Mathematical modeling and analysis of EDM process parameters based on Taguchi design of experiments

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Abstract. Electro Discharge Machining is a process used for machining very hard metals, deep and complex shapes by metal erosion in all types of electro conductive materials. The metal is removed through the action of an electric discharge of short duration and high current density between the tool and the work piece. The eroded metal on the surface of both work piece and the tool is flushed away by the dielectric fluid. The objective of this work is to develop a mathematical model for an Electro Discharge Machining process which provides the necessary equations to predict the metal removal rate, electrode wear rate and surface roughness. Regression analysis is used to investigate the relationship between various process parameters. The input parameters are taken as peak current, pulse on time, pulse off time, tool lift time, and the Metal removal rate, electrode wear rate and surface roughness are as responses. Experiments are conducted on Titanium super alloy based on the Taguchi design of experiments i.e. L27 orthogonal experiments.

1. Introduction

Electrical discharge machining is considered as one of the main non-conventional machining processes used for manufacturing geometrically complex or hard material parts that are extremely difficult to machine by conventional machining processes. New developments in the field of material science have lead to new engineering metallic materials, composite materials, and ceramics, having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity so that they can readily be machined by spark erosion. Electrical discharge machine (EDM) technology is increasingly being used in tool, die and mould making industries, for machining of heat treated tool steels and advanced materials (super alloys, ceramics, and metal matrix composites) requiring high precision, complex shapes and high surface finish. Technologically advanced industries such as aeronautics, nuclear reactors and automobiles have been demanding high strength temperature resistant (HSTR) materials having high strength to weight ratio. Today, these alloys have a wide variety of applications in modern aerospace, marine, automobile sector, atomic power plant reactors, and medical implants owing to their high strength to weight ratios, high strength and toughness at elevated temperatures, excellent corrosion resistance, fracture resistance and low modulus of elasticity, good corrosion resistance in most environments. Titanium and Titanium super alloy has been developed in order to satisfy the needs for a class of strong and light weight materials for aircraft engines and airframe manufacturing. 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 with high productivity and good quality becomes challenging. Owing to their poor machinability, it is very difficult to machine titanium and titanium super alloys economically with traditional mechanical techniques. The main difficulties to machine titanium and titanium super alloys are high cutting temperatures and rapid tool wear.

Electrical discharge machining (EDM) is a relatively modern machining process having distinct advantages over other machining processes and can machine Ti alloys effectively. Researchers made attempts to model EDM process to study improvements in performance measures like material removal rate, surface roughness and tool wear rate. Yusuf Keskin et al. investigated the effects of machining parameters on the surface roughness valley machined by EDM on steel using copper tool electrode. The data obtained for response measures had been analyzed using the Design of experiments method multiple regression method. It was observed that the surface roughness had increasing trend with an increase in the discharge duration due to the more discharge energy released during this time [1,2]. Chen and Madhavian [3] suggested a theoretical model to predict the material removal rate and surface roughness. Later compared the theoretical results with the experimental results and found to be in close agreement. Wang and Tsai [4] conducted a study on modeling of surface roughness in electro discharge machining using both response surface methodology and artificial neural networks. Lee and Li [5] studied the influence of operating parameters on tungsten carbide and its machining characteristics. Wang [6] used a hybrid artificial neural network and genetic algorithm methodology to model and optimize EDM process. Mahapatra and Patnaik [7] developed a relationship between control factors and material removal rate and surface roughness using regression analysis and finally genetic algorithm was used to optimize the process as a multi objective function. Kuang-Yuan Kung et al [8] studied the material removal rate and electrode wear ratio on the powder mixed dielectric fluid for machining of cobalt-bonded tungsten carbide on electrical discharge machine. They employed response surface methodology to plan and analyze the experiments. Prasad and Gopalakrishna [9] developed a mathematical model for material removal rate and surface roughness using central composite rotatable design with five factors and finally optimized them as multiobjective optimization using evolutionary algorithms. Chiang [10] proposed mathematical models using response surface methodology for modeling and analysis of the effects of machining parameters on the performance characteristics of the electro discharge machining process of Al2O3+TiC mixed ceramic to study the influence of four machining parameters the discharge current, pulse on time, duty factor and open discharge voltage on material removal rate, electrode wear ratio and surface roughness. Shabgard and Shotorbani [11] established the relation between input parameters the peak current, pulse-on time and voltage and the process outputs using Design of Experiments (DOE), multi linear regression techniques and response surface methodology. In this present paper the work is reported on titanium alloy taking the input parameters, peak current, pulse on time, pulse off time and tool lift time and developed the mathematical model based on regression method.

