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Modeling and Analysis of Micro-hole in Die-sinking EDM Process through Response Surface Method based on the Central Composite Design

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Abstract

Electrical discharge machining (EDM) is common used process in aviation industries for machining micro-hole on the blade in aeroenging.Ti-6Al-4V is widely applied in frontier for its excellent properties such as a high strength-weight ratio, great heat stability and exceptional corrosion resistance. The micro-hole plays an important role in the micro-parts. In the present study, the mathematics models have been developed for relating the responses as the tool wear ratio and white layer thickness to input parameters like pules-on time, pule-off time and discharge current in a die-sinking EDM process. The response surface methodology has been applied for developing the models using the technique of design of experiment (DOE). The experiment plan adopts the centered central composite design (CCD). The experimental and predicted values were in a good agreement.

Keywords: *Electrical discharge machining (EDM), Central composite design (CCD), Tool wear rate (TWR), Response surface methodology (RSM), Analysis of variance (ANOVA), Recast layer*

1. Introduction

Electrical discharge machining (EDM) is directly to use the electrical energy and heat energy to fabricate the workpiece. In the machining process, the material is wiped out of the workpiece just by a succession of electrical discharges occurring between the workpiece and the electrode which is not contacted with each other and produce local and instantaneous high temperatures [1]. EDM is used widely in machining special structure and complex shape parts in aerospace and nuclear sector by reason of it can machine every conductive material effectively and economically with no obvious mechanical cutting force, which has no limit on the hardness, brittleness tenacity and melting point of the workpiece material. Its typical applications include the processing of cooling holes on turbine blades and fuel nozzles [2, 3]. Because the material is removed by melting and vaporization, the resolidified/recast layer is inevitable to produce on the top surface of the workpiece by subsequently resolidifies and cools at a high rate. When the recast layer is observed by scanning electron microscope, the layer is white and can be called the white layer. It contains numerous pock marks, globules, cracks and microcracks and will influence the fatigue life of parts. Various researchers have made a great deal work to optimize and reveal the relationship between the input parameters

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and output parameters like metal removal rate (MRR), tool wear rate (TWR), and surface finish. However, the efforts are less concentrated towards the white layer thickness and tool wear ratio. According to the research of Ti-6Al-4V alloy machining by EDM about recast layer/white layer is less. Because of the Ti-6Al-4V alloy properties such as high strength-to-weight ratio, high temperature stability and good corrosion resistance are classified as difficult-to-cut materials [4]. However, the Ti-6Al-4V alloy is commonly used in the important industries such as aerospace; the recast layer/white layer machined by EDM will have a great effect on the finished workpiece.

Some investigations have been conducted on MRR, EW and WLT in the EDM/micro-EDM process. H. Ramasawmy [5] made an attempt to investigate the relationship between the EDM process factors (current and pulse on time) and the thickness of the white layer. It correlates the thickness of the white layer with 3D surface roughness parameters and reveals a better correlation between the average thick ness of the white layer and the spatial parameters. Ahmet [6] carried out the experiments to machine the Ti-6Al-4V with different electrode materials (graphite, electrolytic copper and aluminium) using the process parameters (pulse current and pulse duration). It was noted that the value of material removal rate, surface roughness, electrode wear and average white layer thickness increase accompanying with the increasing current density and pulse duration. Among the different electrode materials, the graphite electrode is best choice on material removal rate, electrode wear and surface crack density although the poorer surface finish. Unfortunately, this experiment just reveals the relationship between the average white layer thickness and the process parameters with no mathematic model. Ulas caydas and ahmet hascalik [7] made an attempt to model electrode wear and recast layer thickness through surface methodology (RSM) in a die-sinking EDM process. Analysis of variance (ANOVA) was applied to study and pointed out the pulse current was the most important factor related to the EW and WLT, but the pulse off time is not important factor. B. Jabbaripour [8] changed the main machining parameters just as pulse current, pulse on time and open circuit voltage during EDM tests. Analysis of variance (ANOVA) was done and revealed the current and voltage have significant effect on the MRR, the current. In the same way the pulse on time, voltage and current have significant effect on the tool wear ratio. It was reported that the recast layer thickness has great relationship with the pulse energy based on pulse on time and pulse current variations.

