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Optimizing Rough Cut in WEDMing Titanium Alloy (Ti6Al4V) by Brass Wire Using the Taguchi Method

[1]Danial Ghodsiyeh, [2]Mohammadreza Askaripour Lahiji, [3]Mahdi Ghanbari, [4]Abolfazl Golshan, [5]Mostafa rezazadeh shirdar

[1,5] Faculty of Mechanical Engineering
[2,3] Department of Mathematics, Faculty of science ,
Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[4]Faculty of Mechanical Engineering, Universiti Putra Malaysia, 43300, Serdang, Selangor, Malaysia

ABSTRACT

Determining the optimal cutting parameters has always been a critical matter to achieve high performance in different type of machining. In this study the behaviour of three control parameters base on Design of Experiment (DOE) method during WEDM of titanium alloy (Ti6Al4V) is experimentally studied. A brass wire of 0.25mm diameter was used as tool electrode to cut the specimen. This wire is much chipper than coated wire; this factor can increase the economic profit. Experiments were planned based on the face cantered, central composite design (CCD). Experiments were performed under different cutting conditions of pulse on time, pulse off time and peak current. Analysis of variance (ANOVA) was employed to recognize the level of significance of the machining parameters on the performance characteristics of material removal rate (MRR) and surface roughness (SR). The residual analysis and confirmation runs indicate that the proposed models could adequately describe the performance of the factors those are being investigated. The results are particularly useful for scientists and engineers to determine which subset of the process variable has the maximum influence on the process performance.

KEY WORDS: Taguchi Method, WEDM machining, Rough cut, Hard Brass wire, ANOVA.

1. INTRODUCTION

WEDM is a thermo-electrical process that material is eroded by a series of sparks between the work piece, and the wire electrode (tool) separated by dielectric fluid [1]. The movement of wire is controlled numerically to achieve the desired three-dimensional shape and accuracy of the work piece [2].

The most important performance factors in study of WEDM are material removal rate (MRR), surface finish and cutting width (kerf). Between these factors, the most important one is MRR because optimization the material removal rate will help to reducing the machining time, so increase the production rate considerably [3].

Ti- 6Al-4V has a resistivity on the order of five times larger than steel. Titanium alloys have relatively high melting temperature, low thermal conductivities and high electrical resistivity when compared to other common materials, but electrical resistivity is highly dependent on the temperature. This material has been widely used in space, aerospace, military and commercial applications [4, 5].

Brass wire is common and widely used as wire electrode in WEDM. In order to improve machining performance, coated wire was introduced. The cost ratio of coated wire over brass is almost 2:1. So using brass wire is more economical and acceptable unless the performance advantages of coated wire are truly compelling. Optimizing the material removal rate with Brass wire can help to increase economic benefits in WEDM considerably.

Several researchers have attempted to optimize the performance of WEDM process by different approaches.

Rajurkar and Wang (1993) [6] analyzed the wire rupture phenomena with a thermal model and experimental investigations. It was found that the material removal rate increases with decrease of the pulse interval. Tarng *et al*. (1995) [7] used a neural network system with a simulated annealing (SA) algorithm to clarify the relationships between the cutting parameters and cutting performance. Huang et al. (1999) [8] investigated the effect of machining parameters on the Kerf width, the surface roughness, and the recast layer thikness on the machined work piece surface experimentally. The brass wire had used as a tool electrode and the work piece was SKD11 alloy steel. Rozenek *et al*. (2001)[9] investigated the effect of machining parameters include discharge current, pulse-on time, pulse-off time and voltage on feed rate and surface roughness. They used brass tool as electrode wire and metal matrix composite as a work piece.

Mahapatra and Patnaik (2007) [10] attempted to optimize three main machining performances include MRR, Surface Roughness and cutting width. Taguchi method was used to design the experiments and Genetic

***Corresponding Author**: Danial Ghodsiyeh, Faculty of Mechanical Engineering Universiti Teknologi Malaysia, 81310

Algorithm (GA) was used to optimize different machining parameters to achieve desired quality of the machined product. It was found that; GA method for WEDM may not be useful. The optimal result suggested by GA most of the times cannot be achieved, in reality; due to the absence of the optimal parameter combination in the machine. Taguchi method in compare with GA has more advantage. Singh and Garg (2009) [11] presented the effects of process parameters on material removal rate in WEDM, and it was found that, when the pulse on time and peak current increase material removal rate also increased but with the increase of pulse off time and servo voltage, MRR decrease. Brass wire had used as a tool electrode and H-11 hot die steel was used as a work piece.

