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An Empirical Investigation on Optimization of EDM Process Parameters for Ti-۶Al-۴V Alloy Using Mathematical Modeling and Taguchi Approach

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An Empirical Investigation on Optimization of EDM Process Parameters for Ti-6Al-4V Alloy Using Mathematical Modeling and Taguchi Approach

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Abstract

This paper addresses modeling and optimization of process parameters for electrical discharge machining (EDM) being especially developed for difficult-to-machine materials such as Ti-6Al-4V titanium alloys. The important process variables considered in this study include current, voltage, pulse-on time, pulse-off time, and time on work. The main machining output characteristics in EDM are material removal rate (MRR) and surface roughness (SR). The relationships between these process inputs/outputs have been established using design of experiment (DOE) approach and mathematical modeling. The mathematical models were developed based on the data collected as per Taguchi's DOE matrix. Then, Analysis of Variance (ANOVA) technique has been employed to verify adequacies of the proposed models. In the next step, optimization of EDM process parameters have been carried out using signal to noise (S/N) analysis. In this way, the process variables can be set at proper levels to obtain desired machining outputs. Computational results demonstrate that the proposed approach is quite efficient in modeling and optimizing such machining.

Keywords: "Electrical Discharge Machining (EDM), Design of Experiments (DOE), Analysis of Variance (ANOVA), Signal to Noise (S/N) Ratio, Regression Modeling".

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Introduction

The continuous introduction of new materials and the endless demands on engineers, to produce complicated shapes within tighter tolerances and lower costs, call for more efficient manufacturing techniques. In recent years, the applications of such materials are increasing in many industries because of their exceptional properties. In particular titanium alloys have excellent properties such as high strength–weight ratio, high temperature strength and exceptional corrosion resistance. The most common titanium alloy is the α+β type Ti–6Al–4V which is extensively used in aerospace, biomedical and many other corrosive environments [1]. However, titanium alloys are very difficult to machine due to their extremely low conductivity and modules of elasticity. Titanium is also very chemically reactive with almost all cutting tools. This further impairs its machinability; especially with traditional mechanical cutting [2,3].

The energy-based techniques, like electrical discharge machine (EDM), has continued to advance and gain favor as an alternative to traditional machining methods. Different from traditional machining methods, the material removal in EDM process is done through melting and vaporizing.

In EDM process, the selection of proper process parameters is required in order to achieve optimal machining performance. Usually, the machining parameters are determined based on experience or on handbook values. However, this does not ensure that the selected parameter values result in an optimal machining performance for that particular machining material and environment. Therefore, the optimization of processes parameters requires process analysis to identify the effect of operating variables on achieving desired machining characteristics [4,5].

The machining characteristics, including surface roughness (SR), material removal rate (MRR) and tool wear rate (TWR) for EDMed parts are correlated with machining parameters such as voltage, current, pulse-on time, pulse-off time and time on work.

Various approaches have been employed by researchers to relate input machining parameters to output characteristics. Lin et al. [6] attempted to improve the discharge efficiency of Ti–6Al–4V alloy using a combination of EDM and ultrasonic machining. Ahmet et al. [7] explored the influence of EDM parameters on the surface integrity of Ti–6Al–4V alloy with different electrode materials. Recently, Fonda et al. [8] used EDM technology to machine Ti–6Al–4V alloy to examine the effect of thermal and electrical properties on the material removal rate and machining productivity. As for the optimum choice of EDM's process parameters, Krishna et al. [9] developed a hybrid model using artificial neural networks and a genetic algorithm to optimize the surface roughness in EDM by considering the simultaneous effect of peak current and voltage, where Ti–6Al–4V alloy is one of the materials used in the experiments.

Among various techniques in modeling of machining processes, Design of Experiments (DOE) is a straightforward and easy to follow procedure that needs no guesswork to take the initial experimental steps [10]. This approach facilitates the identification of the influence of individual parameters, establishing the relationship between process parameters and operational conditions, and finally establishing performance at the optimum levels obtained.