In the present investigation, the machined micro-holes in Ti-6Al-4V have been carried out using EDM with the electrode which is made of copper of 500 μm sizes. It is evident that although a number of studies were made on EW, MRR and thickness of the white layer, most of them just note the simple relationship between the process parameters and WLT. In this study, the response surface methodology based on the central composite design (CCD) which is used to predict the TWR and WLT. The experimental trials are performed in the Design-Expert 8.05 software. ANOVA method is utilized to check the validity of the models.

2. Experimental Design and Response Surface Methodology

The response surface method is by constructing a clear form of implicit polynomials to approximate expression function, which use a limited test by regression analysis to fit the analytical expression to replace the real response surface [9]. Response surface method is an interaction of mathematical and statistical techniques for modeling and analysis of machining parameters in the EDM process which contains the discharge current, pulse on time and pulse off time in order to obtain the relationship to the WLT and TWR. In this study, the central composite design (CCD) is used to finish the experimental design [10].

In general, the response of the system y and design factors $(x_1, x_2, \cdots, x_n)$ can be represented as following:

$$y = f(x_1, x_2, \cdots, x_n) + \varepsilon \quad (1)$$

Where y is the response of the system, f is the response function(or response surface), $x_1, x_2, \cdots x_n$ are the independent input variables and ε is the fitting error. In present, most of all use the quadratic model to demonstrate the second-order effect of each variable and the two-way to find the interaction between combinations of these design factors. The quadratic model of y can be written as follows [11]:

$$y = \alpha_0 + \sum_{i=1}^{n} \alpha_i x_i + \sum_{i=1}^{n} \alpha_{ii} x_i^2 + \sum_{i<j}^{n} \alpha_{ij} x_i x_j + \varepsilon \quad (2)$$

Where α_0 is constant, α_i, α_{ii} and α_{ij} are the coefficients of linear, quadratic and cross product terms, respectively. For three variables (n=3), the experimental runs number is 20 which consists 2^3 factor points, 6 axial points and six center points. Design scheme of machining parameters and their levels as shown in Table 1. Table 2 shows that the central composite design composes three input variables; X_1 (Pulse on time), X_2 (Pulse off time), X_3 (Discharge current) .

Table 1. Design scheme of machining parameters and their levels

Parameters	Unit	Symbol	Levels		
			-1	0	1
Pulse on time(t_i)	μs	X_1	32	64	96
Pulse off time(t_s)	μs	X_2	64	96	128
Discharge current (I_p)	A	X_3	3	6	9

Table 2. Design layout and experiment results

Run	Coded factors			Actual factors			Responses variables			
	X_1	X_2	X_3	t_i	t_s	I_p	TWR_{actual}	$TWR_{predicted}$	WLT_{actual}	$WLT_{predicted}$
1	0	0	0	64	96	6	1.88	1.83	14.64	14.90
2	-1	1	1	32	128	9	4.10	4.13	28.67	29.35
3	1	-1	1	96	64	9	4.50	4.55	31.24	31.04
4	1	0	0	96	96	6	1.97	2.08	16.24	15.74
5	0	0	-1	64	96	3	1.15	1.09	13.04	12.53
6	0	-1	0	64	64	6	1.78	1.77	14.33	15.50
7	1	-1	-1	96	64	3	1.27	1.20	13.22	13.11

