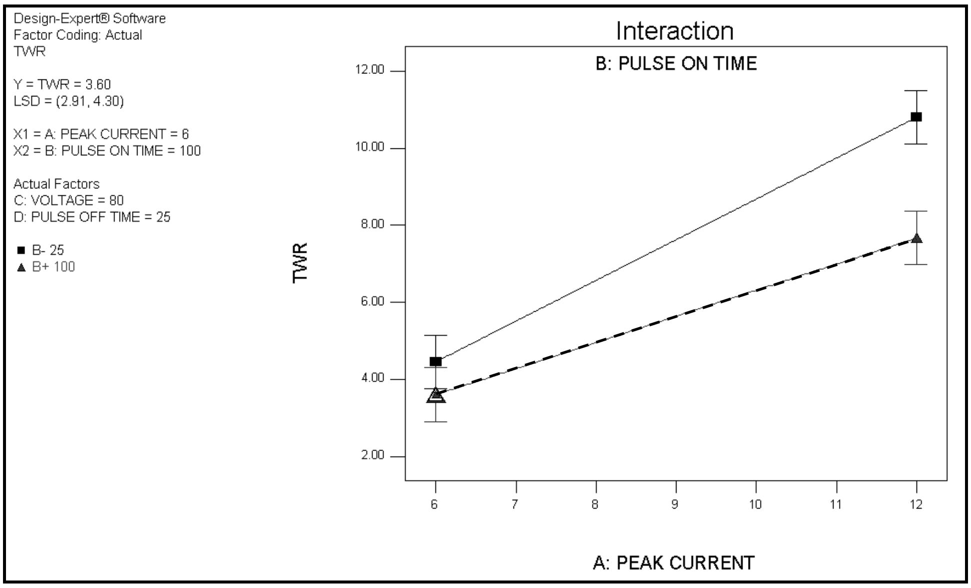


Figure 4.14: Interaction Graph (TWR)

Interaction graph is obtained for interpretation of two factor interactions. Since the two-factor interaction AB is not significant, two curves with no tendency for intersection are obtained as shown in Figure 4.14. The minimum TWR (3.6%) can be obtained by choosing factor B dashed curve at high level with combination of low level factors A, C and D.

4.5 Mathematical Model

The mathematical model for every response can be obtained after the significant effects are determined. The Design Expert software will automatically generate the model taking into consideration the effects of the significant factors.

Model for R_a

The final equation in terms of coded factors:

$$R_a = 2.17 + 0.21(A) + 0.22(B)$$

The final equation in terms of actual factors:

$$R_a = 1.18050 + 0.068750(IP) + 5.9\text{x}10^{-3}(ON)$$

Model for MRR

The final equation in terms of coded factors:

$$MRR = +1.07 + 0.28(A) + 0.19(B) + 0.27(C) - 0.084(D) + 0.16(B)(C)$$

The final equation in terms of actual factors:

$$MRR = 0.056792 + 0.092708(IP) - 7.86667\text{x}10^{-3}(ON) - 1.04167\text{x}10^{-5}(V) - 2.25000\text{x}10^{-3}(OFF) + 1.07917\text{x}10^{-4}(ON)(V)$$

Model for TWR

The final equation in terms of coded factors:

$$TWR = 7.45 + 2.60(A) - 1.00(B) + 0.82(D) - 0.57(A)(B)$$

The final equation in terms of actual factors:

$$TWR = -2.91123 + 1.18439(IP) + 0.018953(ON) + 0.021823(OFF) - 5.05715\text{x}10^{-3}(IP)(ON)$$

The optimum condition for specific response can be obtained from the optimization design via Design Expert software. The suggested combination of parameter is based on output required within the range of investigation. The Table 4.1, 4.2 and 4.3 shows the recommendation setting for minimum R_a, maximum MRR and minimum TWR respectively.

