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**Research Article**

# Optimizing Finishing Process in Wedming of Titanium Alloy (Ti6Al4V) by Brass Wire based on Response Surface Methodology

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**Abstract:** Verifying the optimal cutting parameters in order to achieve high performance in various kinds of machinery has always been a critical matter. This research aims to investigate the behavior of three control parameters according to Design of Experiment (DOE) method while WEDM of titanium alloy (Ti6Al4V) is being examined. The sample was cut by an electrode instrument made of brass wire of 0.25 mm diameter. 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 study 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 outcomes are particularly useful for scientists and engineers to determine which subset of the process variable can optimize the performance.

**Keywords:** ANOVA, finishing process, hard brass wire, taguchi method, WEDM machining

## INTRODUCTION

WEDM (Wire Electric Discharge Machining) is the process of continuous travelling vertical-wire electrode. This process is a thermo-electrical process which material is eroded by a series of sparks between the work piece and the wire electrode (tool) immersed in dielectric fluid (Kuriakose and Shunmugam, 2004).

Dielectric fluid is an electrically nonconducting fluid which also acts as a coolant and flushes away debris. The movement of wire is controlled numerically to achieve the desired three-dimensional shape and accuracy of the work piece (Mahapatra and Amar, 2007). The most important elements of performance in the investigation about WEDM can be considered as Material Removal Rate (MRR), surface finish and sparking gap (Kuriakose and Shunmugam, 2005). Surface roughness is a machining characteristic that plays a very critical role in determining the quality of engineering components. The high quality of surface improves the fatigue strength, corrosion and wears resistance of the work piece (Lopez *et al*., 2012). Kerf width and sparking gap had investigated a similar phenomenon (Fig. 1). They are the measure methods for the amount of material waste while machine operation. They can be utilizing to determine the dimensional accuracy of the finishing part. In addition this element can show the limit for internal corner radius of the product of WEDM process (Parashar *et al*., 2010).

Ti-6A1-4V belongs to the group of alpha-beta titanium alloys. Compared to steel Ti-6A1-4V is five times more resistant. 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. 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. This material has been widely used in space, aerospace, military and commercial applications (Boyer and Gall, 1985; Donachie, 2000).

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.

Another objective of this study is to focus on the importance of assumption checking when using ANOVA. Assumptions of ANOVA were discussed and carefully examined using analysis of residuals. Lastly, a

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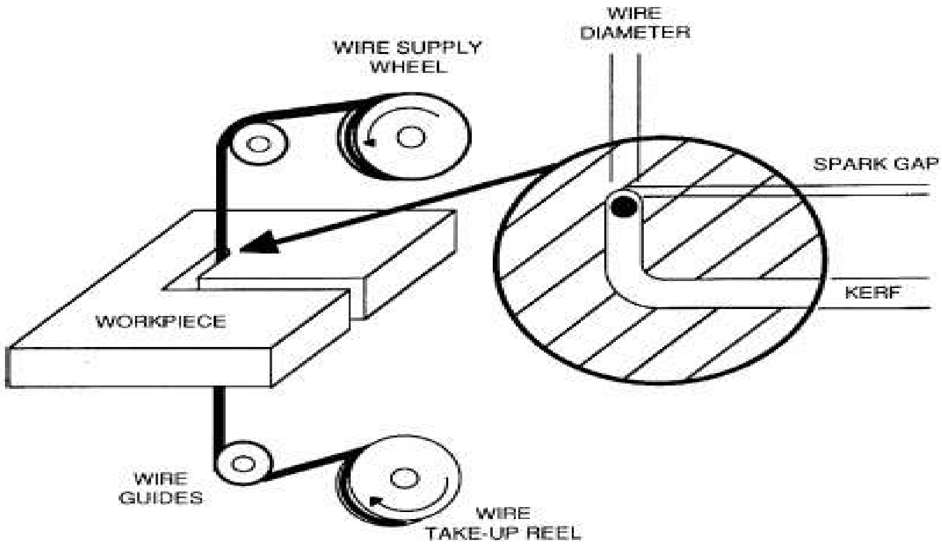


Fig. 1: Details of sparking gap (Scott *et al*., 1991)

mathematical model was developed using multiple regression method to predict surface roughness and sparking gap of wire-EDMed Titanium alloy.

Several methods have been employed to optimize the behavior of WEDM by some researchers.

As stated by Rajurkar and Zaborski (1993) considering the analysis of wire rupture phenomena using thermal model and experimental investigations: it was revealed that the removal rate of material is inversely proportional to the pulse interval. Besides, for cutting stainless steel (Tarng *et al*., 1995) also used a neural network system together with a Simulated Annealing (SA) algorithm to elucidate the relationships between the cutting parameters and cutting performance. Huang *et al*. (1999) studied on the influence of machining parameters on the Kerf width, the surface roughness and the recast layer thickness on the machined work piece surface. The brass wire has been utilized as a tool electrode and the work piece was SKD11 alloy steel. It was found that pulse-on time have a significant effect on cutting performance. Other than that, Rozenek *et al*. (2001) also studied on the effectiveness of machining parameters including discharge current, pulse-on time, pulse-off time and feed rate and surface roughness. In this case, they used brass as electrode wire and metal matrix composite as work piece. 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 shown for automation.