8	1	1	-1	96	128	3	1.23	1.31	15.93	16.27
9	0	0	0	64	96	6	1.88	1.83	14.64	14.90
10	0	0	0	64	96	6	1.88	1.83	14.64	14.90
11	0	0	1	64	96	9	4.20	4.42	29.90	29.22
12	0	1	0	64	128	6	1.78	1.95	20.01	17.71
13	0	0	0	64	96	6	1.88	1.83	14.64	14.90
14	0	0	0	64	96	6	1.88	1.83	14.64	14.90
15	-1	-1	-1	32	64	3	0.90	1.04	11.16	10.66
16	0	0	0	64	96	6	1.88	1.83	14.64	14.90
17	-1	1	-1	32	128	3	0.92	0.82	13.78	14.56
18	1	1	1	96	128	9	5.30	5.12	34.20	34.25
19	-1	-1	1	32	64	9	4.00	3.88	28.40	28.13
20	-1	0	0	32	96	6	1.45	1.50	13.96	13.34

3. Experimental Procedures

In the present investigation, the series of experiment were performed on a die-sinking EDM machine of type MITSUBISHI ELECTRIC-EX22 shown in Figure 1 and the model is FP60E of 8.7 KVA machine unit input. The electrode is made of a pure cylindrical copper rod 500 μm in diameter and 15 mm in height. The physical and mechanical properties of electrode are showed in Table 3, and kerosene was used as a dielectric. Ti-6Al-4V was selected as the work material which is widely used in many industries, the chemical composition of it is given in Table 4 and their physical and mechanical properties are given in Table 5. Each experimental workpiece was cut as a rectangular of 20×15 mm2and the thickness is taken as 500μm. The EDM operating conditions were illustrated in Table 6. The white layer thickness was measured by using scanning electron microscope (JSM-7500F) with high magnification. Tool wear was calculated by using the following formula:

$$TWR = \frac{W_b - W_a}{t} (mg / \min) \quad (3)$$

Where W_b and W_a are the weights of the copper electrode material before and after the machining process, t is the time of machining process in each EDM test. The micro-level balance was used to measure the weights of the copper electrode. The white layer thickness/recast layer thickness was the average layer thickness. The photograph of one hole as taken from SEM is shown from Figure 2 and the white layer/recast layer thickness is clearly visible in the figure. In the Figure 2, the average white layer thickness is calculated at 34.20 μm.