Minimum R_a

Table 4.1: Recommendation setting for Minimum R_a

Number	IP	ON	V	OFF	Ra	Desirability
1	6	25	80.00	100	1.74	0.889
2	6	25	80.00	25	1.74	0.889
3	6	25	160.00	25	1.74	0.889

Maximum MRR

Table 4.2: Recommendation setting for Maximum MRR

Number	IP	ON	V	OFF	MRR	Desirability
1	12	100	160	25	2.05	0.978
2	12	99.9872	160	25.703	2.05	0.977
3	11.9714	99.9999	160	27.9144	2.04	0.972

Minimum TWR

Table 4.3: Recommendation setting for Maximum TWR

Number	IP	ON	V	OFF	TWR	Desirability
1	6.12156	99.5806	127.059	28.4971	3.77	1
2	6.03008	81.2678	109.768	25.6809	3.85	1
3	6.10108	98.8064	154.606	34.4504	3.89	1

4.6 Confirmation Runs

Confirmation run also needs to perform under optimization design in Design Expert software where the combination of factor level is satisfying the requirements of each responses and factors. In confirmation run, the setting values of parameter must be different from experiment runs including centre points. Three set of experiments as shown in Figure 4.15, 4.16 and 4.17 will be performed to compare with predicted response values.

.

Confirmation Report

Two-sided Confidence = 95% n = 1

Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	PEAK CURRENT	12.00	6.00	12.00	0.000	Actual
B	PULSE ON TIME	62.50	25.00	100.00	0.000	Actual
C	VOLTAGE	160.00	80.00	160.00	0.000	Actual
D	PULSE OFF TIME	62.50	25.00	100.00	0.000	Actual

Response	Prediction	Std Dev	SE (n=1)	95% PI low	95% PI high
Ra	2.37	0.09	0.09	2.18	2.57
MRR	1.61	0.08	0.08	1.44	1.79
TWR	10.06	0.84	0.89	8.16	11.95

Figure 4.15: Confirmation run setting 1

Confirmation Report

Two-sided Confidence = 95% n = 1

Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	PEAK CURRENT	6.00	6.00	12.00	0.000	Actual
B	PULSE ON TIME	25.00	25.00	100.00	0.000	Actual
C	VOLTAGE	120.00	80.00	160.00	0.000	Actual
D	PULSE OFF TIME	62.50	25.00	100.00	0.000	Actual

Response	Prediction	Std Dev	SE (n=1)	95% PI low	95% PI high
Ra	1.74	0.09	0.10	1.54	1.94
MRR	0.60	0.08	0.08	0.42	0.77
TWR	5.27	0.84	0.94	3.27	7.27

Figure 4.16: Confirmation run setting 2

Confirmation Report

Two-sided　　Confidence = 95%　　n = 1

Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	PEAK CURRENT	9.00	6.00	12.00	0.000	Actual
B	PULSE ON TIME	62.50	25.00	100.00	0.000	Actual
C	VOLTAGE	160.00	80.00	160.00	0.000	Actual
D	PULSE OFF TIME	100.00	25.00	100.00	0.000	Actual

Response	Prediction	Std Dev	SE (n=1)	95% PI low	95% PI high
Ra	2.17	0.09	0.09	1.98	2.36
MRR	1.25	0.08	0.08	1.08	1.43
TWR	8.27	0.84	0.89	6.37	10.17

Figure 4.17: Confirmation run setting 3

The actual versus predicted responses after machining being carried out is shown in Table 4.4. By considering the actual responses obtained under confirmation run results are lies between the range of 95% PI (prediction interval) low and 95% PI high for all new responses. Finally, it can be confirmed that 95% confident the mathematical model is approved with reasonably accurate that can be used to predict other response within the range of investigation.

Table 4.4: Predicted and actual responses

	Confirmation Run Set 1			Confirmation Run Set 2			Confirmation Run Set 3		
Response	Predicted	Actual	Residual	Predicted	Actual	Residual	Predicted	Actual	Residual
Ra	2.37	2.29	0.08	1.74	1.68	0.06	2.17	2.14	0.03
MRR	1.61	1.76	-0.15	0.60	0.67	-0.07	1.25	1.37	-0.12
TWR	10.06	10.70	-0.64	5.27	5.58	-0.31	8.27	8.46	-0.19

5.0 Discussion

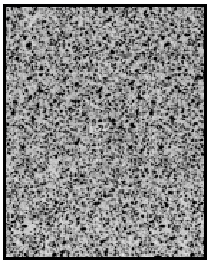
In this paper, the reason of electrode selection, parameter range, effects of variable parameters on surface roughness, material removal rate and tool wear rate will be discussed in detail. Finally, the recommendation of multiple optimum conditions to be used which satisfied of all responses will be proposed.

