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PERFORMANCE EVALUATION OF WIRE ELECTRO DISCHARGE MACHINING ON SILICON CARBIDE

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ABSTRACT

The machining of reaction-bonded silicon carbide (RBSiC) using wire electro-discharge machining (WEDM) with brass wire diameter of 0.25 mm has been used as the tool electrode. The main purpose of this study was to investigate the influenced of various parameters involved namely pulse on (ON), pulse off (OFF), peak current (IP) and servo voltage (SV) on the machining characteristics, namely surface roughness (Ra), sparking gap (Gap) and cutting speed (CS). The Full Factorial Design of Experiment (DOE) approach with two-level was used to formulate the experimental layout, to analyze the effect of each parameter on the machining characteristics and to predict the optimal setting for each WEDM parameters. Confirmation tests were also conducted for the optimum conditions for each machining characteristics in order to verify and compare the results from the theoretical prediction using Design Expert software and experimental confirmation tests. In general, results revealed that pulse on and peak current have appeared to be the significant effect to all responses investigated. Overall, the results from the confirmation tests showed that the percentage of performance was acceptable due to all the results obtained were within the allowable values which was less than 15% of margin error.

Keywords: *wire electro discharge machining, reaction-bonded silicon carbide, pulse on, pulse off, peak current, servo voltage, surface roughness, sparking gap, cutting speed, design of experiment*

1.0 INTRODUCTION

WEDM is a specialized thermal machining process capable of accurately machining parts with varying hardness [1] or complex shapes which have sharp edges that are very difficult to be machined by the main stream machining processes. This practical technology of the

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WEDM process is based on the conventional EDM sparking phenomenon utilizing the widely accepted non-contact technique of material removal. Since the introduction of the process, WEDM has evolved from a simple means of making tools and dies to the best alternative of producing micro-scale parts with the highest degree of dimensional accuracy and surface finish quality [2].

The selection of cutting parameters to obtain optimal cutting efficiency and accurately as well in WEDM is still not fully solved even with the most up-to-date CNC WEDM machine. This is mainly due to the nature of the complicated stochastic process mechanisms in WEDM itself. As a result, the relationships between the cutting parameters and the process performances are quite hard to achieve accurately [3].

Reaction Bonded Silicon Carbide (RBSiC) commonly called as siliconized silicon carbide. This material is formed by preparing a mixture of silicon carbide grain and finely divided carbon usually in the form of graphite. Fabrication of shapes can be done through casting or pressing process. RBSiC is characterized by a high strength, high thermal conductivity and typically low porosity. RBSiC also is serviceable to temperatures approaching the melting point of silicon at approximately 1450^{o}C. Due to the excess silicon metal this grade will conduct electricity. This grade is used in mechanical seal face applications, radiant heating tubes, cyclone apexes [4].

Design of experiment (DOE) is a series of tests in which purposeful changes are made to the input variables of a process or system so that the reasons for change in the output responses can be observed and identified [5]. One of the advantages when implemented this full factorial design is it offers the capability to estimate the correlation between two or more factors at one time, where it is possible with other quality tools. Furthermore, this tool also capable to identify the importance factors in the experiment under a wide range of conditions without sacrifices any factors [6].

2.0 METHODOLOGY

2.1 Two-Level Full factorial Design

Four factors experiment design will be employed with two levels of Full Factorial design experiment. The total number of experiments which is combinations required is 20 experiments (2^4 + 4 center points). This experiment design will include all possible combinations factors at two levels which are called low and high value for each parameter. The arrangements of the factors in this study will be organized by design expert software.

This software will then analyze the interaction of four factors to the responses assisted by Analysis of Variance (ANOVA). ANOVA was performed to find the independent variables that significantly affect the machining characteristics and establish the optimum condition. The final step is run the confirmation tests in order to verify the conclusions from the previous tasks of the experimentation. Confirmation tests are necessary and important step in Full Factorial design as it is a direct proof of the methodology. Then the comparison between confirmation tests and the prediction made from the software is done. The error of margin for the confirmation tests should not be more than 15%. The successfulness of the whole experiment will depend on the results obtained from the confirmation tests.

2.2 Machining Parameters

The setting of the machining parameters is shown in Table 1. All the values are based on literature survey and supervised by a technician. However, the capabilities of the WEDM machine available will be the major consideration in this study.

Table 1: The design machining parameters and its levels.

Machining Parameters	Levels	
	(-1)	(+1)
Pulse duration, ON (µs)	9.5	12.8
Pulse interval, OFF (µs)	8.0	25.7
Peak current, IP (A)	6.6	9.0
Servo voltage, SV (V)	30	60

3.0 Experimental Setup

The experiments of WEDM on RBSiC were conducted using 5-axis Sodick AQ537L machine. Brass wire with 0.25 mm of diameter was selected to be the electrode. Table 2 shows the machining parameters were kept constant throughout the experiment trials.