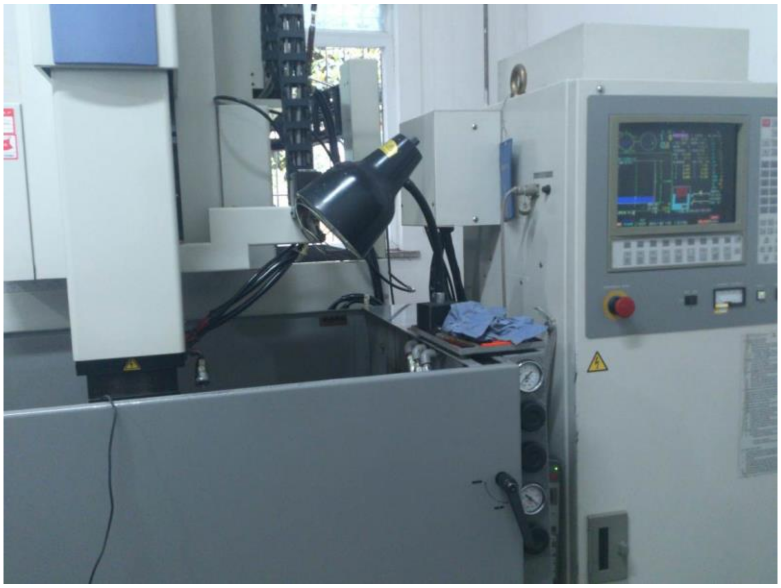

Figure 1. Experimental set-up used for experimentation

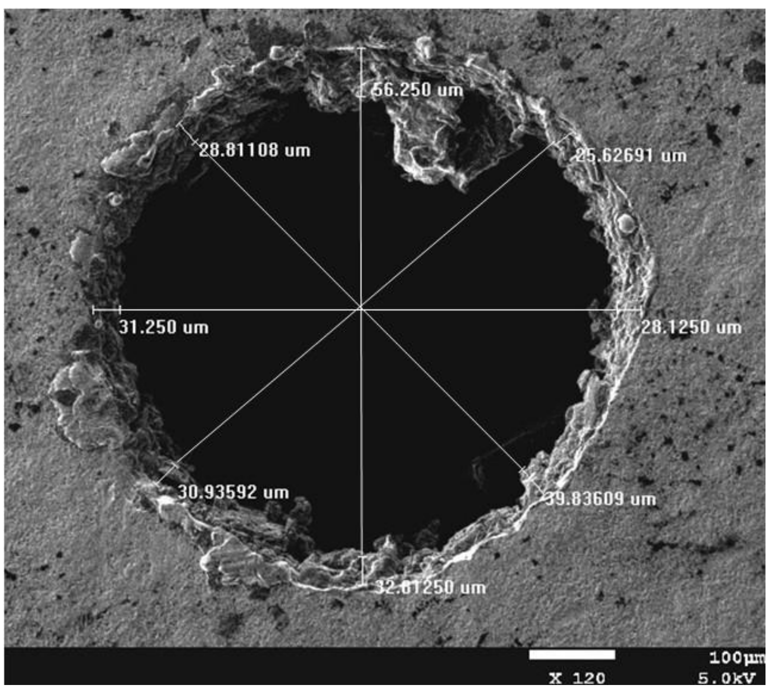

Figure 2. micro-holes corresponding to $I = 9A$, $t_s = 128\mu s$ **and** $t_i = 96\mu s$

Table 3. Electrode material properties

Material	Copper
Density(g/cm^3)	8.905
Melting point (°C)	1083
Electrical resistively(μΩ cm)	8.9
Hardness(HB)	100

Table 4. Chemical composition of Ti-6Al-4V alloy (wt. %)

Ti	89.464
Al	6.08
V	4.02
Fe	0.22
O	0.18
C	0.02
N	0.01
H	0.0053

Table 5. Workpiece material properties

Material	Ti-6Al-4V
Hardness (HV_{20})	600
Melting point (°C)	1660
Ultimate tensile strength (MPa)	832
Yield strength (Mpa)	745
Impact-toughness (J)	34
Elastic modulus (GPa)	113

Table 6. The EDM operating conditions

Working conditions	Description
Electrode material	Copper
Electrode polarity	Negative
Specimen material	Ti-6Al-4V
Working area (mm^2)	50x50
Discharge current(I_p , A)	3-9
pulse on time(T_{on}, μs)	32-96
Pulse off time(T_{off}, μs)	64-128
open discharge voltage(U,V)	210
Dielectric fluid	kerosene

4. Result and discussion

In this study, there are more machining parameters to be considered in EDM process. However, the independent variables as the pulse – on-time (t_i), pulse – off-time (t_s) and pulse current (I) were selected to predict TWR and WLT. The design of machining parameters and their levels for the CCD used was shown in Table 1. According to the relationship in Table 1, the design layout and experiment results as given in Table 2.

4.1. ANOVA analysis

In this study, the analysis of variance (ANOVA) is utilized to summary the above tests performed and analyze the results of the experimental runs. As per this technique, the response variables TWR and WLT were evaluated by the F-test of ANOVA shown in Table 7 and Table 8, respectively. The model should be considered to be significant when the p-values were less than 0.05 and 0.001 when using 5% and 1% significance levels. In the Table 7 and Table 8, the p-values are less than 0.05 which indicate that the model for TWR and WLT are significant. In the same way, the effect of the pulse on time and discharge current were significant which could be seen in the Table 7 and the effect of the discharge current, pulse on time and pulse off time were significant which can be seen in the Table 8. It can be seen that the effects of X_1, X_3, X_1X_3, X_2X_3 and X_3^2 were statistically significant according to the model of TWR when the P value in Table 7. In the same manner, the effects of X_1, X_2, X_3, X_2^2 and X_3^2 were statistically significant. Both of the model TWR and WLT, the discharge current (X_1) played the important role in the machining process.

