Optimizing Finishing process in WEDMing of Titanium Alloy (Ti6Al4V) by Zinc Coated Brass Wire based on Response Surface Methodology

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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 zinc coated brass wire of 0.25mm diameter was used as tool electrode to cut the specimen. Analysis of variance (ANOVA) technique was used to find out the parameters affecting the surface roughness (SR), material removal rate (MRR) and sparking gap (SG). Assumptions of ANOVA were discussed and carefully examined using analysis of residuals. This work has been established as a second-order mathematical model based on the response surface methodology (RSM).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.

1. Introduction

Wire EDM (Electric Discharge Machining) is a thermo-electrical process which that material is eroded by a series of sparks between the work piece and the wire electrode (tool). The part and wire are immersed in a dielectric (electrically non-conducting) fluid which also acts as a coolant and flushes away debris (Kuriakose & Shunmugam, 2004). The movement of wire is controlled numerically to achieve the desired three-dimensional shape and accuracy of the work piece (Mahapatra & Amar Patnaik, 2007).The most important performance factors in study of WEDM are material removal rate (MRR), surface roughness and sparking gap. Optimization the material removal rate will help to increase the production rate considerably by reducing the machining time (Kuriakose & Shunmugam, 2005).

Surface roughness is a machining characteristic that plays a very critical role in determining the quality of engineering components. The good quality of surface improves the fatigue strength, corrosion and wears resistance of the work piece (Lopez *et al*., 2012).Furthermore Kerf width and sparking gap investigate the same phenomena as it shown in Fig.1, and it is the measure of the amount of the material that is wasted during machining. It can determine the dimensional accuracy of the finishing part and the internal corner radius of the product in WEDM operations are also limited by this factor (Parashar *et al*., 2010).

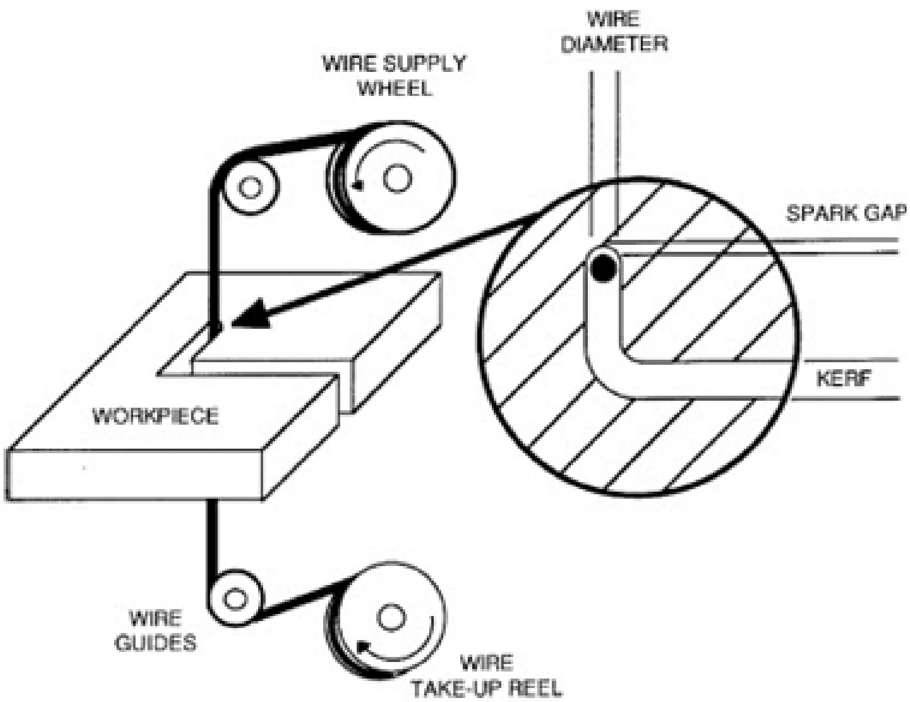
Ti- 6Al-4V has a resistivity on the order of five times larger than steel. Titanium alloys have relatively high melting temperature, low thermal conductivities and high electrical resistivity when compared to other common materials but electrical resistivity is highly dependent on the temperature. This material has been widely used in space, aerospace, military and commercial applications (Boyer & Gall, 1987; Donachie & Matthew, 2000).

Another objective of this paper is to emphasize the importance of assumption checking when using ANOVA. Assumptions of ANOVA were discussed and carefully examined using analysis of residuals. Lastly, a mathematical model was developed using multiple regression method to predict surface roughness and sparking gap of wire-EDMed Titanium alloy.

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

Rajurkar and Wang (1993) analyzed the wire rupture phenomena with a thermal model and experimental investigations. It was found that the material removal rate increases with decrease of pulse interval. Tarng *et al.* (1995) used a neural network system with a simulated annealing (SA) algorithm to clarify the relationships between the cutting parameters and cutting performance for cutting stainless steel. Huang *et al*. (1999) investigated the effect of machining parameters on the Kerf width, the surface roughness, and the recast layer thickness on the machined work piece surface experimentally. The brass wire have used as a tool electrode and the work piece was SKD11 alloy steel. Rozenek *et al*. (2001) 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 work piece.