Table 2: The machine parameters kept constant.

Parameter	Setting Value
Servo speed, SF (mm/min)	1 (at no load)-normal servo control
Wire tension, WT (g)	200
Wire speed, WS (m/min)	10
Flushing pressure, FP (MPa)	0.7
Wire electrode	Brass wire 0.25 mm diameter
Polarity	Work material: positive Wire electrode: negative
Dielectric fluid	Deionized water

The size of RBSiC as the work material was a rectangular plate with dimension 100 x 100 x 5 mm. Then the work material was cut to size using WEDM for 6 mm length with the gap between two cutting experiments is 4 mm. The machined surface roughness then measured using Mitutoyo Formtracer CS-5000 with 5 µm stylus tip and 40^{o} of tip angle. The measurement length is 1.5 mm and it will divide into three sections with a sampling length of 0.08 mm each. The spark gap then was measured using a Profile Projector with 100x magnification. Then the work material is cut as shown in Fig. 1 in order to facilitate post measurements on other equipment such as surface roughness tester.

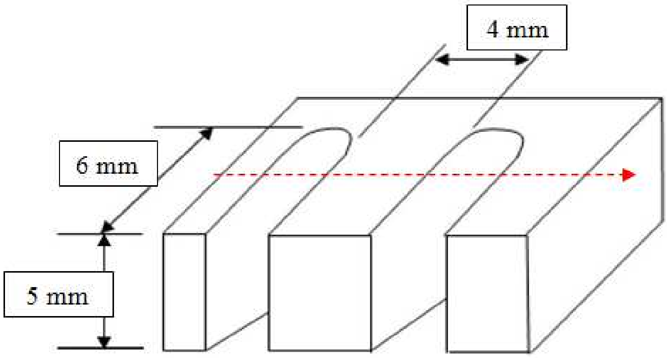

Figure 1 The diagram of cutting direction on the work material.

3.1 Collected Data

All the collected data then transferred into Design Expert software as the input for further analysis. Table 3 indicates the overall experimental results corresponding to each standard generated by software.

Table 3: Experimental results corresponded to each run

Std	Run	Coded Factors				Responses			
		ON (µm)	OFF (µm)	IP (ampere)	SV (volt)	Ra (µm)	Gap (mm)	CS (mm/min)	RL (µm)
1	1	018	015	2211	030	0.781	0.0347	1.89	3.09
2	13	031	015	2211	030	0.950	0.0383	1.91	3.48
3	7	018	063	2211	030	0.740	0.0313	2.50	5.02
4	2	031	063	2211	030	0.927	0.0393	2.89	5.02
5	16	018	015	2215	030	0.903	0.0280	2.21	5.21
6	8	031	015	2215	030	0.989	0.0293	2.73	4.05
7	9	018	063	2215	030	0.878	0.0287	2.75	5.40
8	15	031	063	2215	030	0.950	0.0338	2.98	5.41
9	17	018	015	2211	060	0.712	0.0377	2.32	4.44
10	6	031	015	2211	060	0.901	0.0391	2.68	4.45
11	20	018	063	2211	060	0.805	0.0367	3.05	2.24
12	12	031	063	2211	060	0.879	0.0393	3.09	6.27
13	19	018	015	2215	060	0.847	0.0298	2.98	3.28
14	4	031	015	2215	060	0.897	0.0327	3.37	4.18
15	10	018	063	2215	060	0.908	0.0332	3.43	3.43
16	3	031	063	2215	060	0.920	0.0312	3.51	6.56
17	5	025	039	2213	045	0.810	0.0317	3.67	8.51
18	11	025	039	2213	045	0.866	0.0323	3.50	7.76
19	14	025	039	2213	045	0.841	0.0333	3.39	4.12
20	18	025	039	2213	045	0.857	0.0307	3.21	4.63