Table 7. Analysis of variance for TWR

Source	Sum of squares	Degrees of freedom	Mean square	f-value	Prob.>F	
Model	33.20	9	3.69	182.65	<0.0001	significant
X_1	0.84	1	0.84	41.64	<0.0001	
X_2	0.077	1	0.077	3.83	0.0787	
X_3	27.66	1	27.66	1369.31	<0.0001	
$X_1 X_2$	0.051	1	0.051	2.54	0.1424	
$X_1 X_3$	0.13	1	0.13	6.44	0.0295	
$X_2 X_3$	0.11	1	0.11	5.24	0.0451	
X_1^2	3.282E-003	1	3.282E-003	0.16	0.6954	
X_2^2	3.457E-003	1	3.457E-003	0.17	0.6878	
X_3^2	2.38	1	2.38	117.88	<0.0001	
Residual	0.20	10	0.020			
Lack of fit	0.20	5	0.040			
Pure Error	0.000	5	0.000			
Correlation total	33.40	19				
R^2=0.9940						
R^2(Adj)=0.9885						

Table 8. Analysis of variance for WLT (RLT)

Source	Sum of squares	Degrees of freedom	Mean square	f-value	Prob.>F	
Model	1006.58	9	111.84	129.10	<0.0001	significant
X_1	22.08	1	22.08	25.49	0.0005	
X_2	20.28	1	20.28	23.41	0.0007	
X_3	727.27	1	727.27	839.50	<0.0001	
$X_1 X_2$	0.97	1	0.97	1.12	0.3158	
$X_1 X_3$	2.16	1	2.16	2.50	0.1451	
$X_2 X_3$	0.55	1	0.55	0.64	0.4436	
X_1^2	0.46	1	0.46	0.53	0.4847	
X_2^2	7.60	1	7.60	8.78	0.0142	
X_3^2	97.77	1	97.77	112.86	<0.0001	
Residual	8.66	10	0.87			
Lack of fit	8.66	5	1.73			
Pure Error	0.000	5	0.000			
Correlation total	1015.25	19				
R^2=0.9915						
R^2(Adj)=0.9838						

From the results presented in Table 6 and according to the Eq. 2, we present the full form of the desired models as follows:

TWR model equation:

$$\begin{aligned} TWR &= 3.23855 - 2.08807\times10^{-3} t_i - 0.016085 t_s - 0.88627 I_p \\ &+7.8125\times10^{-5} t_i t_s + 1.32813\times10^{-3} t_i I_p + 1.19792\times10^{-3} t_s I_p \\ &-3.37358\times10^{-5} t_i^2 + 3.46236\times10^{-5} t_s^2 + 0.10338 I_p^2 \end{aligned} \quad (4)$$

WLT model equation:

$$\begin{aligned} WLT &= 30.46327 + 0.032268 t_i - 0.27257 t_s - 5.19180 I_p \\ &+3.39355\times10^{-4} t_i t_s + 5.41667\times10^{-3} t_i I_p - 2.73437\times10^{-3} t_s I_p \\ &-3.97727\times10^{-4} t_i^2 + 1.62376\times10^{-3} t_s^2 + 0.66253 I_p^2 \end{aligned} \quad (5)$$

The Eq. 4 and Eq. 5 can be used to predict the TWR and WLT by using the actual factors just as t_i, t_s and I_P .

