MODELLING AND OPTIMIZATION OF PERFORMANCE CHARACTERISTICS IN ELECTRICAL DISCHARGE MACHINING ON TITANIUM ALLOY

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Abstract: *Electrical discharge machining (EDM) technique possesses noticeable advantages over other machining process and can machine any hard material effectively. Proper selection of parameters in EDM is very much essential to achieve better performance characteristics that are still challenging. This study attempts to investigate the effects of parameters on EDM performance characteristics on Ti-6Al-4V utilizing copper tungsten as electrode and negative polarity of the electrode. Mathematical model associating the influences of these variables and the EDM characteristics such as material removal rate (MRR) and tool wear rate (TWR) are set up in this study. The optimal machining conditioning in favor of MRR and TWR are estimated. Design of experiments method and response surface methodology techniques are adopted to attain the objectives. Analysis of variance (ANOVA) has been performed for the validity test of the fit and adequacy of the proposed models. Optimum MRR is found at high discharge ampere, long pulse on time and short pulse off time. 8A peak current, 10 µs pulse on time and 184 µs pulse interval yields lowest TWR. The result of this investigation guides to required process outputs and economical industrial machining optimizing the input factors.*

Keywords: *Material removal rate, Optimum set up, Response Surface Methodology and Tool wear rate.*

INTRODUCTION

Electric discharge machining is a non-conventional type of precision process employing an electrical spark-erosion procedure between the electrode and the working piece of electrically conductive immersed in a dielectric fluid[1]. Due to its special gains, the EDM has been widely utilized in modern metal industry for producing complex cavities in moulds and dies, which are difficult to manufacture by conventional machining. Its unique characteristic of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinct advantage for manufacturing of mold, die, automotive, aerospace and surgical components[2,3]. Titanium alloys are widely used in aerospace industry as well as in other industry sectors such as compressors used for generation, petrochemical plants and medical devices[4]. Ti-6Al-4V alloy is unique in that it combines attractive properties with inherent machinability. 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. It is very difficult to machine titanium alloys economically with traditional techniques due to their poor machinability[5]. Thus, titanium and titanium alloy, which is difficult-to-cut material, can be machined effectively by EDM[6,7].

Several researches have been carried out for improving the process performance and for detection optimum parameters as follows. The Taguchi method was used to identify the significant parameters in the screening experiments[8]. At this level, three types of materials, namely copper, graphite, and silver–tungsten alloy, were used for the tool; while three different grades of steel as AISI EK2, AISI D2 and AISI H13 were used for the workpiece. From the final results it is appeared that the model is dependent on work and tool materials. The electrical discharge machining of titanium alloy (Ti–6Al–4V) with different electrode materials was performed to explore the influence of EDM parameters on various aspects of the surface integrity of Ti6Al4V[9]. 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[10]. 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. Tomadi et al. researched to get the optimum machining conditions for machining Tungsten Carbide with a Copper Tungsten as electrode[11]. 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. 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[12]. It has been reported that the MRR depend on the tool material and the maximum TWR is reached at the points of maximum MRR.

From the literature study, it was appeared that the EDM performance characteristics are greatly reliant with work and tool materials. Therefore, constant parameters cannot be used for dissimilar work and tool materials. 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 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 EDM criteria i.e. material removal rate and tool wear rate. Machining parameters 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). Second-order polynomial 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 tool wear rate on Ti-6Al-4V has been analyzed.