In an investigation on the influence of the cutting parameters on kerf and material removal rate in WEDM, Tosun *et al*. (2004) utilized the Analysis of Variance (ANOVA).The result shows that peak current and pulse duration have noteworthy influence on surface roughness and kerf width. Kuriakose and Shunmugam (2005) 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 current were considered as three significant factors affecting the machining performance while machining Ti6Al4V.

Mahapatra and Amar (2007) had stated their effort to optimize three major machining performances consisting of MRR, Surface Roughness and cutting width. In their study, Taguchi method was utilized for the designing experiments and Genetic Algorithm (GA) was used to optimize several machining parameters in order to attain desired quality of the machined product. Then, it was found that; GA method for WEDM might not be appropriate and helpful. The optimal outcome proposed by GA is not obtainable in reality; the majority of the times because of lack of the optimal parameter combination in the machine. Then, in the same year, Kanlayasiri and Boonmung (2007) employed the Analysis of Variance (ANOVA) to explore the influence of different cutting parameters on cutting performance in machining of DC53 steel. The outcomes of the analysis in this study reveal that pulse-on time and pulse-peak current are important 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 pressures 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 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 influence material removal rate and surface roughness. Other studies that work on this subject involve (Aspinwall *et al*., 2008; Çaydas *et al*., 2009; Newman *et al*., 2004; Hewidy *et al*., 2005)

Even though 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.

The purpose of the RSM is to creating the optimum situation for the system's function or verifying the region of the factor space, in which the needs for operation are fulfilled. 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:

$$Y_U = b_0 + \sum_{i=1}^{K} b_i X_i + \sum_{i=1}^{K} b_{ii} X_i^2 + \sum_{j>i}^{K} b_{ij} X_i X_j + \ldots + e \tag{1}$$

where,

*i* : The linear coefficient
*j* : The quadratic coefficient
*β* : The regression coefficient
*k* : The number of studied and optimized factors in the experiment
*e* : 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, $\alpha$. The aim of RSM model is to obtain a significant model (Montgomery, 2009).

In this study, experimental procedure and analysis of experiments have been considered. Moreover, the discussions are presented for all of our responses, material removal rate, surface roughness and sparking gap. The regression have found and successfully confirmed by residual analysis and confirmation runs.

## 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 10 mm thickness of the work pieces.

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

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

where,

$W_b$ & $W_a$ : Weights of work piece material before and after machining (g)
Tm : Machining time (sec)
p : The density of Ti6Al4V (0.00442 g/$mm^3$)

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:

$$\text{Sparking gap (mm)} = (\text{average of kerf width-diameter of wire})/2 \tag{3}$$

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

Table 1: Wire EDM operation

| Coded factor | Machining parameters | Levels -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) | | 60 | | |
| Wire speed (m/min) | | 10 | | |
| Wire tension (g) | | 600 | | |
| Flushing pressure (bar) | | 50 | | |
| Tool polarity | | Negative | | |
| Dielectric fluid | | Deionised water | | |
| Wire material | | Hard brass | | |

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 ($mm^3/s$) |
|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | 0.0065 | 1.13 | 0.0129 |
| 2 | 1 | -1 | -1 | 0.0090 | 1.58 | 0.0154 |
| 3 | -1 | 1 | -1 | 0.0040 | 0.98 | 0.0116 |
| 4 | 1 | 1 | -1 | 0.0070 | 1.51 | 0.0137 |
| 5 | -1 | -1 | 1 | 0.0080 | 1.63 | 0.0154 |
| 6 | 1 | -1 | 1 | 0.0140 | 1.88 | 0.0231 |
| 7 | -1 | 1 | 1 | 0.0060 | 1.61 | 0.0149 |
| 8 | 1 | 1 | 1 | 0.0110 | 1.83 | 0.0195 |
| 9 | 0 | 0 | 0 | 0.0070 | 1.65 | 0.0182 |
| 10 | 0 | 0 | 0 | 0.0070 | 1.69 | 0.0175 |
| 11 | 0 | 0 | 0 | 0.0080 | 1.67 | 0.0184 |

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.

The main rolls of the center points include, 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.

Via properly randomizing the experiment, the effects of irrelevant factors or confounding variables that may be present are eliminated. Confidence level of 95% ($\alpha$ = 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.