4.2. Tool wear analysis

In order to model the behavior of TWR for TC_4 and the second-order model was selected taking into account the P values obtained for the lack of fit tests (where the p value is less than 0.0001 respectively). According to this, the model of the TWR turned out to be significant. From the Table 7, the two main significant factors are pulse on time (P value is less than 0.001) and discharge current (P value is less than 0.001). The Figure 3, 4 and 5 are shown the relationship between the two input parameters and tool wear ratio at the middle level of the other two variables. Figure 3 shows the estimated response surface of TWR in function of pulse on time and pulse off time. According to the change of t_i, the tool wear ratio is a constant and although the value of t_s increase. This behavior of TWR with respect to pulse on time, it increases when the value of pulse on time increased. This could be explained by the discharge energy increase and the tool wear will increase at the same time. Figure 4 shows the estimated response surface of TWR in function of discharge current and pulse on time. When the discharge current increase, the tool wear ratio is increased regarding to the discharge energy increasing. From the Figure 4 and Figure 5 the TWR increase sharply by the value of the discharge current increase. However, the value of the pulse on time increase and the TWR increase slowly. In the same manner, the value of the pulse off time increase and the TWR just is a constant. This will be explained by the Table 7, the design factor of the pulse off time is not significant factor.

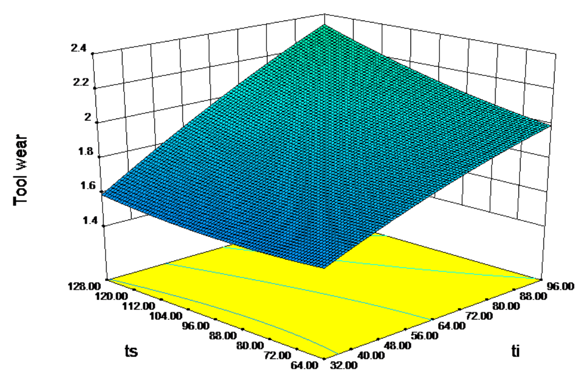

Figure 3. Estimated response surface of TWR vs. t_s and t_i for TC_4

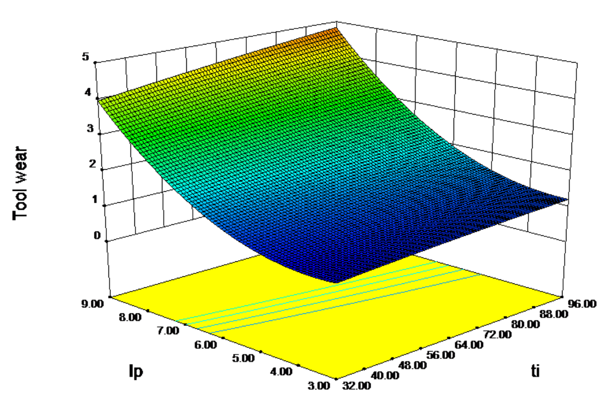

Figure 4. Estimated response surface of TWR vs. I_p and t_i for TC_4

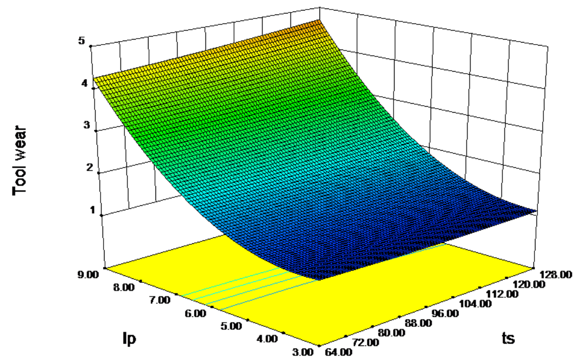

Figure 5. Estimated response surface of TWR vs. I_p and t_s for TC_4

4.3. White layer thickness analysis

In the same way as for the TWR and taking into consideration the P values of the lack of fit tests, the second model was selected to model WLT in the case of TC_4 (P value is less than 0.0001 which indicates that the model is significant). From the Table 8, the significant factors are discharge current, pulse on time and pulse off time that the P values of each other is less than 0.05. It can be clearly seen that the higher value of the discharge current the sharper increase in WLT rather than other input parameters in the Figure 6-8. According to this, the discharge energy increasing lead to the white layer thickness increased. Accompany with the increasing discharge current, the removed material from the machined surface is more when the pulse on time is a constant. The Figure 7 is shown that the value of the pulse on time increase leading to the WLT increasing because of more discharge energy is transformed to surface of workpiece during a single pulse. From the analysis of the model, the pulse off time is significant and the reason will be that the flushing away by dielectric fluid the less volume of molten particles are re-solidified that leads to induce of WLT when the value of the pulse off time increasing.