The Taguchi method, one of the most widely used DOE techniques, not only helps in saving considerable time and cost, but also leads to a more fully developed process [10]. Yan et al. [11] applied a Taguchi static experiment to undertake the study of multiple quality characteristic problems, such as tool wear rate and material removal rate in EDM process. Marafona and Wykes [12] employed a set of Taguchi based experiments to investigate the effects of various process parameters on the surface integrity and material removal rate for EDM machined workpiece. Lee and Yur [13] employed a Taguchi method to determine the main influencing factors affecting the surface characteristics of holes made by EDM. Characteristics such as hole-enlargement, surface roughness, and thickness of the white layer have been analyzed in their study. Lin et al. [14] investigated the effects of EDM parameters on machining characteristics including MRR, TWR and SR, in the machining of SKH 57 HSS. In their work, statistical analysis of experimental data obtained using the Taguchi method.

The main thrust of this research is to establish the relationships between EDM machining input parameters and important output characteristics for titanium alloys. The present work involves a series of experiments, using die sinking EDM with an electrolytic copper electrode on Ti-6Al-4V. The effects of the EDM machining parameters on such performance measures as MRR and SR have been examined. The machining parameters of EDM are numerous, so performing conventional single-factor experiments, to elucidate the effects of all of them on EDM performance, is costly and time-consuming. Therefore, a Taguchi based DOE approach has been employed to experimentally explore the effects of important EDM processes variables on the machining performance measures. The five essential machining parameters that have noticeable impacts on the EDM are current (I), pulse-on time (T_{on}), pulse-off time (T_{off}), gap voltage (V) and time on work (η) [7-9].

Experimental setup and design of experiment

In this study, an Azerakhsh-304H EDM machine has been used to do the experiments ("Figure 1"). Also, 16-mm diameter cylindrical shape pure copper (99% purity and 8.98 g/cm^3 density) electrodes were used as

the EDM tool. Pure kerosene was used as the dielectric fluid in all experiments.
The test specimens were of Ti-6Al-4V alloy with dimensions 90mm×30mm×10mm. A total of 8 tests were performed on each samples (four tests on each side). The experimental setup is illustrated in "Figure 2".

Figure (1) Die-sinking EDM machine used for experiments

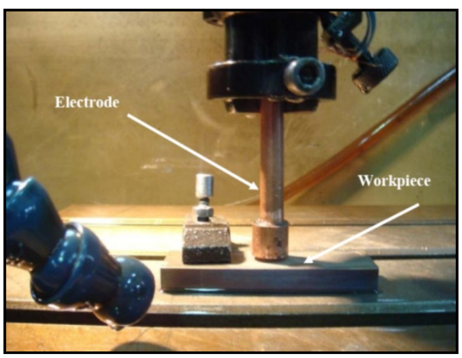

Figure (2) Experimental setup

In this study, the material removal rate (MRR) and surface roughness (SR) are considered as the performance characteristics to evaluate the machining quality. A digital balance with 0.01 gram accuracy has been used to measure MRR (mg/min) by the means of the lost weight of the workpiece under the working time. The surface roughness of the EDMed workpiece is measured in terms of the commonly used Ra (arithmetic average roughness) with a Taylor-Hobson, Surtronic 3+ tester.
The upper and lower ranges of process variables were determined using previous research works [15-16] and a set of preliminary experiments. To gather the required data, the standard L_{36} Taguchi experimental matrix has been selected. For our experiments, this matrix is an orthogonal array with five columns, representing the five process variables, and 36 rows. "Table1" presents the experimental matrix design in which one variable, pulse-off time, has two levels and four variables three levels each.

Table 1- Machining parameters and their levels

Parameters	unit	levels		
		1	2	3
Current (I)	A	6	18	30
Pulse-on time (T_{on})	µs	25	100	200
Gap voltage (V)	V	50	55	60
Time on work (η)	s	0.4	1.0	1.6
Plus-off time (T_{off})	µs	10	75	-

The machining time for each test was 20 minutes and all experiments were repeated twice with the average being taken as the results. Some of the 36 experimental design matrix and the average values of duplicated runs for MRR and SR are listed in "Table 2".

