International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:7, No:3, 2013

Development of Regression Equation for Surface Finish and Analysis of Surface Integrity in EDM

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Abstract**—**Electrical discharge machining (EDM) is a relatively modern machining process having distinct advantages over other machining processes and can machine Ti-alloys effectively. The present study emphasizes the features of the development of regression equation based on response surface methodology (RSM) for correlating the interactive and higher-order influences of machining parameters on surface finish of Titanium alloy Ti-6Al-4V. The process parameters selected in this study are discharge current, pulse on time, pulse off time and servo voltage. Machining has been accomplished using negative polarity of Graphite electrode. Analysis of variance is employed to ascertain the adequacy of the developed regression model. Experiments based on central composite of response surface method are carried out. Scanning electron microscopy (SEM) analysis was performed to investigate the surface topography of the EDMed job. The results evidence that the proposed regression equation can predict the surface roughness effectively. The lower ampere and short pulse on time yield better surface finish.

Keywords**—**Graphite electrode, regression model, response surface methodology, surface roughness.

I. Introduction

THE usage of titanium and its alloys is increasing in many industrial and commercial applications because of these materials' excellent properties such as a high strength–weight ratio, high temperature strength and exceptional corrosion resistance [1]. The most common titanium is the $\alpha+\beta$ type two phase Ti–6Al–4V alloy among several alloying types of titanium. In aerospace industry, titanium alloys have been widely used because of their low weight, high strength or high temperatures stability [2]. Titanium and its alloys are difficult to machine materials due to several inherent properties of the material. In spite of its more advantages and increased utility of titanium alloys, the capability to produce parts products with high productivity and good quality becomes challenging. Owing to their poor machinability, it is very difficult to machine titanium alloys economically with traditional mechanical techniques [3], [4]. The main difficulties to machine titanium alloys are high cutting temperatures and rapid tool wear [5].

Electric discharge machining is a non-traditional type of precision processing using an electrical spark-erosion process between the electrode and the working piece of electrically conductive immersed in a dielectric fluid [6], [7]. Since it has more special gains, the EDM has been widely applied in modern metal industry for producing complex cavities in moulds and dies, which are difficult to manufacture by conventional machining. The use of Electrical Discharge Machining in the production of forming tools to produce plastics moldings, die castings, forging dies etc., has been firmly established in recent years. The EDM is a well-established machining choice for manufacturing geometrically complex or hard material parts that are extremely difficult-to-machine by conventional machining processes [6], [8]. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage for manufacturing of mold, die, automotive, aerospace, and surgical components [9]. Thus, titanium and titanium alloy, which is difficult-to-cut material, can be machined effectively by EDM [10]. The selection of appropriate machining conditions for EDM performance characteristics is based on the analysis relating the various process parameters to the EDM characteristics [5], [11]. Undertaking frequent tests or many experimental runs is also not economically justified. Proper selection of the machining parameters can result in better machining performance as higher material removal, good quality surface finish, and lower tool wear [12], [5]. Several researches have been carried out for improving the process performance and for detection optimum parameters as follows. The electrical discharge machining of titanium alloy (Ti–6Al–4V) with different electrode materials has been accomplished to explore the influence of EDM parameters on various aspects of the surface integrity of Ti6Al4V [1]. The experimental results reveal that the material removal rate, surface roughness, electrode wear and average white layer thickness increase with the increasing of current and pulse duration. The Graphite electrode is beneficial on material removal rate, electrode wear and surface crack density but relatively poorer surface finish. A study has been carried out to develop a mathematical model for optimizing the EDM characteristics on matrix composite Al/SiC material [13]. They used response surface methodology to determine the optimal setting of the EDM parameters such as the metal removal rate, electrode wear ratio, gap size and the surface finish. The effect of the thermal and electrical properties of titanium alloy Ti–6Al–4V on EDM productivity has been detected [2]. They state that the duty factor is a vital EDM machining condition parameter and is an easy means of changing the energy application to the workpiece. The results indicate that as the duty factor increases, the internal workpiece temperature also increases