Creating the optimum situation for the system's function or verifying the region of the factor space is the aim of the RSM, in which the needs for operation are fulfilled. A fine approximate can establish the response and variables' mathematical connection that is the primary step in RSM. In the cases that the system consists of curvature, first-order model should be replaced by the polynomial of higher degree that is the second-order model for this research.

In this research, curvature test was conducted through analysis of variance (ANOVA). And response surface methodology (RSM) approach was used to organize second-order mathematical model. Furthermore, the formula below was applied to calculate and establish the second-order model through ANOVA table (1) [12].

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

In section 2, experimental procedures are considered. Section 3, result and analysis are proposed. In Section 4, dissection has been illustrated with three details, which are Material Removal Rate (MRR), Surface Roughness (SR) and Confirmation Tests. Section 5, the results are demonstrated.

2. Experimental procedures

Table 1: wire EDM operation

			Levels	
Coded factor	Machining Parameters	-1	0	1
A	Pulse ON Time (µs)	8	9	10
B	Pulse OFF Time (µs)	6.5	7.5	8.5
C	Peak Current (A)	32	36	40
	Constant Parameters		Description	
	Machining Voltage		120	
	Servo Voltage (V)		50	
	Wire speed (m/min)		10	
	Wire tension (g)		600	
	Flushing pressure (bar)		55	
	Tool Polarity		Negative	
	Dielectric fluid		Deionised Water	
	Wire material		Hard Brass	

2^k factorial with central composite, considered as full factorial design in the trials, (where k = 3). Therefore, $n_c = 2^k = 8$ corner points at +1 and -1 levels also the of the center point at zero levels was three times. In order to find the optimum region, various levels of machining parameters were chosen to maximize the MRR. The length of cutting on the work pieces with thickness of 10 mm, in each trial, equals 10 mm.
MRR value was obtained by the following equation:

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

While W_b is the weight of work piece material before machining, and W_a represents its weight after machining (g). Tm is machining time (sec) and p is the density of Ti6Al4V (0.00442 g/mm^3). Mitutoyo-Formtracer CS 5000 was utilized to measure the arithmetic surface roughness value (Ra) after it was put into practice. The Ra values of the EDMed surface were computed through calculating the average of surface roughness values of 5 mm measurement length.

2. RESULT AND ANALYSIS

This part consists of full factorial design that shows the results obtained by the test, in table 2:

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	0.2451	2.8
2	1	-1	-1	0.2863	3.1
3	-1	1	-1	0.2386	2.7
4	1	1	-1	0.2651	3
5	-1	-1	1	0.2927	3.5
6	1	-1	1	0.3487	3.9
7	-1	1	1	0.2729	3.4
8	1	1	1	0.3322	3.8
9	0	0	0	0.303	3.3
10	0	0	0	0.2949	3.2
11	0	0	0	0.2973	3.1

A normal probability plot of the effect of parameters on (a) MRR and (b) SR is shown in figure 1. The technique used to find out the true influence that the factors have on response machining performance, was the graphical technique. . A line fitting is drawn through the effects that are close to zero, in this manner, if effects are insignificant, the points should be found close to line. According to figure 1, the main effects consist of peak current (c) and pulse on (A) for SR. In the case of MRR, the main parameters consist of peak current(C), pulse on (A) and pulse off (B) and pulse on time peak current interaction (AC).

