Optimization of micro-EDM drilling on titanium alloy (Ti-6AL-4V) using RSM and Neural Network

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Abstract. In modern manufacturing industries, micro machining technology is widely used to machine micro parts for various applications such as in MEMS, die and tool industries, etc. Micro electric discharge machining (Micro-EDM) is widely used in die and tool making. This paper investigates three different input machining parameters such as pulse on time, pulse off time, and servo voltage of micro electric discharge machining performances of tool wear (TW) and Diametrical accuracy (DA) of a hole on titanium alloy (Ti-6Al-4V) using copper micro electrodes of ø 400µm. The experiments are conducted out with the Box-Behnken design of Response Surface Methodology (RSM). The neural network is used for the optimization of multi response by fitting the regression model. ANOVA is also performed to find the significant contribution of the machining parameter. The predicted optimal machining values with the maximum error of 12.72% for tool wear and 8.78% for diametrical accuracy was achieved on comparing with experimental results.

Keywords: Micro-EDM, Tool Wear, Diametrical accuracy, Response Surface Methodology, Box-Behnken Design, Neural Network.

1. Introduction

In today’s manufacturing scenario, there are vast requirements for the machining of micro holes for different micro parts and components. Micromachining is increased significantly in industries due to the increase in miniaturization of micro parts. To fulfill these manufacturing requirements, different micro-machining techniques are used in industries to improve the surface quality and cost-effectiveness. Micro-EDM is recognized as one of the effective micro machining techniques used in a wide range of industries like automotive, gears, aerospace, electronics, healthcare, watches, etc. Micro-EDM is an unconventional machining process in which the complex 3D components, hard materials can be machined accurately with a good surface finish. The machining of materials in Micro-EDM is done by generating a spark between the tool and the workpiece in the dielectric medium. Regardless of its hardness and toughness, any conductive material can be machined. Titanium alloy is used in a wide range of applications like dental, automobile, bio-medical, due to its lightweight, high strength, and hardness. Among the titanium alloys, Grade 5 (Ti-Al4-6v) material is most commonly used. Machining titanium in the conventional machining process is extremely difficult because of work hardening characteristics and cutting tool materials. Different machining parameters, dielectric fluid, materials are studied by numerous researchers to optimize the effect of various output responses like material removal rate, tool wear rate, surface roughness, and their relationship in micro and Nano manufacturing on the machining accuracy [1-7].

In Electric Discharge Machining process electrode wear is one of the prominent issues as it impairs the accuracy of the work material. Kamal Kumar et al. [8] manufactured tungsten carbide cobalt (WC-Co) micro electrodes for the applications of micro-EDM processes. They fabricated micro
electrodes with a modified electrical discharge drilling machine with a rotating tubular electrode and reported that with the use of this process a large number of electrodes can be easily and quickly fabricated. Arun Kumar et al. [9] investigated the machining rate of electrical discharge drilling with an L9 orthogonal array as design experiments. Tubular electrodes are fabricated with input parameter as discharge current, pulse on time and pulse off time to investigate machining rate and concluded that machining rate is increased with increase in discharge current and pulse on time. Grzegorz Skrabalak [10] studied the electrode tool length for micro hole drilling in the gas nozzle and recommended keeping the electrode length as short as possible to minimize the discharge effect during machining. Guodong Liu et al. [11] proposed a novel method for the fabrication of silicon based tool electrode for the micro-electro chemical machining process. Micro grooves and micro holes are machined with the silicon based tool and investigated the effects of deposition insulating films and their feasibility. Partibhan et al. [12] used a wire electric discharge grinding process to manufacture the micro tool for micro drilling in EDM. The copper micro electrodes was fabricated and micro drilling was performed in the EDM machine. Response surface methodology is used to optimize the tool wear during the micro drilling process. Y.H. Guu et al. [13] examined the stress concentration in titanium alloy during EDM drilling. ANOVA was used to find the optimal parameter and Finite elemental analysis was analyzed to study the stress concentration in drilled micro holes.