5.1 Electrode Selection

The selection of EDM electrode for this investigation based on the finer grain size of graphite. POCO EDM-3 is isotropic ultrafine grain graphite which offers high strength with outstanding wear and fine surface finish characteristics easily machined to thicknesses of 0.1mm or less [11]. The average particle size is less than 5µm and density is 1.81g/cm^3. The Figure 5.1 shows the technical guide and applications used regarding graphite electrode POCO EDM-3 which was chosen for this experiment.

J.A Sanchez *et al.* [12] carried out experimental work on response variables such as R_a, MRR and TWR when EDM on SiSiC. The use of graphite electrode named as POCO EDM-100 as shown in Figure 5.2 had suffered extremely high electrode wear rate during experiments. It is because of POCO EDM-100 having lower hardness, low melting point, low density, bigger average grain size compare to POCO EDM-3 which are well-suited to be used to EDM on SiSiC during investigation.

EDM-3®



Typical Value

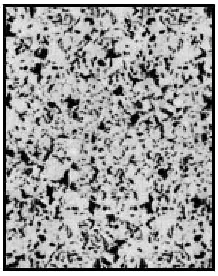
- Average Particle Size: <5 µm
- Flexural Strength: 13,300 psi (935 kg/cm²)
- Compressive Strength: 18,100 psi (1,273 kg/cm²)
- Hardness: 73 Shore
- Electrical Resistivity: 615 µΩin (15.6 µΩm)

Applications

- EDM of fine detailed electrodes
- Punch & die sets
- Plastic injection molds
- Threading electrodes
- Use in aerospace metal cutting

Figure 5.1: POCO EDM-3 Graphite Technical Guide.

EDM-100®



Typical Value

- Average Particle Size: 10 µm
- Flexural Strength: 8,100 psi (569 kg/cm²)
- Compressive Strength: 14,000 psi (984 kg/cm²)
- Hardness: 68 Shore
- Electrical Resistivity: 580 µΩin (14.7 µΩm)

Applications

- Structural ribs
- Roughing or finishing electrodes
- Large featured mold
- High strength large electrodes

Figure 5.2: POCO EDM-100 Graphite Technical Guide.

5.2 Selection of Parameter Range

The selection of parameter range base on two basic criteria, initially the trial and error method and second criteria based on previous researcher had conducted experiments earlier with suitable range of parameters used. According to S. Clijsters *et al.* [10], they proposed range of parameters as shown in Figure 5.3 using copper infiltrated graphite electrode which are most suitable electrode of machining the advanced ceramics. By the way, the disadvantage of copper infiltrated graphite electrode is material cost is very high compare to pure graphite even the finest grain less than 1µm. In addition, the range values of each parameter are varies depending on the finishing or roughing process as required.

Parameters	Levels	
	–	+
i_e	12 A	64 A
t_e	3.2 µs	12.8 µs
t_o	25 µs	100 µs
u_i	–80 V	–120 V

Figure 5.3: Levels of the Parameters by Previous Researcher [10].

(Legend: i_e - discharge current, u_i - open gap voltage, t_e - discharge duration and t_o - pulse interval)

Final selection of parameter range is determined after a few experiments were conducted to confirm the capability and precision of EDM machine regards with those experiments setting without having uncontrollable variation or noise occurs when performing the actual investigation according to design of experiment chosen earlier.

Through observation, using low pulse off time will lead to unstable machining condition because of high carbon deposition at electrode bottom face coming from loose grains of SiSiC. By comparing same parameters setting or procedures on machining of steel at lower pulse off time (10μs or less), nothing unstable process happen. As a conclusion can be made, it is because of graphite electrode and SiSiC comes from carbon substance. Therefore, the loose grains generated inside the gap is easily bond or deposit on graphite electrode bottom face, in that case it will spoil the machined surface. By giving much time or increase pulse off time (25μs or more) the side flushing process will flush away those loose grains near or inside the gap to prevent deposition problem, hence the machining condition will remain stable.