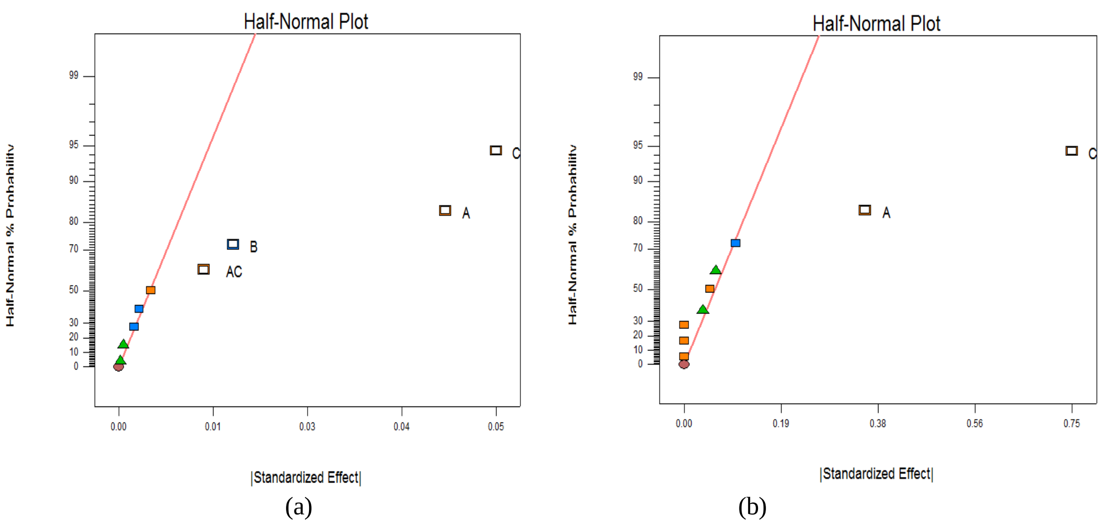


Fig .1: Half normal of probability plot of main effects for (a) MRR and (b) surface roughness (pulse on=A, pulse off =B, peak current =C)

Table 3: ANOVA table for the Material removal rate

Response 1 MRR

ANOVA for selected factorial model

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

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.011	4	2.642E-003	131.29	< 0.0001	significant
A-Pulse On	*4.186E-003*	*1*	*4.186E-003*	*208.04*	*< 0.0001*	
B-Pulse Off	*5.120E-004*	*1*	*5.120E-004*	*25.44*	*0.0040*	
C-Current Pea	*5.586E-003*	*1*	*5.586E-003*	*277.62*	*< 0.0001*	
AC	*2.832E-004*	*1*	*2.832E-004*	*14.08*	*0.0133*	
Curvature	3.802E-004	1	3.802E-004	18.89	0.0074	significant
Residual	1.006E-004	5	2.012E-005			
Lack of Fit	*6.599E-005*	*3*	*2.200E-005*	*1.27*	*0.4688*	*not significant*
Pure Error	*3.462E-005*	*2*	*1.731E-005*			
Cor Total	0.011	10				

Table 3 presents the ANOVA table for material removal rate. The significance of the model is revealed according to the Model F-value of 131.29. There is only a probability of 0.01% that noise causes this “Model F-Value” to happen. If the values of "Prob > F" are smaller than 0.0500, the model terms will be significant; thus, A, B, C and AC are considered as significant model terms. If the values are bigger than 0.1000, the model terms will not be significant. The "Curvature F-value" of 18.89 reveals that the curvature (as measured according to the average of the centres' points and the average of the factorial points’ difference) is significant in the design space. The curvature experiment became significant for MRR; that means, in order to get second order model for this treatment augment experiments must be applied. The "Lack of Fit F-value" of 1.27 reveals that lack of Fit, related to the pure error, is not significant. The possibility of occurring of this “Lack of Fit F-value” because of noise is 46.88%. Because we want to make this fit to the model, it is good to have an insignificant lack of fit.

