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Optimizing Material Removal Rate (MRR) in WEDMing Titanium Alloy (Ti6Al4V) Using the Taguchi Method

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Abstract: Selection of optimal cutting parameters has always been a critical issue to achieve high-quality in the machining process. In this study Design of Experiment (DOE) method for selection of optimal cutting parameters during WEDM of titanium alloy (Ti6Al4V) is experimentally studied. Moreover, the behaviour of three control parameters such as Pulse ON Time (A), Pulse OFF Time (B) and Peak Current (C) on machining performance, including Material Removal Rate (MRR) and Surface Roughness (SR) is studied using Analysis of Variance (ANOVA). This study has been establishedasa second-order mathematical model based on the Response Surface Methodology (RSM). The experimental plan was based on the face cantered, Central Composite Design (CCD). The residual analysis and confirmation runs indicate that the proposed models could adequately describe the performance of the factors that are being investigated. The results are particularly useful for scientists and engineers to determine which subset of the process variable has the greatest influence on the process performance.

Keywords: ANOVA, rough cut, taguchi method, WEDM machining, zinc coated wire

INTRODUCTION

The process of continuous travelling vertical-wire electrode act is known as Wire Electrical Discharge Machining (WEDM). In this process, there is no contact between work piece and electrode,thus materials of any hardness can be cut as long as they can conduct electricity (Kuriakose and Shunmugam, 2004).

The Material Removal Rate (MRR), surface finish and cutting width (kerf), are considered as the most important performance factors in study of WEDM. Optimization the material removal rate will help to increase the production rate considerably by reducing the machining time (Kuriakose and Shunmugam, 2005).

Ti-6A1-4V belongs to the group of alpha-beta titaniumalloys. The combination of high strength to weight ratio, excellent mechanical properties and corrosion resistance, high elastic stiffness and low density make this alloy the best choice for many critical applications. Forexample, this material has been used in space, aerospace, military and commercial applications (Boyer and Gall, 1985; Donachie and Matthew, 2000).

Several researches have been done to optimize the performance of WEDM process by various approaches. Rajurkar and Wang (1993) analyzed the wire rupture phenomena with a thermal model and the experimental investigation established the variation of machining performance with machining parameters. In addition, it was found thatthe material removal rate increasesinitially with decrease of pulse interval time but at a very short interval time, the gap becomes unstable, which causesa reduction in the material removal rate. There is no optimum condition reported. Furthermore, (Kuriakose *et al*., 2003) used Data mining approach to measure the process performance as a function of variety of control setting and to optimize the machining parameters. Moreover, the C4.5 Algorithm has been used to simulate the WEDM data and local optimization has been shownfor automation. Shajan and Shunmugam (2004) discussed to optimize material removal rate and surface roughness simultaneously with applying Non-dominated Sorting Genetic Algorithm (NSGA). The pulse off time, Pulse on and peak currentwere considered as three significant factors affecting the machining performance while machining Ti6Al4V.

Mahapatra and Amar (2007), studied on the significant parameters that influence on machining performance; they utilized D2 tool steel as a work piece. It was found that factors like discharge current, pulse duration and their interactions play a significant role in

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rough cutting operations for maximization of MRR. The optimum conditions have been established for this material via GA method. Vamsi *et al*. (2010) proposed a mathematical model to optimize the surface roughness using GA for WEDMing Ti6Al4V. It was found that by selection of optimum control parameters, 1.85 μm can be obtained, which is quite rough for finishing process. Singh and Garg (2009) presented the effects of process parameters on material removal rate in WEDM and it was found that, the material removal rate directly increases with the increase in pulse on time and peak current while the pulse off time and servo voltage decrease. Other studies that work on this subject involve (Aspinwall *et al*., 2008; Çaydas *et al*., 2009; Newman *et al*., 2004; Hewidy *et al*., 2005)

The objective of RSM is to determine the optimum operation conditions for the system or to determine the region of the factor space in which operating requirements are satisfied. The first step in RSM, the mathematical relationship between response and variables, is generated by good approximation. If there exists curvature in the system, polynomial of higher degree must be used instead of first-order model and for this purpose, the second-order model is considered.