## RESULTS AND ANALYSIS

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

A normal probability plot of the effect of parameters on (a) SG, (b) MRR and (c) SR is shown in Fig. 2. The technique used to find out the true influence that the factors have on response machining

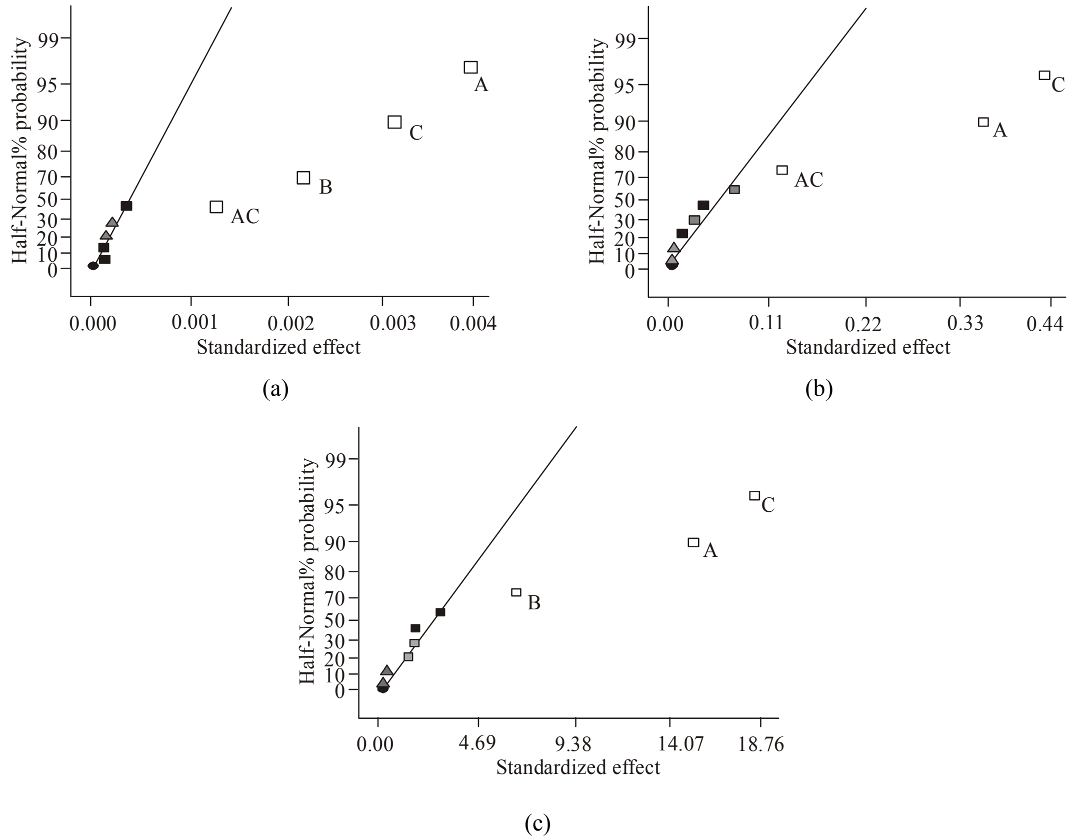


Fig. 2: Half normal of probability plot of main effects for (a) SG, (b) surface roughness, (c) material removal rate (pulse on = A, pulse off = B, peak current = C)

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 peak Current (C), pulse on (A) and pulse on time peak current interaction (AC) for SR. In the case of SG, the main parameters consist of pulse on (A), peak Current (C) and pulse off (B) and pulse on time peak current interaction (AC). Also for MRR peak Current (C), pulse on time (A) and pulse off time (B) became significant factors.

Table 3 presents the ANOVA table for sparking gap. The significance of the model is shown according to the Model F-value of 84.9. There is only a probability of 0.01% that noise causes this “Model F-Value” to take place. 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 7.88 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 0.34 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 4 reveals that the ANOVA table for surface roughness. According to the Model, F-value of 85.03, it is revealed that the model is significant. The probability that noises causes “Model F-Value” to take place 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 18.78 means that the curvature in the design space is significant. Then for SR also the second order model can be obtained by using augment experiments. The "Lack of Fit F-value" of 0.5 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. Furthermore C, A and B are significant parameters that affects material removal rate. The curvature for this response also became significant but with the respect to the range of the parameters this factor should be in the minimum region of the parabola that is not desirable for MRR. Although the RSM have

Table 3: ANOVA table for the sparking gap

| Source | S.S. | df | Mean square | F value | Prob>F | |
|---|---|---|---|---|---|---|
| Model | 6.862E-005 | 3 | 1.716E-005 | 84.900 | <0.0001 | Significant |
| A | 3.403E-005 | 1 | 3.403E-005 | 168.40 | <0.0001 | |
| B | 1.128E-005 | 1 | 1.128E-005 | 55.820 | 0.0007 | |
| C | 1.953E-005 | 1 | 1.953E-005 | 96.650 | 0.0002 | |
| AC | 3.781E-006 | 1 | 3.781E-006 | 18.710 | 0.0075 | |
| Curvature | 1.592E-006 | 1 | 1.592E-006 | 7.8800 | 0.0377 | Significant |
| Residual | 1.010E-006 | 5 | 2.021E-007 | | | |
| Lack of fit | 3.437E-007 | 3 | 1.146E-007 | 0.3400 | 0.8889 | Not significant |
| Pure error | 6.667E-007 | 2 | 3.333E-007 | | | |
| Cor. total | 7.123E-005 | 10 | | | | |

