Numerical Modeling and Multi-Objective Optimization of Micro-Wire EDM Process

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Abstract

With more and more demands of complex micro parts in the field of MEMS, biomedical devices, aerospace, nuclear, electronics, optics, communication, etc., the manufacture of micro products has been a focus in the manufacturing industry. Micro-Wire Electrical Discharge Machining (µ-WEDM) is emerging as one of the popular machining process for precision manufacturing of complex micro parts rapidly and accurately on hard-to-machine materials that are electrically conductive. Determining the optimum machining parameter combination of µ-WEDM in industries mainly rely on the operator’s skill despite extensive researches. In this paper an attempt is made to numerically model the spark erosion rate of µ-WEDM process using finite difference method (FDM) considering circular moving heat source. The temperature distribution along the micro-wire length is used to find the material removal rate for different voltage-capacitance combinations. Also the effect of process parameters in machining Inconel-718 is investigated and optimized using Grey-Taguchi analysis. The Taguchi method based L18 orthogonal array experimental design is used to determine the S/N ratios to indicate the process parameters (voltage, capacitance, feed rate, wire tension and wire feed velocity) which affect the machining performances (MRR and surface roughness) significantly. ANOVA (Analysis of variance) was employed to identify the level of importance of machining parameters on the responses. The experiments were repeated three times and the average value is taken.

Keywords: µ-WEDM, Taguchi Method, Grey Relational Analysis

1. Introduction

Since its introduction to the industry, µ-WEDM is emerging as one of the popular machining process for precision manufacturing of complex micro parts rapidly and accurately on hard-to-machine materials that are electrically conductive. µ-WEDM is a scaled-down version of WEDM to manufacture micro features of size in the range of 1 to 500 µm. Though numerous micro machining techniques like LBM, EBM, EDM, LIGA etc., are there, they are highly expensive, complex involving high maintenance, and are limited to few materials. µ-WEDM works on the same principle as EDM where the workpiece material is removed by a series of discrete sparks occurring between the workpiece and a continuously moving wire separated by a stream of dielectric fluid [Newman et al. 2003]. In µ-WEDM the cutting process is generally carried out by a micro wire electrode of size in the order of 20–70 µm which provides rapid, economic and precise machining for intricate workpieces. In order to avoid wire breakage the discharge power supply should be redesigned to fit the µ-wire in case of µ-WEDM. There are many researches on the modeling of the electrode wear and discharge parameters. Several researchers have attempted to improve the performance characteristics like material removal rate, dimensional accuracy, surface roughness, etc., but the full potential utilization of this process is not completely solved because of its complex, stochastic nature and higher number of variables involved in this operation. Jain [2010] proposed that RC pulse discharge circuit can easily generate a pulse on-time of few nanoseconds making it suitable for µ-WEDM. But due to its low discharge frequency, the time needed to charge the capacitor is more showing a negative effect on its working efficiency. Rahman et al. [2003] found that the specific energy required to remove the material and erosion efficiency is found to be significantly less at lower energies when compared to that at higher energies. Rajurkar et al. [1993] developed a WEDM sparking frequency monitor to detect the thermal load for on-line control to prevent the wire from rupture and carried out an extensive experimental investigation to determine the process performances such as machining rate and surface finish.

Banerjee et al. [2010] proposed a transient thermal analysis for the determination of temperature distribution in the wire of a WEDM process under multiple discharge condition using an explicit FDM. It is found that one-dimensional thermal models can be used for selecting an expert system for the safe
operating conditions of WEDM without the risk of wire breakage. A mathematical model has been developed by Joshi et al. [2010] to predict the cathode erosion rate for single and multi-spark in micro-WEDM. The erosion rate evaluated by the model shows dependence on variables like voltage, wire diameter, number of sparks, and wire vibrations but is independent of the wire velocity.

Shabgardet al. [2013] simulated the temperature distribution on the surface of workpiece and tool during a single discharge in the EDM process using ABAQUS code in finite element software. The profile of temperature distribution was utilized to calculate the discharge crater dimensions. Puri et al. [2003] modeled analytically and investigated the vibrational behaviour of the wire considering multiple spark discharges in WEDM.