Fig.1. *Details of Sparking Gap(Scott, 1991)*



Tosun (2004) investigated the effect of the cutting parameters on kerf and material removal rate in WEDM using analyse of variance (ANOVA).It was found that peak current and pulse duration have significant effect on surface roughness and kerf width.

Mahapatra and Patnaik (2007) attempted to optimize three main machining performances include MRR, Surface Roughness and cutting width. Taguchi method was used to design the experiments and Genetic 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 useful. The optimal result suggested by GA most of the times cannot be achieved in reality; due to absence of the optimal parameter combination in the machine. Taguchi method in compare with GA has more advantage. K. Kanlayasiri and S. Boonmung (2007) used the analysis of variance (ANOVA) to investigate the effects of different cutting parameters on cutting performance in machining of DC53 steel. Results from the analysis in this paper show that pulse-on time and pulse-peak current are significant variables to the surface roughness. Singh and Garg (2009) presented the effects of process parameters on material removal rate in WEDM, and it was found that, when pulse on time and peak current increase material removal rate also increase but with the increase of pulse off time and servo voltage, MRR decrease. Brass wire have used as a tool electrode and H-11 hot die steel was used as a work piece. 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.

Parashar *et al*., (2010) investigate the effects of WEDM parameters on kerf width using Brass wire. It was found that pulse on time and dielectric flushing pressure are the most significant factors that can affect the kerf width. Ghodsiyeh *et al*.,(2012) had stated their effort to optimize rough cut process using zinc coated brass wire as an electrode and titanium alloy (Ti6Al4V) as a work piece. It was found that peak current is the most significant factor that influences material removal rate and surface roughness followed by pulse on time. Other papers that work on this subject involve (Aspinwall & Berrisford, 2008; Çaydas & Hasçalık, 2009; Newman *et al.,* 2004; Hewidy *et al.,* 2005)

Although different mathematical techniques, like artificial neural network, gray relational analysis, simulated annealing, desirability function, Pareto optimality approach, etc. have already been applied for searching out the optimal parametric combinations of WEDM processes, The optimal result suggested by these methods most of the times cannot be achieved, in reality; due to the absence of the optimal parameter combination in the machine. In this aspect Taguchi method in compare with other methods has advantage.

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 Table1 (Montgomery, 2009).

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

Where i is the linear coefficient, j is the quadratic coefficient, and β is the regression coefficient, k is the number of studied and optimized factors in the experiment, and e is the random error. Analysis of variance (ANOVA) has taken into account in order to estimate the suitability of the regression model. To this end, the ratio of variance due to the effect of the model factors and variance resulted from the error terms, F-ratio, was calculated as an ANOVA procedure. F-ratio or variance ratio is employed to determine the significance of the model regarding variance of all the terms at an appropriate level of, α. The aim of RSM model is to obtain a significant model.

Table 1. *Wire EDM operation*

		Levels		
Coded factor	**Machining Parameters**	**-1**	**0**	**1**
A	Pulse ON Time (μs)	1	2	3
B	Pulse OFF Time (μs)	3	4	5
C	Peak Current (A)	4	5.6	7.2

Constant Parameters	Description
Machining Voltage	80
Servo Voltage (V)	40
Wire speed (m/min)	10
Wire tension (g)	600
Flushing pressure (bar)	55
Tool Polarity	Negative
Dielectric fluid	Deionised Water
Wire material	Zinc coated Brass

1.1 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 and analyzing the data.

The machining parameters and levels are shown in Table 1.

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. Therefore, the total number of experimental trials was 11. In each trial, a 10 mm length of cutting was made on 10mm thickness of the work pieces.