EXPERIMENTAL DETAIL

Process Parameters

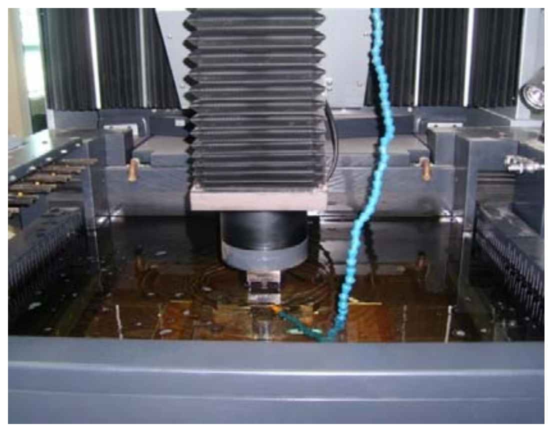
Peak current (I_p) is the maximum current during spark[13]. Pulse on-time (t_i) refers the duration of time (μs) in which the current is allowed to flow per cycle[13,14]. Pulse off-time (t_o) is the duration of time (μs) between the sparks. The experiments are carried out utilizing a numerical control programming electrical discharge machine known as ‘‘LN power supply AQ55L”. In this effort, titanium alloy (Ti-6Al-4V) was selected as the workpiece material and cylindrical copper tungsten electrode was employed to machine the workpiece. The experimental setup is shown in Fig. 1.

The weight of the workpiece and electrode before and after machining were measured by a digital balance. Three observations were taken for each sample and were averaged to get the value of MRR and TWR. 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 Eq. (1)[16,17]:

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

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 4.39 g/cm^3); T is the machining time in minutes.

(a) Photograph of the EDM at machining



b) Photograph of the EDM tank and sample at operational condition.

Figure 1. Experimental setup of electrical discharge machining

The electrode wear rate was calculated from the weight difference of electrode before and after machining as expressed in Eq. (2)[3]:

$$\text{TWR} = \frac{100 \times W_e}{\rho_e \times T} mm^3/\min \qquad (2)$$

where, W_e is the weight loss of the electrode in gm; ρ_e is the density of the electrode material (Density of CuW is 14.45 g/cm^3); T is the machining time in minutes.

Experimental Design

In the present work experiments were designed on the basis of experimental design technique using response surface design method. The set of designed experiments to obtain an optimal response utilizing box-behnken type of design is presented in Table 1.

Table 1. Set of Designed Experiments for Different Parameters

Exp. No.	Peak current (A)	Pulse on time (µs)	Pulse off time (µs)
1	16	205	175
2	30	400	175
3	30	205	50
4	2	205	300
5	16	10	300
6	16	205	175
7	2	400	175
8	2	205	50
9	16	400	50
10	2	10	175
11	16	205	175
12	16	400	300
13	30	205	300
14	30	10	175
15	16	10	50

RESPONSE SURFACE MODELLING

Response surface methodology is an assortment of mathematical and statistical techniques that are useful for the modeling and analysis of problems[3]. A model of the response to some independent input variables can be acquired by applying regression analysis and RSM. 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:

$$Y = C_0 + \sum_{i=1}^{n} C_i x_i + \sum_{i=1}^{n} C_{ii} x_i^2 + \sum_{i=1}^{n-1}\sum_{j=2}^{n} C_{ij} x_{ij} \quad (3)$$

where, Y is the corresponding response, e.g. MRR and TWR 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, the Eq. (3) can be rewritten according to the three variables used as:

$$Y = C_o + C_1x_1 + C_2x_2 + C_3x_3 + C_{11}x_1^2 + C_{22}x_2^2 + C_{33}x_3^2 + C_{12}x_1x_2 + C_{13}x_1x_3 + C_{23}x_2x_3 \quad (4)$$

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 equations of the fitted model for the MRR and TWR are represented in Eq. (5) and Eq. (6) respectively:

For analysis the data, the checking of adequacy of fit of the model is also necessary. 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. Therefore, the adequacy of the above three proposed models have been tested by the analysis of variance and shown in Table 2 and Table 3.

$$\text{MRR} = 0.852417 + 0.814077\, I_p + 0.326286\, t_i - 0.155774\, t_o + 0.501258\, I_p^2 - 0.344412 t_i^2 + 0.059140\, t_o^2 + 0.374812\, I_p t_i - 0.032625\, I_p t_o - 0.007415\, t_i t_o \quad (5)$$

$$\text{TWR} = 0.032433 + 0.018189\, I_p + 0.001250\, t_i - 0.028164\, t_o + 0.032047\, I_p^2 - 0.012880 t_i^2 + 0.035247\, t_o^2 - 0.022050\, I_p t_i - 0.048177\, I_p t_o + 0.004350\, t_i t_o \quad (6)$$

From the fit summary it is obvious that the quadratic model of Eq. (4) is more significant and can be recommended for MRR. The P-values of the lack of fit (0.85 for MRR, and 0.219 for TWR) are 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 Eq. (5) and Eq. (6) have been adequately explained the variation in the machining parameters on MRR and TWR.