2. Methodology

2.1. Regression analysis

Regression analysis includes any techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. More specifically, regression analysis helps us to understand how the typical value of the dependent variable changes when any one of the independent variables is varied, while the other independent variables are held fixed. Most commonly, regression analysis estimates the conditional expectation of the dependent variable given the independent variables. In all cases, the estimation target is a function of the independent variables called the regression function.
The Regression analysis is an empirical modeling approach for determining the relationship between various process parameters and responses with the various searches and desired criteria for the significance of these process parameters in the coupled responses. It is a sequential experimentation strategy for optimizing and building the empirical model. The objective of the regression analysis is to develop the mathematical relation between the responses and machining parameters. In many experimental situations, it is possible to represent independent factors in quantitative form. Then these factors can be thought of as having a functional relationship

\[ Y_u = f(X_1, X_2, X_3, .X_k) \pm e_r, \]

between the response \( Y_u \) and \( X_1, X_2, X_3, .X_k \) of \( k \) independent quantitative factors as shown in equation 1. The function is called response surface or response function. The experimental error is measured by the residual error \( e_r \). A characteristic surface responds for a given set of independent variables. When the mathematical form is not known, it can be approximated satisfactorily within the experimental region by a polynomial. The higher the degree of the polynomial the better is the correlation. The methodology may be applied for developing the mathematical models in the form of multiple regression equations correlating the dependent parameters such as metal removal rate, Tool wear rate, Surface roughness, etc. with more than two independent parameters, in electric discharge machining process the independent parameters are peak current, pulse on time, pulse off time and tool lift time. In applying the regression analysis, the dependent parameter is viewed as fitted mathematical model. For the development of regression equations related to various quality characteristics of machined components, the second-order response surface may be assumed as,

\[ Y_u = \beta_0 + \sum_{i=1}^{k} \beta_i X_{iu} + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} X_{iu} X_{ju} + \sum_{i=1}^{k} \beta_{ii} X_{iu}^2, \]

where \( Y_u \) represents the corresponding response, contains linear, squared and cross-product terms of \( X_{iu} \)'s variables. In the present paper, the code values of \( i^{th} \) machining parameters for \( u^{th} \) response are represented by \( X_{iu} \). The values of \( k \) indicate the number of machining parameters. The terms \( \beta_i, \beta_{ii} \) and \( \beta_{ij} \) are the second order regression co-efficient. The second term under the summation sign of this polynomial equation attributes to linear effects, whereas the third term of the above equation corresponds to the higher order effects and lastly the fourth term of the equation includes the interactive effects of the parameters [13].

2.2. Design of experiments

Experimental design methods are too complex and are not easy to use. When the number of process parameters increases a large number of experiments have to be carried out. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. According to the Taguchi method, a robust design and an orthogonal array are employed for the experimentation. Four machining parameters are considered as controlling factors namely, peak current, pulse on time, pulse off time and tool lift time and each parameter has three levels. Table.1 shows the parameters and their levels considered for the experimentation. The experimental design considered for the investigation based on the L27 orthogonal array. Based on this, 27 experiments are conducted; each having a different combination of levels of factors as shown in Table 3 was carried out. Orthogonal arrays are special standard experimental design that requires only a small number of experimental trials to find the main factor effects on output. The standard Orthogonal arrays available are L4, L8, L12, L16, L18, L9, L27, L32 etc. In this work L27 array is selected based on main factors, interaction effects between variables, the variables are assigned at columns.
Table 1. Selected process parameters in EDM process.