A set of trials was carried out in order to finding suitable machining condition regarding polarity setting. Therefore, it was observed that when using negative polarity of electrode, the process became unstable, leading to high energy sparks that produced extensive damage both on the graphite electrode and on the workpiece [12].

According to fundamental theory of EDM [13], by choosing low peak current and low pulse on time, the machined surface becomes better but at the same time reducing the material removal rate. With appropriate level when considering time constraint and finishing demanded, suitable range of parameter for this investigation chosen as peak current ranging from 6A to12A, pulse on time ranging from 25μs to 100μs, voltage ranging from 80V to 160V and pulse off time ranging from 25μs to 100μs.

5.3 Surface Roughness, R_a

The significant parameter for surface roughness based on ANOVA analysis is peak current (A) and pulse on time (B) with both positive effects. The rest of factors not significant for surface roughness although changing the high or low setting for pulse time off and voltage during investigation. Only the machining time will be different between experiments when using high or low pulse off time and voltage. However there is no significant effect on the surface roughness quality of silicon carbide by changing those values.

Increasing peak current and pulse on time will increase the surface roughness value which is worsen the surface finish of SiSiC [12][14]. This is because, with longer pulse on time apply on the machining process, it will produces bigger size of crater on the surface. The material removal is directly proportional to the amount of energy applied during the pulse on time [15]. This energy is controlled by the peak current and the length of the pulse on time. With longer pulse on time, more workpiece material will be melted away. These resulting crater sizes will be broader and deeper than a crater produced by shorter pulse on time. Finally, the recast layer will be larger and the heat affected zone will be deeper layer on the machined surface.

From the experimental results, the best R_a was obtained is 1.62μm and the worst R_a is 2.71μm.

5.4 Material Removal Rate, MRR

Material removal rate significant parameter according to ANOVA analysis is peak current (A), pulse on time (B), voltage (C) and pulse off time (D). Only pulse off time is negative effect. The rest all is positive effects. Interaction BC seems to be significant effect especially when increasing peak current, pulse on time and voltage at the same time. Pulse off time at low level will be affected much because it will reduce time of machining, thus increase the material removal rate. At the same time precaution must be taken if unstable machining occurs due to excessive carbon being produced inside the gap that will cause carbon deposition on the tool surface.

Sufficient flushing pressure must be taking into account in order to maintain the machining stability when peak current, pulse on time and voltage at high level. As described by previous researcher [10], in order to increase the machining speed and MRR, the discharge current should be chosen in a moderate value, maximize the open gap voltage and prolong the discharge interval.

From the result experiments was carried out, the highest MRR was obtained is 2.09mm^3/min. The lowest MRR is 0.36mm^3/min.

5.5 Tool Wear Ratio, TWR

Tool wear ratio significant parameter based on ANOVA analysis is peak current (A), pulse on time (B) and pulse off time. Interaction of AB seems to be significant effects which are negative effect as well as pulse on time. When applying low peak current, low pulse off time then high pulse on time, TWR will be at low ratio. From the experimental results, the highest TWR was obtained is 13.38%. The lowest TWR is 3.89% as desired.

Besides, the TWR on machining with rotary electrode was less in comparison with stationary electrode [16]. In conventional electrode with loosened SiC deposition occurred in localized area, which inhibited high electrode wear. Arcing during static EDM also found to add carbide deposits on the electrode surface. Current waveforms with higher peak current and longer discharge duration result in higher material removal rate. At the same time, low tool electrode wear can also be satisfied because the carbon layer deposited on the tool electrode is thicker when longer discharge durations are used.

