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Optimization Of Multiple Characteristics Of EDM Parameters Based On Desirability Approach And Fuzzy Modeling

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Abstract

Electrical Discharge Machining (EDM) has emerged as an outstanding approach for cutting conductive metals that are otherwise difficult or impossible to be cut with traditional machining [1]. Moreover, a survey of literature has found that a little of work was carried out in the direction of achieving optimal levels of machining parameters for the super alloy Inconel 718, among other super alloys, which are otherwise difficult to machine. The objective of the present work was to investigate the effects of various EDM input parameters as well as the influence of different tool geometry on Material Removal Rate(MRR), Tool Wear Rate(TWR) and Surface Roughness(SR) on machining of Inconel 718 material by using copper electrode. Five EDM parameters, namely pulse on time ($T_{ON}$), pulse off time ($T_{OFF}$), peak current ($A$), flushing pressure ($P$) and electrode tool geometry (Geo), were considered here. Tool geometry of the electrodes was circle (C), square (S), rectangle (R) and triangle (T). Four different levels for the five input parameters were planned as per the $L_{16}$ orthogonal array. The parameters were optimized using multi-objective optimization technique of desirability approach and the significance of each parameter was analyzed by Analysis Of Variance (ANOVA). In addition, Fuzzy Logic Model (FLM) was used to better understand the input and output responses. With the desirability approach, it was sought to optimize the values for copper electrode for maximum MRR and minimum TWR and SR. Overall, the rectangular tool geometry emerged successful. A comparison of the performances of the electrode by desirability approach and ANOVA showed that the current was the most influencing factor, followed by pulse on time and pulse off time. It was also observed that the rectangular tool geometry provided better results as compared to other tool geometries. Validation tests for FLM were carried out and show closer relationship with the experimental results.

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1. Introduction

Rapid innovations in the fields of space research, missile and nuclear industry require highly complicated and precise components made out of advanced materials. Innovative materials such as superalloys, composites, and ceramics are difficult to be processed [2] by conventional machining techniques, from the standpoint of economic production and environmental safety [3]. These challenges have facilitated the development of non-conventional machining techniques [4]. It is well known that conventional methods are inadequate to machine innovative materials such as tungsten, hardened steel, tantalum, high-strength steel alloys, superalloys like Inconel 718, as well as to produce complex geometrical shapes in the hard and temperature-resistant alloys and die steels [5]. EDM has been widely used to produce dies and moulds since it was developed in the late 1940s [6]. It works based on the thermoelectric energy between the workpiece and the electrode [7-8]. A pulse discharge applied in a small gap between the workpiece and the electrode was found to remove the unwanted material from the parent metal through melting and vaporizing. The electrode and the workpiece must have electrical conductivity in order to generate a spark [9]. EDM uses electricity as energy source and conductive materials as tool. In EDM, direct contact between the electrode and the workpiece is avoided, thus eliminating mechanical stresses, chatter and vibration problems during machining [10].

Quantization of the performance measures is necessary to understand the levels of significance of the machining parameters. Using two grades of WC-Co, Mahadavinejad [11] has investigated with a predictive controller model based on neural networks. The test results confirm the capability of the predictive controller model with increase in efficiency of 32.8% in MRR. Karthikeyan et al. [12] have applied Response Surface Methodology (RSM) to EDM characteristics. Ghoreishi and Tabari [13] have built models for EDM performance parameters using the Taguchi methodology and RSM. Some information on the choice of cutting parameters for machining Inconel 718 is available in Ramakrishnan and Karunamoorthy [14]. During machining of Inconel 718 by die sinking EDM, a high discharge current shall induce spark energy, which facilitates more tool wear [15]. High flushing pressure will remove the eroded particles from the gap between tool and workpiece more effectively, which in effect will increase the TWR. Bozdana et al. [16] have presented a comparative study on machining and surface characteristics of through and blind holes on Ti-6Al-4V and Inconel 718 by fast hole rotary EDM process using tubular hollow copper and brass electrodes. The brass electrode exhibited higher MRR than copper electrode on both Inconel 718 and Ti-6Al-4V. MRR of Inconel 718 was higher than that of Ti-6Al-4V due to the effect of melting point. The choice of the shape of tool electrodes greatly influences the MRR, TWR and SR. However, limited research is available on tool geometry influences on process performance. Pellicer et al.[17] have studied the influences of different input parameters as well as tool electrode geometry on MRR, depth, slope, width and SR of copper electrode on AISI H13 tool steel. They observed that tool geometry had no influence on MRR and SR. Due to better radial wear, square and rectangle geometry performed the best. Triangle was not suitable for complex geometries due to wear. Sohani et al. [18] have investigated the effects of tool shape factor with size consideration in sink EDM process by RSM model. The results showed that circular tool geometry yielded higher MRR and lower TWR as compared to triangular, rectangular and square cross-sectioned tool geometry.