4.0 RESULT AND DISCUSSION

4.1 Surface Roughness, Ra

The analysis shows the significant factors were main factor A, C and two- factor interaction AC as shows in Fig. 2. The "Curvature F-value" is 2.67 implied the curvature as measured by difference between the average of the center points and the average of the factorial points in the design space is not significant relative to the noise. There is a 12.31% chance that a "Curvature F-value" this large could occur due to noise. The "Lack of Fit F-value" of 2.08 implied the lack of fit is not significant relative to the pure error. There is a 29.83% chance that a "Lack of Fit F-value" this large could occur due to noise. Subsequently the model was fitted the data well and no axial-point needs to be added 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	0.076	3	0.025	22.51	< 0.0001	significant
A-ON	*0.044*	*1*	*0.044*	*38.97*	*< 0.0001*	
C-IP	*0.022*	*1*	*0.022*	*19.73*	*0.0005*	
AC	*9.950E-003*	*1*	*9.950E-003*	*8.81*	*0.0096*	
Curvature	3.014E-003	1	3.014E-003	2.67	0.1231	not significant
Residual	0.017	15	1.129E-003			
Lack of Fit	*0.015*	*12*	*1.260E-003*	*2.08*	*0.2983*	*not significant*
Pure Error	*1.817E-003*	*3*	*6.057E-004*			
Cor Total	0.096	19				

Figure 2 Revised ANOVA for Ra.

The R-value as shown in Fig. 3 is about 0.8182 (closer to one) for the response, it indicated that all the source of variation in the process were controlled and high precision optimum parameter setting can be obtained. The "Pred R-Squared" of 0.6870 is in reasonable agreement with the "Adj R-Squared" of 0.7819. "Adeq Precision" of 10.685 is an adequate signal to measure the signal to noise ratio because greater than 4 and can be used to navigate in design space.

Std. Dev.	0.034	R-Squared	0.8182
Mean	0.87	Adj R-Squared	0.7819
C.V. %	3.87	Pred R-Squared	0.6870
PRESS	0.030	Adeq Precision	10.685

Figure 3 Determination of prediction R-Square for Ra

The One Factor Effects Plot as shown in Fig. 4 illustrates when factor A increased from 9.5 to 12.8 µs, the value of Ra also increased dramatically from 0.822 to 0.927 µm with increment of 12.8%. When factor C increased from 6.6 to 9.0 ampere, the Ra also increased dramatically from 0.837 to 0.912 µm with increment of 9.0%.

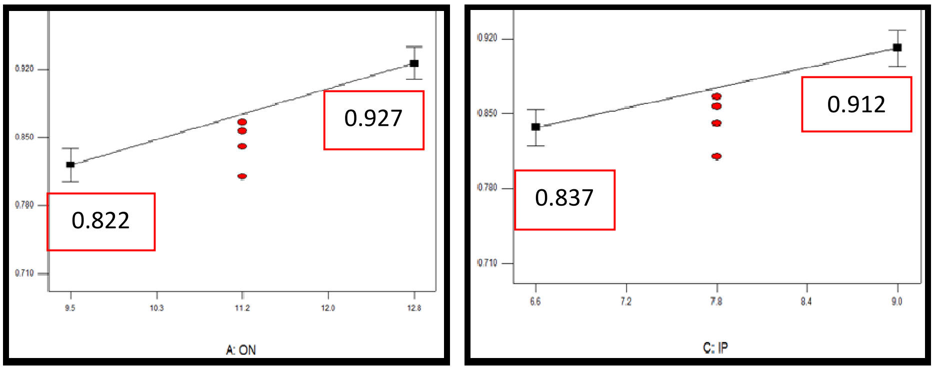

Figure 4 One Factor Effect Plot for Ra

Fig. 5 below shows the residuals lay on a straight line. This indicated the error is normally distributed.

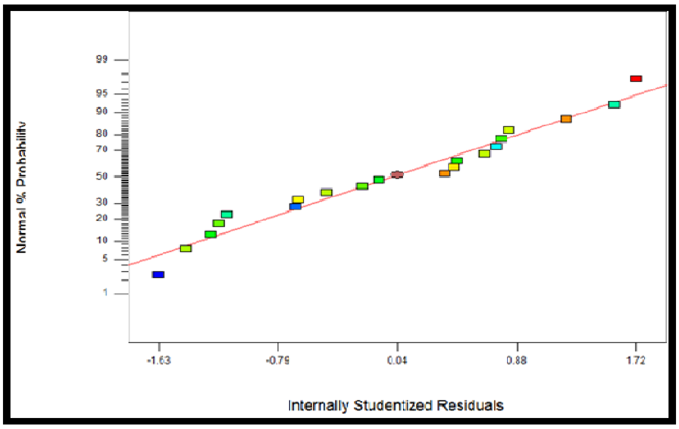

Figure 5 Normal Plot of Residuals for Ra

Fig. 6 revealed that they have no obvious pattern and unusual structure. This implies that the models proposed are adequate and there is no reason to suspect any violation of the independence or constant variance assumption.