Dilshad Ahmad Khan *et al.* [17] reported that at low current and at higher pulse duration hydrocarbon dielectric decomposes and fee carbon stick with the tip of tool , this carbon layer prevents the further tool wear. From the experimental work carried out, it was found that as the pulse on time increases relative electrode wear decreases. It could be due to the adhesion of carbon layer to the tip of tool which reduces the tool wear and in turn relative tool wear ratio. Therefore, at lower pulse duration the relative electrode wear is more and at higher pulse duration it decreases. Besides, the energy dissipation into the anode (workpiece) is greater than into the cathode (electrode). Nevertheless, in sinking EDM, polarity of the tool electrode is normally positive except when very short discharge duration is used. This is because the carbon layer which is deposited on the anode surface due to thermal dissociation of the hydrocarbon oil protects the anode surface from wear. Since the carbon layer is thick when the discharge duration is long, the tool electrode wear ratio is low with the polarity of positive tool electrode under the pulse condition of longer discharge durations. On the contrary, a negative tool electrode is used considering the energy distribution in the cases of finish machining and micromachining where deposition of carbon layer is inadequate.

5.6 Recommendation Optimum Conditions of All Responses

In order to get optimum setting that satisfies all three responses involved at once, 20 setting combinations with higher desirability is suggested via Design Expert as shown in Table 5.1.

Table 5.1: Recommendation Solution for Optimum Condition of All Responses

Number	IP	ON	V	OFF	Ra	MRR	TWR	Desirability
1	6.00001	83.6937	160	25.0011	2.09	1.34	3.79	0.694
2	6.00002	84.4627	159.988	25.0034	2.09	1.35	3.78	0.694
3	6.00729	84.0289	160	25.0005	2.09	1.35	3.79	0.694
4	6.00034	82.2108	159.998	25.0014	2.08	1.33	3.80	0.694
5	6.05649	83.9198	160	25.0006	2.09	1.35	3.83	0.694
6	6.00849	85.0363	159.76	25.0018	2.10	1.35	3.78	0.693
7	6.02377	78.4073	160	25.0007	2.06	1.29	3.87	0.693
8	6.00006	90.9491	160	25.0008	2.13	1.41	3.70	0.693
9	6.17317	85.8792	160	25.0008	2.11	1.38	3.89	0.693
10	6.06249	83.5067	160	26.363	2.09	1.34	3.87	0.693
11	6.00006	77.375	160	25.1564	2.05	1.28	3.86	0.693
12	6.08341	78.4181	160	25.0003	2.06	1.30	3.91	0.693
13	6.01299	92.0307	159.998	25.0007	2.14	1.42	3.70	0.693
14	6.00038	84.1101	160	28.0545	2.09	1.34	3.85	0.693
15	6.00999	77.8463	160	26.3955	2.05	1.28	3.89	0.693
16	6.00043	93.1281	159.838	25	2.14	1.43	3.68	0.692
17	6.00275	82.0678	160	28.7088	2.08	1.32	3.89	0.692
18	6.00494	74.0128	159.979	25.0067	2.03	1.25	3.90	0.691
19	6.22949	83.0169	160	25	2.10	1.36	3.97	0.691
20	6.00002	97.9385	160	26.1428	2.17	1.47	3.65	0.691

The optimum setting for multiple desired predictions also can be visualized by contour graph and three-dimensional surface as depicted in Figure 5.1 and 5.2 respectively.

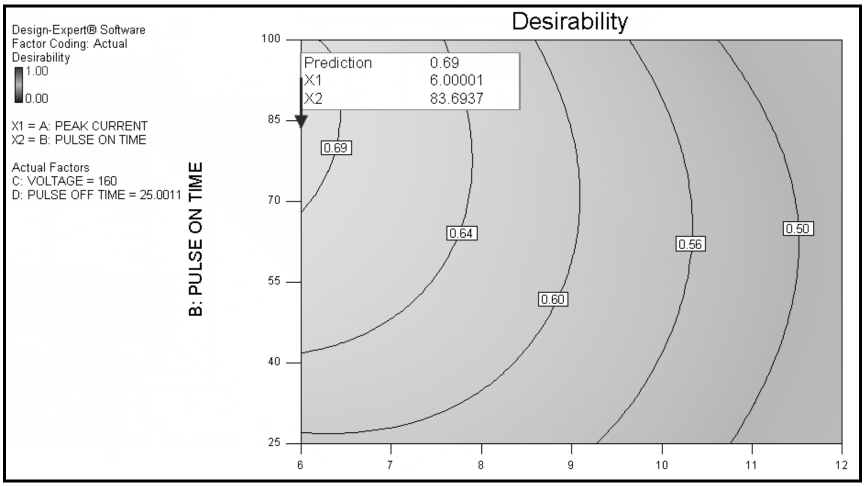


Figure 5.1: Contour Graph (Optimum All Responses)