Somasekhar et al. [2010] used a factorial design to predict the performance measures in µ-WEDM of aluminium. It is found that capacitance, voltage and feed rate affect the responses significantly. Bhattacharyya et al. [2006] used Taguchi and Gauss elimination method for parametric optimization of process parameters in machining PRAISiCMCC. Yang et al. [2012] used Taguchi’s Orthogonal array and BPNN to predict MRR, surface roughness and corner deviation in cutting tungsten and a multi objective optimization of process parameters was done.

Inconel-718 is a nickel based super-alloy, possessing high strength at elevated temperatures and also resistance to oxidation and corrosion. Rapid work hardening and poor thermal conductivity of Inconel makes it a difficult metal to shape and machine using traditional techniques.

From the literature it is observed that most of the researches were done in EDM and WEDM and other workpiece materials. So the main objective of this work is to numerically model the µ-WEDM process and also to investigate the effect of process parameters inµ-WEDM of Inconel-718 and to optimize the process parameters for maximum MRR and minimum surface roughness.

2. Problem Description

The heat flow across the plasma channel for a moving heat source is given by the governing differential equation, considering energy balance over infinitesimal control volume as

\[
\frac{\partial^2 \theta}{\partial x^2} - n \frac{\partial \theta}{\partial x} - m^2 + \frac{g}{k_w} = \frac{1}{\alpha_w} \frac{\partial \theta}{\partial t}
\]

(1)

where, \( n = \frac{\rho c v_w m}{k_w} \)

The boundary conditions for the model considered in figure 1 is

- \( \theta = 0 \) over the region at \( \tau = 0 \)
- \( \frac{\partial \theta}{\partial x} = 0 \) on the edges of the region far away from the discharge location at \( \tau > 0 \)

2.1 Assumptions

- The plasma characteristics in EDM and micro-WEDM are considered to be identical.
- The material of the wire is homogeneous, isotropic, axisymmetric and has uniform properties.
- Plasma channel is not affected by wire motion.
- Each individual discharge has been considered as a small circular point heat source. Spark radius is independent of time.
- Conduction is the main heat-transfer medium and convective heat-transfer coefficient is assumed to be constant.
- The thermo-physical properties of workpiece material remains same over the range of temperature.

![Figure 1 Physical Model Considered](image.png)

For individual discharge, the heat source is of radius equal to that of wire \( r_0 \) and height equal to diameter \( 2R_p \) of plasma channel . The uniformly distributed internal heat generation \( (g) \) is calculated by the following relation

\[
g(R_p) = \frac{W}{2\pi r_0^2 R_p}
\]

(2)
during discharge duration and is equal to zero during off time.

Using central difference along x-axis, the governing differential equation can be written in the following explicit finite difference form as

\[
\theta_{i+1}^{p+1} = \frac{\alpha_w \Delta \tau}{\Delta x^2} \left[ 1 + \frac{n \Delta x}{2} \right] \theta_{i-1}^p + \frac{1 - \frac{\alpha_w \Delta \tau}{\Delta x^2} (2 + m^2 \Delta x^2)}{\Delta x^2} \theta_{i}^p + \frac{\alpha_w \Delta \tau}{\Delta x^2} \left[ 1 - \frac{n \Delta x}{2} \right] \theta_{i+1}^p + \frac{g \alpha_w \Delta \tau}{k_w}
\]

(3)

A computer program using C- code is written to solve the above equation to find the temperature distribution along the wire length by knowing the
properties of the wire for single spark. This is used to calculate material removal rate.

The properties of tungsten wire taken are: density 19,250 kg/m³; specific heat, Cₚ=130 J/kg K; thermal conductivity, kₔ=173 W/mK; thermal diffusivity 6.5×10⁻⁶m²/s; convective heat-transfer coefficient, 10,000 W/m²K; wire diameter 70µm, wire velocity 60 µm/min.

From figures 2 and 3 it is found that the temperature increases with an increase in voltage(V) and capacitance (C). This is because discharge energy (E=0.5CV²) increases with V and C for the same time duration. Also maximum temperature is seen at center of the wire since it is close to the workpiece.

2.2 Evaluation of MRR

For evaluation of the material removal rate for single spark, considering spherical symmetry of the heat affected zone around the workpiece, the work done by DiBitonto et al. (1989) and Joshi et al. (2010) is taken as reference.

The maximum erosion rate is given by

\[
V_w = \frac{16\pi X^3 \tau_{\partial}^{3/2} F_c U L}{3(\tau_{\partial} + \delta^s)(T_m - T_w)\rho C_p} \quad (4)
\]

\[
V_{\omega}^* = \frac{V_w}{J} \quad (5)
\]

Eqn. (5) is dimensionless form of eqn. (4), where I is current in the wire and J is erodibility.

