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PREDICTION OF SURFACE ROUGHNESS OF TI-6AL-4V IN ELECTRICAL DISCHARGE MACHINING: A REGRESSION MODEL

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ABSTRACT

This paper develops a single order mathematical model for correlating various electrical discharge machining (EDM) parameters and performance characteristics by utilizing relevant experimental data obtained through experimentation. In addition to the effect of peak ampere, the effect of pulse on time and pulse off time on surface roughness has also been investigated. Experiments have been conducted on titanium alloy Ti-6Al-4V with a copper electrode retaining negative polarity as per the Design of Experiments. Response surface methodology techniques are utilized to develop the mathematical model as well as to optimize the EDM parameters. An analysis of variance has been performed for the validity test of fit and adequacy of the proposed models. It can be seen that increasing pulse on time causes a fine surface until a certain value, beyond which the surface finish deteriorates. The excellent surface finish is investigated in this study for the case of pulse on time below 80 µs. This result acts as a guide for selecting the required process outputs and most economic industrial machining conditions for optimizing the input factors.

Keywords: Ti-6Al-4V; EDM; pulse on time; pulse off time; single order model; surface finish.

INTRODUCTION

In the aerospace industry, titanium alloys are used widely because of their low weight, high strength, and high temperature stability (Fonda, Wang, Yamazaki & Akutsu, 2008). Titanium and its alloys are materials that are difficult to machine owing to several inherent properties of the material. Despite its advantages and the increased utility of titanium alloys, the capability of high productivity in producing good quality product parts remains challenging. Owing to their poor machinability, it is very difficult to machine titanium alloys economically with traditional mechanical techniques (Rahman, Wang & Wang, 2006). Electric discharge machining (EDM) is a non-traditional type of precision processing using an electrical spark-erosion process between the electrode and the working piece of electrically conductive material immersed in a dielectric fluid (Prabhu & Vinayagam, 2009). EDM has proved especially valuable in the machining of super-tough and any electrically conductive materials (Lee & Li, 2001). It has been applied widely in modern metal industry for producing complex cavities in molds and dies, which are difficult to manufacture by conventional machining. Its unique feature of using thermal energy to machine electrically conductive parts, regardless of hardness, has been its distinctive advantage for the manufacture of molds, dies and automotive, aerospace, and surgical components (Ponappa, Aravindan, Rao, Ramkumar & Gupta, 2010; Singh, 2010). Thus, titanium and titanium alloy, which are difficult-to-cut materials, can be machined effectively by EDM (Yan, Tsai & Huang, 2005). Proper selection of the machining parameters can result in a higher material removal rate, better surface finish, and a lower electrode wear ratio (Lin, Lin & Ko, 2002). A study has been carried out to develop a mathematical model for optimizing the EDM characteristics on a matrix composite Al/SiC material (Habib, 2009). They used response surface methodology (RSM) 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 (Fonda et al., 2008). They state that the duty factor, the ratio of pulse duration to total pulse time, is a vital EDM condition parameter, which is an easy means for changing the energy application to the workpiece. However, results indicate that as the duty factor increases, the internal workpiece temperature also increases, which causes poor EDM productivity and quality. The optimal duty factor in terms of productivity and quality was found at around 7%.

Proper selection of EDM parameters for the best process performance, especially for titanium alloys, is still a challenging task (Mandal, Pal & Saha, 2007). Optimal selection of process parameters is essential because it is a costly process to increase the production rate considerably by reducing the machining time. Thus, the present paper emphasizes the development of models for correlating the various machining parameters, such as peak current (I_P), pulse on time (t_i), and pulse off time (t_o) on the important characteristics criteria, i.e., surface roughness (SR) (Wang & Tsai, 2001). Machining parameter optimization for the titanium alloy material Ti-6Al-4V has been carried out using the techniques of the design of experiments method and RSM. The single order model is used to predict the responses of the EDM process. In addition, the effect of input parameters on the characteristics of machining, such as material removal rate and surface roughness on Ti-6Al-4V has been analyzed.