Although a literature search revealed the abundance of studies in machining of Inconel 718, most of it has investigated a limited number of process parameters on the performance measures of EDM. In this work, different tool geometries are incorporated to enhance the effectiveness of the EDM process. Though many studies have been taken up to test the influence of MRR, TWR and SR individually upon Inconel 718, the research scope is very limited about multi objective optimization of the metal in question and about modeling of FLM to develop close relationship between input responses against its output responses. The present work fills the gap of multi objective optimization and non linear fuzzy logic modelling.

2. Experimental Work

The 3mm thickness sheet of Inconel 718 plates was cut into the required size 100X50X3 mm using wire cut
EDM process and machined by using copper electrode with different tool geometries like circle, square, rectangle and triangle shape. The drilling operations were performed with copper electrode tool material with different tool geometries using die sinking EDM machine. The weight of the workpiece and electrodes were measured using precise electronic balance machine before and after the machining process over. After completion of each machining operations, the workpiece and electrode was blown by compressed air using air gun to ensure no debris and dielectric were present. In the present study, four level process parameters i.e. $T_{ON}=38,63,83\&93\mu s$, $T_{OFF}=2,7,8\&9\mu s$, $A=4,12,14\&15Amp$, $P=2,5,7\&9$ kgf/cm$^2$ and Geo=C,S,R&T are considered. The rest of EDM parameters kept as constant during the experimentation.

3. Desirability Approach

The desirability function approach to optimize multiple equations simultaneously was originally proposed by Harrington [19]. Essentially, the approach is to translate the functions to a common scale [0, 1], combine them using the geometric mean and optimize the overall metric. The desirability approach involves transforming each estimated response, $y_i$, into a unit less utility bounded by $0<d_i<1$, where a higher ‘$d_i$’ value indicates that response value $y_i$ is more desirable, if $d_i=0$ this means a completely undesired response [20].

Step 1: Calculate the individual desirability index ($d_i$) for the corresponding responses using the formula proposed by the Derringer and Suich [21]. There are three forms of the desirability functions according to the response characteristics.

i. Nominal - the best

$$d_i = \begin{cases} 
\left( \frac{y_j - y_{\min}}{T - y_{\min}} \right)^s, & y_{\min} \leq y_j \leq T, \ s \geq 0 \\
\left( \frac{y_j - y_{\max}}{T - y_{\min}} \right)^s, & T \leq y_j \leq y_{\max}, \ s \geq 0 \\
0, & \text{otherwise}
\end{cases}$$

The value of $y_j$ is required to achieve a particular target T. When the ‘$y$’ equals to T, the desirability value equals to 1; if the departure of ‘$y$’ exceeds a particular range from the target, the desirability value equals to 0, and such situation represents the worst case.

ii. Larger-the better

$$d_i = \begin{cases} 
0, & y_j \leq y_{\min} \\
\left( \frac{y_j - y_{\min}}{y_{\max} - y_{\min}} \right)^r, & y_{\min} \leq y_j \leq y_{\max}, \ r \geq 0 \\
1, & y_j \geq y_{\min}
\end{cases}$$

The value of ‘$y_j$’ is expected to be the larger the better. When the ‘$y$’ exceeds a particular criteria value, which can be viewed as the requirement, the desirability value equals to 1; if the ‘$y$’ is less than a particular criteria value, which is unacceptable, the desirability value equals to 0.
iii. Smaller-the better

\[ d_i = \begin{cases} 1, & y_j \leq y_{\min} \\ \left( \frac{y_j - y_{\max}}{y_{\min} - y_{\max}} \right)^r, & y_{\min} \leq y_j \leq y_{\max}, r \geq 0 \\ 0, & y_j \geq y_{\min} \end{cases} \]  

(3)

The value of ‘y_j’ is expected to be the smaller the better. When the ‘y’ is less than a particular criteria value, the desirability value equals to 1; if the ‘y’ exceeds a particular criteria value, the desirability value equals to 0. In this study, “smaller the better” and “larger the better” characteristics are applied to determine the individual desirability values for minimize the TWR, SR and maximize the MRR.