| Parameter       | Symbol | units | Level 1 | Level 2 | Level 3 |
|-----------------|--------|-------|---------|---------|---------|
| Peak current    | Ip     | Amp   | 9       | 12      | 15      |
| Pulse on time   | Ton    | µs    | 10      | 20      | 50      |
| Pulse off time  | Toff   | µs    | 20      | 50      | 100     |
| Tool lift time  | Tlift  | µs    | 5       | 10      | 20      |

Table 2. Chemical composition of work material.

| Element | Base  | 5.5-6.8% | 0.13% | 0.5-2% | 1.5-2.5% | 0.15% | 0.3% | 0.8-2.5% | 0.3% |
|---------|-------|----------|-------|--------|----------|-------|------|----------|------|
| Titanium| Al    | C        | Mo    | Zr     | Si       | Fe    | P    | V        |      |

as stipulated by orthogonal array. Some columns can be kept dummy, but no row should be left out. Once the orthogonal array is selected, the experiments are selected as per the level combinations; all the experiments must be conducted. The interaction effect columns can be kept dummy while conducting experiments, but to be considered for analysis.

3. Experimental work

3.1. Experimental setup

We constructed an appropriate mathematical model to predict the value of MRR, EWR and SR. Experiments were carried out on die sinking EDM of type Askar microns, model V3525 with servo head constant gap voltage, positive polarity. Commercial 30 Grade EDM Oil was used as Dielectric fluid. The investigation was done on Titanium super alloys with Brinell hardness number 35 HB. The chemical composition of work material is given in Table 1. The size of work pieces is 50mmX30mmX6mm and the diameter copper electrode is 12mm have been taken for the study. Preliminary experiments were conducted by varying the process input parameters for finding range of parameters. L27 orthogonal array was used to design the number of experiments. The results obtained were analyzed and the models were produced using MINITAB Software. Tool material is of copper because of easy available in market and lower in cost.

3.2. Selection of input parameters

The input parameters are selected based on the preliminary experiments and the operational limitations of the EDM machine. The selected input parameters (peak current, pulse on time and pulse off time and tool lift time) are shown in Table 1, and the output parameters are...
Metal removal rate (MRR), Tool wear rate (TWR) and Surface roughness (SR) have been taken for the study.

3.3. Calculation of MRR and TWR
To calculate the value of MRR and TWR, the tool electrode and tool are to be weighted, for this purpose we used SHIMADZU PHILLIPPINES, Digital sensitive weighting balance which is of 1mg accuracy. The work piece sample is weighted before machining and after machining and the MRR is obtained using the following equation.

\[ MRR = \frac{wp_1 - wp_2}{T}, \]

where \( wp_1 \) and \( wp_2 \) are the weights of the workpiece before and after machining in mg/min respectively, \( T \) is the machining time in minutes. Similarly TWR is calculated taking the weights of the tool electrode before and after machining and is obtained by using following equation

\[ TWR = \frac{wt_1 - wt_2}{T}, \]

where \( wt_1 \) and \( wt_2 \) are the weights of the tool electrode before and after machining in mg/min respectively. The SR was measured on HANDYSURF. Three measurements of SR had been taken at different locations and the average values are taken for the analysis. The experiments are conducted according to L27 orthogonal array and the results are shown in Table 3.

4. Mathematical models
Regression analysis combines mathematical and statistical techniques for empirical model building. A model of the response to certain independent input variables can be obtained by conducting experiments and applying regression analysis. The mathematical models commonly used are represented by,

\[ Y = \Phi(I_p, T_{on}, T_{off}, T_{lift}) \pm \varepsilon_r, \]

where \( Y \) is the machining response, \( \Phi \) is the response function and \( I_p, T_{on}, T_{off} \) and \( T_{lift} \) are machining independent variables and \( \varepsilon_r \) is the error. The general second-order polynomial response equation is mostly used. It also confirms that this model provides an excellent explanation of the relationship between the Independent factors and the responses. The second order response surface representing the MRR, TWR and SR can be expressed as a function of machining parameters \( I_p, T_{on}, T_{off} \) and \( T_{lift} \). The relationship between the response and machining parameters has been expressed based on equation 2 as follows.