Table 2. ANOVA for Material Removal Rate

Source of variation			Degree of freedom	Sum of squares	Mean squares	F-ratio	P
Regression							
	Linear		3	6.34760	2.11587	9.29	0.002
	Quadratic		9	8.39508	2.11587	10.21	0.010
Residual Error							
	Linear	Lack-of-Fit	9	2.47798	0.27533	20.94	0.046
		Pure Error	2	0.02629	0.01315		
	Quadratic	Lack-of-Fit	3	0.4305	0.14350	10.92	0.085
		Pure Error	2	0.02629	0.01315		
Total							
	Linear		14	8.85188			
	Quadratic		14	8.85188			

Table 3. ANOVA for Tool Wear Rate

Source of variation			Degree of freedom	Sum of squares	Mean squares	F-ratio	P
Regression							
	Linear		3	0.009005	0.003002	1.59	0.247
	Quadratic		9	0.029261	0.003251	33.07	0.001
Residual Error							
	Linear	Lack-of-Fit	9	0.020673	0.002297	61.64	0.016
		Pure Error	2	0.000075	0.000037		
	Quadratic	Lack-of-Fit	3	0.000417	0.000139	3.73	0.219
		Pure Error	2	0.000075	0.000037		
Total							
	Linear		14	0.029753			
	Quadratic		14	0.029753			

RESULS AND DISCUSSION

Analysis of the EDM parameters on MRR

The influence of peak current and pulse on time are presented in Fig. 2–3. These figures show that as peak current increases the material removal rate increase through all pulse on time. For the same peak current, an increase in the pulse on time results in higher material erosion rate. However, for too long on time the erosion rate eventually starts decreasing after reaching an optimal value of MRR. In EDM technique, primarily electrical energy turns into thermal energy through a series of successive sparks between the electrode and the work piece. The thermal energy is consumed in generating high temperature plasma, eroding the work piece material.

Material removal is proportional to the amount of applied energy during on-time which is a function of peak current and pulse duration. Thus, increase in peak current or pulse on time or high ampere and long on-time combination raises the discharge energy and accordingly the MRR increases. The similar findings has been examined by[10,14]. The reason of other circumstances can be argued as while pulse duration is too long, the plasma channel is so much expanded that the density of electrical discharge energy of a unit area may be reduced. As a result, the long pulse on time (>250 µs) reduces the material removal rate. Wu et al. state the same consequence[18].

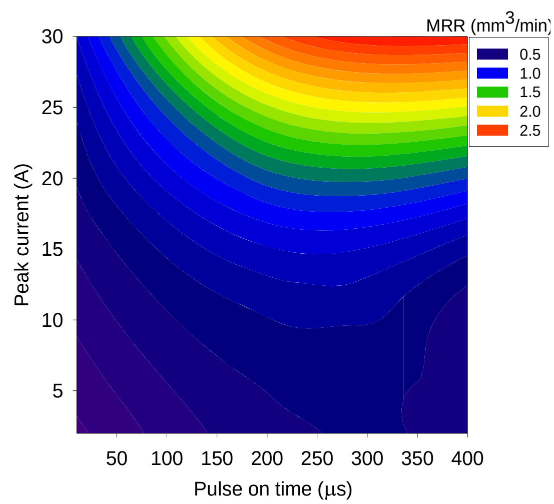


Figure 2. 2-D contour plot of the effect of peak current and pulse on time on MRR.