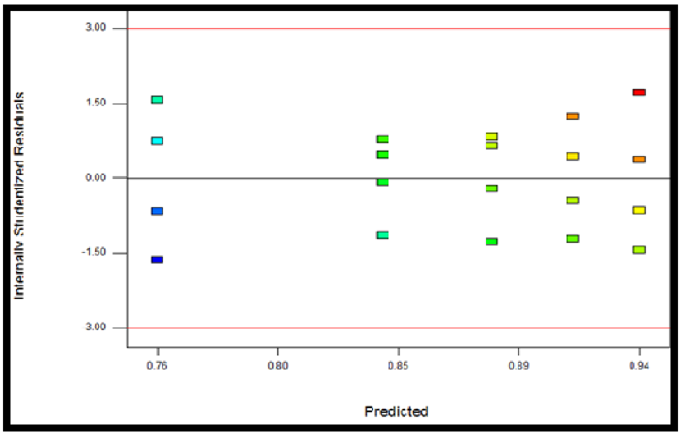

Figure 6 Residuals versus Predicted Plot for Ra

Any increase in the pulse on increases the plasma channel diameter that reduces both energy density and impulsive force. The melted debris cannot be removed completely due to reduction in impulsive force and forms an apparent globule-like recasted layer to degrade surface roughness [7]. The phenomenon that occurs when machining of RBSiC is also different with other metallic materials due to higher electrical conductivity of Si matrix compared with SiC grain, Si matrix tended to be removed first by melting or vaporization at the surface. Then the SiC grain will detach when the bonding force is reduced surrounding neighbor atom. This behavior causes the machining surface of RBSiC material to have a worse surface roughness compared to the most metallic materials.

At low peak current setting, intensity of current charge to the work material is lower and lead to a small effect to erosion of material.

4.2 Sparking Gap, Gap

As shown in Fig. 7, the significant factors identified were factor A, C and D. The “Curvature F-value” is 4.20 implied the curvature as measured by difference between the average of the center points and the average of the factorial points in the design space is not significant relative to the noise. There is a 5.84% chance that a “Curvature F-value” this large could occur due to noise. The “Lack of Fit F-value” of 2.78 implied the lack of fit is not significant relative to the pure error. There is a 21.64% chance that a “Lack of Fit F-value” this large could occur due to noise. Subsequently the model was fitted the data well and no axial-point needs to be added for further analysis.

ANOVA for selected factorial model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	2.038E-004	3	6.792E-005	23.57	< 0.0001	significant
A-ON	*3.278E-005*	*1*	*3.278E-005*	*11.38*	*0.0042*	
C-IP	*1.544E-004*	*1*	*1.544E-004*	*53.58*	*< 0.0001*	
D-SV	*1.661E-005*	*1*	*1.661E-005*	*5.76*	*0.0298*	
Curvature	1.209E-005	1	1.209E-005	4.20	0.0584	not significant
Residual	4.322E-005	15	2.881E-006			
Lack of Fit	*3.966E-005*	*12*	*3.305E-006*	*2.78*	*0.2164*	*not significant*
Pure Error	*3.560E-006*	*3*	*1.187E-006*			
Cor Total	2.591E-004	19				

Figure 7 Revised ANOVA for Gap

R-value as shown in Fig. 8 is about 0.8250 (closer to one) for the response, it indicated that all the sources of variation in the process were controlled and high precision optimum parameter setting can be obtained. The “Pred R-Squared” of 0.7034 is in reasonable agreement with the “Adj R-Squared” of 0.7900. “Adeq Precision” of 13.094 is an adequate signal to measure the signal to noise ratio because greater than 4 and can be used to navigate in design space.

Std. Dev.	1.697E-003	R-Squared	0.8250
Mean	0.034	Adj R-Squared	0.7900
C.V. %	5.06	Pred R-Squared	0.7034
PRESS	7.683E-005	Adeq Precision	13.094

Figure 8 Determination of Prediction R-Square for Gap

By referring to Fig. 9 when the factor A increased from 9.5 to 12.8 μs, the value of Gap also increased dramatically from 0.0325 to 0.0354 mm with increment of 8.9%. When factor C increased from 6.6 to 9.0 ampere, the Gap decreased from 0.0371 to 0.0308 mm with decrement of 20.5%. For factor servo voltage, when the factor D increased from 30 to 60 volt, the value of Gap also increased dramatically from 0.0329 to 0.0350 mm with increment of 6.4%.