If n is the no. of sparks, for multi sparking the erosion rate is given by

\[
V_n = n(V_{\omega}^*) \quad (6)
\]

The natural frequency of the vibrating wire is given by

\[
f_v = \frac{i}{2L} \frac{F}{\rho S} \quad (7)
\]

where F is wire tension, r is density of wire material, S is surface area of wire, L is distance between wire guides and i is 0, 1, 2 etc

The final erosion rate considering wire vibrations is

\[
V_f = \frac{V_n}{f_{d}/f_v} \quad (8)
\]

where f_d is the frequency of discharge.

3. Experimental Procedure

Since µ-WEDM is a complex micro machining process only five dominant factors were considered. The Taguchi method based L18 Mixed-Orthogonal Array is used as experimental design and the experimental results are analyzed using Design Expert software version 7.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Factor (or Parameter)</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
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<tr>
<td>1</td>
<td>A Wire Feed Velocity (µm/min)</td>
<td>60</td>
<td>100</td>
<td>---</td>
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<tr>
<td>2</td>
<td>B Gap Voltage (V)</td>
<td>80</td>
<td>115</td>
<td>150</td>
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<td>3</td>
<td>C Capacitance (µF)</td>
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<td>D Feed Rate (µm/min)</td>
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<td>E Wire Tension (g)</td>
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<td>12.375</td>
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</table>

Machine: Micro Machining Centre (DT-110)

Responses: MRR, Surface Roughness (SR)

Workpiece: Inconel-718 (2mm thick)

Wire material: Tungsten (70µm diameter)

Dielectric: EDM-3 Oil

Microslot machined: 5mm length

Figure 4 ISHIKAWA Diagram for responses
Table 2 Experimental Results

<table>
<thead>
<tr>
<th>Run order</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>MRR (mm³/hr)</th>
<th>SR (µm)</th>
<th>S/N Ratio</th>
<th>GRC</th>
<th>GRG</th>
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<td>1.36</td>
<td>-8.174</td>
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</table>

4. Results and Discussions

The mean values of the results obtained for experiments performed by using Taguchi’s L18 orthogonal array experimental design are summarized in Table 2. According to the Taguchi method, the S/N ratio is the ratio of signal to noise where signal represents the desirable value and noise represents the undesirable value. It is a summary statistic, and is denoted by \( \eta \) with a unit of dB. According to Taguchi methodology, the characteristic that a larger value represents better machining performance as in the case of MRR is known as “higher the better” (HB) type of problem. The summary statistics \( \eta (\text{dB}) \) of the HB performance characteristic is expressed as:

\[
\eta = -\log_{10}\left[\frac{1}{n} \sum_{i=1}^{n} y_i^2\right]; i = 1, 2, \ldots n
\]

Similarly the characteristic that a smaller value represents better machining performance as in the case of Surface Roughness is known as “smaller the better” (SB) type of problem. The summary statistics \( \eta (\text{dB}) \) of the SB performance characteristic is expressed as:

\[
\eta = -\log_{10}\left[\frac{1}{n} \sum_{i=1}^{n} y_i\right]; i = 1, 2, \ldots n
\]

4.1 Material Removal Rate

The adequacy of the relationship among the parameters is checked by ANOVA approach. Tables 3 and 4 show the ANOVA, F-test values and % contribution showing the effectiveness of individual process parameter on the machining performances, such as MRR and surface roughness.

Table 3 ANOVA for MRR

<table>
<thead>
<tr>
<th>SI No</th>
<th>Factor</th>
<th>DoF</th>
<th>SOS</th>
<th>Varian ce</th>
<th>F-value</th>
<th>p-value</th>
<th>% contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>1</td>
<td>0.007</td>
<td>0.00784</td>
<td>0.53</td>
<td>0.486</td>
<td>0.368</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>2</td>
<td>0.71</td>
<td>0.355</td>
<td>24.07</td>
<td>0.000</td>
<td>33.33</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>2</td>
<td>0.87</td>
<td>0.435</td>
<td>29.63</td>
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<td>40.84</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>2</td>
<td>0.22</td>
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<td>7.01</td>
<td>0.017</td>
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<td>0.015</td>
<td>5.63</td>
<td>0.000</td>
<td>5.634</td>
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<tr>
<td>7</td>
<td>Total</td>
<td>17</td>
<td>0.213</td>
<td>0.0223</td>
<td>15.16</td>
<td>0.000</td>
<td>Significant</td>
</tr>
<tr>
<td></td>
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<td>2.01</td>
<td>0.223</td>
<td>15.16</td>
<td>0.000</td>
<td>Significant</td>
</tr>
</tbody>
</table>
in this case B, C, D and E are significant model terms. “Adeq Precision” measures the signal to noise ratio. A ratio greater than 4 is desirable. The obtained ratio of 13.59 indicates an adequate signal. From the % contribution it is found that capacitance is the most influencing factor followed by voltage, feed rate and wire tension. Since the % contribution of wire feed velocity falls below 10% it is considered as statistically insignificant.