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which causes poor machining productivity and quality. The optimal duty factor in terms of productivity and quality was found at around 7%. Tomadi et al. researched to get the optimum machining conditions for machining Tungsten Carbide with a Copper Tungsten as electrode [14]. They investigated that in the case of the surface roughness, the most influential factors are voltage followed by the pulse off time, while the peak current and pulse on time have no significant. For material removal rate pulse on time is the most influential, followed by voltage, peak current, and pulse off time. In the case of electrode wear, it was observed that the most influential is pulse off time, followed by the peak current. In order to obtain optimum circumstances low values of peak current, pulse off time and voltage for good surface finish and likewise high values of peak current and voltage to get high material removal and also to attain low electrode wear high pulse off time and low peak current should be used. To investigate the relationships and parametric interactions between the variables on the material removal rate using response surface methodology experiments have been conducted on AISI D2 tool steel with Cu electrode [15]. It was acquired that discharge current, pulse duration, and pulse off time affect the material removal significantly. Their observation illustrates that the highest material removal rate values appeared at the higher ampere and pulse on time and at the lower pulse off time. Research have been attained to assess the effect of three factors-tool material, grit size of the abrasive slurry and power rating of ultrasonic machine on machining characteristics of titanium (ASTM Grade I) using full factorial approach for design and analysis of experiments [16]. It has been investigated that the surface finish obtained in USM is better than many of the other non-traditional techniques. It Shabgard and Shotorbani determined second-order polynomial models that fitted the characteristics of EDM on FW4 steel. The relationships between the input parameters and the material removal and surface roughness were investigated by applying design of experiment and response surface methodology [17].

The main performance characteristics in EDM process comprise material removal rate, tool wear rate and surface roughness [18]. It is difficult to acquire the accurate quantification of these performance characteristics because there are various uncertain factors and non-linear terms. Proper selection of machining parameters for the best process performance is still a challenging job [19]. Thus, the present paper emphasizes the development of regression model or equation for correlating the various machining parameters such as peak current (I_P), pulse on time (T_{on}), pulse off time (T_{off}) and servo voltage (S_v) on important machining criteria namely surface roughness (*SR*). Modeling has been carried for surface roughness of Ti-6Al-4V and negative polarity of Graphite electrode using the techniques of design of experiments method and response surface methodology. Besides this, scanning electron microscopy also followed to investigate the surface structure of the EDMed job. Although a few similar studies are obvious; alternate parameters with moderate range, electrode as well as polarity can be argued as innovation.

II. Experimental Details

Pulse on time (t_i) refers the duration of time (μs) in which the current is allowed to flow per cycle [20]. Pulse off time and also known as pulse interval (t_o) is the duration of time (μs) between the sparks. The surface roughness of the work-piece can be expressed in different ways including arithmetic average (R_a), average peak to valley height (R_z), or peak roughness (R_P), etc. Generally, the *SR* is measured in terms of arithmetic mean (R_a) which according to the ISO 4987: 1999 is defined as the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement [21], [22]. Arithmetic mean or average surface roughness, R_a is considered in this study for assessment of roughness. In this study the factors are selected in accordance with the literature consulted as well as drawing from personal experience. Finally the ranges of these parameters were selected on the basis of preliminary experiments.

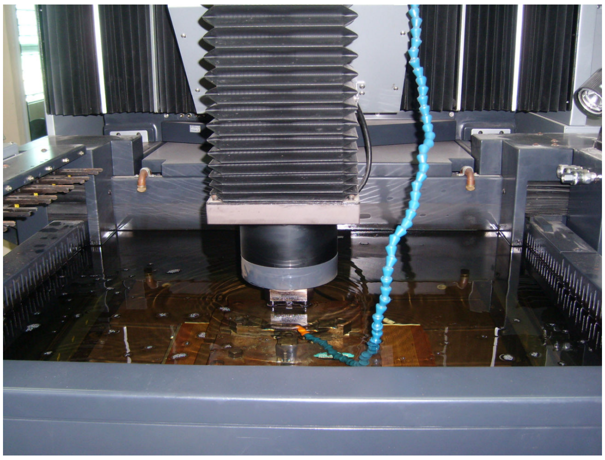


Fig. 1 Experimental setup of electrical discharge machining

The experimental setup is shown in Fig. 1. The machining was carried out for a fixed time interval. Surface roughness was assessed with Perthometer, Mahr as shown in Fig. 2. Five observations were taken for each sample and were averaged to get the value of surface roughness, R_a. Experiments were conducted on AQ55L Die Sinking EDM machine. The experiment has been performed with negative polarity of the electrode. In this study, Ti-6Al-4V is selected as the work material. Graphite with diameter 20 mm has been used to machine titanium alloy material. The four independent parameters — peak current (I_p), pulse on time (T_{on}), pulse off time (T_{off}) and servo voltage (S_v) were chosen for the study