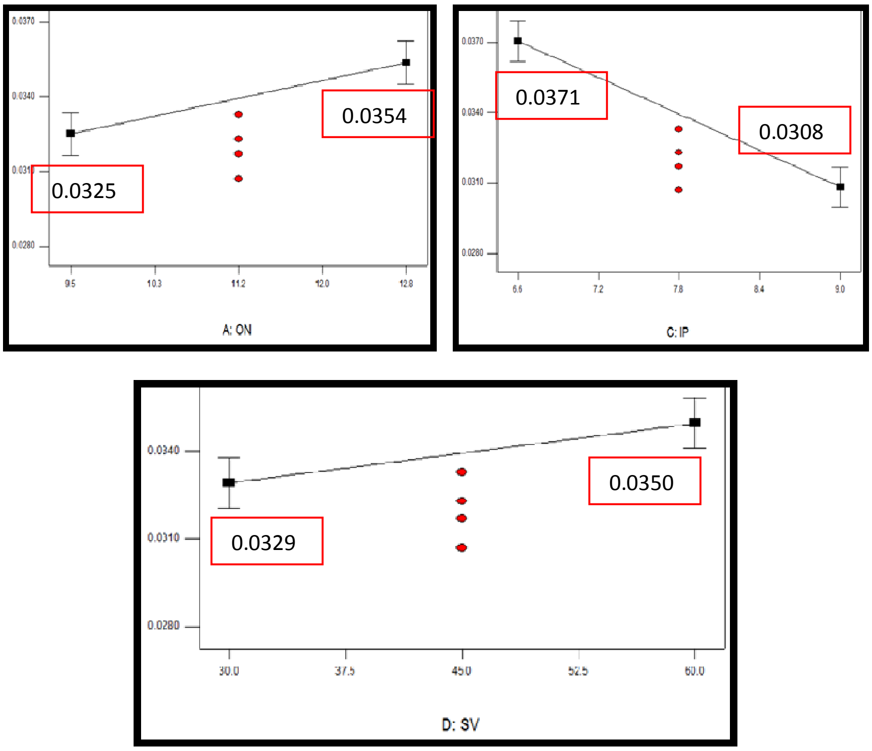

Figure 9 One Factor Effects Plot for Gap

Fig. 10 shows the residuals lay on a straight line. This indicated the error is normally distributed.

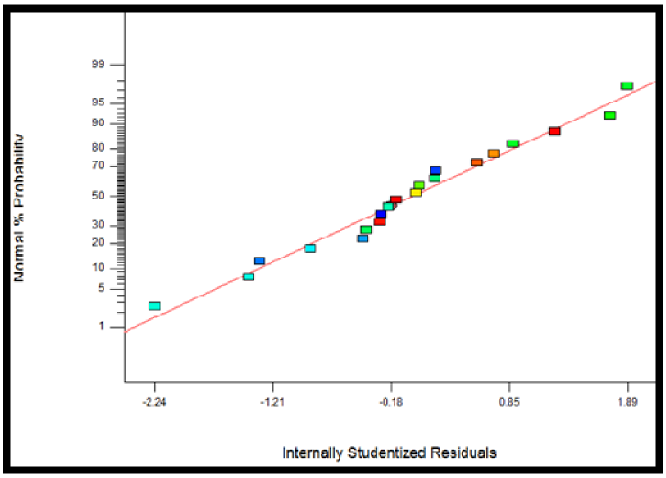

Figure 10 Normal Plot of Residuals for Gap

Fig. 11 reveals that they have no obvious pattern and unusual structure. This implies that the models proposed are adequate and there is no reason to suspect any violation of the independence or constant variance assumption.

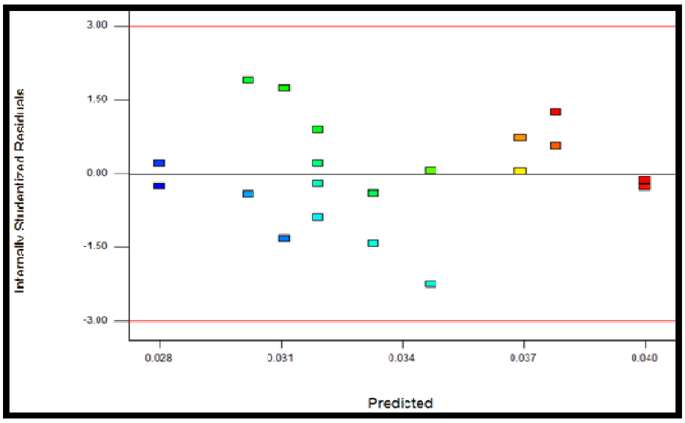

Figure 11 Residuals versus Predicted for Gap

Shorter the pulse on the shorter the time for machining took place resulted in a narrower gap. The decrement the power density for the wire to discharge sparks and to elevate the temperature in the gap, hence the lower the power the lower also the sparking gap.

The expected effect was that the increasing factor C will decrease the sparking gap since greater sparking power is obtained.

Although by applying a smaller servo voltage may increased the machining rate, however this condition may lead to the machining state at the gap become unstable and thus resulting in wire breakage [8].