EXPERIMENTAL DETAILS

The experiments are carried out utilizing a numerical control programming to EDM known as the "LN power supply AQ55L". The EDM has provision for movement in three axes: longitudinal (X-axis), lateral (Y-axis), and vertical, in the direction of the electrode (Z-axis) and it also has a rotary U-axis with maximum rpm ±40. In this effort, titanium alloy (Ti-6Al-4V) was selected as the workpiece material and a cylindrical copper electrode was employed to machine the workpiece. Pulse on time (ti) refers to the duration (µs) for which current is allowed to flow per cycle (Puertas & Luis, 2003). Pulse off time (t_o) is the duration (µs) between sparks. The machining was usually carried out for a fixed time and the listing of the experimental parameters is presented in Table 1. The surface roughness was assessed by using the Surface Roughness

Perthometer manufactured by Mahr (Surf PS1). Three observations were taken for each sample and averaged in order to obtain the value of roughness (R_a). The surface roughness of the workpiece can be expressed in different ways, including the arithmetic average (R_a), average peak-to-valley height (R_z), or peak roughness (R_P), etc. Generally, SR is measured in terms of the arithmetic mean according to ISO 4287: 1999, which is defined as the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement (Wu, Yan, Huang & Chen, 2005). Hence, the arithmetic mean or average SR is considered in this study for the assessment of roughness.

Table 1. Experimental settings.

Working parameters	Description
Workpiece material	Ti-6Al-4V
Size of workpiece	22 mm × 22 mm × 20 mm
Electrode material and size	Copper
Size of electrode	ϕ 19 mm × 50 mm (length)
Electrode polarity	Negative
Dielectric fluid	Commercial Kerosene
Applied voltage	120 V
Servo voltage	70 V
Flushing pressure	1.75 MPa
Machining time	30 Minutes

Experimental Design

The main objective of the experimental design is study the relations between the response as a dependent variable and the various parameter levels. It provides the prospect of studying not only the individual effects of each factor, but also their interactions (Singh, 2011). The design of experiments for exploring the influence of various predominant EDM process parameters, e.g., peak current, pulse on time, and pulse off time on the machining characteristics of the material removal rate (MRR) modeled. In the present work, experiments were designed based on the experimental design technique of RSM. The coded levels for all process parameters used are displayed in Table 2. The set of designed experiments in order to obtain an optimal response utilizing the Box-Behnken type of design is presented in Table 3.

Table 2. Machining parameters and their levels.

Designation	Process parameters	Levels		
		-1	0	1
x_1	Peak current (A)	2	16	30
x_2	Pulse on time (μs)	10	205	400
x_3	Pulse of time (μs)	50	175	300

Table 3. Set of designed experiments for different parameters.

Expt. No.	Peak current (A)	Pulse on time (μs)	Pulse of time (μs)
1	0	0	0
2	1	1	0
3	1	0	-1
4	-1	0	1
5	0	-1	1
6	0	0	0
7	-1	1	0
8	-1	0	-1
9	0	1	-1
10	-1	-1	0
11	0	0	0
12	0	1	1
13	1	0	1
14	1	-1	0
15	0	-1	-1

Regression Model

In this work, RSM is utilized for determining the relations between the various EDM process parameters and the various machining criteria, and for exploring their effects on the response of the surface finish. To perform this effort, single order response surfaces in mathematical models can be developed. In the general case, the response is expressed by the linear equation of the form (Habib, 2009):

$$Y = C_0 + \sum_{i=1}^{n} C_i x_i \tag{2}$$

where Y is the corresponding response, SR yield by the various EDM process variables and x_i (*1,2, . . . , n*) are coded levels of n quantitative process variables, and the terms C_0, and C_i are the single order regression coefficients. The second term under the summation sign of this polynomial equation is attributable to the linear effect. Equation (2) can be rewritten as in (3), according to the three variables (Habib, 2009):

$$Y = C_o + C_1 x_1 + C_2 x_2 + C_3 x_3 \tag{3}$$

where x_1, x_2, and x_3 are peak current (I_p), pulse on time (t_i), and pulse off time (t_o), respectively.

The values of the different constants of (3) have been evaluated, as shown in Table 4, by using statistical software. It is observed in Table 4 that the linear terms I_p and t_i are significant; however, the term t_o is non-significant. Based on (3), the final mathematical relationship for correlating SR and the considered process variables was obtained as follows:

$$SR = 4.1514 + 1.7596 I_P + 1.0722 t_i + 0.2940 t_o \tag{4}$$

For data analysis, the checking of adequacy of fit of the model is also essential. The adequacy verification of the model includes the test for significance of the regression model, the test for significance on model coefficients, and the test for lack of fit. An analysis of variance for the adequacy of the model is performed in the subsequent step and shown in Tables 4 and 5. The F ratio is calculated for 95% level of confidence. A P-value of less than 0.05 is considered significant and a P-value greater than 0.05 is considered non-significant.