Chauhan et al. [14] implemented response surface methodology to optimize machining parameters in turning titanium alloy. Kumar et al. [15] investigated the machining of metal matrix composite in EDM for the machining parameter such as discharge current, pulse on time, gap voltage on material removal rate, electrode wear, and surface roughness. In this experiment, they used cryogenic cooling of liquid nitrogen copper electrodes for machining of material in EDM. Mustafa Ay et al. [16] evaluated grey relational analysis to find the optimum response of EDM drilling of Inconel-718 alloy. Hole taper ad hole dilation was measured and using this method significant improvement in hole quality was achieved. Ramesh et al. [17] employed a fuzzy-based optimization technique to analyze the cutting parameters during the turning operation of titanium alloy material. Sagar U.Sapkal et al. [18] analyzed the EDM machining parameters for micro hole drilling in titanium alloy material by rotating electrode. To achieve maximum MRR and minimum surface finish Natarajan et al. [19] used the RSM method to predict the optimal values on the micro-end milling. Arunachalam et al. [20] carried out multi response optimization using Taguchi and grey relation analysis on micro EDM. Based on the performance characteristics of the machining process, pulse on time was determined as the most significant parameter. Shiba Narayan Sahu et al. [21] experimented using full factorial design and an artificial neural network (ANN) is used to predict the response equation. Based on the multi objective optimization the fitting equation from ANN is used in genetic algorithm (GA) to predict an optimal value for tool wear rate and MRR. Sampath Velpula et al. [22] used ANN to predict and analyze the machining parameters of the EDM process to obtain the response for tool wear rate and MRR. The experiments were performed using the box-behnken design of the RSM technique. Naveen Babu et al. [23] investigated the MRR and surface roughness on Inconel 750 in WEDM. Executed ANN and particle swarm based multi objective optimization techniques to achieve optimal MRR and surface roughness.

This paper focuses on the effects of output response such as tool wear and diametrical accuracy (overcut) of a drilled hole in the micro-EDM process using titanium alloy. The micro electrodes are fabricated using the wire electric discharge grinding (WEDG) process. The effects of various machining parameters which affect the machining performances such as pulse on time, pulse off time and servo voltage are examined. Optimal parameters of the machining process for micro-EDM are obtained based on the desirability function approach of multi objective technique.

2. Materials and methods

2.1 Materials

In this experimental work, copper (Cu) material was selected as an EDM tool electrode material. The copper electrode is selected because of its high industrial usage and produces a good surface finish under the condition of parameter selection. The cylindrical copper rods are machined through hybrid machining Wire Electrical Discharge Grinding (WEDG) processes. The copper rods are machined appropriately around ø 400µm and the workpiece material selected for micro drilling was a thin plate.
of titanium alloy (Ti-4Al-6V) grade 5 of dimension 60 × 60 × 4 mm. The chemical composition of the titanium alloy is shown in Table 1. EDM oil of commercial grade is used as a dielectric fluid during machining operations.

Table 1. Chemical composition of Ti-6Al-4V

| Element | Al  | V   | Fe  | O   | C   | N   | Y   | Ti   |
|---------|-----|-----|-----|-----|-----|-----|-----|------|
| Weight (%) | 6.11 | 4.0 | 0.18 | 0.18 | 0.01 | 0.01 | <0.005 | 89.505 |

2.2 Response surface methodology

Response surface methodology is a statistical and numerical optimization technique used to design experiments and optimize process parameters [24,25]. RSM was used to model a response surface equation to obtain the required significant variable that produces an optimal response value within the experimental conditions. The box-behnken design technique does not have an embedded factorial design. This technique has design combinations at the midpoints of the experimental space and requires a minimum of three continuous factors. In this micro drilling operation, 15 experimental runs have been considered using the Minitab software.

3. Experimentation

The experiments were performed on an EDM machine (Mitsubishi) tool. The fabricated microelectrodes for the micro drilling process are shown in Fig 1. The level of parameters is selected based on the survey of literature and pilot experiments. The input parameters such as servo voltage, pulse on time, and pulse off time are selected as design variables and their range is shown in Table 2.

Table 2. Level of parameters

| Parameters         | Low (−1) | Medium (0) | High (+1) |
|--------------------|----------|------------|-----------|
| Servo voltage (V)  | -2       | 0          | 2         |
| Pulse on time (μs) | 3        | 6          | 9         |
| Pulse off time (μs)| 9        | 10.5       | 12        |

The experiments are conducted based on the design of experiments on the titanium alloy work material to obtain the output response values for tool wear and diametrical accuracy of the hole. The experimental setup for micro-EDM drilling is shown in Fig 2.
Figure 2. Experimental setup of Micro drilling in die-sinker EDM.

Micro holes on Titanium alloy, where the micro drilling of Ø 400 µm is performed with the help of Ø 400 µm copper electrodes. The copper electrodes for micro drilling as shown in figure 1 are used as electrode tool in the micro-EDM drilling process. The tool wear for each electrode is observed during the micro drilling process with the selected machining parameters.

The Tool Wear of microelectrodes is measured with the help of diameter reduction during micromachining. The diameter of the microelectrodes before and after micro drilling is measured with a polarized light optical microscope. The difference in diameters before and after micro drilling gives Tool Wear measurement as shown in equation 1.

\[ TW = D_i - D_f \]  

Where,

- **TW**: Tool Wear
- **D_i**: Diameter of microelectrode before drilling
- **D_f**: Diameter of microelectrode after drilling

With the help of this equation, the tool wear for all the 15 numbers of microelectrodes are analyzed.