4.3 Cutting Speed, CS

From the revised ANOVA as shown in Fig. 12, the significant factors identified are factor A, B, C, D and two factor interaction BC. The "Curvature F-value" for this analysis is 64.39 implied the curvature as measured by difference between the average of the center points and the average of the factorial points in the design space is significant relative to the noise. The "Lack of Fit F-value" of 0.49 implied the lack of fit is not significant relative to the pure error.

ANOVA for selected factorial model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	3.55	5	0.71	31.40	< 0.0001	significant
A-ON	0.26	1	0.26	11.33	0.0051	
B-OFF	1.06	1	1.06	46.78	< 0.0001	
C-IP	0.82	1	0.82	36.30	< 0.0001	
D-SV	1.30	1	1.30	57.57	< 0.0001	
BC	0.11	1	0.11	5.00	0.0436	
Curvature	1.46	1	1.46	64.39	< 0.0001	significant
Residual	0.29	13	0.023			
Lack of Fit	0.18	10	0.018	0.49	0.8287	not significant
Pure Error	0.11	3	0.037			
Cor Total	5.30	19				

Figure 12 Revised ANOVA for CS

Since the curvature is significant, it shows that second order equation is required for the response. Subsequently the analysis should be proceeding by adding a particular number of experimental runs in order to develop the second order equation. Centre Composite Design is done with one run per axial point and two additional center points. The alpha was setting as face centered at the same block making another ten experiments need to be implemented.

After all the data is tabulated in the software, the revised ANOVA will be used to determine the significant factor of the experiment. The results are shows in Fig. 13. The "Lack of Fit F-value" of 2.91 implied the lack of fit is not significant relative to the pure error. There is 11.98% chance that a "Lack of Fit F-value" this large could occur due to noise. Subsequently the model already fitted the data well. From the revised ANOVA also, factor B, C), D and D^2 are determined as the significant factors due to the p-value that less than 0.05.

	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	7.16	4	1.79	19.36	< 0.0001	significant
B-OFF	0.82	1	0.82	8.89	0.0063	
C-IP	0.65	1	0.65	7.05	0.0136	
D-SV	1.19	1	1.19	12.86	0.0014	
D^2	4.50	1	4.50	48.65	< 0.0001	
Residual	2.31	25	0.092			
Lack of Fit	2.13	20	0.11	2.91	0.1198	not significant
Pure Error	0.18	5	0.037			
Cor Total	9.47	29				

Figure 13 Revised ANOVA after the Augment Design for CS

The R-Square value as shown in Fig. 14 is 0.7560 it indicated that all the sources of variation in process were under controlled so that a high precision optimum parameter setting can be obtained. The "Pred R-Squared" is 0.6664 also in reasonable agreement with the "Adj

R-Squared" of 0.7169. "Adeq Precision" of 13.412 is an adequate signal to measure the signal to noise ratio because greater than 4 and can be used to navigate in design space.

Std. Dev.	0.30	R-Squared	0.7560
Mean	3.11	Adj R-Squared	0.7169
C.V. %	9.78	Pred R-Squared	0.6664
PRESS	3.16	Adeq Precision	13.412

Figure 14 Determination of R-Square for CS

By referring to Fig. 15, when factor B increased from 8.0 to 25.7 µs, the value of CS also increased dramatically from 3.37 to 3.80 mm/min with increment of 12.8%. When factor C increased from 6.6 to 9.0 ampere, the CS increased from 3.39 to 3.77 mm/min with increment of 11.2%. When factor D increased from 30 to 60 volt, the value of CS also increased proportionally from 2.53 mm/min up to 4.01 mm/min and started to decrease until 3.05 mm/min.