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

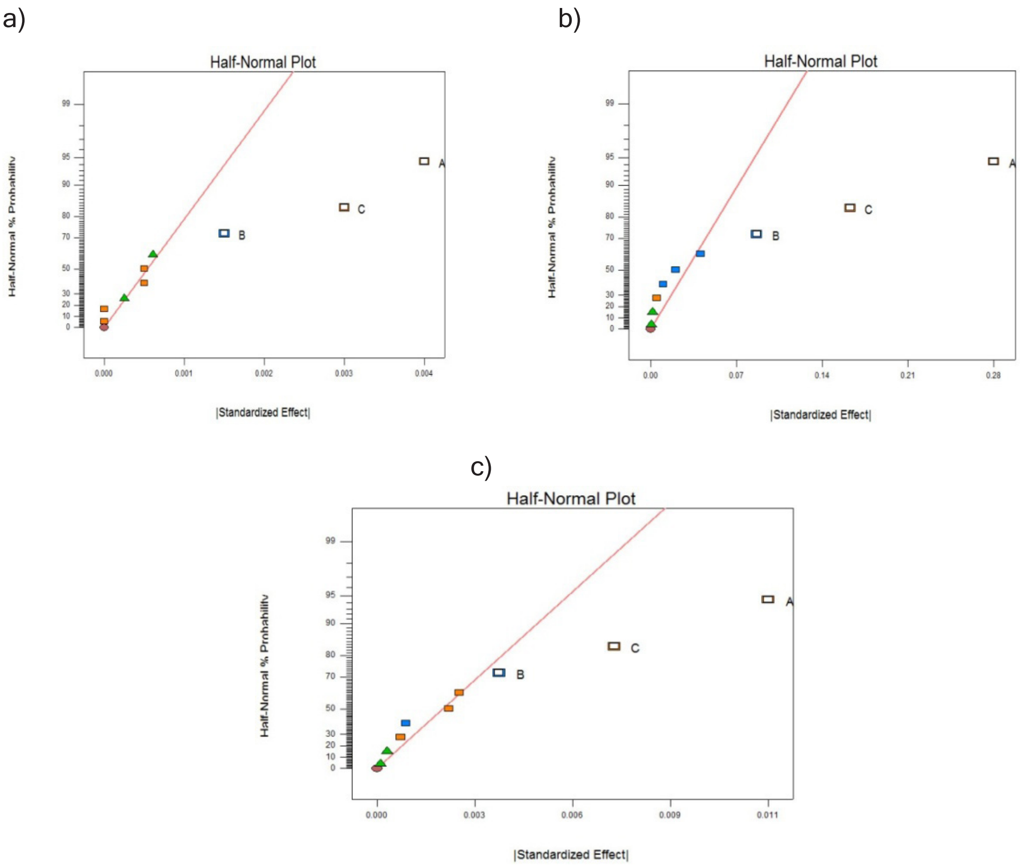
$$MRR= \frac{Wa-Wb}{Tm\ p}\ (mm^3/sec) \qquad (2)$$

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/)

The kerf width was measured using Mitutoyo Profile Projector PJ-3000 to calculate sparking gap. The following equation is used to determine the Sparking gap value:

Sparking gap (mm) = (average of kerf width-diameter of wire)/2 (3)

Fig.2. *Half normal of probability plot of main effects for (a) SG , (b) surface roughness and (c) material removal rate (pulse on=A, pulse off =B, peak current =C)*



Where average of kerf width was calculated based on mean value between measurement of kerf width at top and bottom sides. The arithmetic surface roughness value (Ra) was adopted and measurements were carried on the machined surface using a Mitutoyo-Formtracer CS 5000. The Ra values of the EDMed surface were obtained by averaging the surface roughness values of 5 mm measurement length.

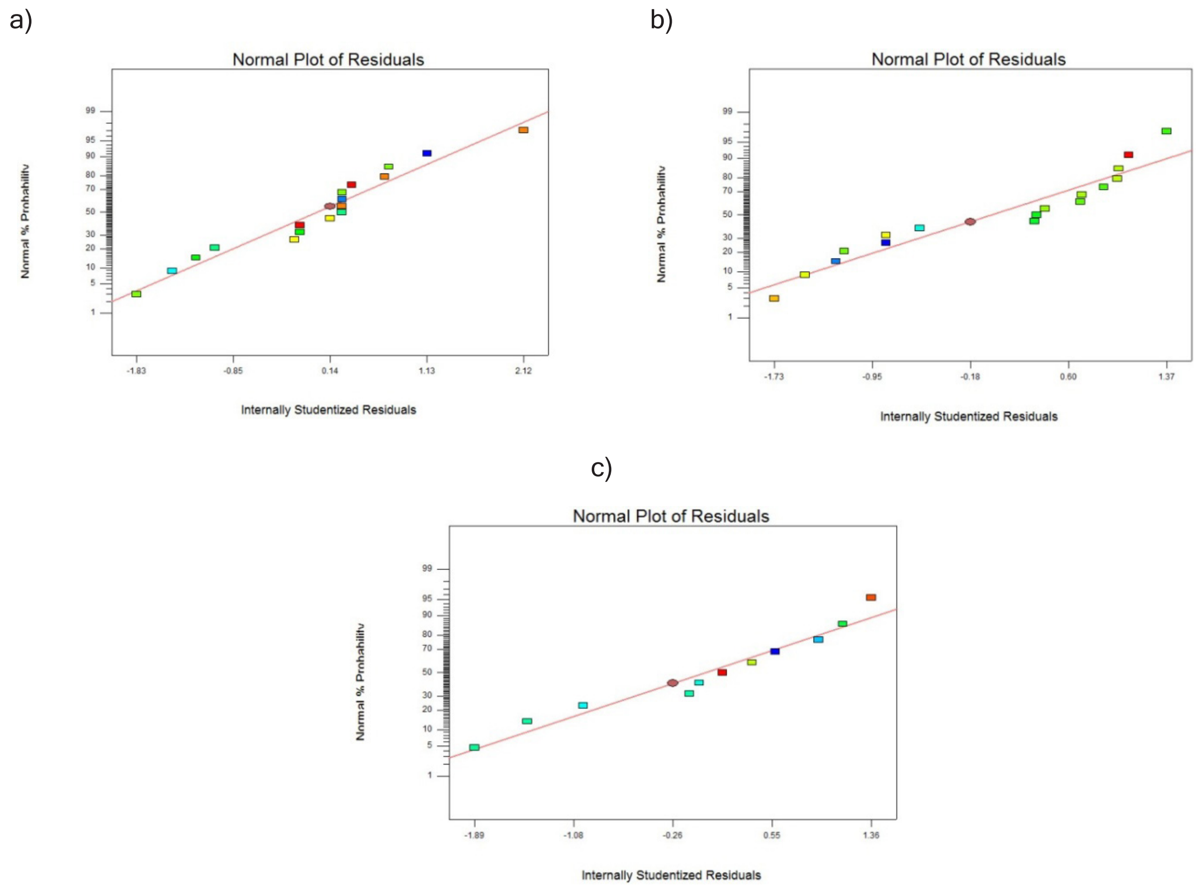
In this experiment, there were three controlled variables investigated including pulse-on time (ON), pulse-off time (OFF) and pulse-peak current (IP). Two levels of each factor were selected for the 2^k experiment as shown in Table 1. These machining conditions were chosen based on typical operating conditions of the machine recommended for finishing operation.