The diametrical accuracy was obtained by measuring the diameters of the machined holes using a polarized optical microscope. Diametrical accuracy (overcut) was estimated as the difference of entry diameters of micro-hole and diameter of micro-tool and mathematically expressed in Equation 2.

\[ DA = (D - D_t) \]  

Where,

- **DA**: Diametrical Accuracy
- **D**: Diameters of micro-hole
- **D_t**: Diameter of tool electrode

The machined microelectrodes and workpiece (Titanium alloy) are shown in Figures 3 and 4 respectively. In figure 4 we can observe the variation in the diameter of the hole. More current on copper leads to inconsistency in the material removal which may cause diameter variation.
Figure 5. Microscope image of Tool and workpiece (titanium alloy) after micro drilling

Figure 5 shows the microscopic image of the machined micro hole and the electrode. The micro electrode can be seen that there is a large amount of side and end wear that occurred during the machining process. The dimensions of the electrode and micro hole values are calculated and examined further by the prediction model.

4. Results and Discussion

4.1 multilayer perception neural network for TW and DA

In this study, the models are developed in ANN to predict the output response values of Tool wear and diametrical accuracy of the micro hole in titanium alloy. The network structure of the model consists of three input nodes they are servo voltage, Pulse on time, and Pulse off time in the input layer and fourteen hidden neurons and the hidden neuron consists of weights and two nodes in the output layer that gives us the predicted Tool wear and Diametrical accuracy of the micro hole. The dataset for each model consists of 15 samples out of which 70% is used for training the network, 15% is used for testing the network and the remaining data samples are used for validation i.e. 11 samples are used for training the network 2 samples are used for testing and 2 samples for validating the network. The network is trained until the desired R-value is achieved (i.e. R > 0.8). The R-value gives the co-relation fit of the developed model, only if R>0.8 the prediction done by the model will be close to the experimentally measured values. Table 3 as shown provides the experimentally measured output values for experimental design.

| SI. No. | Servo voltage (V) | Pulse on time (µs) | Pulse off time (µs) | Tool wear (µm) | Diameter Accuracy (µm) |
|---------|-------------------|--------------------|---------------------|----------------|------------------------|
| 1       | 2                 | 6                  | 9                   | 7.63           | 215.19                 |
| 2       | -2                | 9                  | 10.5                | 15.00          | 143.79                 |
| 3       | 0                 | 6                  | 10.5                | 6.37           | 195.79                 |
| 4       | 0                 | 9                  | 12                  | 13.91          | 240.86                 |
| 5       | 0                 | 3                  | 12                  | 18.62          | 205.48                 |
| 6       | 0                 | 3                  | 9                   | 19.39          | 271.18                 |
| 7       | -2                | 3                  | 10.5                | 23.28          | 161.29                 |
| 8       | 2                 | 3                  | 10.5                | 17.08          | 239.39                 |
| 9       | 0                 | 6                  | 10.5                | 7.54           | 184.71                 |
| 10      | 2                 | 6                  | 12                  | 13.54          | 287.87                 |
| 11      | -2                | 6                  | 12                  | 24.51          | 256.35                 |
| 12      | 0                 | 9                  | 9                   | 4.38           | 247.81                 |
| 13      | 0                 | 6                  | 10.5                | 7.41           | 194.63                 |
| 14      | 2                 | 9                  | 10.5                | 2.45           | 393.11                 |
| 15      | -2                | 6                  | 9                   | 12.49          | 234.70                 |
The predicted tool wear and diametrical accuracy values by ANN model for the given input parameters respectively. It is observed that the experimentally measured output response values are in good agreement with the predicted output response values. The relative percentage error between the predicted values and experimental results are closer to the experimental values with a maximum deviation of tool wear and Diametrical accuracy as 12.72% and 8.78% respectively.

Figure 6 shows that for the predicted model the R-value is 0.987. Therefore the ANN gives us a good prediction of tool wear and diametrical accuracy. The Mean Square Error (MSE) is found to be 0.229 and the experimental results show that the accuracy of the prediction is acceptable.