Table 4: ANOVA table for the surface roughness

| Source | S.S. | df | Mean square | F value | Prob>F | |
|---|---|---|---|---|---|---|
| Model | 0.680 | 3 | 0.230 | 85.030 | <0.0001 | Significant |
| A | 0.260 | 1 | 0.260 | 98.860 | <0.0001 | |
| C | 0.380 | 1 | 0.380 | 144.00 | <0.0001 | |
| AC | 0.033 | 1 | 0.033 | 12.230 | 0.0129 | |
| Curvature | 0.050 | 1 | 0.050 | 18.780 | 0.0049 | Significant |
| Residual | 0.016 | 6 | 2.658E-003 | | | |
| Lack of fit | 0.015 | 4 | 3.787E-003 | 9.4700 | 0.0978 | Not significant |
| Pure error | 8.000E-004 | 2 | 4.000E-004 | | | |
| Cor. total | 0.740 | 10 | | | | |

Table 5: ANOVA table for the material removal rate

| Source | S.S. | df | Mean square | F value | Prob>F | |
|---|---|---|---|---|---|---|
| Model | 1294.77 | 3 | 431.59 | 73.290 | <0.0001 | Significant |
| A | 500.470 | 1 | 500.47 | 84.990 | <0.0001 | |
| B | 90.5600 | 1 | 90.560 | 15.380 | 0.0078 | |
| C | 703.740 | 1 | 703.74 | 119.51 | <0.0001 | |
| Curvature | 243.110 | 1 | 243.11 | 41.290 | 0.0007 | Significant |
| Residual | 35.3300 | 6 | 5.8900 | | | |
| Lack of fit | 31.0000 | 4 | 7.7500 | 3.5800 | 0.2302 | Not significant |
| Pure error | 4.33000 | 2 | 2.1700 | | | |
| Cor. total | 1573.22 | 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) | Material removal rate ($mm^3/s$) |
|---|---|---|---|---|---|---|
| 12 | -1 | 0 | 0 | 0.007 | 1.55 | 0.0162 |
| 13 | 1 | 0 | 0 | 0.011 | 1.78 | 0.0200 |
| 14 | 0 | -1 | 0 | 0.008 | 1.71 | 0.0196 |
| 15 | 0 | 1 | 0 | 0.005 | 1.66 | 0.0177 |
| 16 | 0 | 0 | -1 | 0.006 | 1.61 | 0.0165 |
| 17 | 0 | 0 | 1 | 0.012 | 1.84 | 0.0217 |

Table 7: Modified ANOVA table for the sparking gap after RSM

| Source | S.S. | df | Mean square | F value | Prob>F | |
|---|---|---|---|---|---|---|
| Block | 1.747E-007 | 1 | 1.747E-007 | | | |
| Model | 1.056E-004 | 7 | 1.508E-005 | 26.94 | <0.0001 | Significant |
| A | 4.202E-005 | 1 | 4.202E-005 | 75.06 | <0.0001 | |
| B | 1.562E-005 | 1 | 1.562E-005 | 27.91 | 0.0007 | |
| C | 3.423E-005 | 1 | 3.423E-005 | 61.13 | <0.0001 | |
| AC | 3.781E-006 | 1 | 3.781E-006 | 6.750 | 0.0317 | |
| $A^2$ | 3.253E-006 | 1 | 3.253E-006 | 5.810 | 0.0425 | |
| $B^2$ | 4.970E-006 | 1 | 4.970E-006 | 8.880 | 0.0176 | |
| $C^2$ | 3.253E-006 | 1 | 3.253E-006 | 5.810 | 0.0425 | |
| Residual | 4.479E-006 | 8 | 5.599E-007 | | | |
| Lack of fit | 3.812E-006 | 6 | 6.354E-007 | 1.910 | 0.3834 | Not significant |
| Pure error | 6.667E-007 | 2 | 3.333E-007 | | | |
| Cor. total | 1.102E-004 | 16 | | | | |

applied for this factor it is a not mean that this factor have been optimize. Actually just for obtain more accurate mathematical relationship between factors the RSM have done for this response.

According to Table 3, 4 and 5, ANOVA analysis reveals the significance of curvature test for SG, MRR 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

Table 8: Modified ANOVA table for the surface roughness after RSM

| Source | S.S. | df | Mean square | F value | Prob>F | |
|---|---|---|---|---|---|---|
| Block | 0.067 | 1 | 0.067 | | | |
| Model | 0.750 | 4 | 0.190 | 38.63 | <0.0001 | Significant |
| A | 0.280 | 1 | 0.280 | 58.26 | <0.0001 | |
| C | 0.390 | 1 | 0.390 | 80.93 | <0.0001 | |
| AC | 0.033 | 1 | 0.033 | 6.710 | 0.0251 | |
| $A^2$ | 0.042 | 1 | 0.042 | 8.630 | 0.0135 | |
| Residual | 0.053 | 11 | 4.844E-003 | | | |
| Lack of fit | 0.052 | 9 | 5.832E-003 | 14.58 | 0.0658 | Not significant |
| Pure error | 8.000E-004 | 2 | 4.000E-004 | | | |
| Cor. total | 0.870 | 16 | | | | |