Table 4. Estimated regression coefficients.

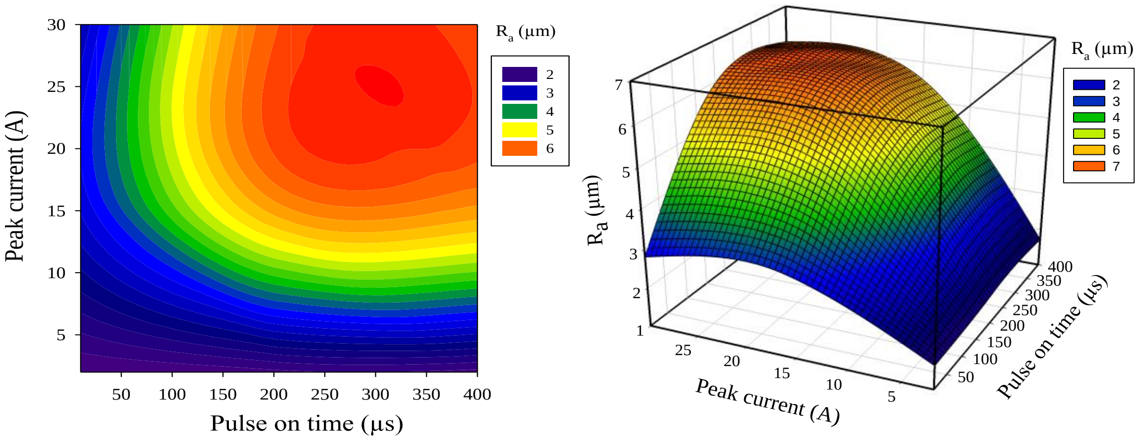
Term	Coefficient	SE Coef	T	P	Remark
Constant	4.1514	0.3386	12.261	0.000	Most significant
Peak current (A)	1.7596	0.4636	3.795	0.003	Significant
Pulse on time (µs)	1.0722	0.4636	2.313	0.041	Significant
Pulse off time (µs)	0.2940	0.4636	0.634	0.539	Non-significant

Table 5. Analysis of variance.

Source of variation	Degree of freedom	Sum of squares	Mean squares	F-ratio	P
Regression	3	34.6589	11.5530	6.72	0.008
Linear	3	34.6589	11.5530	6.72	0.008
Residual error	11	18.9151	1.7196		
Lack-of-Fit	9	18.4756	2.0528	9.34	0.100
Pure Error	2	0.4394	0.2197		
Total	14	53.5740			

RESULTS AND DISCUSSION

Figure 1 exhibits the influence of peak current and pulse on time on SR. It can be observed from the plots that an increase in peak current produces a rough surface. This is because when the pulse current increases, a more intense discharge strikes the surface and a greater quantity of molten and floating metal is suspended in the electrical discharge gap during EDM. The higher pulse energy increases the metal removal rate and that affects the SR (Habib, 2009). Therefore, an increase in peak amperes increases the discharge energy and the energy intensity deteriorates the surface finish of the workpiece. Similarly, SR increases as the pulse on time increases. Long pulse duration causes more heat transfer to the sample and the dielectric fluid is unable to clear away the extra molten material because the flushing pressure is constant. In other words, while the pulse on time is increased, the melting isothermals penetrate further into the interior of the material and the molten zone extends further into material, which produces a greater white layer thickness. Accordingly, as the pulse duration increases, the SR increases; this result is supported by the work of Hascalık and Caydas (2007). Small pulse duration causes more discharges per second. Thus, by applying the same current, short pulse on time creates smaller craters producing a fine surface finish. An excellent surface finish is detected in this experiment while the pulse on time is below 80 µs for all values of peak current.