Table 2- Experimental design and results

No.	parameters					MRR (mg/min)	SR (µm)
	T_{off} (µs)	T_{on} (µs)	I (A)	η (Sec.)	V_{gap} (V)		
1	1	1	1	1	1	0.33	1.80
2	1	2	2	2	2	3.83	3.02
3	1	3	3	3	3	8.00	6.99
4	1	1	1	1	1	0.33	1.97
5	1	2	2	2	2	3.83	3.38
6	1	3	3	3	3	7.67	7.54
7	1	1	1	2	3	0.67	2.28
8	1	2	2	3	1	4.50	3.58
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
29	2	2	1	3	3	1.67	1.88
30	2	3	2	1	1	2.17	3.58
31	2	1	3	3	3	15.67	5.43
32	2	2	1	1	1	1.00	2.01
33	2	3	2	2	2	2.17	4.41
34	2	1	3	1	2	9.67	5.70
35	2	2	1	2	3	0.33	1.93
36	2	3	2	3	1	2.50	4.36

Analysis of the experimental results

Analysis of the parameters influences

Basically, in the EDM process MRR is in the category of the higher-the better performance characteristic. "Figure 3" depicts the plots of process parameters affecting MRR, which is given by Taguchi analysis in Minitab 14® software. As shown, by increasing electrical current the MRR increases rapidly. Although with a lower rate, pulse-on time has similar direct effect on MRR. Other two process variables, voltage and work on time, have negligible impacts on this measure of performance, as illustrated in this figure.

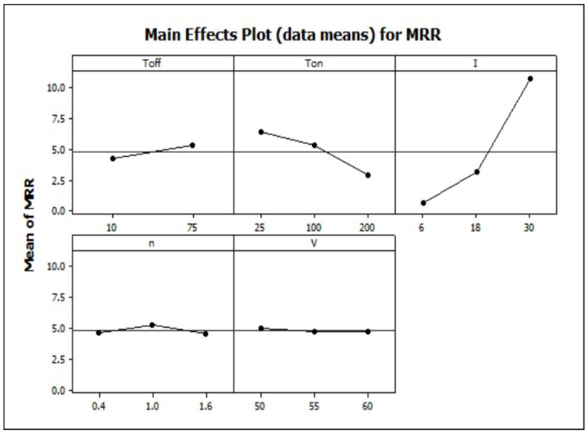

Figure (3) Plot of factor effects on MRR

Unlike MRR, it is desirable to lower surface roughness and hence SR is in the category of the lower-the-better. "Figure 4" illustrates the effects of different process parameters on SR. It shows that current has the most significant effect on SR; that is, by increasing current, SR increases significantly. The effects of other process parameters are somehow minor compare to of current, as shown by this figure.

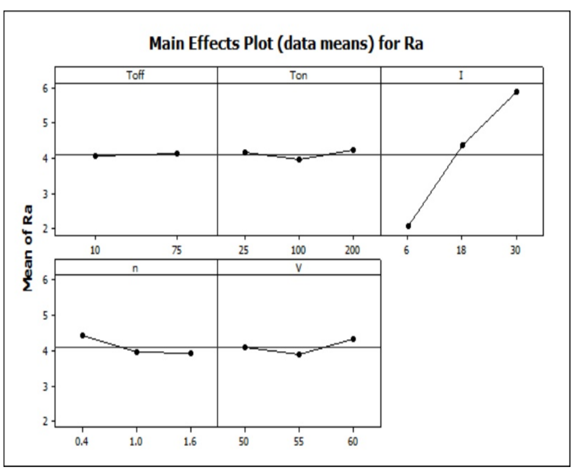

Figure (4) Plot of factor effects on surface roughness

Mathematical modeling of MRR and SR

Regression analysis has been performed on the experimental data to establish the mathematical relationships between process variables and performance characteristics (MRR and SR). Among various regression functions fitted on the data, the quadratic function showed the best fit. The modified quadratic models for MRR and SR are as follows:

$$MRR = - 0.350 + 0.015\, I^2 - 0.001\, T_{on}\times I + 0.008\, T_{off}\times \eta + 0.00013\, T_{on}\times V \quad (1)$$

$$SR = 1.62 - 0.0282\, T_{on} + 0.000437\, T_{off}\times I + 0.000470\, T_{on}\times I + 0.000431\, T_{on}\times V + 0.00174\, I\times V \quad (2)$$