In the present study, Analysis of Variance (ANOVA) is presented for curvature test. The second-order mathematical model has been constructed by the Response Surface Methodology (RSM) approach. In addition, the ANOVA table to achieve the second-order model can be calculated by following formula (1) (Montgomery, 2009):

$$Y_U = b_0 + \sum_{i=1}^{K} b_i X_i + \sum_{i=1}^{K} b_{ii} X_i^2 + \sum_{j>i}^{K} b_{ij} X_i X_j \qquad (1)$$

In this study, experimental procedure and analysis of experiments have been considered. Moreover, the discussions are presented with both of our responses, material removal rate and surface roughness.

Experimental procedures: Experimental trials were carried out in a WEDM linear motor 5-ax-Sodick series AQ537L. The experimental setup is as following: Zinc coated brass wire of 0.25 mm diameter is employed as electrode, titanium based-alloy (Ti6Al4V, Composition: C = 0-0.08%, Fe = 0-0.25%, Al = 5.5-6.76%, O = 0-0.2%, N = 0-0.05%, V = 3.5-4.5%, H = 0-0.375%, balance Ti). Response Surface Methodology (RSM) approach was used to design the experiments and optimization process. Design Expert 7.0.0.0 software has been utilized for optimization.

The machining parameters and levels are shown in Table 1.

In the experiments, 2^k factorial with central composite, known as full factorial design, was used (in this case $k = 3$). Thus $n_c = 2^k = 8$ corner points at +1 and -1 levelsand a centre point at zero levelswere repeated three times.

Table 1: Wire EDM operation

Coded factor	Machining parameters	Levels -1.0	0.0	1.0
A	pulse on time (μs)	8.0	9.0	10.0
B	pulse off time (μs)	6.5	7.5	8.5
C	peak current (A)	32.0	36.0	40.0
Constant parameters			description	
Machining voltage			120	
Servo Voltage (V)			50	
Wire speed (m/min)			15	
Wire tension (g)			600	
Flushing pressure (bar)			55	
Tool polarity			negative	
Dielectric fluid			deionised water	
Wire material			zinc coated brass	

Table 2: Design of experiments matrix and results

Std order	Pulse on time (μs)	Pulse off time (μs)	Peak current (A)	MRR mm^3/S	Surface roughness (Ra) (μm)
1	-1	-1	-1	0.3382	2.75
2	1	-1	-1	0.3934	2.95
3	-1	1	-1	0.3167	2.64
4	1	1	-1	0.3606	2.91
5	-1	-1	1	0.401	3.52
6	1	-1	1	0.4468	3.87
7	-1	1	1	0.3882	3.38
8	1	1	1	0.4225	3.75
9	0	0	0	0.3645	3.21
10	0	0	0	0.367	3.28
11	0	0	0	0.3762	3.31

To achieve the optimum region to maximize the MRR, The different levels of machining parameters have been selected. In each trial, a 10 mm length of cutting was made on 10 mm thickness of the work pieces.

The following equation has been used to compute the MRR value:

$$\text{MRR} = \frac{Wa - Wb}{Tm\,p} \quad (mm^3/sec) \qquad (2)$$

where, W_b and W_a are weights of work piece material before and after machining (g), respectively. Tm is machining time (sec) and p is the density of Ti6Al4V (0.00442 g/mm^3)

The arithmetic surface Roughness value (Ra) was implemented and measurements were carried on by using a Mitutoyo-Formtracer CS 5000. Moreover, The Ra values of the EDMed surface were obtained by averaging the surface roughness values of 5 mm measurement length.