\[ Y_u = \beta_0 + \beta_1 I_p + \beta_2 T_{on} + \beta_3 T_{off} + \beta_4 T_{lift} + \beta_5 I_p T_{on}, \]

\[ + \beta_6 I_p T_{off} + \beta_7 I_p T_{lift} + \beta_8 T_{on} T_{off} + \beta_9 T_{on} T_{lift}, \]

\[ + \beta_{10} T_{off} T_{lift} + \beta_{11} I_p^2 + \beta_{12} T_{on}^2 + \beta_{13} T_{off}^2 + \beta_{14} T_{lift}^2. \]

To obtain predictive quantitative relationships, it is necessary to model the machining responses and the process variables. In the present work, the mathematical models were developed on the basis of EDM experimental results using MINITAB-17. From the observed data for MRR, TWR and SR, the response function has been determined using polynomial second order equations, as given below.

\[ MRR = 16.96 - 3.25 I_p + 0.945 T_{on} - 0.0822 T_{off} + 0.089 T_{lift} - 0.01335 I_p T_{on}, \]

\[ + 0.00045 I_p T_{off} - 0.0576 I_p T_{lift} + 0.001547 T_{on} T_{off} - 0.00356 T_{on} T_{lift} \]

\[ + 0.00270 T_{off} T_{lift} + 0.2039 I_p^2 - 0.01213 T_{on}^2 - 0.000445 T_{off}^2 + 0.01017 T_{lift}^2, \]
### Table 3. Experimental results.

| Level of parameters | Experimental results |
|---------------------|----------------------|
| S.No | Ip | Ton | Toff | Tlift | MRR (mg/min) | TWR (mg/min) | SR (µm) |
| 1 | 1 | 1 | 1 | 1 | 8.233 | 1.247 | 5.830 |
| 2 | 1 | 1 | 2 | 2 | 4.100 | 0.607 | 4.432 |
| 3 | 1 | 1 | 3 | 3 | 1.666 | 0.577 | 3.651 |
| 4 | 1 | 2 | 1 | 2 | 11.570 | 0.453 | 5.642 |
| 5 | 1 | 2 | 2 | 3 | 8.520 | 0.280 | 6.100 |
| 6 | 1 | 2 | 3 | 1 | 5.333 | 0.517 | 6.763 |
| 7 | 1 | 3 | 1 | 3 | 8.661 | 0.156 | 7.641 |
| 8 | 1 | 3 | 2 | 1 | 12.100 | 0.416 | 8.745 |
| 9 | 1 | 3 | 3 | 2 | 7.933 | 0.223 | 5.910 |
| 10 | 2 | 1 | 1 | 2 | 8.331 | 0.760 | 7.010 |
| 11 | 2 | 1 | 2 | 3 | 4.000 | 0.320 | 6.352 |
| 12 | 2 | 1 | 3 | 1 | 3.166 | 0.830 | 8.485 |
| 13 | 2 | 2 | 1 | 3 | 7.367 | 0.743 | 7.219 |
| 14 | 2 | 2 | 2 | 1 | 12.133 | 0.710 | 8.531 |
| 15 | 2 | 2 | 3 | 1 | 5.833 | 0.396 | 7.219 |
| 16 | 2 | 3 | 1 | 2 | 10.667 | 0.326 | 7.514 |
| 17 | 2 | 3 | 2 | 2 | 5.200 | 0.210 | 7.118 |
| 18 | 2 | 3 | 3 | 3 | 5.833 | 0.837 | 7.479 |
| 19 | 3 | 1 | 1 | 3 | 8.367 | 1.303 | 8.454 |
| 20 | 3 | 1 | 2 | 1 | 10.967 | 1.720 | 9.923 |
| 21 | 3 | 1 | 3 | 2 | 4.833 | 0.913 | 7.031 |
| 22 | 3 | 2 | 1 | 1 | 22.567 | 2.583 | 10.178 |
| 23 | 3 | 2 | 2 | 2 | 16.667 | 1.893 | 9.264 |
| 24 | 3 | 2 | 3 | 3 | 7.600 | 0.837 | 6.777 |
| 25 | 3 | 3 | 1 | 2 | 11.443 | 0.970 | 10.869 |
| 26 | 3 | 3 | 2 | 3 | 8.330 | 1.063 | 8.580 |
| 27 | 3 | 3 | 3 | 1 | 14.103 | 1.300 | 11.010 |