Analysis of variance (ANOVA) has been performed on the above models to assess their adequacies, within the confidence limit of 95%. ANOVA results indicate that the models are adequate within the specified confidence limit. The calculated determination coefficients (R^2) for these models were 95.7% for MRR and 93.8% for SR.

To further investigate the accuracy of the proposed model, the results of several experimental tests were verified against the predicted values by equations (1) and (2). The new process variables and results of 3 sample verification tests are tabulated in "Table 3 and Table 4". As shown, the highest error is about 7% and 8% for MRR and SR respectively. Other tests showed similar error patterns. Given the results of adequacy tests and various uncontrollable factors in real machining environments, these errors are quite justified. Hence, the model may be considered quite accurate for EDM process of Ti-6Al-4V alloy.

Table 3- New process variables for model validation

Run	T_{off} (µm)	T_{on} (µm)	I (A)	η (Sec)	V (V)
1	75	100	24	1	55
2	75	150	18	0.7	55
3	75	50	12	0.7	55

Table 4- Results of validation experiments

Results of the model		Results of experiments		Error (%)	
MRR	SR	MRR	SR	MRR	SR
6.9	5.38	6.8	5.26	-1.8	-2.32
3.1	4.53	3.3	4.18	7.0	-8.31
1.9	3.22	2.0	3.26	5.0	1.26

Signal to noise analysis

Signal to noise ratio (SNR) analysis is used to determine the optimal values of process parameters with respect to MRR and SR. The rationale behind S/N analysis is to find a set of parameters for which signals are predominant. This rationale eventually leads to a situation in which the system is least sensitive to noises.

The commonly used procedure in S/N analysis is to calculate the ratio (η) for each parameters combination and to select the one with the largest η as the optimal combination [10]. Based on the specific measure of performance, the S/N ratio calculation may be selected either “the higher the better, HB” or “the lower the better, LB,” as are given in the following equations:

$$\textbf{HB}: \ \eta = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{z_i^2} \right) \quad (3)$$

$$\textbf{LB}: \ \eta = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} z_i^2 \right) \quad (4)$$

In the above equations, η is the signal to noise ratio, y_i is the experiment output response (here MRR and SR) and n is the number of replications [10]. The S/N ratio response graphs, plotted in "Figure 5", reveal that MRR is maximized when some process parameters are at their highest values while others are at their lowest possible settings. This is consistent with the discussion provided on the ANOVA results presented above. For our case, the optimal combination of parameters settings for maximizing MRR is as follows; I=30 A; T_{on}=25 µs; T_{off} =75 µs; V=50 V and η=0.4 s.

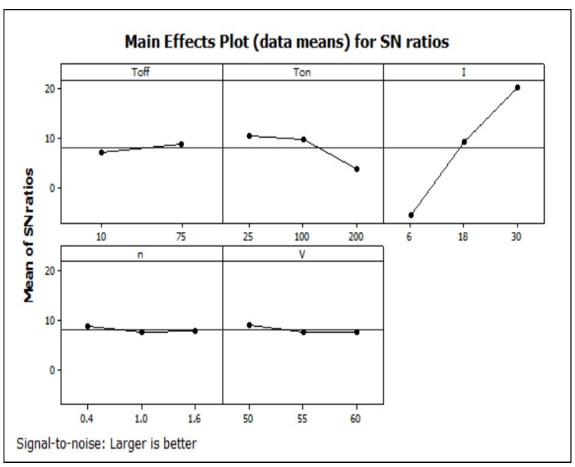

Figure (5) Plot of main effects for signal to nose ratio for MRR

In the same manner as for MRR, "Figure 6" shows the S/N ratio response graphs for SR. "Figure 6" demonstrates that minimum surface roughness occurs when parameters settings are as follows: I=6 A; T_{on}=100 µs ; T_{off} =10 µs; V=55 V and η=1.6 s. This figure also reveals that pulse current and pulse-on time have significant effects on SR; which is consistent (a testimony with the) with the ANOVA results.