RESULTS AND ANALYSIS

The results of experiment have been illustrated with full factorial design, shown in the Table 2:

After putting the data from Table 2 to the Design Expert 7.0.0.0 software the following figures and tables have been obtained. Figure 1 presents a normal probability plot of the effect of parameters on:

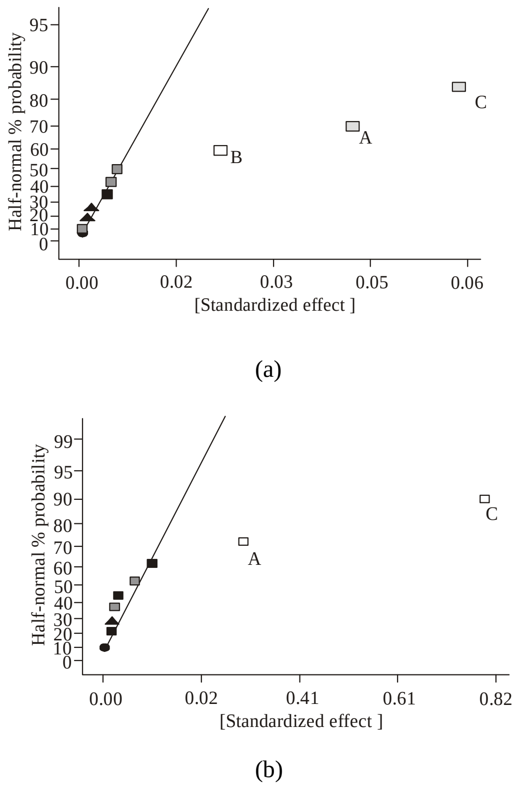

Fig. 1: Half normal of probability plot of main effects for (a) MRR and (b) surface roughness A: pulse on; B: pulse off; C: peak current

- MRR
- SR

The real effect of the factors on response machining performance is selected by the graphical technique. A line fitting is drown through the effects that are close to zero, in the manner, if effects are insignificant, the points should befound close to line. In the Fig. 1, the main effects are peak current (C) and pulse on (A) for SR. For MRR, the main parameters are peak current (C), pulse on (A) and pulse off (B).

Table 3 shows the ANOVA table for material removal rate.The Model F-value of 115.2 implies that the model is significant. There is only a 0.01% chance that this "Model F-Value" could occur due to noise. Values of "Prob>F" less than 0.0500 indicatesthat the model terms are significant. In this case A, B and C are significant model terms. Values greater than 0.1000 reveals, that the model terms are not significant. The "Curvature F-value" of 11.82 implies the curvature (as measured by difference between the average of the centres' points and the average of the factorial points) in the design space is significant. The curvature test became significant for MRR; it means that we have to use augment experiments to obtain second order model for this performance. The "Lack of Fit F-value" of 0.97 implies that the Lack of Fit is not significant relative to the pure error. There is a 56.5% chance that this "Lack of Fit F-value" could occur due to noise. Since we want to fit the model, Non-significant lack of fit is good.

Table 3: ANOVA table for the material removal rate

Response 1 MRR
ANOVA for selected factorial modle
Analysis of variance table [Partial sum of squares - Type III]

Source	SS	df	MS	F- value	p-value	Prob>F
Model	0.013	3	4.282E-003	115.20	< 0.0001	significant
A-pulse on	4.014E-003	1	4.014E-003	107.99	< 0.0001	
B-pulse off	1.044E-003	1	1.044E-003	28.09	0.0018	
C-peak curren	7.788E-003	1	7.788E-003	209.51	< 0.0001	
Curvature	4.394E-003	1	4.394E-004	11.82	0.0138	significant
Residual	2.230E-004	6	3.717E-005			
Lack of Fit	1.471E-004	4	3.677E-005	0.97	0.5650	not significant
Pure Error	7.593E-005	2	3.796E-005			
Cor Total	0.014	10				

Table 4: ANOVA table for the surface roughness

Response 2 MRR
ANOVA for selected factorial modle
Analysis of variance table [Partial sum of squares - Type III]