Table 4: ANOVA table for the Surface Roughness

Response 2 Ra

ANOVA for selected factorial model

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

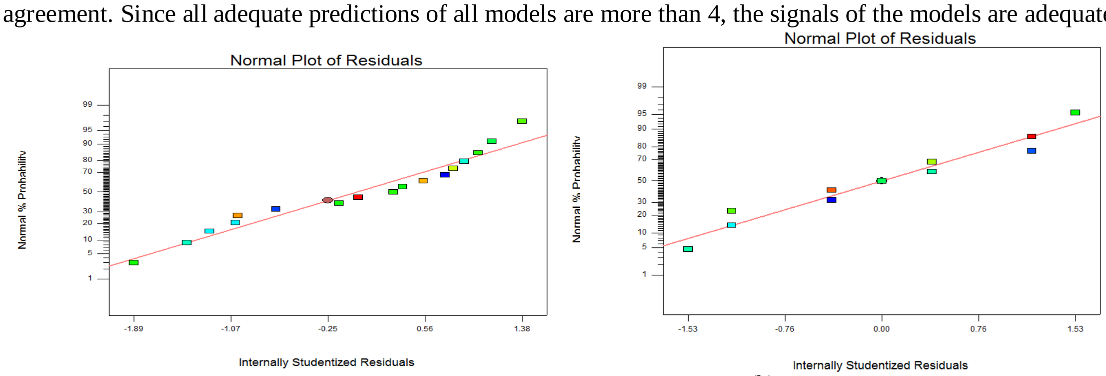
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.37	2	0.68	106.56	< 0.0001	significant
A-Pulse On	*0.24*	*1*	*0.24*	*38.11*	*0.0005*	
C-Current Pea	*1.12*	*1*	*1.12*	*175.00*	*< 0.0001*	
Curvature	0.012	1	0.012	1.91	0.2096	not significant
Residual	0.045	7	6.429E-003			
Lack of Fit	*0.025*	*5*	*5.000E-003*	*0.50*	*0.7700*	*not significant*
Pure Error	*0.020*	*2*	*1.000E-002*			
Cor Total	1.43	10				

Table 4 shows the ANOVA table for surface roughness. According to the Model, F-value of 106.56, it is revealed that the model is significant. The probability that noises causes “Model F-Value” to happen to be just 0.01%. If the values of “Prob > F” is smaller than 0.0500, it means that the model terms are significant. Thus, A and C are considered as significant model terms. If the values are bigger than 0.1000, it means that, the model terms are not significant. According to the "Curvature F-value" of 1.91 means that the curvature in the design space is not significant related to the noise. The probability that this "Curvature F-value" happens because of noise is 20.96%. The "Lack of Fit F-value" of 0.5 reveals that the Lack of Fit is not significant related to the pure error. The probability of this "Lack of Fit F-value” to happen because of noise is 77%.

Table 5: Summery of ANOVA analysis for quadratic Reduced Model

Response	R^2	Adj R^2	Pred R^2	Adeq Precision
MRR	0.9906	0.9830	0.9505	34.592
Surface Roughness	0.9682	0.9591	0.9236	22.751

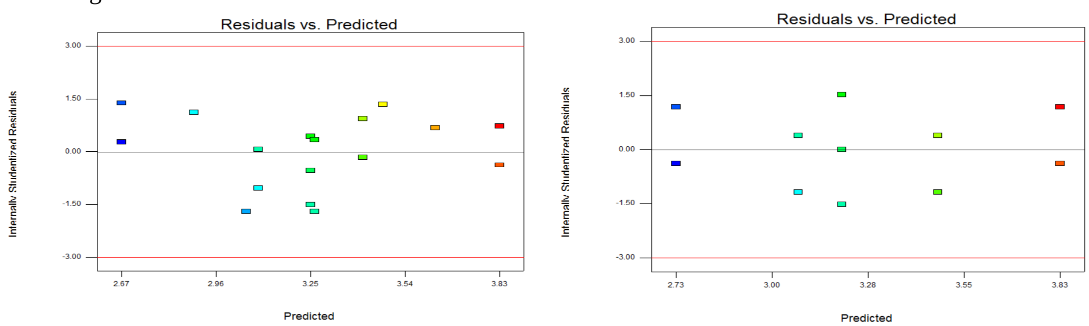
Since all of the R^2 values are high and close to one, as it shows in table 5, the results seem satisfactory. The difference between values of adjusted and predicted - R^2 that is smaller than 0.2, shows them to be in agreement. Since all adequate predictions of all models are more than 4, the signals of the models are adequate.



(a) (b)

Fig. 2: Normal Plot of Residuals (a) MRR, (b) SR

In figure 2, the normal plots of residuals for the quadratic models are shown. According to the normal probability plots, the distribution of the residuals along the normal probability line is normal indicating that the error distribution for all groups of data is almost normal. As a result, the models are sufficient. According to residual versus predicted plots in figure 3, all data presented are in the range, and no abnormal trends have observed. If the assumption is satisfied, the residual plot should be structureless. As the figure 3 shows, both residual figures seem to be structureless.