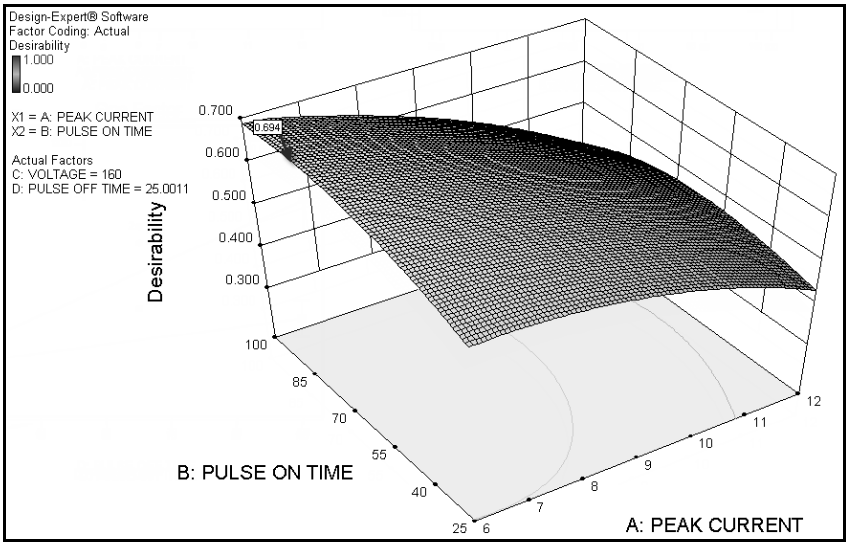


Figure 5.2: Three-Dimensional Surface (Optimum All Responses)

6.0 Conclusion

The endless interest in the study of die sinking EDM when machining conductive ceramics is a consequence of the problems encountered when using conventional machining process. In this work, a study on the influence of the most relevant EDM factors over surface roughness (R_a), material removal rate (MRR) and tool electrode wear (TWR) has been carried out.

The study has been made for a conductive ceramic known as siliconised silicon carbide (SiSiC). In order to achieve this, DOE and multiple linear regression statistical techniques have been employed to model the previously mentioned response variables by means of equations in the form of polynomials. The design finally chosen to accomplish the present study was a full factorial 2^4. The design factors selected in this case were peak current, pulse on time, voltage and pulse off time where all of them are parameters widely used by the machinists to control the EDM machine generator.

First-order models were proposed by ANOVA analysis to determine R_a, MRR and TWR via mathematical model. Thus, no needs for second-order models since the curvature are not significant effects it can fit the entire model as desired.

In the case of R_a, the only influential design factors, for a confidence level of 95%, were: peak current (A) and pulse on time (B). In order to achieve minimum value of R_a within work interval of research study, design factors: A and B should be fixed as low as possible.

However, in the case of MRR, most of influential design factors take place. For a confidence level of 95%, were: peak current (A), pulse on time (B), voltage (C), pulse off time (D) and interaction of BC. In order to obtain a high value of MRR within the work interval of this study, design factors: A, B, C and BC should be fixed as high as possible with low design factor D.

With regard to TWR and arranged in descending order of importance, peak current, pulse on time, pulse off time and interaction between peak current and pulse on time (AB) turned out to be the influential factors for a confidence level of 95%. The variation tendency of TWR obtained in the case of peak current was the one that was expected in advance, whereas the opposite behaviour was obtained in the case of pulse on time and interaction AB. Moreover, in the case of pulse off time, it was verified that decrease the value will lead to unstable machining condition, thus increase in the wear on the electrode due to high carbon deposition adhere on the electrode surface. As a result, it will spoil the finish surface. Flushing pressure must be sufficient enough in order to wash away high carbon or loose grain generated near the cutting area.