Source	SS	df	MS	F-value	p-value	Prob>F
Model	1.51	2	0.76	143.46	< 0.0001	significant
A-pulse on	0.18	1	0.18	33.55	0.0007	
C-peak curren	1.34	1	1.34	253.36	< 0.0001	
Curvature	4.500E-003	1	4.500E-003	0.85	0.3864	not significant
Residual	0.037	7	5.276E-003			
Lack of Fit	0.032	5	6.333E-003	2.40	0.3193	not significant
Pure Error	5.267E-003	2	2.633E-003			
Cor Total	1.56	10				

Table 5: Summery of ANOVA analysis for quadratic reduced model

Response	R^2	Adj R^2	Pred R^2	Adeq precision
MRR	0.9829	0.9744	0.9438	31.639
Surface roughness	0.9731	0.9517	0.9070	19.268

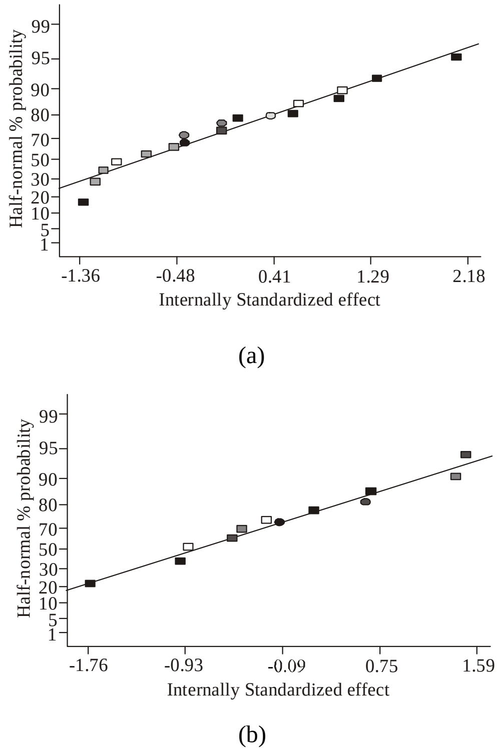

Fig. 2: Normal plot of residuals (a) MRR, (b) SR

Table 4 demonstrates the ANOVA table for surface roughness. The Model F-value of 143.46 impliesthat the model is significant. There is only a 0.01% chance that this "Model F-Value" could occur due to noise. Values of "Prob>F" less than 0.0500 indicatesthat the model terms are significant. In this case, A and C are significant model terms. Values greater than 0.1000 indicates, themodel terms are not significant. The "Curvature F-value" of 0.85 implies that the curvature in the design space is not significant relative to the noise. There is a 38.46% chance that this "Curvature F-value" could occur due to noise. The "Lack of Fit F-value" of 2.4 implies the Lack of Fit is not significant relative to the pure error. There is a 31.93% chance that this "Lack of Fit F-value" could occur due to noise.

The Table 5 indicates that all of the R^2 values are high and close to one, which is desirable. The difference between values of adjusted and predicted-R^2 is less than 0.2, indicatingthat they are in agreement. The models havean adequate signal because the adequate predictions of all models are above 4.

Figure 2 shows the normal plots of residuals for the quadratic models. The normal probability plots illustrate that residuals are normally distributed along the normal probability line. It means that the error distribution is approximately normal for all series of data, which indicate that the models are adequate. Figure 3 shows residual versus predicted plots in which all data is shown to be in the range and no abnormal trend exists.