Center points experiment has two important roll. First, it allows the experimenter to obtain an estimate of the experimental error. Second, if the sample mean is used to estimate the effect of a factor in the experiment then center points permits the experimenter to obtain a more precise estimate of the effects. In these experiments, the order of the experiment has performed randomly because ANOVA requires that the observations or errors be independently distributed random variables. Randomization usually makes this assumption valid. By properly randomizing the experiment, the effects of extraneous factors or confounding variables that may be present are averaged out. Confidence level of 95% (α = 0.05) was used throughout analyses of the experiment and Fisher's F-test verified the statistical significance of the model.

Although analysis of variance has been widely used in metal machining research, assumptions of this analytical technique are not much mentioned. In applying ANOVA technique, certain assumptions must be checked through analysis of residuals before interpreting and concluding the results. Only interpreting the results from *p*-values of the ANOVA table without carefully checking its assumptions is very uncertain and unreliable, and it is easy to obtain misleading results. A typical check for normality assumption could be made by constructing a normal probability plot of the residuals. Each residual is plotted against its expected value under normality. If the residual distribution is normal, this plot will be a straight line. In visualizing the plot, the central values of the plot should be more emphasized than on the extremes.

Plotting the residuals in time order of data collection is helpful in checking independence assumption on the residuals. The residual plot should be structureless; that is, they should contain no obvious patterns. This technique is the traditional checking technique for independence assumption. However, it is quite subjective to determine the pattern of the plot. The assumption of constant variance is typically checked by plotting residuals versus predicted values. If the assumption is satisfied, the residual plot should be structureless.

Fig.3. *Normal Plot of Residuals (a) SG, (b) SR and (c) MRR*



2. Result and analysis

This part consists of full factorial design that shows the results obtained by the test (Table 2). A normal probability plot of the effect of parameters on (a) SG, (b) SR and (c) MRR are shown in Fig.2. 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 drown 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 Fig.1, the main effects consist of pulse on (A), peak current (C), and pulse off time (B) for all responses.

Table 3 presents the ANOVA table for sparking gap. The significance of the model is revealed according to the Model

F-value of 36.33. There is only a probability of 0.03% 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 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 22.09 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 SG; that means, in order to get second order model for this treatment augment experiments must be applied. The "Lack of Fit F-value" of 0.25 reveals that lack of Fit, related to the pure error, is not significant. Because we want to make this fit to the model, it is good to have an insignificant lack of fit.

Table 2. *Design of experiments matrix and results*

Std Order	Pulse ON Time (μs)	Pulse Off Time (μs)	Peak Current (A)	Sparking Gap (mm)	Surface roughness (Ra) (μm)	Material Removal Rate(MRR) (mm3/s)
1	-1	-1	-1	0.008	1.45	0.0247
2	1	-1	-1	0.012	1.71	0.0352
3	-1	1	-1	0.007	1.38	0.0206
4	1	1	-1	0.01	1.69	0.02805
5	-1	-1	1	0.011	1.64	0.0278
6	1	-1	1	0.015	1.92	0.0417
7	-1	1	1	0.009	1.53	0.0265
8	1	1	1	0.014	1.78	0.0401
9	0	0	0	0.012	1.73	0.0276
10	0	0	0	0.014	1.75	0.026
11	0	0	0	0.013	1.74	0.0299