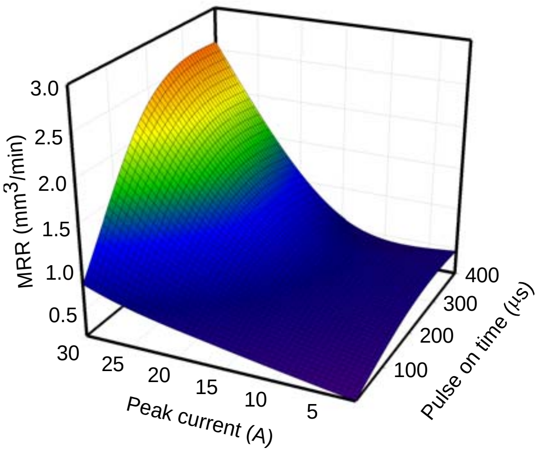


Figure 3. 3-D surface plot of the effect of peak current and pulse on time on MRR.

The Fig. 4–5 yields the effect of peak current and pulse off time on MRR. The influence of peak current on MRR already defined formerly. These 2-D contour plot and 3-D surface plot exhibits the dissimilar effect of pulse off time on material removal. At peak current about 2-20 A the MRR primarily increases till certain pulse interval thereafter started to decrease with increase of pulse interval. This is due to the fact that 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. Otherwise overheating is commenced on the surface of the workpiece. Relatively very little difference is observed in temperature variation in the sample while the pulse off time 100 and 200 µs unlike others off time. The material removal also depends on the temperature of the workpiece and its existence. Thus, it is obvious that increase pulse interval increases the MRR up to certain pulse off time and 100-200 µs off-time yields the higher MRR. It is supported by the study of Kansal et al[19].

On the other hand, the MRR decreases as pulse off time increases till certain value of off time and then increasing tendency is observed while the discharge current above 20 A. It is also investigated from the experimental result that the short pulse off time permits maximum material removal rate at all amperes. During pulse interval no energy is applied to the workpiece surface. The short off-time facilitate the time available for the application of heat energy on the workpiece surface moreover a decrease in pulse off time increases the top surface temperature of the workpiece. Thus, the material is eroded at faster rate and consequently the more MRR is acquired at short pulse off time. The same observation is reported by several authors[10,19].

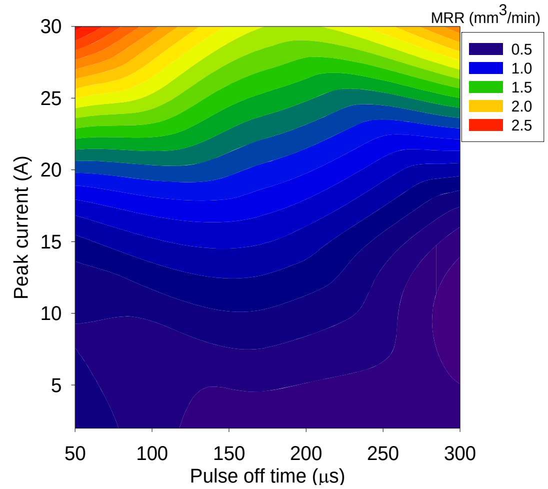


Figure 4. 2-D contour plot of the effect of peak current and pulse off time on MRR.

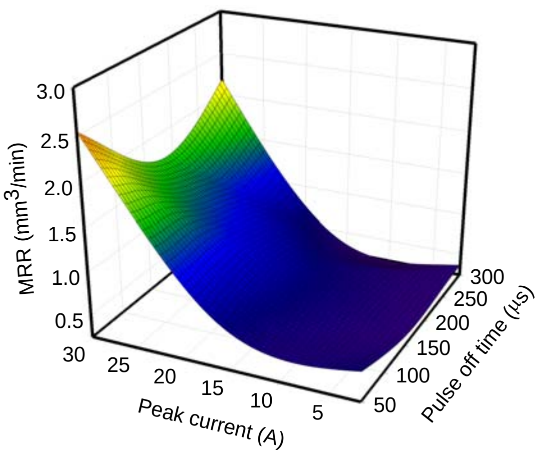


Figure 5. 3-D surface plot of the effect of peak current and pulse off time on MRR.

