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Modeling of Material Removal on Machining of Ti-6Al-4V through EDM using Copper Tungsten Electrode and Positive Polarity

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***Abstract*—**This paper deals optimized model to investigate the effects of peak current, pulse on time and pulse off time in EDM performance on material removal rate of titanium alloy utilizing copper tungsten as electrode and positive polarity of the electrode. The experiments are carried out on Ti6Al4V. Experiments were conducted by varying the peak current, pulse on time and pulse off time. A mathematical model is developed to correlate the influences of these variables and material removal rate of workpiece. Design of experiments (DOE) method and response surface methodology (RSM) techniques are implemented. The validity test of the fit and adequacy of the proposed models has been carried out through analysis of variance (ANOVA). The obtained results evidence that as the material removal rate increases as peak current and pulse on time increases. The effect of pulse off time on MRR changes with peak ampere. The optimum machining conditions in favor of material removal rate are verified and compared. The optimum machining conditions in favor of material removal rate are estimated and verified with proposed optimized results. It is observed that the developed model is within the limits of the agreeable error (about 4%) when compared to experimental results. This result leads to desirable material removal rate and economical industrial machining to optimize the input parameters.

***Keywords*—**Ti-6Al-4V, material removal rate, copper tungsten, positive polarity, RSM.

I. Introduction

TITANIUM alloys have received considerable interest recently due to their excellent corrosion resistance, high strength-to-weight ratio, high strength at elevated temperatures and biological compatibility. In this manner, they are used in a wide range of applications in the aerospace, automotive, chemical and medical industries. However, the main reason for the increase in demand for titanium in the past few years has been the large consumption in the aerospace sector [1]. The excellent strength-to-weight ratio of titanium alloys provides a decrease of aircraft weight and, therefore, a reduction in fuel consumption and emissions. Moreover, the other typical aerospace material, aluminum, is electrochemically incompatible with the increasingly applied composite materials that form a galvanic couple. Titanium does not pose this problem and, thus, is replacing aluminum in many applications [2]. In spite of the optimal features of titanium alloys, their usage is limited by the high costs, which arise because of the complex procurement process of titanium and their processing difficulties, e.g. poor machinability [3]. In fact, as reported [4], titanium alloys are some of the hardest materials to cut because of their poor thermal conductivity, strength at high temperatures and chemical reactivity with tool materials. The most common titanium alloy is Ti6Al4V, which accounts for more than 50% of the titanium-alloy production. Manufacturing industry is becoming ever more time conscious with regard to the global economy, and the need for rapid prototyping and small production batches is increasing. These trends have placed a premium on the use of new and advanced technologies for quickly turning raw materials into usable goods; with no time being required for tooling.

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 immersed in a dielectric fluid [5]. 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]. 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 [7]. Thus, titanium and titanium alloy, which is difficult-to-cut material, can be machined effectively by EDM [8].

Proper selection of the machining parameters can result in a higher material removal rate, better surface finish, and lower

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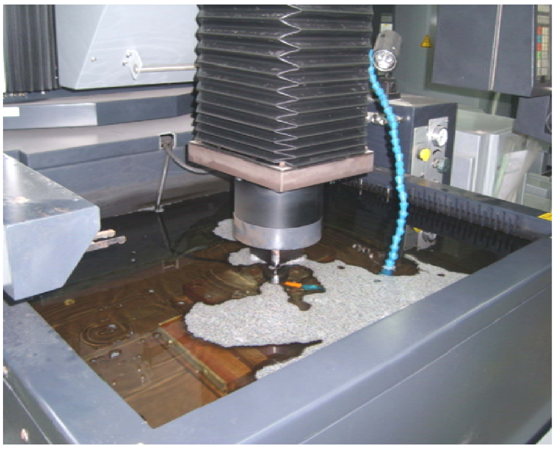
electrode wear ratio [9]. The electrical discharge machining (EDM) of titanium alloy (Ti–6Al–4V) with different electrode materials has been accomplished to explore the influence of EDM parameters on various aspects of the surface integrity of Ti6Al4V [10]. A study has been carried out to develop a mathematical model for optimising the EDM characteristics on matrix composite Al/SiC material [11]. 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 [12]. To investigate the relationships and parametric interactions between the variables on the material removal rate (MRR) using response surface methodology experiments have been conducted on AISI D2 tool steel with Cu electrode [13]. It was acquired that discharge current, pulse duration, and pulse off time affect the MRR significantly. Their observation illustrates that the highest MRR values appeared at the higher ampere and pulse on time and at the lower pulse off time. Optimal selection of process parameters is very much essential as this is a costly process to increase production rate considerably by reducing the machining time. Thus, the present paper emphasizes the development of optimization models to correlate the various machining parameters such as peak current (I_P), pulse on time (t_i) and pulse off time (t_o) on material removal rate (MRR). Machining parameters optimization for the titanium alloy material Ti-6Al-4V carried out using the techniques of design of experiments (DOE) method and response surface methodology (RSM). The effect of input parameters on MRR in EDM process of Ti-6Al-4V has been analyzed.