The optimization to all design factors which reflect to particular response as desired has been established with confidence level of 95%. In order to optimize or propose the cutting condition, it is depending on what kind of process output or finishing allowance is required when EDM on silicon carbide as follows four criteria:

i. Minimize surface roughness (Finishing process)
ii. Maximize material removal rate (Roughing process)
iii. Minimize tool wear rate (Micromachining process)
iv. Combination of optimum cutting condition

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Faculty of Mechanical Engineering, Universiti Teknologi Malaysia and Production Technology Department of German Malaysian Institute.

REFERENCES

[1] M.P. Jahan, M. Rahman, Y.S. Wong, "A Review on The Conventional and Micro-Electro discharge Machining of Tungsten Carbide." International Journal of Machine Tools & Manufacture 51 (2011) 837–858.
[2] Guo XZ, Yang H, Zhang LJ, Zhu XY. "Sintering behavior, microstructure and mechanical properties of silicon carbide ceramics containing different nano-TiN additive." Ceramics International, 36 (2010) 161–5.
[3] Okada A. "Automotive and industrial applications of structural ceramics in Japan." Journal of the European Ceramic Society, 28 (2008) 1097–104.
[4] Agarwal S, Rao PV. "Experimental investigation of surface or subsurface damage formation and material removal mechanisms in SiC grinding." International Journal of Machine Tools Manufacture, 48 (2008) 698–710.
[5] L. Yin, E. Y. J. Vancoille, L. C. Lee, H. Huang, K. Ramesh and X. D. Liu. "High-quality grinding of polycrystalline silicon carbide spherical surfaces." Wear, 256 (1-2) (2004) 197-207.
[6] Frantiska Frajkorova , Miroslav Hnatko, Zoltan Lences, Pavol Sajgalik. "Electrically conductive silicon carbide with the addition of Ti NbC." Journal of the European Ceramic Society 32 (2012) 2513–2518.
[7] K.H. Ho, S.T. Newman. "State of the art electrical discharge machining (EDM)." International Journal of Machine Tools & Manufacture 43 (2003) 1287–1300
[8] Renjie Ji, Yonghong Liu, Yanzhen Zhang, Baoping Cai, Jianmin Ma, Xiaopeng Li. "Influence of dielectric and machining parameters on the process performance for electric discharge milling of SiC ceramic." Int J Adv Manuf Technol (2012) 59 127–136.
[9] C.J. Luis, I. Puertas, G. Villa. "Material removal rate and electrode wear study on the EDM of silicon carbide." Journal of Materials Processing Technology 164–165 (2005) 889–896.
[10] S. Clijsters, K. Liu, D. Reynaerts, B. Lauwers. "EDM technology and strategy development for the manufacturing of complex parts in SiSiC" Journal of Materials Processing Technology 210 (2010) 631–641.
[11] www.poco.com "POCO®, EDM-100®, EDM-3®, EDM-AF5®, EDM-C3® and EDM-200C® are registered trademarks of Poco Graphite, Inc. " EDM-95967-0312.
[12] J. A. Sanchez, I. Cabanes, L. N. Lopez de Lacalle, A. Lamikiz. "Development of Optimum Electrodischarge Machining Technology for Advanced Ceramics" The International Journal of Advanced Manufacturing Technology (2001) 18:897–905.

[13] Hassan El-Hofy. "Advanced Machining Processes: Nontraditional and Hybrid Machining Processes." The McGraw-Hill Companies, Inc, New York (2005).
[14] I. Puertas, C.J. Luis, G. Villa. "Spacing roughness parameters study on the EDM of silicon carbide." Journal of Materials Processing Technology 164–165 (2005) 1590–1596.
[15] H.K. Kansal, Sehijpal Singh, P. Kumar. "Parametric optimization of powder mixed electrical discharge machining by response surface methodology." Journal of Materials Processing Technology 169 (2005) (3), 427–436.
[16] B.Mohan, A.Rajadurai, K.G.Satyanarayana."Effect of SiC and rotation of electrode on electric discharge machining of Al-SiC composite." Journal of Materials Processing Technology 124 (2002) 297-304.
[17] Dilshad Ahmad Khan, Mohammad Hameedullah. "Effect of tool polarity on the machining characteristics in electric discharge machining of silver steel and statistical modelling of the process." International Journal of Engineering Science and Technology.