Table 3. ANOVA for the sparking gap

Source	Sum of square	df	Mean square	F value	Prob>F	
Model	5.450E-005	3	1.817E-005	36.33	0.0003	Significant
A	3.200E-005	1	3.200E-005	64.00	0.0002	
B	4.500E-006	1	4.500E-006	9.00	0.0240	
C	1.800E-005	1	1.800E-005	36.00	0.0010	
Curvature	1.105E-005	1	1.105E-005	22.09	0.0033	Significant
Residual Lack of Fit	3.000E-006 1.000E-006	6 4	5.000E-007 2.500E-007	0.25	0.8889	not significant
Pure Error	2.000E-006	2	1.000E-006			
Cor. total	6.855E-005	10				

Table 4 shows the ANOVA table for surface roughness. According to the Model, F-value of 97.48, 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, B 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 30.91 means that the curvature in the design space is significant. Then for SR also the second order model can be achieved by applying augment experiments. The "Lack of Fit F-value" of 10.62 reveals that the Lack of Fit is not significant related to the pure error.

Table 5 shows the ANOVA table for material removal rate. According to this table the model is significant. Like other response A, C and B are significant parameters that affects material removal rate. The equation for material removal rate from the results in ANOVA in Table 5 derived in terms of coded factors as follows.

MRR =+0.031+0.005.681 * A –0.001.769 * B+0.003.444 * C (4)

According to Table 3 and 4, ANOVA analysis reveals the significance of curvature test for SG and SR; 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. ($n_a = 2^k = 6$) . For the new experiments, new block have designed because the new experiments have done with different condition like different operator and different day.

Table 4. *ANOVA table for the Surface Roughness*

Source	Sum of square	df	Mean square	F value	Prob>F	
Model	0.22	3	0.072	97.48	< 0.0001	Significant
A	0.15	1	0.15	203.93	< 0.0001	
B	0.014	1	0.014	19.48	0.0045	
C	0.051	1	0.051	69.03	0.0002	
Curvature	0.023	1	0.023	30.91	0.0014	Significant
Residual Lack of Fit	4.450E-003 4.250E-003	6 4	7.417E-004 1.062E-003	10.62	0.0879	not significant
Pure Error	2.000E-004	2	1.000E-004			
Cor. total	0.24	10				

Table 5. *ANOVA table for the Material removal rate*

Source	Sum of square	df	Mean square	F value	Prob>F	
Model	3.781E-004	3	1.260E-004	25.08	0.0009	Significant
A	2.582E-004	1	2.582E-004	51.38	0.0004	
B	2.503E-005	1	2.503E-005	4.98	0.0671	
C	9.488E-005	1	9.488E-005	18.88	0.0048	
Curvature	1.648E-005	1	1.648E-005	3.28	0.1202	not significant
Residual Lack of Fit	3.015E-005 2.246E-005	6 4	5.025E-006 5.616E-006	1.46	0.4449	not significant
Pure Error	7.687E-006	2	3.843E-006			
Cor. total	4.247E-004	10				

Table 6. *Experimental Results Augment CCD*

Std Order	Pulse ON Time (µs)	Pulse OFF Time (µs)	Peak Current (A)	SG mm	Surface roughness (Ra) (µm)
12	-1	0	0	0.01	1.63
13	1	0	0	0.014	1.82
14	0	-1	0	0.013	1.75
15	0	1	0	0.012	1.68
16	0	0	-1	0.011	1.7
17	0	0	1	0.015	1.77