TABLE I
DESIGN SCHEME OF PROCESS PARAMETERS AND THEIR LEVELS

Designation	Process parameters	Levels	
		Low	High
x_1	Peak Current (A)	1	29
x_2	Pulse on time (µs)	10	350
x_3	Pulse of time (µs)	60	300
x_4	Servo voltage (V)	75	115

TABLE II
SET OF DESIGNED EXPERIMENTS USING DISTINCT PARAMETERS

Experiment No.	Peak Current (A)	Pulse on time (µs)	Pulse off time (µs)	Servo voltage (V)
1	0	0	0	0
2	-1	1	1	-1
3	2	0	0	0
4	0	0	0	0
5	0	0	0	-2
6	0	0	0	0
7	-1	-1	-1	-1
8	1	1	1	-1
9	-1	1	1	1
10	0	0	0	0
11	-1	-1	1	1
12	0	0	-2	0
13	-1	1	-1	-1
14	1	-1	-1	1
15	1	-1	1	1
16	-1	-1	-1	1
17	1	1	1	1
18	1	1	-1	-1
19	-2	0	0	0
20	0	0	0	0
21	0	0	2	0
22	0	0	0	0
23	1	-1	1	-1
24	1	1	-1	1
25	1	-1	-1	-1
26	0	0	0	2
27	-1	1	-1	1
28	0	-2	0	0
29	-1	-1	1	-1
30	0	2	0	0
31	0	0	0	0

The ranges of these parameters were selected on the basis of preliminary experiments conducted by using one variable at a time approach. Table I gives the levels of various parameters and their designation. The response parameter in the present study was surface roughness. The surface roughness was measured in terms of arithmetic mean roughness of the evaluated roughness profile (R_a in µm).

The main objective of the experimental design is studying the relations between the response as a dependent variable and the various parameter levels. It provides a prospect to study not only the individual effects of each factor but also their interactions. The design of experiments for exploring the influence of various predominant EDM process parameters as peak current, pulse on time, pulse off time and servo voltage on the machining characteristics such as surface finish (R_a) were modeled. In the present work, experiments were designed on the basis of experimental design technique using response surface design method. The coded levels for all process parameters used are displayed in Table II.

Fig. 2 Perthometer for measurement the surface roughness of the sample

III. DEVELOPMENT OF REGRESSION MODEL BASED ON RSM

After knowing the values of the measured response, the values of the different regression coefficients of second order polynomial mathematical equation (1) have been estimated. The mathematical model based on the response surface methodology have been developed by utilizing test results obtained through the entire set of experiments by using a computer software, MINITAB.

A. Model for Surface Roughness

In statistics, response surface methodology explores the relationships between several explanatory variables and one or more response variables. The main idea of RSM is to use a set of designed experiments to obtain an optimal response. In this work, RSM is utilized for establishing the relations between the different EDM process parameters with a variety of machining criteria and exploring their effects on the response as *SR*. To perform this task second order polynomial response surface mathematical models can be developed. In the general case, the response surface is described by an equation of the form [5]:

$$Y = C_0 + \sum_{i=1}^{n} C_i x_i + \sum_{i=1}^{n} C_{ii} x_i^2 + \sum_{i=1}^{n-1}\sum_{j=2}^{n} C_{ij} x_{ij} \quad (1)$$

where, Y is the corresponding response, *SR* yield by the various EDM process variables and the x_i (1, 2, ……, n) are coded levels of n quantitative process variables, the terms C_0, C_i, C_{ii} and C_{ij} are the second order regression coefficients. The second term under the summation sign of this polynomial equation is attributable to linear effect, whereas the third term corresponds to the higher-order effects; the fourth term of the equation includes the interactive effects of the process parameters. In this research, (1) can be rewritten according to the three variables used as:

$$Y = C_o + C_1x_1 + C_2x_2 + C_3x_3 + C_4x_4 + C_{11}x_1^2 + C_{22}x_2^2 + C_{33}x_3^2 + C_{44}x_4^2 + C_{12}x_1x_2 + C_{13}x_1x_3 + C_{23}x_2x_3 + C_{14}x_1x_4 + C_{24}x_2x_4 + C_{34}x_3x_4 \quad (2)$$

where: x_1, x_2, x_3 and x_4 are peak current (I_p), pulse on time (T_{on}), pulse off time (T_{off}) and servo voltage (S_v) respectively.