\[
TWR = 6.12 - 0.900I_p - 0.0117T_{on} - 0.0001T_{off} - 0.10441T_{lift} + 0.00029I_pT_{on} \\
-0.0011I_pT_{off} - 0.0511I_pT_{lift} + 0.000183T_{on}T_{off} + 0.000665T_{on}T_{lift} + 0.000234T_{off}T_{lift} + 0.0485I_p^2 - 0.000313T_{on}^2 - 0.000014T_{off}^2 + 0.00414T_{lift}^2 (8)
\]

\[
SR = -0.64 + 0.785I_p + 0.175T_{on} + 0.0302T_{off} - 0.311T_{lift} - 0.00220I_pT_{on} \\
-0.00130I_pT_{off} - 0.01460I_pT_{lift} + 0.000034T_{on}T_{off} + 0.00065T_{on}T_{lift} + 0.0001652T_{off}T_{lift} + 0.000101I_p^2 - 0.000973T_{on}^2 - 0.000052T_{off}^2 + 0.01780T_{lift}^2 (9)
\]

\( R^2 \)- values of models for MRR, TWR and SR are 95.36%, 90.55% and 93.43% respectively. This shows the second order regression model is accurate. The \( R^2 \) is defined as the ratio of variability explained by the model to the total variability in the actual data and is used as a measure of the goodness of fit [12].

### 5. Results and discussion

As shown in the main effects plot for MRR shown in figure 2, the MRR increases with increase in peak current because of the depth of craters more due to the higher intensity of the sparks,
Table 4. Response table for means of MRR.

| Level | Ip    | Ton   | Toff  | Tlift |
|-------|-------|-------|-------|-------|
| 1     | 7.568 | 5.963 | 10.775| 11.004|
| 2     | 7.670 | 10.632| 9.720 | 9.042 |
| 3     | 11.442| 10.086| 6.185 | 6.635 |
| Delta | 3.873 | 4.670 | 4.589 | 4.369 |
| Rank  | 4     | 1     | 2     | 3     |

Table 5. Response table for means of TWR.

| Level | Ip     | Ton    | Toff  | Tlift |
|-------|--------|--------|-------|-------|
| 1     | 0.4973 | 0.9197 | 0.9568| 1.0799|
| 2     | 0.5109 | 0.9243 | 0.8150| 0.7164|
| 3     | 1.3980 | 0.5622 | 0.6344| 0.6099|
| Delta | 0.9007 | 0.3621 | 0.3223| 0.4700|
| Rank  | 1      | 3      | 4     | 2     |

Table 6. Response table for means of SR.

| Level | Ip    | Ton   | Toff  | Tlift |
|-------|-------|-------|-------|-------|
| 1     | 6.079 | 6.796 | 7.939 | 8.675 |
| 2     | 7.591 | 7.510 | 7.716 | 7.199 |
| 3     | 9.121 | 8.484 | 7.136 | 6.917 |
| Delta | 3.041 | 1.687 | 0.803 | 1.758 |
| Rank  | 1      | 3      | 4     | 2     |

similar trend was observed with pulse on time up to 20sec then it causes to decrease because of the working current increases due to the increase in pulse on time which causes to form a carbon layer on tool surface at higher working currents. Working current is calculated based on equation 10.