Fig.4. *Residual versus predicted plots (a) SG, (b) SR and (c) MRR*

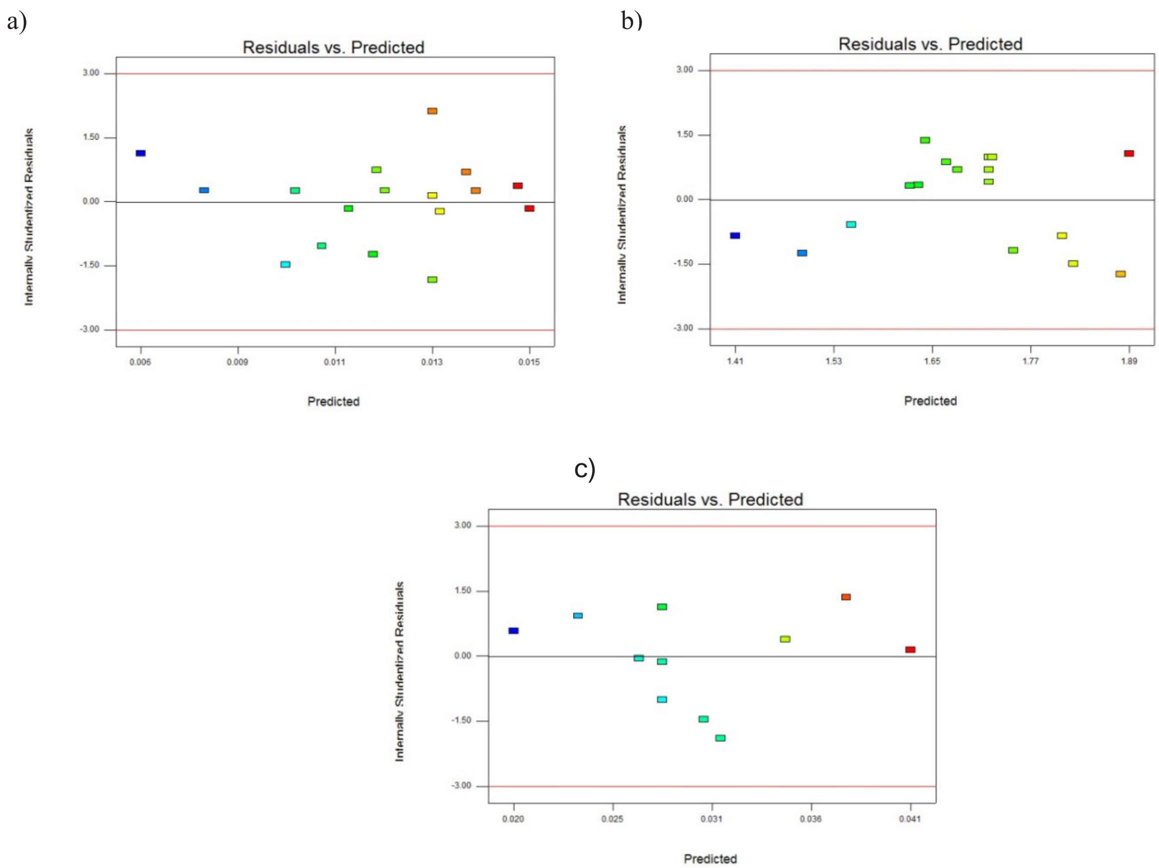


Fig.5. *Box-Cox plot for Sparking Gap data*

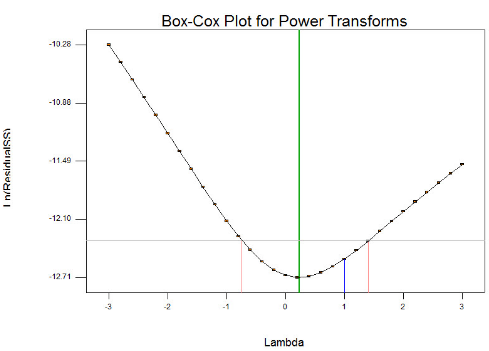


Fig.6. *3D surface graph for Sparking Gap*

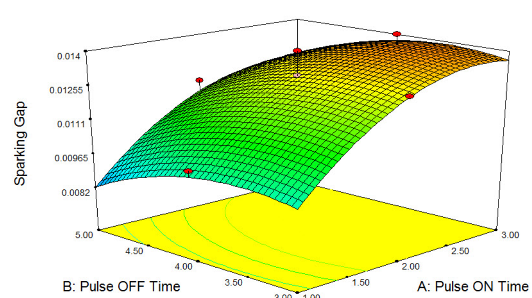


Fig.7. *3D surface graph for Sparking Gap*

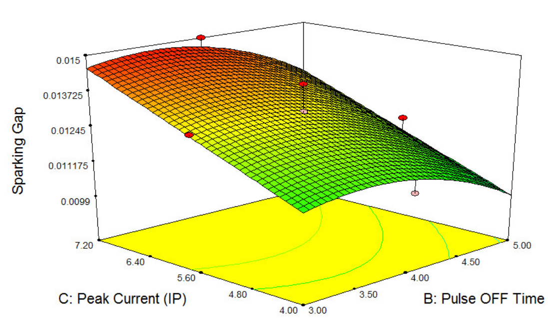


Fig.8. *Box-Cox plot for SR data*

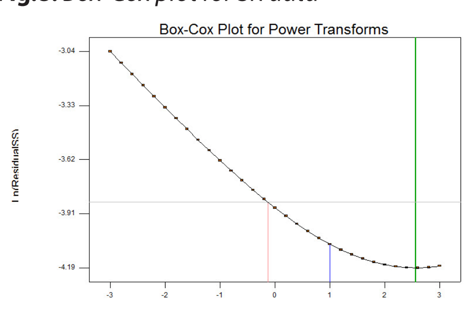


Table 7. *Modified ANOVA table for the Surface roughness after RSM*

Source	Sum of square	df	Mean square	F value	Prob>F	
Block Model	0.014 0.25	1 4	0.014 0.063	40.27	< 0.0001	Significant
A	0.17	1	0.17	107.01	< 0.0001	
B	0.017	1	0.017	10.81	0.0072	
C	0.050	1	0.050	32.42	0.0001	
B2	0.017	1	0.017	10.86	0.0071	
Residual Lack of Fit	0.017 0.017	11 9	1.555E-003 1.878E-003	18.78	0.0515	not signifi-cant
Pure Error	2.000E-004	2	1.000E-004			
Cor. total	0.28	16				

