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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 the various electrical discharge machining (EDM) parameters and performance characteristics utilizing relevant experimental data as obtained through experimentation. Besides the effect of the peak ampere, pulse on time and pulse off time on surface roughness has been investigated. Experiments have been conducted on titanium alloy Ti-6Al-4V with copper electrode retaining negative polarity as per Design of experiments (DOE). Response surface methodology (RSM) techniques are utilized to develop the mathematical model as well as to optimize the EDM parameters. Analysis of Variance (ANOVA) 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 the fine surface until a certain value and afterward deteriorates in the surface finish. The excellent surface finish is investigated in this study in the case of the pulse on time below 80 μs. This result guides to pick the required process outputs and economic industrial machining conditions optimizing the input factors.

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

INTRODUCTION

In aerospace industry, titanium alloys have been widely used because of their low weight, high strength and high temperatures stability (Fonda et al., 2008). 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 (Rahman et al., 2006). 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 (Prabhu and Vinayagam, 2009). EDM has proved especially valuable in the machining of super-tough and any electrically conductive materials (Lee and Li, 2001). It has been widely applied in modern metal industry for producing complex cavities in moulds 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 manufacturing of mold, die, automotive, aerospace and surgical components (Ponappa et al., 2010). Thus, titanium and titanium alloy, which is difficult-to-cut material, can be machined effectively by EDM (Yan et al., 2005). Proper selection of the machining parameters can result in a higher material removal rate, better surface finish, and lower electrode wear ratio (lin et al., 2002). A study has been carried out to develop a mathematical model for optimising the EDM characteristics on matrix composite Al/SiC material (Habib, 2009). 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 (Fonda et al., 2008). They state that the duty factor, ratio of pulse duration to total pulse time, is a vital EDM 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, 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 electrical discharge machining parameters, especially for titanium alloys, for the best process performance is still a challenging job (Mandal et al., 2009). Optimal selection of process parameters is very much essential as this 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 and Tsai, 2001). Machining parameter optimization for the titanium alloy material Ti-6Al-4V has been carried out using the techniques of design of experiments (DOE) method and response surface methodology (RSM). The single-order model is used to predict the responses of the EDM process. Also the effect of input parameters on the characteristic 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 electrical discharge machine known as ‘‘LN power supply AQ55L”. The EDM has the provisions of movement in three axes such as longitudinal (*X*-axis), lateral (*Y*-axis) and vertical direction of the electrode (*Z*-axis) and has also a rotary *U*-axis with maximum rpm ±40. In this effort, titanium alloy (Ti-6Al-4V) was selected as the workpiece material and cylindrical copper electrode were employed to machine the workpiece. Pulse on-time (ti) refers the duration of time (μs) in which the current is allowed to flow per cycle (Puertas and Luis, 2003). Pulse off-time (t_o) is the duration of time (μs) between the sparks. The machining was usually carried out for a fixed time and the listing of experimental parameters is scheduled in Table 1. The surface roughness was assessed with Surface Roughness Perthometer manufactured by Mahr (Surf PS1). Three observations were taken for each sample and were averaged to get the value of roughness (R_a). 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 the arithmetic mean according to ISO 4287: 1999 which defined as the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement (Wu et al., 2005). Hence, arithmetic mean or average surface roughness is considered in this study for assessment of roughness.

Table 1. Experimental settings

Working parameters	**Description**
Work piece material	Ti-6Al-4V
Size of work piece	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 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, e.g. peak current, pulse on time and pulse off time on the machining characteristics of MRR modeled. In the present work experiments were designed based on experimental design technique using response surface design method. The coded levels for all process parameters used are displayed in Table 2. The set of designed experiments to obtain an optimal response utilizing 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, response surface methodology is utilized for determining the relations between the various EDM process parameters with the various machining criteria and exploring their effects on the responses of 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 the x_i $(1,2, \ldots, n)$ are coded levels of n quantitative process variables, 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 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 Equation (3) have been evaluated as shown in Table 4 using statistical software. It is observed in Table 4 that the linear term's I_p and t_i are significant nevertheless the term t_o is non-significant. Based on Equation (3), the final mathematical relationship for correlating the 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, test for significance on model coefficients, and test for lack of fit. Analysis of variance (ANOVA) for the adequacy of the model is then performed in the subsequent step and shown in Table 4-5. The F ratio is calculated for 95% level of confidence. The P-value which is less than 0.05 is considered significant and the P-value greater than 0.05 is not significant.

Table 4. Estimated regression coefficients

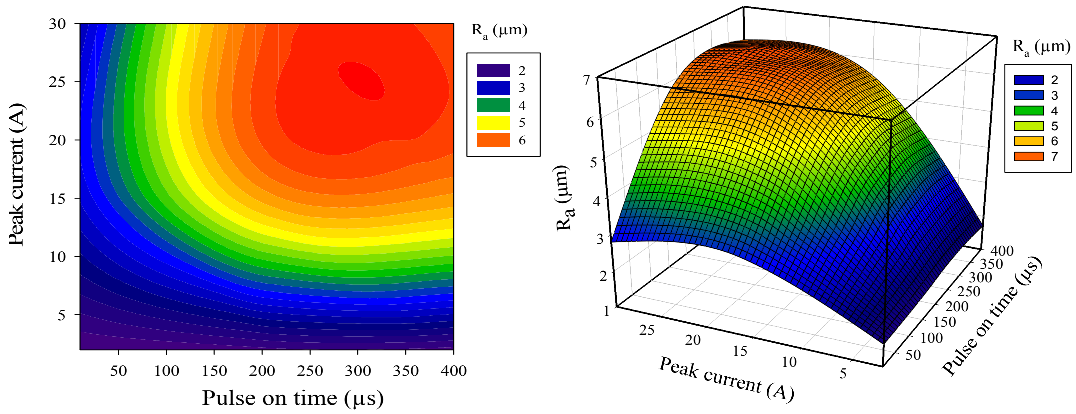
Term	Coefficient	SE Coef	T	P	Remark
Constant	4.1514	0.3386	12.261	0.000	Most significant
Peak current (A)	1.7596	0.4636	3.795	0.003	Significant
Pulse on time (μs)	1.0722	0.4636	2.313	0.041	Significant
Pulse off time (μs)	0.2940	0.4636	0.634	0.539	Non Significant