Table 9: Modified ANOVA table for the material removal rate after RSM

| Source | S.S. | df | Mean square | F value | Prob>F | |
|---|---|---|---|---|---|---|
| Block | 1.876E-005 | 1 | 1.876E-005 | | | |
| Model | 1.315E-004 | 7 | 1.879E-005 | 82.770 | <0.0001 | Significant |
| A | 4.285E-005 | 1 | 4.285E-005 | 188.79 | <0.0001 | |
| B | 8.100E-006 | 1 | 8.100E-006 | 35.690 | 0.0003 | |
| C | 6.003E-005 | 1 | 6.003E-005 | 264.47 | <0.0001 | |
| AB | 1.531E-006 | 1 | 1.531E-006 | 6.7500 | 0.0317 | |
| AC | 7.411E-006 | 1 | 7.411E-006 | 32.650 | 0.0004 | |
| $A^2$ | 5.096E-006 | 1 | 5.096E-006 | 22.450 | 0.0015 | |
| $B^2$ | 1.761E-006 | 1 | 1.761E-006 | 7.7600 | 0.0237 | |
| Residual | 1.816E-006 | 8 | 2.270E-007 | | | |
| Lack of fit | 1.369E-006 | 6 | 2.282E-007 | 1.0200 | 0.5713 | Not significant |
| Pure error | 4.467E-007 | 2 | 2.233E-007 | | | |
| Cor. total | 1.521E-004 | 16 | | | | |

Table 10: Summery of ANOVA analysis for quadratic reduced model

| Response | $R^2$ | Adj $R^2$ | Pred $R^2$ | Adeq precision |
|---|---|---|---|---|
| Sparking gap | 0.9593 | 0.9237 | 0.7822 | 18.919 |
| Surface roughness | 0.9335 | 0.9094 | 0.8314 | 19.964 |
| Material removal rate | 0.9864 | 0.9745 | 0.9111 | 31.272 |

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 6 indicates the experimental results after adding central composite design experiments. Table 7, 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. 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. In this table, the Model F-value of 26.94 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, $A^2$, $B^2$, $C^2$ and AC are significant model terms. It is likely to have an improved model by omitting those insignificant model 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:

$$\text{Sparking Gap} = +\ 7.608E\text{-}003 + 2.050E\text{-}003 * A - 1.250E\text{-}003 * B + 1.850E\text{-}003 * C + 6.875E\text{-}004 * A * C + 1.118E\text{-}003 * A^2 - 1.382E\text{-}003 * B^2 + 1.118E\text{-}003 * C^2 \tag{4}$$

In Table 8, the Model F-value of 38.63 implies the model is significant. Values of "Prob>F" less than 0.0500 indicate, the model terms are significant. In this case A, C, $A^2$ and AC are significant model terms. In this model also backward elimination procedure with 0.05 α 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:

$$Ra = +\ 1.68 + 0.17 * A + 0.20 * C - 0.064 * A * C - 0.11 * A^2 \tag{5}$$

As it shown in Table 9 the model for MRR became significant and for this factor A, B, C, $A^2$, $B^2$ and AC and AB interaction are significant model terms. The equation for material removal rate from the results in ANOVA in Table 5 derived in terms of coded factors as follows:

$$MRR = +\ 0.019 + 2.070E\text{-}003 * A - 9.000E\text{-}004 * B + 2.450E\text{-}003 * C - 4.375E\text{-}004 * A * B + 9.625E\text{-}004 * A * C - 1.334E\text{-}003 * A^2 - 7.843E\text{-}004 * B^2$$

For all models the block effects are not significant, it means that the mentioned different condition can't affect the results.