Table 8. *Summery of ANOVA analysis for quadratic Reduced Model*

Response	R2	Adj R2	Pred R2	Adeq Precision
Sparking Gap	0.9574	0.9362	0.8970	22.145
Surface Roughness	0.9361	0.9128	0.8456	20.574
Material Removal Rate	0.9262	0.8892	0.7477	14.416

Table 9. *Model summary statistics for Sparking Gap*

Source	R2	Adj. R2	Pred. R2	
Linear	0.8193	0.7742	0.6998	
2FI	0.8251	0.7086	0.0625	
Quadratic	0.9651	0.9128	0.7443	Suggested

Table 10. *Model summary statistics for Surface Roughness*

Source	R2	Adj. R2	Pred. R2	
Linear	0.8193	0.7742	0.6998	
2FI	0.8251	0.7086	0.0625	
Quadratic	0.9651	0.9128	0.7443	Suggested

Fig.9. *3D surface graph for Surface Roughness*

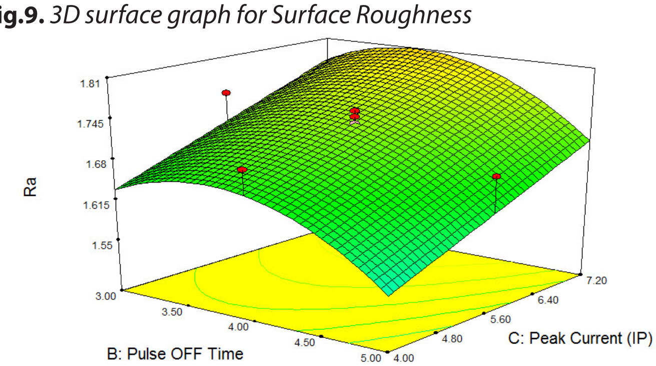


Table 11. *Results of confirmation experiments*

Model	Sparking Gap	Surface Roughness	Material Removal Rate
Error	4.379%	3.737%	2.675%

Table 12. *Contraints for optimization of pretreatment parameters*

Name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
Pulse ON Time (µs)	In range	1	3	1	1	3
Pulse off Time (µs)	In range	3	5	1	1	3
Peak Current (A)	In range	4	7.2	1	1	3
Surface Roughness	minimum	1.38	1.92	1	1	3
Sparking Gap	minimum	0.007	0.015	1	1	3
Material Removal Rate	maximum	0.0206	0.0417	1	1	3

Table 13. *The optimal condition for each parameter*

Condition	Pulse ON Time (µs)	Pulse off Time (µs)	Peak Current (A)	Optimum response	Desirabil-ity
Sparking Gap	1.1	4.75	4.25	0.00688 mm	1
Surface Roughness	1	5	4	1.42 µm	0.923
Material Removal Rate	3	3	7.2	0.0406	0.948
Multi-objectives	1	3	4		0.761

`Table 7 indicates the ANOVA table after adding central composite design experiments. In this table, the Model F-value of 44.99 implies the model is significant. Values of "Prob > F" less than 0.0500 indicate, the model terms are significant. In this case A, B, C, $A^2$and B^2 are significant model terms. It is likely to have an improved model by omitting those insignificant model terms. In order to test the significance of individual model coefficients, the model can be optimized by adding or deleting coefficients through backward elimination, forward addition or stepwise elimination/addition/exchange. Table 6, shows the ANOVA table resulted from reduced quadratic model for sparking gap by implementing the backward elimination procedure with 0.05 alpha out to automatically reduced insignificant terms.

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

$$\text{Sparking Gap} = +0.013 +0.002 * A -0.0007 * B +0.0016 * C - 0.001325 * A^2 - 0.0008.253 * B^2 \qquad (5)$$

In Table 7, the Model F-value of 40.27 implies the model is significant. Values of "Prob > F" less than 0.0500 indicate, the model terms are significant. In this case A, B, C and B^2 are significant model terms. In this model also backward elimination procedure with 0.05 alpha out has used to improve model by omitting insignificant factors.

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

$Ra = +1.73 + 0.13 * A - 0.041 * B + 0.071 * C - 0.069 * B^2$ (6)

For both models the block effects are not significant, it means that the mentioned different condition can't affect the results. Since all of the R^2 values are high and close to one, as it shows in Table 8, the results seem satisfactory. The difference between values of adjusted and predicted - 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. The S/N ratio, which is presented as adequate precisions, are 22.145 , 20.574 and 14.416 which indicates that models are desirable to navigate design space.