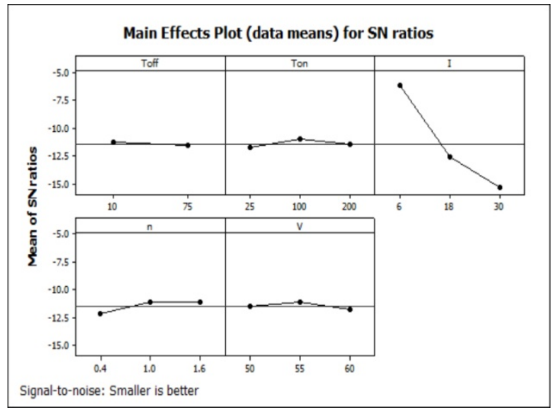

Figure (6) Plot of main effects for signal to nose ratio for surface roughness

Running verification experiments

To evaluate the adequacy of the proposed approach and statistical analysis, a set of verification test has been carried out based on the predicted values.

The optimal levels of the process parameters are predicted based on the values given in "Table 2". "Table 5", shows the comparison between the predicted and experimental results using optimal process parameters. As indicated, the differences between predicted and actual process outputs are less than 7%. Given the nature of EDM process and its many variables, these results are quite acceptable and prove that the experimental results are correlated with the estimated values.

Table 4- Results of the verification experiments

Optimal condition				
Process output	Prediction	Experiment	Difference	Error (%)
MRR	18.25	17.12	1.13	6.1
SR	1.23	1.31	0.08	6.5
Parameter setting for SR (T_{on} =100 µs, T_{off} =10 µs, I =6 A, η =1.6 S, V =55 V)				
Parameter setting for MRR (T_{on} =25 µs, T_{off} =75 µs, I =30 A, η =0.4 S, V = 50 V)				

Conclusion

Electrical discharge machining (EDM) is now a well-established machining process in many manufacturing industries. It is widely used to shape geometrically complex or difficult-to-machine materials such as heat treated steels, super alloys and ceramics. This paper reports the results of an experimental investigation to study the effects of five important machining parameters on material removal rate and surface roughness in EDM of Ti-6Al-4V alloy. The five parameters of EDM processes studied here include pulse current, pulse-on-time, pulse-off-time, time on work and gap voltage. The experimental data were gathered using L_{36} Taguchi orthogonal array. This has been performed in an efficient way and without necessity to carry out a large number of experiments. Various regression functions were fitted on the experimental data to relate process parameters to the process response characteristics (MRR and SR). Then, the modified second order model was selected as the best representative of EMD process, based on the ANOVA results with 95% confidence interval. Further confirmation experiments showed no more than 8% errors in real tests.

Optimizing of process parameters is an important step in the Taguchi methods to achieve high quality product with required output characteristics. In this research, a Taguchi based orthogonal array with signal to noise (S/N) ratio method was employed to optimally determine combination of parameters for maximization of MRR as well as minimization of SR, two conflicting process outputs. The optimal combination of parameters settings for maximizing MRR is as follows; I=30 A; T_{on}=25 µs; T_{off} =75 µs; V =50 V and η=0.4 s. For the case of minimizing SR, the optimal set of process parameters found to be: I=6 A; T_{on}=100 µs; T_{off}=10 µs; V=55 V and η=1.6 s. As indicated, the differences between predicted and actual process outputs are less than 7%. Given the nature of EDM process and its many variables, these results are quite adequate and prove that the experimental results are correlated with the estimated values. It is noted that the optimal set of process parameter values can easily be determined for any weighted combination of response characteristics.

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