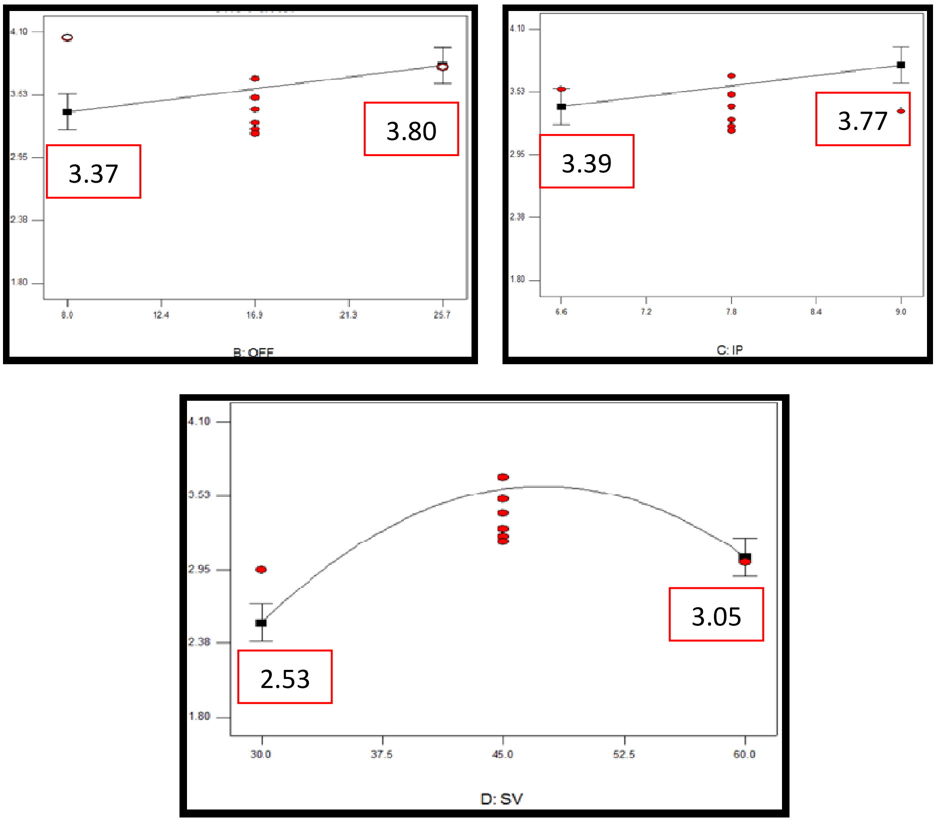

Figure 15 One Factor Effects Plot for CS

Fig. 16 shows the residual lie on a straight line and indicated that the error was normally distributed. Hence, it was proven that all the source of noise was successfully controlled and thus the validity of the model was established.

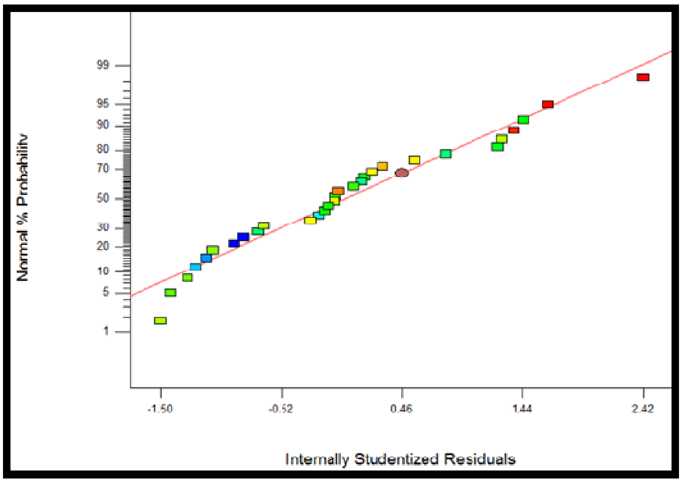

Figure 16 Normal Plot of Residuals for CS

Fig. 17 reveals that they have no obvious pattern and unusual structure. This implies that the models proposed are adequate and there is no reason to suspect any violation of the independence or constant variance assumption.

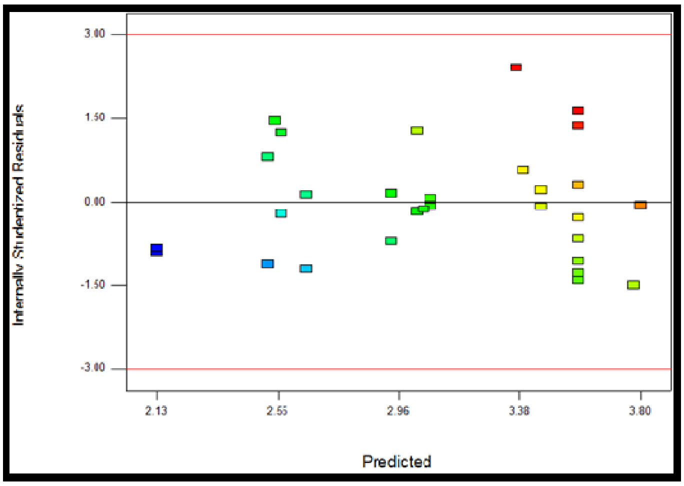

Figure 17 Residuals versus Predicted for CS

Insufficient off time can lead to erratic cycling and retraction of the advancing servo, thus slowing down the operation cycle [9]. Therefore, it is important to set the pulse off at the compatible setting in order to stabilize the machining process and achieved the optimum condition of cutting speed.

The peak current affected the intensity of discharged energy. Higher energy density causes the machining process to become faster.