(a) (b)

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

The following equation for surface roughness obtained according to ANOVA in table 4 based on coded factors.

$$Ra = + 3.28 + 0.18\ A + 0.38\ C \quad (3)$$

According to table 3, ANOVA analysis reveals the significance of curvature test for MRR; therefore, the second order will be applicable and suitable for the above mentioned model.

Also, an RSM designed model – central composite design – was applied for acquiring the second-order models.

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 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	0.2708	2.9
13	1	0	0	0.316	3.6
14	0	-1	0	0.2956	3.1
15	0	1	0	0.2979	3.3
16	0	0	-1	0.2651	3
17	0	0	1	0.3293	3.7

Table7: ANOVA table for the material removal rate after RSM

Response 1 MRR

Transform: Power Lambda: 1 Constant: 0

ANOVA for Response Surface Reduced Cubic Model

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

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Block	1.893E-004	1	1.893E-004			
Model	0.014	13	1.086E-003	62.73	0.0158	significant
A-Pulse On	*1.022E-003*	*1*	*1.022E-003*	*59.01*	*0.0165*	
B-Pulse Off	*2.645E-006*	*1*	*2.645E-006*	*0.15*	*0.7336*	
C-Current Pea	*2.061E-003*	*1*	*2.061E-003*	*119.05*	*0.0083*	
AB	*1.624E-005*	*1*	*1.624E-005*	*0.94*	*0.4349*	
AC	*2.832E-004*	*1*	*2.832E-004*	*16.36*	*0.0560*	
BC	*9.245E-006*	*1*	*9.245E-006*	*0.53*	*0.5409*	
A^2	*1.197E-004*	*1*	*1.197E-004*	*6.92*	*0.1192*	
B^2	*3.068E-005*	*1*	*3.068E-005*	*1.77*	*0.3146*	
C^2	*2.316E-005*	*1*	*2.316E-005*	*1.34*	*0.3669*	
ABC	*4.050E-005*	*1*	*4.050E-005*	*2.34*	*0.2657*	
A^2B	*1.340E-004*	*1*	*1.340E-004*	*7.74*	*0.1086*	
A^2C	*5.153E-005*	*1*	*5.153E-005*	*2.98*	*0.2266*	
AB^2	*1.210E-007*	*1*	*1.210E-007*	*6.990E-003*	*0.9410*	
Pure Error	3.462E-005	2	1.731E-005			
Cor Total	0.014	16				

Table 7 indicates the 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 model had been modified as it is shown in the following table.

Table 8: Modified ANOVA table for the material removal rate after RSM

ANOVA for Response Surface Reduced Quadratic Model

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

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Block	1.893E-004	1	1.893E-004			
Model	0.014	5	2.758E-003	75.95	< 0.0001	significant
A-Pulse On	*5.208E-003*	*1*	*5.208E-003*	*143.42*	*< 0.0001*	
B-Pulse Off	*3.807E-004*	*1*	*3.807E-004*	*10.48*	*0.0089*	
C-Current Pea	*7.596E-003*	*1*	*7.596E-003*	*209.19*	*< 0.0001*	
AC	*2.832E-004*	*1*	*2.832E-004*	*7.80*	*0.0190*	
A²	*3.205E-004*	*1*	*3.205E-004*	*8.83*	*0.0140*	
Residual	3.631E-004	10	3.631E-005			
Lack of Fit	*3.285E-004*	*8*	*4.106E-005*	*2.37*	*0.3302*	*not significant*
Pure Error	*3.462E-005*	*2*	*1.731E-005*			
Cor Total	0.014	16				

In table 8, the Model F-value of 75.95 implies the model is significant. Values of "Prob > F" less than 0.0500 indicate, the model terms are significant. In this case A, B, A^2, C and AC are significant model terms. The obtained R-squared value equals 97.43% and the adj R-squared is 96.15%. Both of them are high and appropriate. R-squared and Adeq- Precision are expected to be 0.9268 and 29.25, respectively. The signal to noise ratio is practically determined by Adeq Precision. The appropriate ratio is higher than 4. Moreover, adj R-Squared and Pred R- Square are in agreement.