Analysis of the EDM parameters on TWR

The influence of peak current and pulse duration on the tool wear rate are plotted in Fig. 6–7. It can be ascertain in this study that the tool wear rate increases as discharge ampere increases throughout almost all pulse duration. In another words the higher the peak ampere the more the TWR and the converse is also obvious. This is due to that high dischrage current cause higher thermal loading on both electrode and work piece resulting higher amount of material remove from either electrodes. The similar effect is observed in the research of Shabgard and Shotorbani[20]. On the other hand with increase pulse on time the TWR increases up to certain pulse duration and henceforth started to decrease. Dhar, et al. noticed the same influence of on time on TWR[21]. It can be explained as a large released discharge energy, driven by discharge current and pulse on time, exhibit the large TWR. The too long pulse duration widen the spark diminishing energy intensity at a particular spot and eventually the electrode erosion is decreased. Although the tool wear rate at long pulse duration and the TWR at short pulse duration almost similar, comparatively the minimum TWR is found at short pulse on time whilst the peak current 2–12 A and above 25 A on the other hand long pulse duration permit the minimum TWR whilst peak current 12–25 A.

The effect of peak current and pulse off time are presented in Fig. 8–9. The obtained result in this experiment exhibits that initially the TWR increases till certain pulse interval and then decreases with pulse off time increase while the discharge current about 2–20 A. However in the case of high peak current, the dissimilar effect of pulse off time on tool wear is appeared. As the pulse off time increase the TWR trends to decrease. At too short pulse interval, there are not enough time to clear the debris from the gap between the tool and workpiece and also for de-ionisation of the dielectric arcing occurs and the TWR is increased.

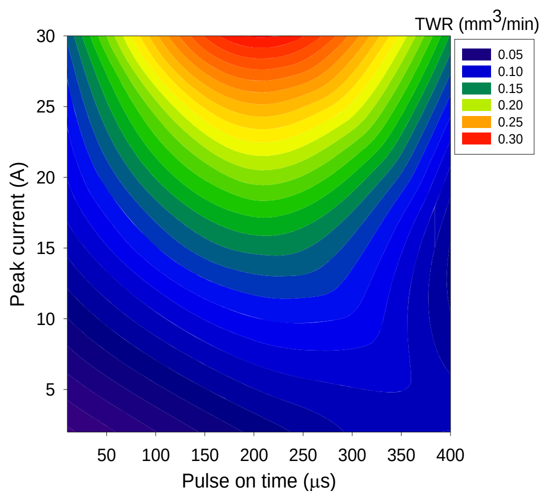


Figure 6. 2-D contour plot of the effect of peak current and pulse on time on TWR.

Lee and Li[18,22] distinguished the same effect. At peak current 2–20 A, the long pulse off time, 250–300 µs produce the lowest TWR whereas the minimum electrode wear is observed at 200–250 µs pulse off time as peak current above 20 A. It can be concluded in this experiment that the higher pulse off time yields less tool wear and the range of pulse off time is decreased with ampere that generates lower electrode wear.

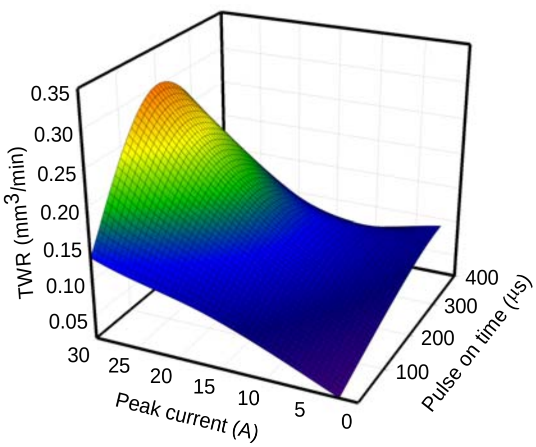


Figure 7. 3–D surface plot of the effect of peak current and pulse on time on TWR.