II. Material and Methodology

Pulse on time (t_i) refers the duration of time (µs) in which the current is allowed to flow per cycle [14]. Pulse off time and also known as pulse interval (t_o) is the duration of time (µs) between the sparks. The experiments are carried out utilizing a numerical control programming 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 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 Tungsten (CuW) electrode were employed for machining the workpiece. The experimental setup is shown in Fig. 1. The machining was usually carried out for a fixed time interval. The listing of experimental parameters is scheduled in Table I. The weight of the workpiece and electrode before and after machining were measured by a digital balance, AND GR-200 with readability of 0.1mg and the surface roughness was assessed with Perthometer, Mahr Surf PS1.



(a) EDM at machining state.

(b) EDM tank with electrode and workpiece.

Fig. 1 Experimental setup of electrical discharge machining.

The amount of metal removed was measured by taking the difference in weights of the workpiece before and after electrical discharge machining. The MRR is expressed as the weight of material removed from workpiece over a period of machining time in minutes [15]. The MRR was calculated by the formula as expressed in (1) [11]:

$$\text{MRR} = \frac{1000 \times W_w}{\rho_w \times T} mm^3/\text{min} \qquad (1)$$

where, W_w is the weight loss of the workpiece in gm;
ρ_w is the density of the workpiece material (Density of Ti-6Al-4V is 4.37 g/cm^3);
T is the machining time in minutes;

TABLE I
EXPERIMENTAL SETTINGS

Parameters	Description
Work piece material	Ti-6Al-4V
Work piece size	25 mm × 25 mm × 20 mm
Electrode material	Copper Tungsten
Electrode size (diameter × length)	20 mm × 44 mm
Electrode polarity	Positive
Dielectric fluid	Commercial Kerosene
Applied voltage	120 V
Servo voltage	70 V
Flushing pressure	1.75 MPa
Machining time	30 Minutes

A. Design of Experiment

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 and pulse off time on the machining characteristics such as material removal rate was 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. The set of design parameters of experiments to obtain an optimal response utilizing box-behnken type of design is presented in Table III.

TABLE II
MACHINING PARAMETERS AND THEIR LEVELS

Designation	Process parameters	Levels		
		Lowest	Medium	Highest
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 III
DESIGN PARAMETERS

Experiment No.	Peak Current (A)	Pulse on time (µs)	Pulse off 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

B. Response Surface Approach

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 MRR. To perform this task second order polynomial response surface mathematical models can be developed. In the general case, the response surface is described as (2):

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

where, Y is the corresponding response of MRR 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, 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. Equation (2) can be rewritten according to the three variables used as in (3):

$$\begin{aligned} Y &= C_0 + C_1 x_1 + C_2 x_2 + C_3 x_3 + C_{11} x_1^2 + C_{22} x_2^2 \\ &+ C_{33} x_3^2 + C_{12} x_1 x_2 + C_{13} x_1 x_3 + C_{23} x_2 x_3 \end{aligned} \tag{3}$$

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. Equation of the fitted model for MRR is represented in (4):

$$\begin{aligned} \text{MRR} &= 0.90095 + 0.86652\, I_p + 0.40632\, t_i - 0.07574\, t_o \\ &+ 0.23562\, I_p^2 - 0.23825 t_i^2 - 0.04123\, t_o^2 \\ &+ 0.35298\, I_p t_i - 0.02454\, I_p t_o - 0.04957\, t_i t_o \end{aligned} \tag{4}$$

The adequacy of the above three proposed models have been tested on behalf of both cases, linear and quadratic by means of analysis of variance (ANOVA) as shown in Table IV. 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 Table 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-value of the residual error in quadratic term 0.142 for MRR is not less than α-level (0.05). The results of the analysis justifying the closeness of fit of the mathematical models are enumerated. Therefore it can be concluded that the evolved models given by (4) has been adequately explained the variation in the machining parameters on MRR.