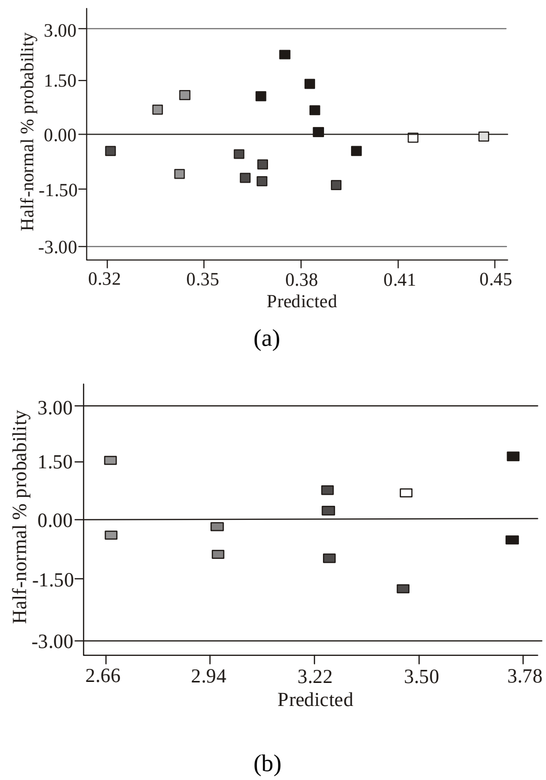

Fig. 3: Residual versus predicted plots (a) MRR, (b)

Table 6: Experimental results augment CCD for MRR

Std order	Pulse on time (µs)	Pulse off time (µs)	Peak current (A)	MRR mm^3/S	Surface roughness (Ra) (µm)
12	-1	0	0	0.3492	3.01
13	1	0	0	0.3912	3.47
14	0	-1	0	0.3906	3.28
15	0	1	0	0.3605	3.15
16	0	0	-1	0.3394	2.98
17	0	0	1	0.3894	3.77

The equation for Surface roughness from the results in ANOVA in Table 6 derived in terms of coded factors as follows:

$$Ra = +3.22 +0.15\ A + 0.41\ C \quad (4)$$

ANOVA analyzes in Table 3 shows that curvature test for MRR is significant; hence the second-order model is valid for this model. To obtain the second-order model central composite design which is one of the RSM designed model have been used.

Table 7: ANOVA table for the material removal rate after RSM

Response 1 MRR

ANOVA for Response Surface Reduced Cubic Model

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

Source	SS	df	MS	F- value	p-value	Prob>F
Block	3.507E-004	1	3.507E-004			
Model	0.016	13	1.242E-003	32.71	0.0300	significant
A-pulse on	8.820 E-004	1	8.820 E-004	23.23	0.0404	
B-pulse off	4.530E-004	1	4.530E-004	11.93	0.0746	
C-peak curren	1.250E-003	1	1.250E-003	32.93	0.0291	
AB	6.498E-005	1	6.498E-005	1.71	0.3209	
AC	4.513E-005	1	4.513E-005	1.19	0.3894	
BC	3.698E-005	1	3.698E-005	0.97	0.4277	
A^2	6.199E005	1	6.199E005	1.63	0.3296	
B^2	2.724E-004	1	2.724E-004	7.17	0.1157	
C^2	2.200E-006	1	2.200E-006	0.058	0.8322	
ABC	5.000E-009	1	5.000E-009	1.317E-004	0.9919	
A^2B	2.103E-005	1	2.103E-005	0.55	0.5343	
A^2C	6.150E-005	1	6.150E-005	1.62	0.3310	
AB^2	3.136E-006	1	3.136E-006	0.083	0.8008	
Pure Error	7.593E-005	2	3.796E-005			
Cor Total	0.017	16				

Table 8: ModifiedANOVA table for the material removal rate after RSM

ANOVA for Response Surface Reduced Cubic Model

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

Source	SS	df	MS	F-value	p-value	Prob>F
Block	3.507E-004	1	3.507E-004			
Model	0.016	4	3.962E-003	117.29	< 0.0001	significant
A-pulse on	4.893E-003	1	4.893E-003	144.86	< 0.0001	
B-pulse off	1.476E-003	1	1.476E-003	43.71	< 0.0001	
C-peak curren	8.976E-003	1	8.976E-003	265.75	< 0.0001	
B^2	5.010E-004	1	5.010E-004	14.83	0.0027	
Residual	3.715E-004	11	3.715E-004			
Lack of Fit	2.956E-004	9	3.285E-005	0.87	0.6425	not significant
Pure Error	7.593E-005	2	3.796E-005			
Cor Total	0.017	16				

To obtain second order mathematical model, we have used six experiments on axial points, which are explained in following table. ($n_a = 2^k = 6$).