The regression equation of the fitted model for the *SR* is represented in (3):

$$SR = -5.904 + 0.519389\, I_p + 0.0270171\, T_{on} + 0.00933860\, T_{off} + 0.144279\, S_v - 0.0161716\, I_p^2 - 8.65309\times10^{-5} T_{on}^2 - 3.45793\times10^{-5} T_{off}^2 - 8.87854\times10^{-4} S_v^2 + 0.00151447\, I_p T_{on} - 2.21101\times10^{-4} I_p T_{off} + 3.18750\times10^{-4} I_p S_v + 5.35049\times10^{-6} T_{on} T_{off} - 5.89706\times10^{-6} T_{on} S_v - 1.97917\times10^{-6} T_{off} S_v \quad (3)$$

B. Analysis of Variance (ANOVA)

The first-order and second order polynomial responses have been accomplished, consequently the analysis of variance are shown in Tables III, IV. However, the second order regression has been shown here because of its adequacy. The variance is the mean of the squared deviations about the mean or the sum of the squared deviations about the mean divided by the degrees of freedom. The fundamental technique is a partitioning of the total sum of squares and mean squares into components such as data regression and its error. The number of degrees of freedom can also be partitioned in a similar way as discussed in Tables III, IV. The usual method for testing the adequacy of a model is carried out by computing the F-ratio of the lack of fit to the pure error and comparing it with the standard value. The values of P (<α-level) in the analysis ascertain that the regression model is significant. The P-values of the residual error in the case of first order model is less than α-level (0.05) which reveals that the lack-of-fit is significant. On the other hand, in the Table IV the P-value of linear, square and interaction terms are less than α-level (0.05). Accordingly, these terms have the significant effect on the proposed regression model. Since the P-value of the residual error (0.501) is more than the α-level (0.05), lack-of-fit is insignificant. The standard error of the regression for first-order (S) is 1.24346 whilst for second order polynomial is 0.187992. The coefficients of regression (R^2) for first and second order polynomial models are 81.55% and 99.74% respectively. The lower value of S and higher value of R^2 yield the more adequacy of the model. The results of the analysis justifying the closeness of fit of the mathematical models are enumerated. Therefore it can be concluded that the evolved model given by (3) has been adequately explained the variation in the machining parameters on *SR*.

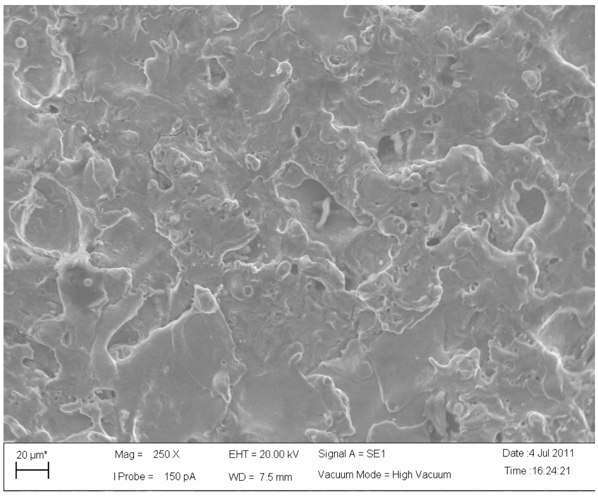
TABLE III
ANALYSIS OF VARIANCE FOR *SR* CONSIDERING LINEAR TERMS

Source of variation	Degree of freedom	Sum of squares	Mean squares	F-ratio	P
Regression	4	177.683	44.4208	28.73	0.000
Linear	4	177.683	44.4208	28.73	0.000
Residual Error	26	40.201	1.5462		
Lack-of-Fit	20	39.995	1.9997	58.19	0.000
Pure Error	6	0.206	0.0344		
Total	30	217.884			