Fig. 3 indicates 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 4 shows residual versus predicted plots in which all data is shown to be in the range, and no abnormal trend exists. As it mentioned before if the assumption is satisfied, the residual plot should be structureless. As the Fig. 3 shows, all residual figures seem to be structureless. These figures show the residuals after applying RSM.

3. Dissection

3.1 Sparking Gap (SG)

The examination of the results shows the data located in the optimum region, and the second- order model completely valid for SG. While according to Box-Cox plot for SG in figure 5, the data are approximately in the best possible and optimum region of the parabola.

Analyzing the results reveals that pulse on time significantly affects SG. Increasing the pulse on time will affect the time of each discharge and raise the sparking gap. This factor contributed 46.68 % in SG, which is the highest contribution. Moreover, peak current is another main factor that influenced on SG. The energy of each discharge will be raised with the increase of peak current, and more quantity of material is removed. This factor contributed 26.26% in SG. Furthermore pulse off time is another factor that found to be significant. This factor represent the time between each discharge. This factor contributed 6.56% in SG. . According to figure 6 curvatures is significant in the SG interaction plot. Lower setting for pulse on time and higher setting for pulse off time were required to achieve lower SG.

The influence of peak current and pulse off time on SG is revealed in Figure 7 so that in order to obtain better SG, it is necessary to adjust the pulse off time at a higher level and decrease peak current. The outcome will match the results obtained by Tosun et al., (2004) and Kanlayasiri and Boonmung's, (2007) results.

The model summary statistics for sparking gap is given in Table 9. Table 9 reveals that the best recommended models are quadratic and linear model.

Surface Roughness (SR)

The examination of the results shows the second- order model is valid for surface roughness and the data located in the optimum region. While according to Box-Cox plot for SR in figure 8, the data are more or less in the optimum region of the parabola.

Analyzing the results reveals that SR considerably affects by pulse on time. By increasing pulse on time, "double sparking" and localized sparking will be more possible to happen. Poor surface finish will be the outcome of double sparking. This factor contributed 61.92% in SR, which is the highest contribution. Moreover, peak current is another main factor that influenced on SR. 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. This factor contributed 20.96 % in SR. According to Figure 9 curvatures is significant in the SR interaction plot. The lower peak current and higher pulse off time are more favourable for surface. The outcome of surface roughness conforms what Sarkar *et al*., 2008, Kanlayasiri (2007) and Kuriakose (2004) obtained. The model summary statistics for surface roughness is given in Table 10. Table 10 reveals that the best recommended model is quadratic model.

Material Removal Rate

Analyzing the results for this factor reveals that Pulse on time significantly affects MRR. Increasing the pulse on time will affect the time of each discharge and raise the material removal rate. This factor contributed 60.79% in MRR, which is the highest contribution. .Moreover; peak current is another main factor that influenced on MRR. The energy of each discharge will be raised with the increase of peak current, and more quantity of material is removed. This factor contributed 22.34% in MRR. Also pulse off time contributes 5.89% in MRR which is quite low contribution. In this study the curvature for material removal rate was not significant. Thus the

RSM method hasn't applied for MRR. These results are in agreement with Sarkar et al., (2005) and Kuriakose and Shunmugam's (2005) results.

Confirmation Tests

In order to verify the adequacy of the model and mathematical equation development, confirmation test is required to be 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.

Table 12 shows the summary of constraints used during optimization process. Finally, in Table 13, the best combination of parameters can be accessed for each optimal condition. In this table, the results for both responses are in the optimum region. In this study, the same importance has chosen for all responses, thus multi objective condition can simultaneously satisfies all of the requirements. In this table, the result for surface roughness and sparking gap are in the optimum region, but for material removal rate just the local optimization can be achieved. The results of this study are suitable for finishing operation.

4. Conclusion

In this research the effect of machining parameters including pulse on time, pulse off time and peak current on surface roughness, sparking gap and material removal rate of titanium (Ti- 6Al-4V) was studied. Statistical optimization model (a central composite design couple with response surface methodology) overcomes the limitation of classical methods and was successfully employed to obtain the optimum process conditions while the interactions between process variables were demonstrated.

It was considered that the potential of WEDM procedure applying zinc coated brass wire in machining of Ti-6A1-4V gets to 1.38 µm of surface roughness and 0.007 mm of sparking gap. Pulse on time is considered as the most important factor for sparking gap and peak current have the same roll for surface roughness. 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 Sparking gap, surface roughness at the optimum region of the procedure. Several optimal conditions can be gotten from the analysis, including the multi-objectives condition which can be set by Pulse on time: 1µs, pulse off time 3 µs, peak current: 4 A. The predicted result is sparking gap 0.00788 mm, surface roughness: 1.52 µm and material removal rate 0.025 mm^3/s. Empirical equations to predict surface roughness, sparking gap and material removal rate are obtained and successfully verified in the confirmation tests.

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