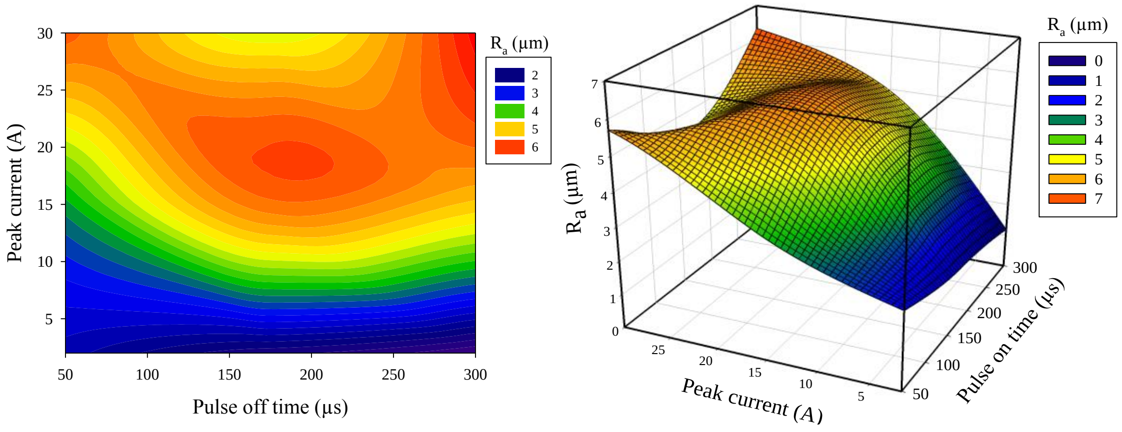
(a) 2-D contour plot (b) 3-D surface plot

Figure 1. Effect of peak current and pulse on time on R_a.

It is apparent from Figure 2 that a low pulse off time provides a better surface finish and an increasing pulse off time deteriorates the surface finish until a certain value of the pulse interval, beyond which the surface finish improves. This can be explained by the high frequency and low power combination leading to a low material removal rate and a fine surface finish (Drof & Kusiak, 1994). Accordingly, a short pulse off time forms the higher frequency that yields the lower SR. On the other hand, a long pulse off time yields low metal removal, such that smaller and shallower craters are attained. The long pulse interval provides a good cooling effect and sufficient time for molten material and debris to be flushed from the gap between the electrode and workpiece. Thus, a long pulse off time presents low SR (Rahman, Khan, Kadirgama, Noor & Bakar, 2010). The finest surface is acquired in this research with low ampere values and long pulse off time. This study corroborated that a pulse off time ≤ 80 µs yields comparatively the better surface finish with ampere values of greater than 5. Therefore, it can be concluded in this investigation that the influence of peak current on SR is more significant than that of pulse off time for long pulse intervals. The influence of pulse off time on SR is more significant than the ampere value at low pulse intervals. This can also be found in the research of Kiyak and Cakir (2007). An attempt is made to estimate the optimum machining setting in order to build the best possible MRR and surface finish within the experimental constraints. The obtained optimum values of the parameters are shown in Table 6. Optimum machining parameter combinations for different EDM characteristics are also tested, as shown in Table 7, through confirmation experiments that verify reasonably good concurrence with the prediction of the RSM.

Table 6. Optimal values.

Process parameters	Optimum values
Peak current (A)	2
Pulse on time (µs)	10
Pulse off time (µs)	300



(a) 2-D contour plot (b) 3-D surface plot

Figure 2. Effect of peak current and pulse off time on R_a.

Table 7. Confirmation tests and their comparison with results

Trial No.	Optimum conditions	Surface Roughness (µm)		Error (%)
		Experimental	Predicted	
1	I_p = 2 A, t_i=10 µs and t_o=300 µs	1.0830	1.02555	5.30
2	I_p = 2 A, t_i=10 µs and t_o=300 µs	0.9836	1.02555	-4.26

CONCLUSIONS

An increase of peak current causes a rough surface finish. The product of high ampere and high pulse on time deteriorate the surface finish even more. The finest surface finish is observed at a pulse on time of about <50 µs for all values of ampere. The combination of high ampere (>15 A) and long pulse duration (>180 µs) generate the poorest surface in this experiment. A fine surface finish is obtained at low pulse off time, and an increasing pulse off time deteriorates the surface finish until a certain value of pulse interval, beyond which the quality of the surface finish improves. The influence of peak current on SR varies with pulse interval and correspondingly, the effect of pulse off time on SR fluctuates with peak ampere. The empirical values of the EDM parameters for optimum machining efficiency are 2 A peak current, 10 µs pulse on time, and 300 µs pulse off time.

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