TABLE IV
ANALYSIS OF VARIANCE (ANOVA)

Source of variation	Degree of freedom	Sum of squares	Mean squares	F-ratio	P
Regression					
Linear	3	7.37355	2.45785	25.65	0.000
Quadratic	9	8.33958	0.92662	52.74	0.000
Error					
Linear	11	1.05388	0.09581	27.24	0.036
Quadratic	5	0.08785	0.01757	6.20	0.142
Total					
Linear	14	8.42743			
Quadratic	14	8.42743			

III. RESULTS AND DISCUSSION

Fig. 2 and Fig.3 are presented the influence of peak current and pulse on time on material removal rate. The experimental results evidence that increasing peak ampere increase the material removal rate for pulse on time. In EDM process, the material removal rate is a function of electrical discharge energy. The increase of peak current generates high energy intensity and due to this energy melts more material from the workpiece. Thus material removal rate increases with increases of peak current. The effect of pulse on time on MRR is appeared as, the MRR increases with increase of pulse on time at all amperes. In general, the power of the spark and frequency defined by the number of pulse per second determine the process performance [16]. The low frequency and high power combination results in high metal removal. As pulse on time increases the frequency reduces and consequently the long pulse duration increases material removal. It is revealed from the results that the combination of high pulse on time and high power conceive more MRR. The same results are achieved by the researches of [13] and [17].

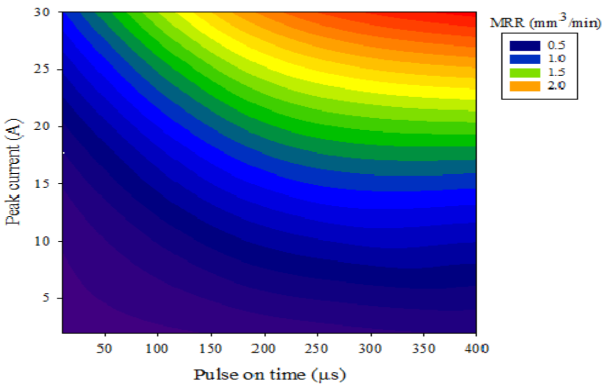


Fig. 2 The effect of peak current and pulse on time against material removal rate (2-D contour plot).

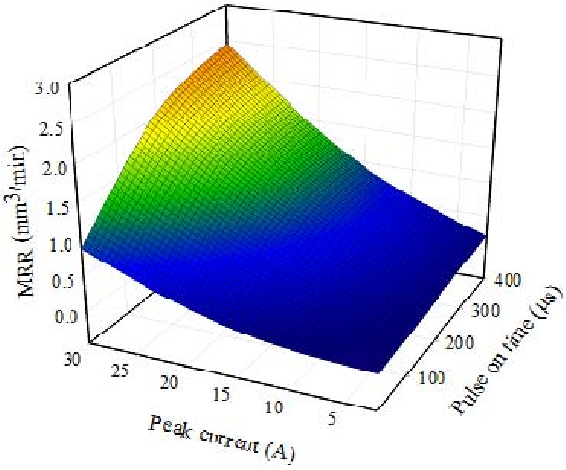


Fig. 3 The effect of peak current and pulse on time against material removal rate (3-D contour).

The impact of peak current and pulse off time on MRR are illustrated in the Fig. 4 and Fig. 5. These 2-D contour plot and 3-D surface plot shows that increasing peak current increases the MRR on the other hand the pulse off time exhibits dissimilar effect on MRR. At the range of discharge current 2-23A, the MRR initially increases little and then decreases with increasing pulse off time however at the peak current >23 the MRR decreases with pulse off time. In another words, the short the pulse off time the more the MRR and the long the pulse off time the small the MRR while peak current >23. The reason of first observation can be explained as the pulse interval must be sufficiently long so that the plasma generated by the previous discharge can be deionized and the dielectric breakdown strength around the previous discharge location can be recovered [18]. The insufficient interval time between pulse discharges results thermal overheating and a non uniform erosion of the workpiece. Thus, increase the pulse interval increases the MRR up to certain pulse off time. The cause of the second phenomenon is that during the pulse off time no energy is applied to the workpiece surface and results low MRR. Then again, since the time available for the application of heat energy on the workpiece surface, the top surface temperature of the workpiece increases as the pulse off time decreases. Thus, the material is eroded at faster rate and that commence MRR more at the short pulse off time. The same observation is reported by [13],[19] and [20]. It can be perceived from the plots 4-5 that almost 150 μs and 80 μs pulse interval acquired the maximum MRR at peak current 2-23A and >23A respectively.