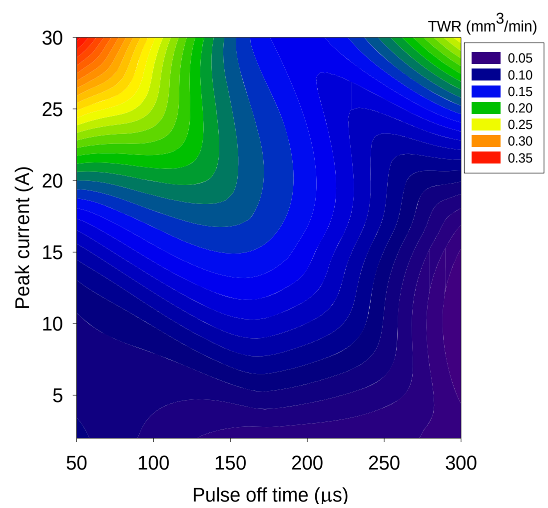


Figure 8. 2-D contour plot of the effect of peak current and pulse off time on TWR.

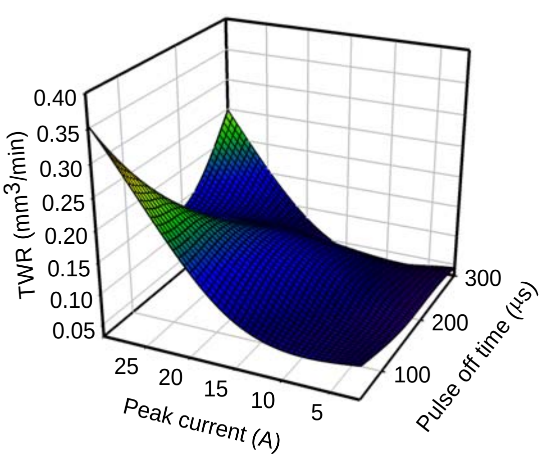


Figure 9. 3-D surface plot of the effect of peak current and pulse on time on TWR.

Optimum Settings of the EDM Process

An attempt is executed to estimate the optimum machining condition that facilitates the best possible MRR within the experimental constraints. The obtained optimum values of the parameters are shown in Table 4. Optimum machining parameter combinations for different EDM characteristics are also tested as shown in Table 5 and Table 6 through confirmation experiments that verify reasonably good concurrence with prediction of response surface method.

Table 4. Optimal Set-Up in the Case of MRR and TWR

Process parameters	Optimum setting	
	For MRR	For TWR
I_p (A)	30	8
t_i (µs)	400	10
t_o (µs)	50	184

Table 5. Confirmation Test and Their Comparison with Results for MRR

Optimum conditions	MRR (mm^3/min)		Error
	Trial	Predicted	%
I_p = 30 A, t_i=400 µs and t_o=50 µs	2.6749	2.7793	-3.90
I_p = 30 A, t_i=400 µs and t_o=50 µs	2.6963	2.7793	-3.08

Table 6. Confirmation Test and Their Comparison with Results for TWR

Optimum conditions	TWR (mm^3/min)		Error
	Trial	Predicted	%
I_p =8 A, t_i= 10 µs and t_o=184 µs	0.00593	0.00560	5.45
I_p =8 A, t_i= 10 µs and t_o=184 µs	0.00589	0.00560	4.80

CONCLUSION

It was attempted to investigate the influence of the peak current, pulse on time and pulse off time on the EDM performance characteristics and to construct mathematical model. From the analysis of the experimental interpretation the following conclusion can be stipulated. Material removal is influenced greatly 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 pulse current and pulse on time and in contrast decreases as pulse off time increases.

i. High discharge current causes more electrode wear. Short and long pulse on time persuades low TWR and 150-250 µs on-time erode electrode more. Long pulse off time permit low tool wear and the value of pulse off time that assign minimum wear varies with peak current. To achieve appreciable tool erosion the pulse ampere and off-time should be kept as low and high 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 off time in the case of MRR. 8 A peak current, 10 µs pulse on time and 184 µs pulse off time allot optimum tool wear rate.

Further study will be held to attain mathematical model and optimum set-up on behalf of the performance characteristics in EDM on Ti-5Al-2.5Sn and Ti-15V-3Cr-3Al-3Sn.

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