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

Figures 1 exhibits the influence of peak current and pulse on time on surface roughness. It is observed from the plots that increase peak current produce rough surface. This is due to the fact that when the pulse current increase, more intensely discharges to strike the surfaces and a great quantity of molten and floating metal suspended in the electrical discharge gap during EDM. The higher pulse energy increases the metal removal rate and that set off the rough surface (Habib, 2009). Therefore, increase peak ampere increases the discharge energy and energy intensity that deteriorates in the surface finish of the workpiece. Similarly surface roughness increases as the pulse on time increase. Long pulse duration causes the more heat transfer into the sample and the dielectric fluid is unable to clear away the molten material, as 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 and this produce a greater white layer thickness. Accordingly, as the pulse duration increase the surface roughness increase that can be supported by Hascalık and Caydas (2007). Accordingly, as the pulse duration increase the surface roughness increase that can also be supported by Hascalık and Caydas (2007). Small pulse duration causes more discharges per second. Thus applying the same current, short pulse on time creates smaller craters producing a fine surface finish. The excellent surface finish is detected in this experimentation while the pulse on time below 80 μs at the all values of peak current.



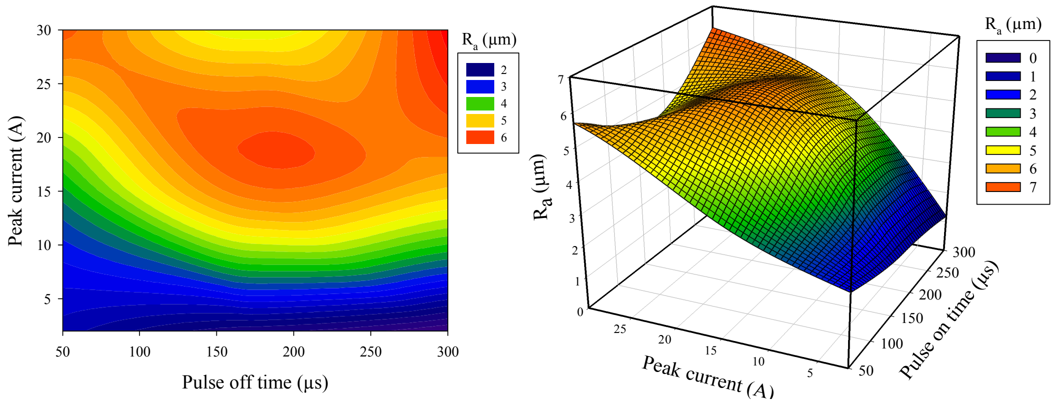
(a) 2-D contour plot (b) 3-D surface plot

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

It is apparent to Figure 2 that the low pulse off time provides the better surface finish and increasing pulse off time deteriorates in surface finish untila certain value of the pulse interval and subsequently improves the surface finish. It can be explained as the high frequency and low power combination lead to low material removal rate and fine surface finish (Drof and Kusiak, 1994). Accordingly short pulse off time forms the higher frequency that yields low surface roughness. On the other hand, long pulse off time yields low metal removal so that smaller and shallow craters are attained. The long pulse interval provides good cooling effect and enough time to flush away the molten material and debris from the gap between the electrode and workpiece. Thus, long pulse off time presents low surface roughness (Rahman et al., 2010). Finest surface is acquired in this research at the low ampere and long pulse off time. This study corroborated that the pulse off time $\leq$ 80 µs yields comparatively the better surface finish at the ampere of greater than 5. Therefore, it can be concluded in this investigation that the influence of peak current on SR is more significant than the pulse off time at the long pulse intervals. Differently influence of pulse off time on SR is more significant than the ampere at the low pulse intervals. It can also be found in the research of (Kiyak and Cakir, 2007). An attempt is fulfilled to estimate the optimum machining setting 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 response surface method.

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 test 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

Increase peak current causes the rough surface finish. The product of high ampere and high pulse on time deteriorate in the surface finish more. The finer surface finish is observed at about the pulse on time <50 µs for the all values of ampere. The combination of high ampere (>15 A) and long pulse duration (>180 µs) generate the worst surface in this experiment.Fine surface finish is obtained at the low pulse off time and increasing pulse off time deteriorates in surface finish untilthe certain value of the pulse interval and subsequently improves the surface finish. The influence of peak current on SR varies as the pulse interval and correspondingly the effect of pulse off time on SR fluctuates as peak ampere. The empirical values of the EDM parameters for optimum machining efficiency are 2 A peak current, 10 µs pulse on time and 300µs pulse off time.

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