After Quadratic Equation led to the coded factors for Augment Central Composite Design, the equations below was obtained as the last experimental models.

$$MRR = + 0.30 + 0.023\ A - 6.170\ E\text{-}003\ B + 0.028\ C + 5.950\ E\text{-}003\ A\ C - 9.549\ E\text{-}003\ A^2 \quad (4)$$

4. DISCUSSION

4. 1. Material Removal Rate (MRR)

The examination of the results shows the data located in the optimum region, and the second- order model completely valid for MRR. While according to Box-Cox plot for MRR in figure 4, the data are approximately in the best possible and optimum region of the parabola.

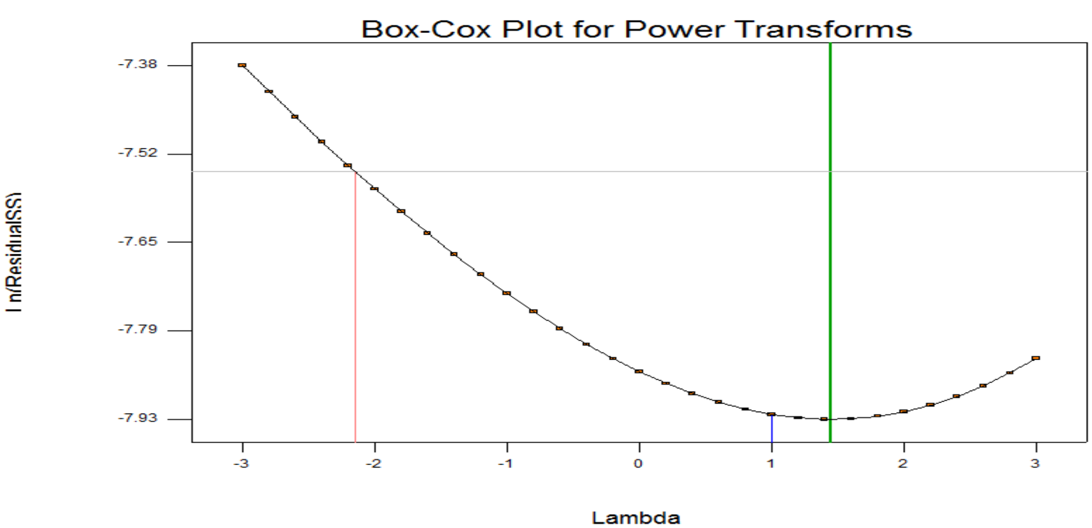


Fig. 4: Box-Cox plot for MRR data

Examining results through analysis shows the significant influence of peak current on MRR. By boosting peak current, the energy released through each discharge promotes further amount of material removal rate. Machining time may decrease in such a situation leading to raising the amount of productivity. This factor has the most level of contribution in MRR among other factors which is as big as 50.56%. In addition, one other major factor affecting MRR is considered as Pulse on time which will influence the time takes for every discharge and increase the material removal rate if the pulse on time rises. The effect of this factor in MRR is equals 37.89%. As figure 5 indicates, in order to obtain a bigger MRR peak current, as well as pulse on time, need to be adjusted high.