Although increasing servo voltage decreased the electric sparks and slowed down the machining rate, the electric discharge was able to be stabilized by pulse on-time setting. The maximum level of cutting speed is then achieved at 4.01 mm/min at servo voltage setting of 48.75 volt. It shows that the stable spark is achieved at the optimum condition.

4.4 Mathematical Model

$$\text{Ra (coded)} = 0.87 + 0.052\,(A) + 0.037\,(C) - 0.025\,(A)(C)$$

$$\text{Ra (actual)} = -0.81805 + 0.13002\,(ON) + 0.17152\,(IP) - 0.012595\,(ON)(IP)$$

$$\text{Gap (coded)} = 0.034 + 1.431 \times 10^{-3}\,(A) - 3.106 \times 10^{-3}\,(C) + 1.019 \times 10^{-3}\,(D)$$

$$\text{Gap (actual)} = 0.041406 + 8.67424 \times 10^{-4}\,(ON) - 2.58854 \times 10^{-3}\,(IP) + 6.79167 \times 10^{-5}\,(SV)$$

$$\text{CS (coded)} = 3.58 + 0.21\,(B) + 0.19\,(C) + 0.26\,(D) - 0.79\,(D^2)$$

$$\text{CS (actual)} = -\,5.94518 + 0.024137\,(OFF) + 0.15856\,(IP) + 0.33324\,(SV) - 3.5123 \times 10^{-3}\,(SV^2)$$

4.5 Confirmation Run

Table 4: Optimization condition and predicted response

No.	Coded Factor				Predicted responses		
	ON	OFF	IP	SV	Ra	Gap	CS
1	018	063	2215	060	0.863531	0.030752	3.4084
2	018	058	2212	060	0.797039	0.034071	3.1590
3	018	063	2215	030	0.870085	0.028388	2.9144

Table 5: Comparison Test Results for Ra

No. of set	Prediction (Design Expert)	Experimental (Confirmation Test)	Residual of Response	Error Margin (%)
1	0.8635	0.899	0.0355	4.11
2	0.7970	0.805	0.0080	1.00
3	0.8701	0.891	0.0209	2.40

Table 6: Comparison Test Results for Gap

No. of set	Prediction (Design Expert)	Experimental (Confirmation Test)	Residual of Response	Error Margin (%)
1	0.0308	0.0317	0.0009	2.92
2	0.0341	0.0330	-0.0110	-3.24
3	0.0284	0.0293	0.0009	3.17

Table 7: Comparison Test Results for CS

No. of set	Prediction (Design Expert)	Experimental (Confirmation Test)	Residual of Response	Error Margin (%)
1	3.4084	3.3333	-0.0751	-2.20
2	3.1590	3.0769	-0.0821	-2.60
3	2.9144	2.8571	-0.0573	-1.96

The predicted and actual experimental values were compared and the residual and the percentage error calculated. All these values were presented in Tables 5, 6 and 7. The percentage error range between the actual and predicted value for Ra is 1.0 ~ 4.11 µm, Gap is -3.24 ~ 3.17 and CS is -1.96 ~ -2.60 mm/min.

5.0 CONCLUSION

ANOVA analysis revealed that Ra was significantly affected by pulse on-time and peak current. Gap was significantly affected by pulse on-time, peak current and servo voltage. Finally, CS was significantly affected by pulse off-time, peak current and servo voltage. The optimum condition for minimum Ra can be achieved when the pulse on-time is at the low level (9.5 µs) and peak current is at low level (6.6 ampere).

The optimum condition for minimum Gap can be achieved by setting the pulse on-time at the low level (9.5 µs), peak current is at high level (9.0 ampere) and servo voltage is at low level (30 volt). The optimum condition for maximum CS can be achieved when the pulse off-time is at high level (25.7 µs), peak current is at high level (9.0 ampere) and servo voltage is at approximately center point (47.4 volt). The empirical models for all responses were proved to be within 95% predictive interval of confirmation tests to approximate the real WEDM of RBSiC.

The margin errors from all responses were acceptable as the results indicated lower than the allowable set of margin error which is 15%.The optimum setting conditions were obtained from the numerical optimization of Design Expert software which considered all factors that satisfy the desired conditions by minimization of Ra, minimization of Gap, maximize the CS and minimize the RL. The setting was pulse on-time at 9.5 µs, pulse off-time at 25.7 µs, peak current at 9.0 ampere and servo voltage at 60 volt. Machining RBSiC required high sparking power. This is due to the high electrical resistivity and thermal conductivity of the material. High peak current is needed to initiate and stabilize the spark presence. High thermal conductivity will cause the heat to easily lose and finally reducing the heat energy efficiency during the process.

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