\[
IW = (IP) \times D, \quad (10)
\]

\[
D = \frac{T_{on}}{T_{on} + T_{off}}. \quad (11)
\]

where \(IW\) = Working current in Amperes; \(IP\) = Peak current in Amperes; \(D\) = Duty ratio, \(T_{on}\) =Pulse on time, \(T_{off}\) =Pulse off time. MRR decreases with increase in pulse off time and tool lift time because of the idle time increases. As shown in the main effects plot for TWR shown in figure 3. TWR increases with increase in current because of the depth of craters increases due to the higher intensity of the sparks which causes higher temperatures, however, from the response tables for means of the MRR, TWR and SR, It is found that the percentage of variation of MRR by varying the input factors, peak current, pulse on time, pulse off time and tool lift time are 8.33%, 2.20%, 1.25% and 6.66% respectively. The percentage of variation of TWR by varying the input factors, peak current, pulse on time, pulse off time and tool lift time are 8.33%, 3.33%, 1.25% and 6.67% respectively. The percentage of variation of SR by varying the input factors, peak current, pulse on time, pulse off time and tool lift time are 8.33%, 2.50%, 1.25% and 6.66% respectively. The variation of the responses MRR and SR are higher with respect to the variation of the current, and least variation of the responses is observed with the variation of the pulse off time. The main effects plots are generated based on the response.
Figure 2. Effects of process parameters on Metal Removal Rate.

Figure 3. Effects of process parameters on Tool Wear Rate.

Figure 4. Effects of process parameters on Surface Roughness.

tables 4, 5 and 6 for the means of responses MRR, TWR and SR and are shown in figures 2, 3 and 4 respectively. TWR increases with increase in pulse on time up to 20sec then it causes to decrease because of the working current increases due to the increase in pulse on time which causes to form a carbon layer on tool surface at higher working currents. TWR decreases with increase of the other parameters. It is observed from the main effects plot for SR shown in figure 4, SR increases with increase in peak current and pulse on time because of higher depths of craters formed on the machined surface where as increase in pulse off time and tool lift time causes SR to decrease the surface finish of the machined surface is more with increase in pulse off.
time and tool lift time but the MRR is less and peak current is the found to the most important factor effecting the responses.

It is found from the figure 6 that there is an interaction between the process parameters in affecting the tool wear rate since the responses at different levels of process parameters for a given level of parameter value are not parallel. It is seen from the figures 5 and 7 that there is weak interaction between the process parameters in affecting the metal removal rate and surface roughness since the responses at different levels of process parameters for a given level of parameter value are almost parallel.
6. Conclusion

In this study, the MRR, TWR and SR in EDM process of Titanium alloy using copper electrode were modeled and analyzed based on the Taguchi design of experiments and regression analysis. The input parameters peak current, pulse on time, pulse off time and tool lift time is employed to carry out the experimental study. The following conclusions were drawn based on the study.

- Peak current was found to be the most important factor effecting the MRR, TWR and SR.
- Increase in peak current causes MRR, TWR and SR to increases continuously.
- Increase in pulse on time causes MRR and TWR to increase up to second level then started to decrease but increase in pulse on time causes SR to increase.
- Increase in tool lift time causes MRR, TWR and SR to decrease continuously.
- Increase in pulse off time causes MRR, TWR to decrease, however, SR to decrease up to level 2, followed to increase till level 3.
- It is found that the percentage of variation of responses (MRR, TWR and SR) by varying the input factors, peak current, pulse on time, pulse off time and tool lift time are 8.33%
- It is found that the percentage of variation of responses MRR, TWR and SR by varying the input factor pulse on time are 2.201 %, and 3.33% and 2.50% respectively.
- There is weak interaction between the process parameters affecting the metal removal rate and surface roughness as compared to affecting the Tool wear rate.
- $R^2$ - values of models for MRR, TWR and SR are 95.36%, 90.55% and 93.43% respectively.

The research findings along with various mathematical models will provide effective guide line to result parameter settings for achieving required MRR, TWR and SR during the machining of titanium super alloy on EDM.

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