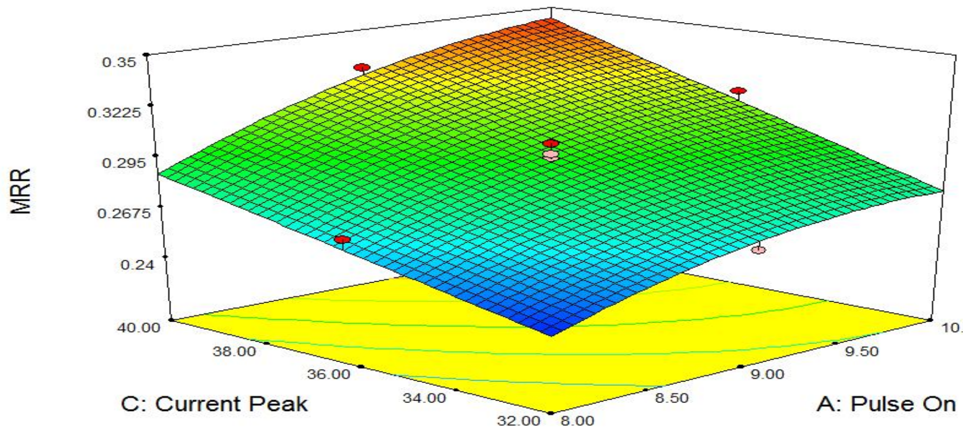


Fig. 5:3D surface graph for Material Removal Rate

The influence of pulse on time and pulse off time on MRR is revealed in figure 6 so that MRR interaction plot has a significant curvature. In order to obtain more MRR, it is necessary to adjust the pulse off time at a lower level and increase pulse on time. The outcome will match the results obtained by Sarkar et al., (2005) and Kuriakose and Shunmugam's (2005) [3, 13].

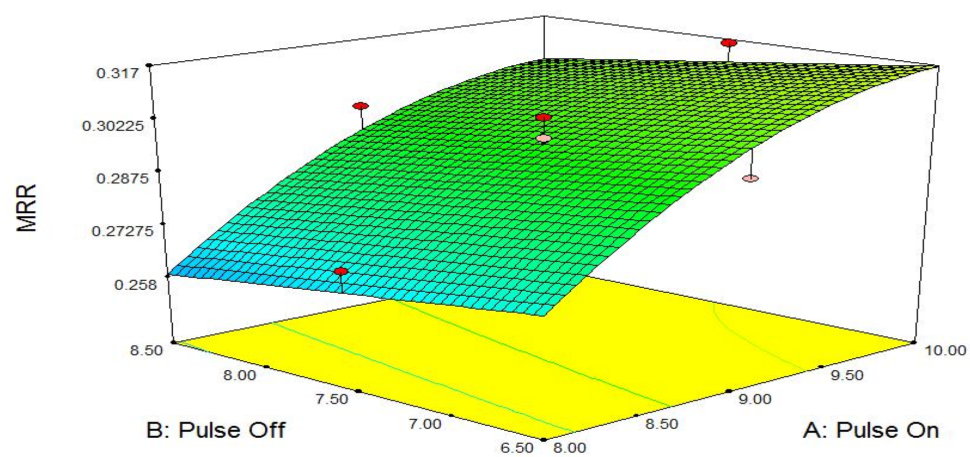


Fig. 6:3D surface graph for Material Removal Rate

4. 2. Surface Roughness (SR)

According to results obtained from ANOVA analysis, the most significant influential factor affecting surface roughness is peak current that precedes pulse on time. Again it is worth to repeat that the energy of every discharge is affected by pick current. The higher each discharging happens; the bigger and deeper crater is created by the released energy, and also rippled surface is larger and deeper, resulting in influence on the surface roughness. Less pick current is more desirable for achieving a better surface finish, because an enhanced machining performance is shown by lower roughness value. This factor can be observed to put in 78.82% in affecting surface roughness, as it is revealed in ANOVA model.

Pulse on time duration can be considered as another main factor that can control surface roughness. The contribution of this factor in the above mentioned model equals 17.17%. Moreover, when the pulse ON rises, Ra rises too because machining takes longer time to operate. As a result, “double sparking” and localized sparking will be more possible to happen. Poor surface finish will be the outcome of double sparking, because the single preliminary phase sparks to have a main role in material removal rate. Thus “lower is better”. The lower pulse on time is more favourable to surface roughness [14].

The outcome of surface roughness conforms what Kuriakose and Shunmugam’s (2004) obtained [1].
In both responses, the obtained results prove that as it was predicted, pulse On time and Peak current have effects on MRR as well as surface roughness and there is negative relation between these two factors. [15]

4. 3. Confirmation Tests

In order to determining the adequacy of the model and mathematical equation development, confirmation test is needed to be performed. The values for confirmation test that were expected through evaluation were recommended by the Design Expert software. Three tests were conducted for each model. The average of error for each model is revealed in each model. Table 9 shows the average of error for each model.

Table 9: Results of confirmation experiments

Model	MRR	Surface Roughness
Error	8.352%	7.433%

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, While, in the case of surface roughness; the only accomplishment is local optimization. In this study, material removal rate was the first priority of machining performance, and the result is suitable for rough cutting.