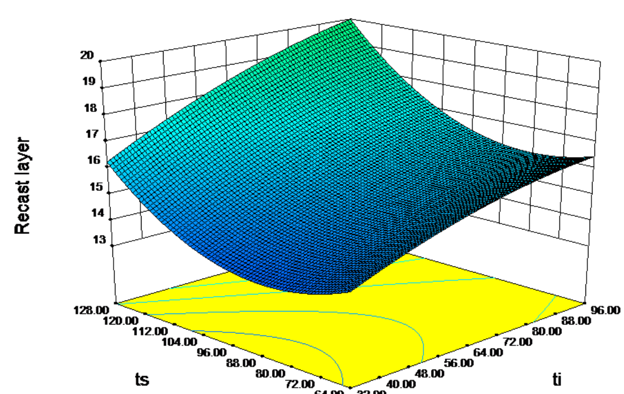

Figure 6. Estimated response surface of WLT vs. t_s and t_i for TC_4

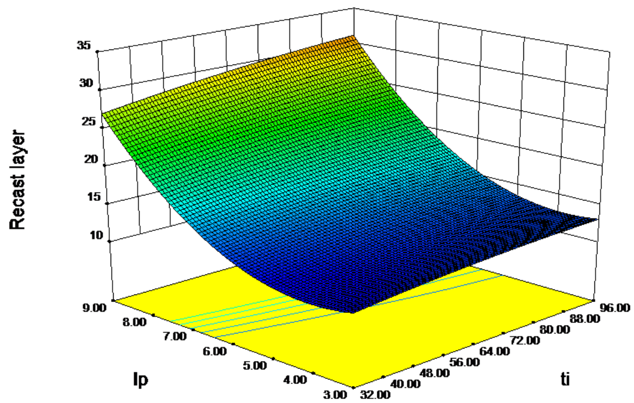

Figure 7. Estimated response surface of WLT vs. I_p **and** t_i **for** TC_4

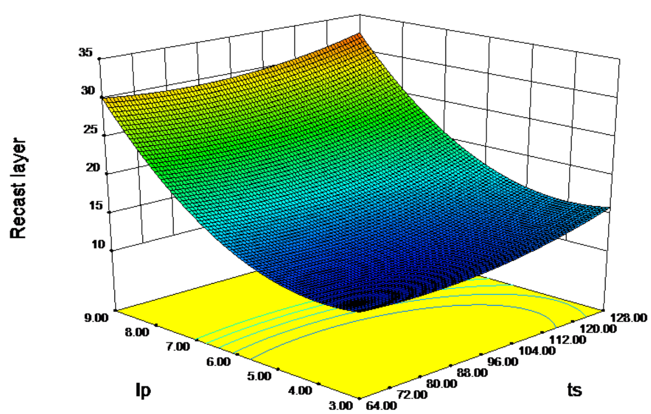

Figure 8. Estimated response surface of WLT vs. I_p **and** t_s **for** TC_4

5. Conclusion

In this study, the TWR and WLT in die-sinking EDM process were modeled and analyzed the influence of three machining variables (namely, discharge current. pulse on time and pulse off time) on the performance of the EDM machined Ti-6Al-4V alloy through response surface methodology (RSM) and central composite design. Analysis of variance (ANOVA) was applied to study. The predicted values match the experimental values reasonably well, with R^2 of 0.9258 for TWR and R^2 of 0.9295 for WLT. This study demonstrates this method can be successfully used to model it. Discharge current was the significant factor of the three input parameters to affect the both TWR and WLT, some difference unlike the others reported the pulse off time had some effect on the WLT. The lower discharge current, lower pulse on time and longer pulse off time could minimize the WLT. Obviously, this method can cost less to obtain information for any system with the fewest number of experiments.

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