Table 7 indicatesthe ANOVA table after adding central composite design experiments. This table shows not modified ANOVA table for the effect of different parameters and their interaction on MRR. Since there are many insignificant model terms (not counting those required to support hierarchy), model reduction is necessary to improve the model with the respect to F-value.The modelhad been modified as it is shown in the following table.

In Table 8, the Model F-value of 117.29 implies the model is significant. Values of "Prob>F" less than 0.0500 indicate, themodel terms are significant. In this case A, B, B^2 and C are significant model terms.

The R-squared value and adj R-squared are 97.71 and 96.88%, respectively, which are high and desirable. Predicted R-squared and Adeq-Precision are 0.9449 and 37.207, respectively.

Adeq Precision actually measures the signal to noise ratio. A ratio greater than 4 is desirable. Also the Pred R-Square is in reasonable agreement with theAdj R-Squared.

The following equations are the final empirical models in terms of coded factors for Augment Central Composite Design resulted from Quadratic Equation:

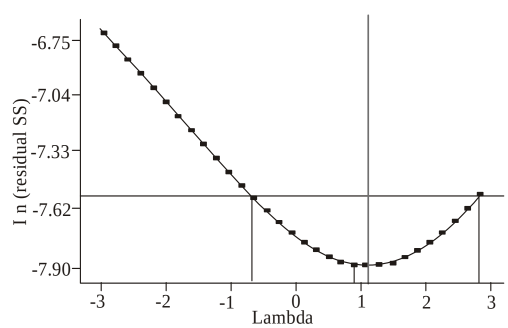

Fig. 4: Box-cox plot for MRR data

$$MRR = 0.37+0.022\ A-0.012\ B+0.030\ C+0.012\ B^2 \quad (5)$$

DISSECTION

Material Removal Rate (MRR): To examine the results,the data are in the optimum region,and the second-order model is totally valid for MRR. In Fig. 4, Box-Cox plot for MRR, it is shown that the data are in the optimum region of the parabola.

Analyzing the results revealsthat peak current significantly affects MRR. The energy of each discharge