Step 2: Compute the composite desirability \(d_G\). The individual desirability index of all the responses can be combined to form a single value called composite desirability \(d_G\) by the following Equation (4).

\[ d_G = \sqrt{w_1 d_1^{w_1} \times w_2 d_2^{w_2} \ldots \times w_i d_i^{w_i}} \]  

(4)

Step 3: Determine the optimal parameter and its level combination. The higher composite desirability value implies better product quality. Therefore, on the basis of the composite desirability \(d_G\), the parameter effect and the optimum level for each controllable parameter are estimated. For example, to estimate the effect of factor ‘i’, we calculate the composite desirability values (CDV) for each level ‘j’, denoted as CDV_{ij}, and then the effect, \(E_i\) is defined as:

\[ E_i = \max (\text{CDV}_{ij}) - \min (\text{CDV}_{ij}) \]  

(5)

If the factor i is controllable, the best level \(j^*\), is determined by

\[ j^* = \max_j (\text{CDV}_{ij}) \]  

(6)

Step 4: Perform ANOVA for identifying the significant parameters. ANOVA establishes the relative significance of parameters. The calculated total sum of square values is used to measure the relative influence of the parameters.

Step 5: Calculate the predicted optimum condition. Once the optimal level of the design parameters has been selected, the final step is to predict and verify the quality characteristics using the optimal level of the design parameters.

4 Results and Discussions

4.1 Steps in Desirability approach and ANOVA

Step 1: The values of computed individual desirability for each quality using Equations 2 and 3. The calculated values are presented in Table 1.

Step 2: The composite desirability values \([d_G]\) are calculated using Equation 4. The equal weightage of 0.33 was considered for all parameters and the calculated results are given in Table 1.

| Desirability Descriptions | Desirability Values for 16 Experiments |
|---------------------------|---------------------------------------|
|                           | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
| Individual desirability of | 0.43 | 1.00 | 0.85 | 0.92 | 0.98 | 0.76 | 0.99 | 0.93 | 0.95 | 0.96 | 0.04 | 0.78 | 0.90 | 0.71 | 0.77 | 0.00 |
Step 3: By using Equations 5 and 6, the main parameter effects are calculated and tabulated in Table 2. The factor effects are plotted in Figure 1 (a) for copper.

Table 2. Main factors effect on desirability

| PARAMETRS/ LEVELS | 1  | 2  | 3  | 4  | DIFFERENCE(a) | RANK | OPTIMUM LEVEL(j) |
|-------------------|----|----|----|----|---------------|------|------------------|
| T<sub>ON</sub>    | 0.65 | 0.69 | 0.50 | 0.48 | 0.22          | 2    | 2                |
| T<sub>OFF</sub>   | 0.65 | 0.63 | 0.52 | 0.53 | 0.13          | 4    | 1                |
| A                 | 0.21 | 0.68 | 0.68 | 0.75 | 0.54          | 1    | 4                |
| P                 | 0.51 | 0.56 | 0.56 | 0.68 | 0.17          | 3    | 4                |

Step 4: From Table 2 and Figure 1, the optimal parameters are obtained and also observed that, there is one particular level for each factor for which the responses are either maximum or minimum.

To test the optimum output values of desirability approach, experiments are conducted in EDM by using the input parameters (T<sub>ON</sub>=63μs, T<sub>OFF</sub>=5μs, A=15A, P=9kgf/cm<sup>2</sup> and Geo=R) are obtained through desirability approach as shown in Table 2. The outputs values of MRR, TWR & SR are 0.254g/min, 0.0085g/min & 0.459μm respectively. When comparing these values with individual optimum responses obtained in the L16 array of experiments, the desirability approach gives optimum result for all responses in one set of input.