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	0.3487 mm^3/sec
Surface Roughness	8	7	32	2.696 μm
Multi-objectives	9.2	6.5	35	

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

5. Conclusion

- It was considered that the potential of WEDM procedure applying wire in machining of Ti-6A1-4V gets to 0.348 mm^3/ sec of MRR. It means this wire is comparable with coated wires.
- Peak current is considered as the most important factor in terms of both responses that is followed by pulse on time. In both responses, there is a tendency to rise due to peak current raising that has an effect on the energy released through each discharge. Moreover, time of every discharge is affected by pulse on time duration.
- It is possible to predict MRR at the optimum region of the procedure; whereas, it is just possible to obtain the surface roughness in local optimization (in the range of each element)
- Several optimal conditions can be gotten from the analysis, including the multi-objectives condition which can be set by Pulse on time: 9.2μs, pulse off time 6.5 μs, peak current: 35 A. The predicted result is MRR 0.296 mm^3/second surface roughness: 3.1575μm.
- Empirical equations to predict surface roughness and material removal rate are obtained and successfully verified in the confirmation tests.
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REFERENCES

[1] Kuriakose, S., Shunmugam, M.S., (2004) Characteristics of wire-electro discharge machined Ti6Al4V surface, *Materials Letters* 58: 2231– 2237.

[2] Datta, S., Mahapatra S. S., Modeling, (2010) ‘’simulation and parametric optimization of wire EDM process using response surface methodology coupled with grey-Taguchi technique’’ International Journal of Engineering, Science and Technology Vol. 2, No. 5, pp. 162-183.

[3] Kuriakose, S., Shunmugam, M.S., (2005), Multi-objective optimization of wire electro discharge machining process by Non-Dominated Sorting Genetic Algorithm, *Journal of Materials Processing Technology* 170: 133–141.

[4] Boyer, H.E., Gall T.L., (1985) Metals Handbook, American Society for Metals, Metals Park, Ohio, pp. 9.1–9.12.

[5] Donachie, Jr., Matthew J. (2000).’’ Titanium - A Technical Guide (2nd Edition)’’ (ASM International) pp 318-323.

[6] Rajurkar, K.P., Wang, W.M., (1993), “Thermal modeling and on-line monitoring of wire-EDM”, *Journal of Materials Processing Technology*, Vol. 38, No. 1-2 : 417-430.

[7] Tarng, Y.S., Ma, S.C. and Chung, L.K. (1995). Determination of optimal cutting parameters in wire electrical discharge machining.*International Journal of Machine Tools and Manufacture*, Vol. 35, No 129, pp.1693–170.

[8] Huang, J.T., Liao, Y.S. and Hsue, W.J., (1999). Determination of finish-cutting operation number and machining parameters setting in wire electrical discharge machining. *Journal of Materials Processing Technology*, Vol. 87, pp. 69–81.

[9] Rozenek, M., Kozak, J., DabroVwki, L. and LubkoVwki, K., (2001). Electrical discharge machining characteristics of metal matrix.composites. *Journal of Materials Processing Technology*, Vol. 109, pp. 367–370.

[10] Mahapatra, S.S., Amar Patnaik, (2007), Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method *International Journal of Advanced Manufacturing Technology*, Vol. 34, No.9-10 : 911-925.

[11] Singh, H., Garg, R.(2009) Effects of process parameters on material removal rate in WEDM , Journal of Achievements in Materials and Manufacturing Engineering V. 32 : 70-74.

[12] Montgomery, D.C., (2009), Design and Analysis of Experiments, 7th Edition, John Wiley & Sons (Asia) Pte Ltd : 207-264.

[13] Sarkar, S, S. Mitra, B. Bhattacharyya, (2005) Parametric analysis and optimization of wire electrical discharge machining of γ -titanium aluminide alloy, *Journal of Materials Processing Technology* 159: 286–294.

[14] Sarkar, S., Sekh, M., Mitra, S., Bhattacharyya, B., (2008) Modeling and optimization of wire electrical discharge machining of γ-TiAl in trim cutting operation, *Journal of Materials Processing Technology* 205; 376–387.

[15] Poro´s, D., Zaborski, S.,(2009) Semi-empirical model of efficiency of wire electrical discharge machining of hard-to-machine materials, *Journal of materials processing technology* 209: 1247–1253.