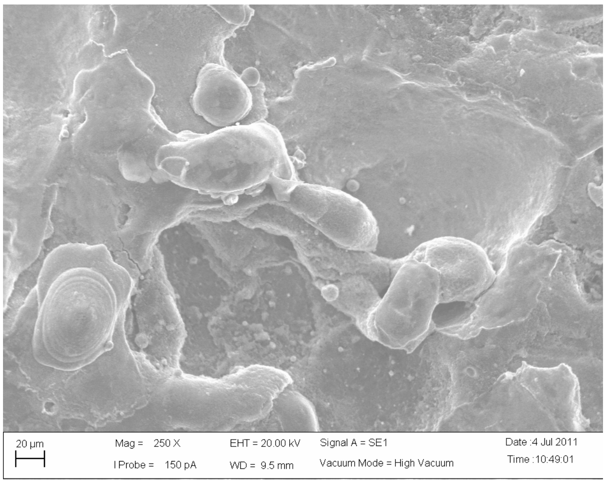
TABLE IV
ANALYSIS OF VARIANCE FOR *SR* CONSIDERING FULL QUADRATIC TERMS

Source of variation	Degree of freedom	Sum of squares	Mean squares	F-ratio	P
Regression	14	217.318	15.5227	439.23	0.000
Linear	4	177.683	44.4208	1256.92	0.000
Square	4	26.485	6.6213	187.35	0.000
Interaction	6	13.150	2.1917	62.02	0.000
Residual Error	16	0.565	0.0353		
Lack-of-Fit	10	0.359	0.0359	1.05	0.501
Pure Error	6	0.206	0.0344		
Total	30	217.884			

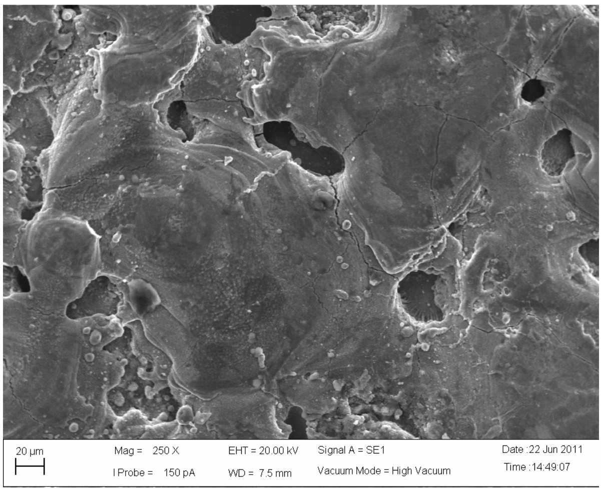
IV. SURFACE TOPOGRAPHY OF THE EDMED WORKPIECE



(a) Discharge ($I_p \times T_{on}$) = 2A× 95 µs



(b) Discharge (I_p×T_{on}) = 15 A× 180 µs



(c) Discharge (I_p×T_{on}) = 29A×320 µs

Fig. 3 SEM micrographs of EDM surface for different discharge intensity

Fig. 3 shows the SEM micrograph of EDMed surface for distinguish energy intensity as I_p×T_{on}= 2A×95 µs, I_p×T_{on}= 15A× 180 µs and I_p×T_{on}= 29A× 320 µs. In high energy intensity machining, the machined surfaces can be seen to crater more as compared with lower intensity as Figs. 3 (a)-(c). The surface roughness is getting worse with current and pulse on time. At the lower pulse current and pulse on time, the surface craters are less and shallow, and so, the workpiece surface finish is better as Fig. 3 (a). In contrast, machining with high intensity causes more craters and as a result, increases the surface roughness. A large discharging energy causes violent sparks and impulsive forces and results in a deeper and larger erosion crater on the surface as shown in Fig. 3 (c).

V. Conclusion

It was attempted to formulate a mathematical equation using EDM factors as pulse on time, pulse off time and servo voltage in favor of response surface roughness. The adequacy of the developed model has been justified through analysis of variance. ANOVA proves that the developed mathematical equation is adequate and can predict the surface roughness of titanium alloy Ti-6Al-4V successfully. The surface topography of the machined samples obtained by scanning electron microscope evidence that the higher the energy intensity the worse surface. Consequently, the combination of low ampere and short pulse on time facilitate fine surface.

Acknowledgment

The authors would like to express their thanks to the Universiti Malaysia Pahang, Malaysia for support to carry out this research work.

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