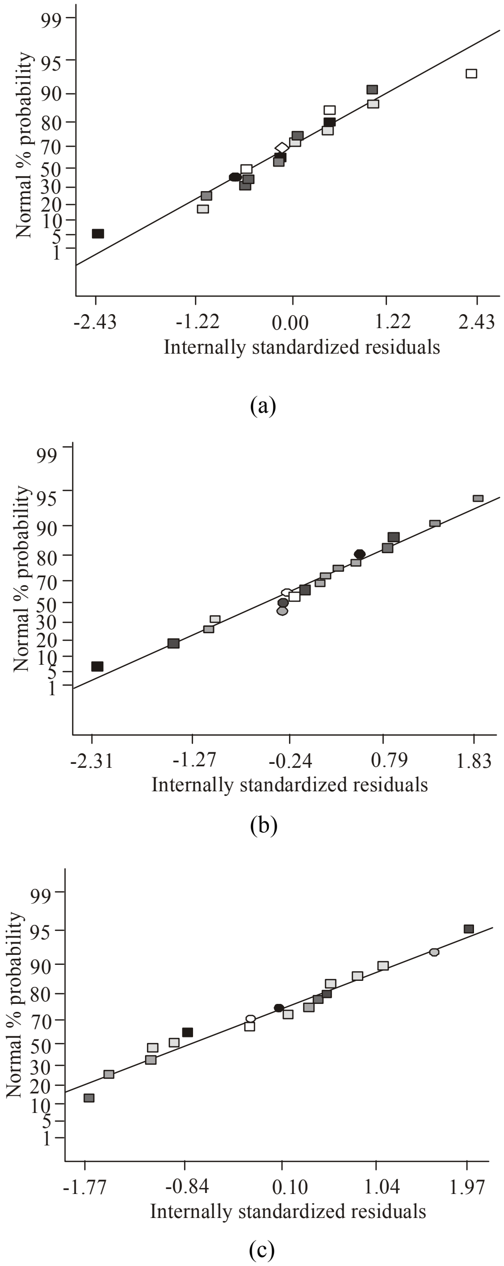


Fig. 3: Normal plot of residuals (a) SG, (b) SR, (c) MRR

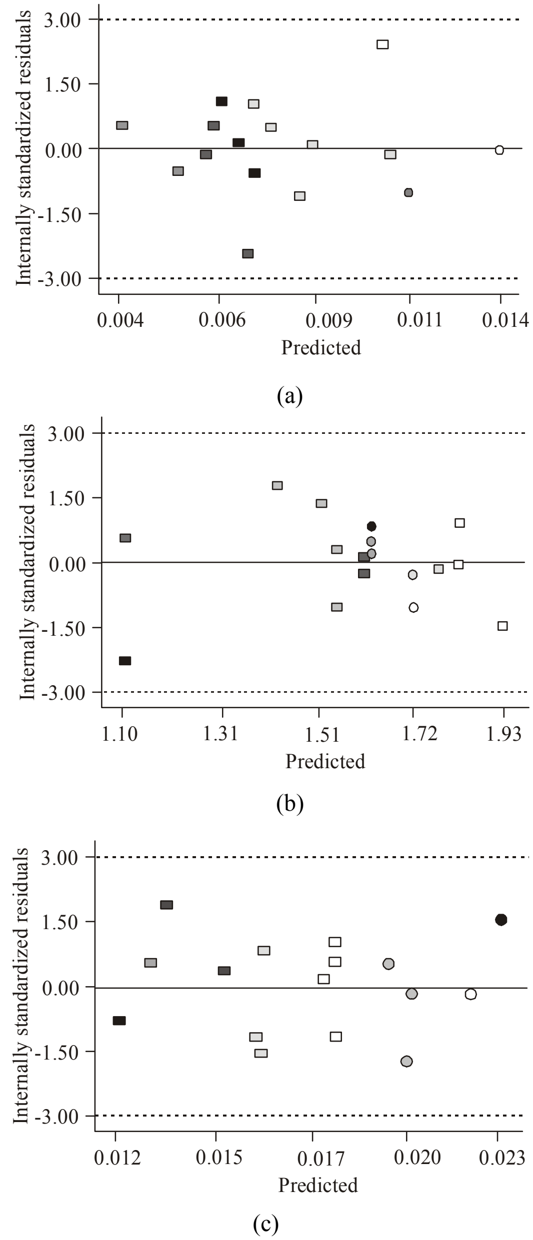


Fig. 4: Residual versus predicted plots (a) SG, (b) SR, (c) MRR

Since all of the $R^2$ values are high and close to one, as it shows in Table 10, 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. The S/N ratio, which is presented as adequate precisions, are 18.919, 19.964 and 31.272 which indicates that models are desirable to navigate design space.

Figure 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 and 4 shows, all residual figures seem to be structureless. These figures show the residuals after applying RSM.

## DISSECTION

**Sparking Gap (SG):** The examination of the results shows the data located in the optimum region and the

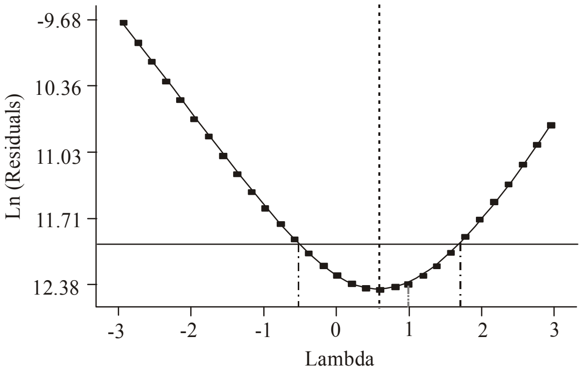


Fig. 5: Box-cox plot for sparking gap data

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

Analyzing the results shows 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 47.78% 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 27.42% 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 15.84% in SG. According to Fig. 6 curvatures is significant in the SG interaction plot. Lower setting for pulse on time and peak current were required to achieve lower SG.