Step 5. The calculated results of ANOVA are presented in Table 3.
Table 3. ANOVA analysis of copper electrode

| FACTOR | SS  | DOF | MS   | F_CAL | F_TAB | %CONT |
|--------|-----|-----|------|-------|-------|-------|
| TON    | 0.142 | 3   | 0.047 | 5.067 |       | 13.720 |
| TOFF   | 0.052 | 3   | 0.017 | 1.873 | 9.277 | 5.071 |
| A      | 0.751 | 3   | 0.250 | 26.841|       | 92.673 |
| P      | 0.060 | 3   | 0.020 | 2.153 |       | 5.829 |
| Geo    | 0    | 0   | 0.000 | 0.000 |       | 0.000 |
| Error  | 0.028 | 3   | 0.009 |       |       | 2.707 |
| Total  | 1.034 | 15  |       |       |       |       |

Based on the experimental results, the input parameters and its individual parameters contributions are identified using ANOVA technique and the values are presented in Table 3. From Table 3 MRR, TWR and SR of Inconel 718 material were significantly affected by the process parameters such as pulse on time, peak current, pulse off time and flushing pressure. The increase in pulse on time and peak current led to an increase in heat input. Therefore, more material removal was achieved. Higher pulse off time would increase the contact time made between the electrodes and higher flushing pressure will remove more debris from electrodes, thus decreasing TWR and SR. The rectangular tool geometry has obtained the best results compared to other tool geometry.

5. Fuzzy Logic Model

Due to the complex and non-linear relationship between the input parameters and output performance measures, it is quite difficult to develop a process model for EDM. Unfortunately, no efficient, generalized approach to model the EDM process has been reported for studying and predicting MRR, TWR and SR. In this work, an attempt was made to develop a comprehensive intelligent approach to model the die-sinking EDM process using fuzzy logic. A fuzzy set is a set without a crisp boundary. The fuzzy inference system or fuzzy model is a computing framework based on fuzzy set theory, fuzzy if-then rules and fuzzy reasoning. The fuzzy inference system consists of three components, namely rule base, data base and reasoning mechanism. A fuzzy logic unit consists of a fuzzifier, membership functions, a fuzzy rule base, an inference engine, and a defuzzifier [21]. The input and output values are fuzzified using membership functions. The fuzzy reasoning works on fuzzy rules to generate a fuzzy value to be used by inference engine. Finally, fuzzy value is converted into a crisp output by defuzzifier. Generally, defuzzification is done according to the Centre of Area (COA) method. MATLAB R2011b fuzzy logic tool box was used to build the FLM of EDM process.

The first step in generating a fuzzy logic is to identify the ranges of input and output variables. Then, the range of each process variable is divided into groups of fuzzy subsets. Each fuzzy subset is given a proper name and assigned a membership function. The membership function is assigned without depending on the results of the experiments. In general, membership functions are classified into trapezoidal, triangular and square or their combinations. Based on the number of trials, Gaussian membership functions were selected for this study. The notations used in fuzzy subsets were as follows: EL - Extreme Low, L - Low, LM - Low Medium, M - Medium, LA - Low Average, A - Average, LH - Low High, H - High, EH - Extreme High. For all inputs, four input functions were considered, namely low, medium, average and high, represented by L, M, A, H, respectively. Similarly, for output variables, nine different functions were considered, namely extreme low, low, low medium, medium, low average, average, low high, high and extreme high, represented by EL, L, LM, M, LA, A, LH, H, EH, respectively.

The relationship between input and output in a fuzzy system is characterized by a set of linguistic statements. There are no systematic tools for forming the rule base of the FLM. The fuzzy control rules can be derived from experience and knowledge of control engineering [22]. One experiment results in one fuzzy rule. If all the fuzzy
rules are saved in a data base, a fuzzy rule base is established. The number of fuzzy rules in a fuzzy system is related to the number of fuzzy sets for each input variable. In this study, 16 fuzzy rules were established as shown in Table 4.