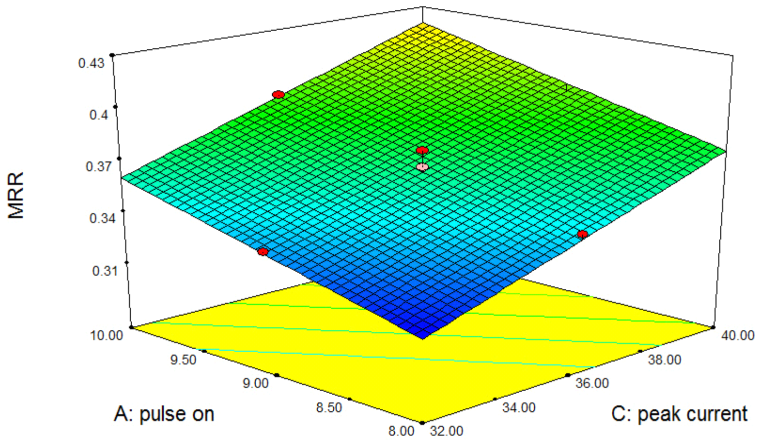

Fig. 5: 3D surface graph for material removal rate

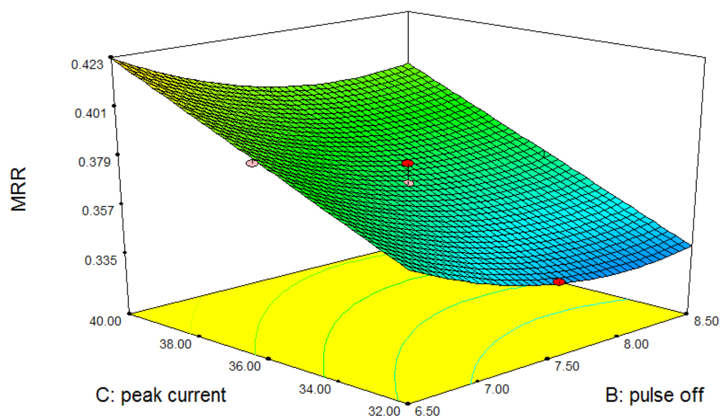

Fig. 6: 3D surface graph for material removal rate

will be raisedwith the increase of peak current and more quantity of material is removed. This condition could reduce machining time and thus increase productivity. This factor contributed 57.65% in MRR, which is the highest contribution. Moreover, Pulse on time is another main factor that influenced on MRR. Increasing the pulse on time will affectthe time of each discharge and raise the material removal rate. This factor contributed 29.72% in MRR. Figure 5 shows that both peak current and pulse on time should be set at high to achieve higher MRR.

Figure 6 shows the effect of peak current and pulse off timeon MRR. According to this figure curvature is significant in the MRR interaction plot. Lower setting for pulse off time and higher peak current were required to achieve higher MRR. These results are in agreement with Sarkar *et al*. (2005) and Kuriakose and Shunmugam (2005) results.

Surface Roughness (SR): In ANOVA analysis, the most significant factor that influences surface roughness is peak current followed by pulse on time. As it was mentioned before, peak current influences the energy of each discharge. The higher discharge the energy produces the bigger and deeper craters and rippled surface are, which affect the surface roughness. As the lower surface roughness value can represent better machining performance, lower peak current is preferable to get better surface finish. ANOVA model shows that this factor contributed 85.95% in influencing surface roughness.

Another important factor to control surface roughness is Pulse on time duration. In the model, the contribution of this factor is 11.38%. In addition, Ra increased when the pulse ON increased due to longer time for machining, which led to the higher possibility of “double sparking” and localized sparking to occur. Double sparking can cause the poor surface finish since only the initial phase sparks to contribute to the material removal. Hence “lower is better”. For surface roughness, the lower pulse on time is better (Sarkar *et al*., 2008)

The result for surface roughness is in agreement with Kuriakose and Shunmugam (2004) results.

Table 9: Results of confirmation experiments

Model	MRR (%)	Surface roughness (%)
Error	3.595	4.725

Table 10: The optimal condition for each parameter

Condition	Pulse on time (µs)	Pulse off time (µs)	Peak current (A)	Optimum response
MRR	10	6.5	40	0.444 mm^3/sec
Surface roughness	8	8.4	32	2.6637 µm
Multi-objectives	10	6.5	33	

The results for both responses are in agrees with the theory that MRR and surface roughness are influenced by pulse ON time and Peak current and these factors have an opposite relationship (Poro´s and Zaborski, 2009).

Confirmation tests: In order to verify the adequacy of the model and mathematical equation development, confirmation test is required tobe performed. Predicted values for confirmation tests were suggested by the Design Expert software. For each model, three experiments have been done. Table 9 shows the average of error for each model.

Finally, in Table 10, the best combination of parameters can be accessed for each optimal condition. In this table,the result for MRR is in the optimum region, but for surface roughness just the local optimization can be achieved. In this study, material removal rate was the first priority of machining performance and the result is suitable for rough cutting.

In the multi-objectives condition, both of the response was considered with the same importance. The optimization goals for each optimization are, minimum for surface roughness and maximum for MRR.

CONCLUSION

- The capability of WEDM process in machining Ti-6A1-4V has been found to reach 0.444 mm^3/sec of MRR.
- The most significant factor for bothresponses is peak current followed by pulse on time. Both responses tend to increase with increasing of peak current, which influenced on the energy of each discharge. Furthermore, pulse on time duration influenced on time of each discharge.
- MRR is capable of being predicted at the optimum region of the process. But optimum value of surface roughness can only be achieved in local optimization (within the range of each factor).
- Several optimal conditions can be gotten from the analysis, including the multi-objectives condition which can be set by Pulse on time: 10 µs, pulse off time 6.5 µs, peak current: 33 A. The predicted result is MRR 0.3913 mm^3/second surface roughness: 3.122 µm.
- Empirical equations to predict surface roughness and material removal rate are obtained and successfully verified in the confirmation tests.

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