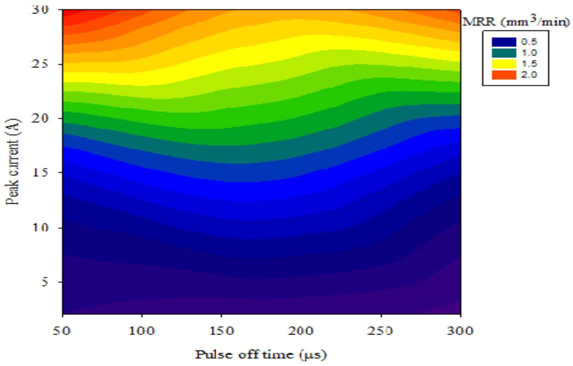


Fig. 4: The effect of peak current and pulse off time on material removal rate (2-D contour plot).

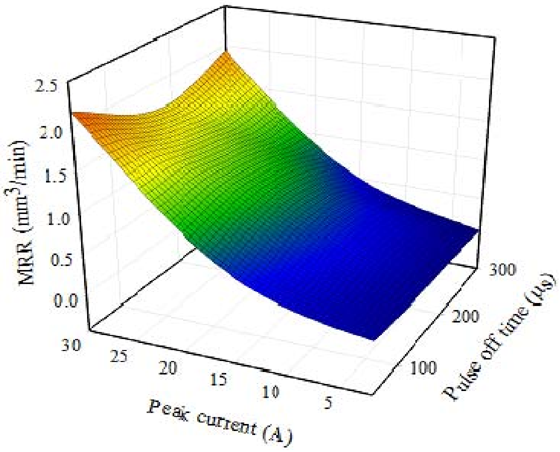


Fig. 5 The effect of peak current and pulse off time against material removal rate (3-D surface plot).

A. Optimum Settings in EDM process and Validation

The settings for titanium alloys have to be further optimized experimentally. It is also aimed to select appropriate machining conditions for the EDM process based on the analysis relating the various process parameters to MRR. It is aimed to develop a methodology using an input–output pattern of data from an EDM process to solve both the modeling and optimization problems. The main objective of this research is to model EDM process for optimum operation representing a particular problem in the manufacturing environment where, it is not possible to define the optimization objective function using a smooth and continuous mathematical formula. It has been hard to establish models that accurately correlate the process variables and performance of EDM process. An attempt is fulfilled to estimate the optimum machining setting to build the best possible material removal rate, surface finish and electrode wear rate within the experimental constraints. The obtained optimum values of the parameters in EDM on Ti-6Al-4V utilizing Copper Tungsten as electrode are shown in Table V. Optimum machining parameter combinations for different EDM characteristics are tested and presented in Table VI through confirmation experiments that verify reasonably good concurrence with prediction of response surface method.

TABLE V
OPTIMAL SET-UP FOR MRR

Process parameters	Optimized Settings
Peak current (A)	30
Pulse on time (µs)	400
Pulse off time (µs)	50

TABLE VI
CONFIRMATION TEST AND THEIR COMPARISON WITH EXPERIMENTAL RESULTS

TRIAL NO.	OPTIMUM CONDITIONS	MRR (µM) EXPERIMENTAL	MRR (µM) PREDICTED	ERROR (%)
1	I_p = 30A, t_i=400 µs and t_o=50 µs	2.5573	2.63277	2.95
2	I_p = 30 A, t_i=400 µs and t_o=50 µs	2.5462	2.63277	3.40

IV. CONCLUSION

This experiment was accomplished to investigate the influence of the peak current, pulse on time and pulse off time on the EDM performance characteristics. It was also attempted to formulate mathematical model for the responses such as material removal rate, surface roughness and tool wear rate and finally to detect the optimal settings of the parameters for the same EDM characteristics. The conclusions from the analysis of this experimental interpretation can be stipulated as follows.

i. The MRR is influenced considerably by peak ampere and pulse on time. A significant impact of pulse off time on the material removal rate is also investigated. The material removal rate increases with current and as well as pulse on time. The different effect of pulse off time on material removal rate is noticed. The influence of pulse interval on MRR changes with peak ampere. Medium value of pulse off time about 150 µs and low value of pulse off time about 80 µs persuade the largest MRR while the discharge current are 2-23A and >23A respectively.
ii. The empirical values of the EDM parameters for optimum machining efficiency are 30 A peak current, 400 µs pulse on time and 50 µs pulse interval in the case of MRR. Likewise the detected values of EDM parameters in the case of optimal surface finish are 2 A discharges current, 400 µs pulse on time and 232 µs pulse off time. Similarly 12 A peak current, 10 µs pulse duration and 280 µs pulse off time settings allow the optimal tool wear rate.

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