The output responses of the fuzzy process can be viewed only in fuzzy values and they need to be defuzzified. In this study, the centroid defuzzification method was chosen, as it could produce the centre of area of the possible distribution of the inferenced output.

Table 4. Fuzzy expressions of input and output parameters for copper electrode

| Rules | IF |
|-------|----|
|       | T<sub>ON</sub> | con | T<sub>OFF</sub> | con | A | con | P | con | Geo | con | MRR | TWR | SR |
| 1     | L and | L and | L and | L and | L and | L and | EL | EL | M   |
| 2     | L and | M and | M and | M and | H and | H and | EH | L  | LH  |
| 3     | L and | A and | A and | A and | M and | M and | LA | EL | LA  |
| 4     | L and | H and | H and | H and | A and | A and | LH | EH | EH  |
| 5     | M and | L and | M and | A and | A and | A and | H  | L  | LH  |
| 6     | M and | M and | L and | H and | L and | M and | EL | LM |     |
| 7     | M and | A and | H and | L and | H and | H and | EL | LA |     |
| 8     | M and | H and | A and | M and | L and | LH | L  | EH |     |
| 9     | A and | L and | A and | H and | H and | H and | LM | H  |     |
| 10    | A and | M and | H and | A and | L and | L and | LH | L  | LH  |
| 11    | A and | A and | L and | M and | A and | L and | EL | H  |     |
| 12    | A and | M and | H and | L and | M and | M and | L  | A  |     |
| 13    | H and | L and | H and | M and | M and | A and | LM | H  |     |
| 14    | H and | M and | A and | L and | A and | LM | L  | LM |     |
| 15    | H and | A and | M and | H and | L and | LA | L  | LH |     |
| 16    | H and | H and | L and | A and | H and | EL | EL | EL |     |

Comparisons of predicted values of MRR, TWR and SR using FLM against experimental values for different sets of input values are shown in Figure 2(a-c) for copper electrode. The Figure 2(a) shows the predicted values of fuzzy model with experimental values for MRR and Figure 2(b) shows the predicted values of fuzzy model with experimental values for TWR. Figure 2(c) shows the predicted values of fuzzy model with experimental values for TWR.

![MRR](image-url)

Fig 2(a) Comparison of Fuzzy values with MRR
The Figure 2(a-c) shows the fuzzy predicted values are very closer with the experimental values of MRR, TWR & SR of copper electrodes.

6. Validation of FLM

To validate the FLM for MRR, TWR & SR, the inputs arrived in desirability approach (Table 2) are given to FLM and the outputs are noted (Table 5). The outputs of experimental results and FLM are compared and it shows the FLM output parameters have closer agreement with the experimental results. Thus the FLM is validated with 5% error which is due to errors in machining, measurement and modeling.

Table 5. Validation of FLM

| Fuzzy values | Experimental values |
|--------------|---------------------|
| MRR g/min    | MRR g/min           |
| TWR g/min    | TWR g/min           |
| SR μm        | SR μm               |
| 0.2537       | 0.254               |
| 0.0019       | 0.0085              |
| 2.341        | 1.459               |
7. Conclusion

- The present study investigated the machining responses (MRR, TWR and SR) using copper electrode of Inconel 718 workpiece.
- The multi-objective optimization desirability approach was employed for simultaneous optimization of response characteristics. The optimal sets of process parameters for the selected performance measures were identified. The results of multi-objective optimization desirability tests were pulse on time 63 μs, pulse off time 5 μs, peak current 15 A, flushing pressure 9 kgf/cm², and rectangular tool geometry.
- From the above, higher current (15A) and flushing pressure (9kgf/cm²) was preferred. Medium pulse on time (63 μs) was suitable for copper electrode. Rectangular tool geometry was best for copper electrode.
- The significance and contribution of each parameter was analyzed using ANOVA. From this, the contribution of peak current (72.67%) was high followed by pulse on time (13.07%). Tool geometry was not the most significant factor to affect the performance measures.
- The proposed fuzzy model provides a more precise and easy selection of EDM input parameters for the required MRR, TWR and SR, thereby to optimize machining conditions and reduce costs. The fuzzy model was shown to be able to predict the experimental results with accuracy of 95%. The validation of fuzzy results with experimental findings proved the high accuracy of the model.

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