4.2 Mean effective and surface plots for Tool wear
The results, to find the optimal process parameters are discussed with the use of various tools like ANOVA and S/N Ratio to find out the significant effect of machining parameters on diametrical accuracy. The analysis was performed for a confidence level of 95% The result of ANOVA for Tool Wear and examined that the Pulse on time with a percentage contribution of 40.56% is the most influencing parameter to obtain the minimal Tool Wear, Servo voltage, and pulse off time comes next with a percentage contribution of 29.58% and 20.71% respectively which has a less influence for the Tool Wear. The experimental results for tool wear and its corresponding S/N ratio Curve for the micro electrode as shown in figure 8.
Figure 7. Main effect plots of S/N ratio for Tool Wear

The optimum parameter value which gives good tool wear was inferred by analyzing from the graphical plot of S/N ratios shown in Figure 7. The increase in Pulse on time and Servo voltage gives out more thermal energy which causes better removal of material. Similarly, better tool wear at longer the pulse off time could be seen for a high pulse off time. The amount of working time of the tool to reduce automatically which may lead to a reduction of Tool Wear. The plot showed the optimum parameters for tool wear for micro machining of copper rods as servo voltage of -2V, pulse on time of 3µs, and pulse off time of 12µs.

Figure 8 and 9, shows that the tool wear is minimum when the pulse on time at 9 µs and pulse off time at 9 µs. With the high pulse on time of 9µs to maintain the duty cycle in a proportional way for machining and to reduce the Tool Wear. When the pulse on time and servo voltage is maximum at 9 µs and 2V the tool wear is less and this is because the current is directly proportional to the voltage.
Figure 10. Surface plot of TW Vs T_{OFF} Time, SV

Figure 10, shows that when an increase in a servo voltage and decrease in a pulse off time, reduces the tool wear during machining. From the plot, the tool wear of the electrode increases when the voltage drops down, and an increase in pulse off time. This clearly shows that an increase in current, increases the discharge amount of spark and that leads to the increase in tool wear. From the surface plots, the optimal parameter to obtain the tool wear is observed when the servo voltage at -2V, pulse on time at 3 µs, pulse off time at 12 µs respectively.

4.3 Mean effective and surface plots for Diametrical Accuracy

The ANOVA was performed for diametrical accuracy and the results stated that the servo voltage with the percentage contributions of 50.69% have a great influence on the diametrical accuracy followed by pulse on time 25.24% and pulse off time 16.31% respectively. The smaller the better characteristic for diametrical accuracy was considered for obtaining optimal machining performance. The experimental results for diameter accuracy and its corresponding S/N ratio are provided in figure 11.

Figure 11. Main effect plots of S/N ratio for Diametrical accuracy

The optimum parameter value which gives good diametrical accuracy was inferred by analyzing from the graphical plot of S/N ratios shown in Figure 11. The Increase in Pulse on time and Servo voltage gives out more thermal energy which causes better removal of material. The higher the current which causes more material removal may cause diametric variations. Similarly, a better diameter at shorter the pulse off time could be seen for a smaller pulse off time. During more pulse off time, there was more thermal energy which could cause variations in the diameter. The surface plots showed the optimum parameters for diameter accuracy of the micro hole in titanium alloy as servo voltage of 2V, pulse on time of 9µs, and pulse off time of 12µs.
Figure 12. Surface plot of DA Vs TON, TOFF Time

Figure 12, shows that the diametrical accuracy of the micro hole increases when both the pulse on time and pulse off time is minimum. The higher the current which causes more material removal and causes the diametric variations. And figure 13, shows that the diametrical accuracy Vs the pulse on time and the servo voltage. From the figure, it is observed that when the servo voltage and pulse on time are minimum the accuracy of the diameter of the micro hole is high. Because the current and the number of sparks that erode the material is minimum and gives good diametrical accuracy during the micro drilling process.

Figure 13. Surface plot of DA Vs TON Time, SV

Figure 14. Surface plot of DA Vs TOFF Time, SV

From the surface plot figure 14, it is observed that during more pulse off time there was more thermal energy which could cause variations in the diameter. The higher the current which causes more material removal may cause diametric variations. Similarly, a better diameter at shorter the pulse off time could be seen for a smaller pulse off time. Larger discharging energy causes violent sparks and results in deeper erosion, resulting in high material removal during the micro drilling. The surface plot leads to the conclusion that a better diameter accuracy can be get with a servo voltage at 2V, pulse on time at 9 µs, and pulse off time at 12 µs.

5. Conclusion
In this work, multi response optimization was performed to examine the tool wear and diametrical accuracy (overcut) of the hole in the micro-EDM drilling process. The copper micro electrodes of ø 400µm are fabricated and micro-EDM drilling was performed on the titanium alloy material. RSM was used to model the design experiments and neural networks were implemented to optimize the response parameters for the micro-EDM drilling process. From the study, it was evident that Pulse on time is the most dominating parameter for TW with a percentage of 40.56%, and servo voltage is the most dominating parameter for DA with a percentage contribution of 50.69%. Prediction of Tool Wear and Diametrical accuracy has been found using the ANN model with the maximum error of 12.72% for tool wear and 8.78% for diametrical accuracy comparing with experimental results and the R-value of the network model is found to be 0.987.
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