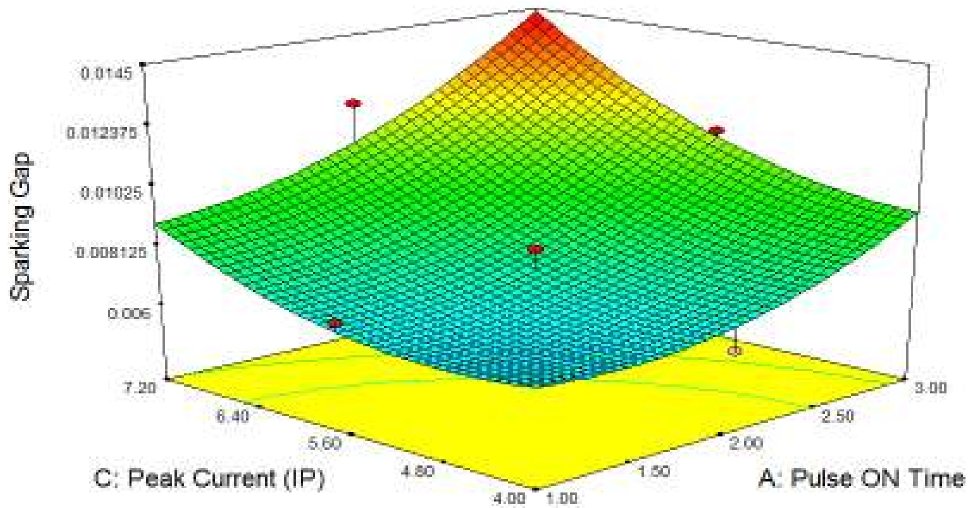


Fig. 6: 3D surface graph for sparking gap

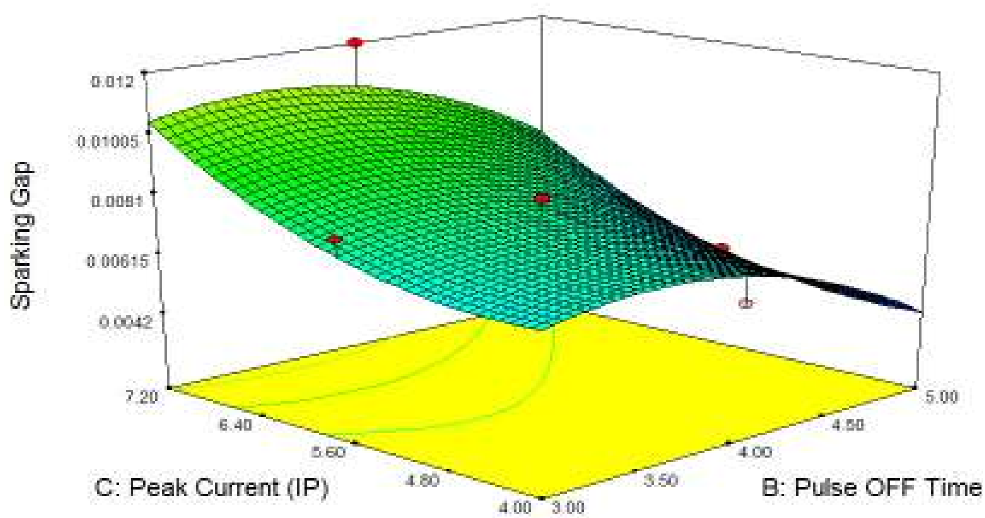


Fig. 7: 3D surface graph for sparking gap

Table 11: Model summary statistics for sparking gap

| Source | $R^2$ | Adj. $R^2$ | Pred. $R^2$ | |
|---|---|---|---|---|
| Linear | 0.8348 | 0.7935 | 0.6636 | Suggested |
| 2FI | 0.8697 | 0.7828 | 0.5586 | |
| Quadratic | 0.9599 | 0.8997 | 0.6073 | Suggested |

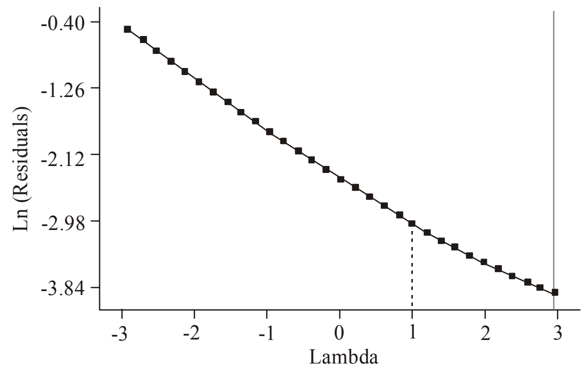


Fig. 8: Box-Cox plot for SR data

The influence of peak current and pulse off time on SG is revealed in Fig. 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 is matched with the results obtained by Tosun *et al*. (2004) and Kanlayasiri and Boonmung (2007) results.

The model summary statistics for sparking gap is given in Table 11. Table 11 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 Fig. 8, the data are more or less in the optimum region of the parabola.

Analyzing the results reveals that SR considerably affects by peak current. 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 51.45% in SR, which is the highest contribution. Moreover, pulse on time is another main factor that influenced on SR. 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 35.32% in SR. According to Fig. 9 curvatures is significant in the SR interaction plot. Thus “lower is better”. The lower pulse on time and peak current are more favourable for surface (Sarkar *et al*., 2008). The outcome of surface roughness conform what Kanlayasiri (2007) and Kuriakose and Shunmugam (2004) obtained.