Table 4 ANOVA for Surface Roughness (SR)

“Adeq Precision” measures the signal to noise ratio. A ratio greater than 4 is desirable. The obtained ratio of 18.23 indicates an adequate signal. From the % contribution it is found that voltage is the most influencing factor followed by capacitance, feed rate and wire tension.

Figure 7 S/N ratio (dB) by factor level for SR

The mean S/N ratio (dB) by factor level for surface roughness is shown in figure 7. From that S/N response graph it can be concluded that the optimal parametric combination for lesser surface roughness is A1B2C1D2E3. With increase in voltage spark intensity increases and hence roughness also increases as more material is removed. With increase in capacitance frequency of sparking will be more and there is a chance of debris to remain in the machining zone creating secondary sparks, increasing the SR. With increase in wire tension, wire vibrations decreases and hence surface roughness improves.

4. Multi-Objective Optimization

In any machining process it is desired that MRR should be maximum and surface roughness to be minimum. The multi objective optimization of maximizing MRR and minimizing surface roughness simultaneously was carried out to find the optimum values of process parameters using Grey Relational Analysis (GRA). In case when experiments are ambiguous or when the experimental method cannot be carried out exactly, grey analysis helps to compensate for the shortcomings in statistical regression. The stepwise procedure of GRA is given below.

Step 1: Normalization of S/N ratio
Step 2: Determination of deviation sequences
Step 3: Calculation of grey relational coefficient (GRC)\[
\xi_i(k) = \frac{A_{\text{min}} + \xi A_{\text{max}}}{A_{\text{q}(k)} + \xi A_{\text{max}}} (11)
\]
Step 4: Determination of grey relational grade (GRG)\[
\gamma_i = \frac{1}{n} \sum_{k=1}^{n} (\xi_i(k)) (12)
\]
The grey relational grade \(\gamma\) represents the level of correlation between the reference sequence and the
Numerical Modeling and Multi-Objective Optimization of Micro-Wire EDM Process

Step 5: Determination of optimum parameters
From table 2 the optimum parameter combination is found to be A1B2C2D2E3 which gives 0.9875 (mm$^3$/hr)MRR and 1.32 (µm)SR.

5. Conclusions
In this present study, an attempt was made to numerically model the µ-WEDM process. The validation for erosion rate is in the scope of future work. The effect of process parameters in machining Inconel-718 using µ-WEDM has been investigated and a multi objective optimization was done to maximize MRR and minimize surface roughness using GRA. The results obtained from this present study is as follows:

From the model considered temperature increases with an increase in voltage (V) and capacitance (C) since discharge energy increases. Also maximum temperature is seen at the center of the wire since it is close to the workpiece.

From the experiments, as the voltage increases, both MRR and SR increases up to a certain value and then decreases. This is because when the voltage reaches a certain limit, there is a possibility of short circuiting and arcing in the small inter-electrode gap decreasing the MRR and increasing SR.

As the capacitance increases, frequency of sparking increases and hence MRR increases. At higher capacitance the charging and discharging time is more. Also the total energy that is used in the machining zone get reduced due to the unwanted debris.

At higher discharge energies surface roughness is found to be more because of larger crater size and also due to secondary sparking and unwanted debris. So proper flushing is necessary at higher discharge energies.

With increase in feed rate more heat is available at spark gap increasing MRR.

With increase in wire tension, wire vibrations decreases and hence surface roughness improves. So high wire tension without wire breakage should be employed.

The optimum parameter combination using GRA is found to be A1B2C2D2E3 which gives 0.9875 (mm$^3$/hr)MRR and 1.32 (µm)SR.

6. References