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

Table 12: Model summary statistics for surface roughness

| Source | $R^2$ | Adj. $R^2$ | Pred. $R^2$ | |
|---|---|---|---|---|
| Linear | 0.8553 | 0.8191 | 0.7029 | |
| 2FI | 0.8997 | 0.8329 | 0.4345 | |
| Quadratic | 0.9666 | 0.9166 | 0.6457 | Suggested |

Table 13: Results of confirmation experiments

| Model | Sparking gap | Surface roughness | Material removal rate |
|---|---|---|---|
| Error | 8.268% | 7.738% | 8.863% |

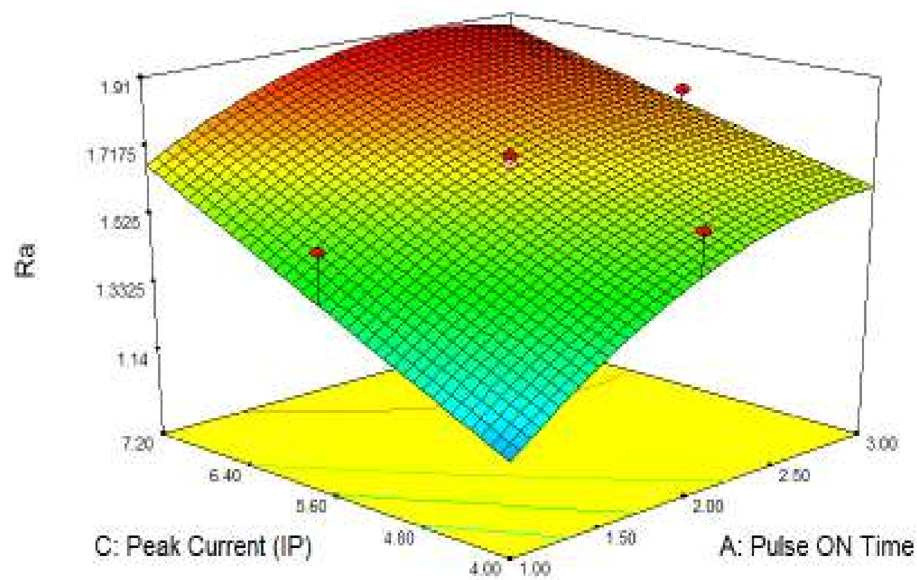


Fig. 9: 3D surface graph for surface roughness

Table 14: Constraints 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 | 7.2000 | 1 | 1 | 3 |
| Surface roughness | Minimum | 0.9800 | 1.8800 | 1 | 1 | 3 |
| Sparking gap | Minimum | 0.0040 | 0.0140 | 1 | 1 | 3 |
| Material removal rate | Maximize | 0.0116 | 0.0231 | 1 | 1 | 3 |

Table 15: The optimal condition for each parameter

| Condition | Pulse on time (µs) | Pulse off time (µs) | Peak current (A) | Optimum response | Desirability |
|---|---|---|---|---|---|
| Sparking gap | 1.5 | 5 | 4.75 | 0.00399 mm | 1 |
| Surface roughness | 1 | 3 | 4 | 1.144 µm | 0.817 |
| Material removal rate | 3 | 3.5 | 7 | 0.0231379 | 1 |
| Multi-objectives | 1.5 | 4 | 4.5 | | 0.704 |

The model summary statistics for surface roughness is given in Table 12. Table 12 reveals that the best recommended model is quadratic model.

**Material removal rate:** Analyzing the results reveals that peak current significantly affects MRR. The energy of each discharge will be raised with 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 44.73% 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 affect the time of each discharge and raise the material removal rate. This factor contributed 31.81% in MRR. Figure 5 shows that both peak current and pulse on time should be set at high to achieve higher MRR. Also pulse off time contributes 5.76% in MRR which is quite low contribution. As it mentioned although the curvature for this response is significant, this response is not in the optimum region. These results are in agreement with Sarkar *et al*. (2005) and Kuriakose and Shunmugam (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 13 shows the average of error for each model.

Table 14 shows the summary of constraints used during optimization process. Finally, in Table 15, the best combination of parameters can be accessed for each optimal condition. In this table, the results for all 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. The results of this study are suitable for finishing operation.

## CONCLUSION

In this research the effect of machining parameters including pulse on time, pulse off time and peak current on surface roughness and sparking gap 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. The following conclusions were drawn from this study:

- It was considered that the potential of WEDM procedure applying Brass wire in machining of Ti-6A1-4V gets to 1.144 µm of surface roughness and 0.00399 mm of sparking gap. It means this wire is comparable with coated wires in finishing process.
- Peak current found to be the most important factor for surface roughness and material removal rate while Pulse on time has the same roll for sparking gap. 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 and 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: 1.5 µs, pulse off time 4 µs, peak current: 4.5 A. The predicted result is sparking gap 0.00399 mm and surface roughness: 1.144 µm and material removal rate 0.0156 $mm^3/s$.
- 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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