Optimization of Material Removal Rate and Surface Roughness for Micro ECM of Inconel 718 alloy utilizing Grey Relational Technique

Madhankumar S1, Rajesh S2, Balamurugan R3, Tharun Sri Ram N1, Venuprasath S1, Tazmeel Ahamed S1
1Department of Mechatronics Engineering, Sri Krishna College of Engineering and Technology, Coimbatore, Tamil Nadu, India - 641008.
2Department of Mechanical Engineering, R.M.K. Engineering College, Tiruvallur, India – 601206.
3Department of Automobile Engineering, Bannari Amman Institute of Technology, Erode, India - 638401.

*Corresponding author, Email Id: madhankumars@skcet.ac.in

Abstract. Material removal rate (MRR) and surface roughness (SR) are vital factors of micro-electrochemical machining (ECM). This machining method is focused on redox reaction. The intensity of machining relies mostly on molecular masses, its current density, the electrolytes and the duration in metal-working. In order to learn the results of MRR and SR on Inconel 718 alloy, tests were performed by considering various criteria employing stainless steel electrodes. Throughout this present context, the optimization is focused on the Taguchi functional grey method. Predictor variables are designed utilizing the Taguchi concept with 3 different process variables, namely electrolyte concentration, feed rate and voltage. In addition to the MRR and surface roughness, the overcut was used as success metrics within that report. The outcome of this study shows that the voltage appears to be the leading variable for the intended performance requirements and also that the optimum values are observed. The confirmatory examination was performed to verify the findings obtained by the grey relational method.

1 Introduction

Hard and tough to process materials like carbon steels, stainless steel, nickel-based alloys as well as other high strength temperature-resistant alloys become commonly used for the aviation and nuclear reactor sectors attributable to certain strong strength-to-weight rate, toughness and heat-resistant properties. With these materials, traditional edged machine machining becomes extremely impractical as well as the level of precision or surface quality is not up to the level. The precision and efficiency of its machining method is assessed by the processing variables. There are many processing variables available namely voltage, pulse on time, pulse off time, current, feed rate and electrolyte concentration. Therefore, it necessitates to always identify the optimal outcomes for the attainment of the finest process variables. In this respect, multiple studies have been carrying out through ECM in various materials including numerous modeling methods have been implemented in an attempt to discover an efficient level [1]. Provided multi-objective optimization for Titanium alloys in electrochemical digging utilizing Grey relational based Taguchi process [2]. Analyzed on electrochemical machining of contemporaneous titanium, nickel-based alloys as well as reviewed for some of its application for the machining of aeromotor elements, ECM provides an effective alternative process for the preparation of derivative markets awesome post such as molds, jet engine items as well as
micro dimensional parts[3]. Probed an ECM process for varying electrolyte proportions but presumed that toxic effects would lead to increased precision[4]. The ECM method for nickel-based content has been investigated and has been demonstrated that perhaps the production of a better component can be accomplished by following the same breakdown of electrical and chemical activity[5]. Explained these same generations throughout the ECM with cylinder-Steels, using different electrolytes, but also stated that even the dielectric rotational speed had been the powerful factor affecting the MRR[6]. Studied a particular feature of an ECM process, including the electrolytic rotation speed, the voltage decided to apply, the chloride output impedance in order to determine the greatest available performance assessment processing parameters, notably MRR, tool wear, excellent surface as well as machine expense [7]. The option of input variables to assess the greatest available machining efficiency is still a difficult issue. Studied numerically EDM of different nickel-based including Inconel and 718 alloys, utilizing the Taguchi concept plan to enhance efficiency features[8]. Different multi-criteria decision-making mechanism grey relational analysis used for EDM of stainless steel. The gray method focused on Taguchi was used to resolve the multi-objective optimization problem of the WEDM technique [9], [10].

Through this discussion, ECM optimization has been performed on different metals and indeed the present research investigated the different output performance variable MRR, SR and overcut as during Inconel 718 micro ECM using three input variables namely electrolyte concentration, feed rate and voltage. Afterward, certain interventions are outlined and the optimization value of its variables are eventually determined utilizing grey relational technique.

2 Materials and methods

Inconel 718 alloy has been chosen to research work material. Taguchi model (L9 orthogonal string) is designed for Inconel 718 specimen and thus the work material has a span of 50 mm, a breadth of 50 mm and a depth of 0.5 mm. The distribution of the 718-alloy material is studied from [11], [12] is mentioned in Table 1[13].

| Element | Ni | Cr | Nb | Cu | Ti | Si | Fe | Mo | Al | Mn | C |
|---------|----|----|----|----|----|----|----|----|----|----|---|
| Min     | 50 | 17 | 4.75 | -  | 0.65 | - | 15 | 2.8 | 0.2 | - | - |
| Max     | 55 | 21 | 5.5 | 0.3 | 1.15 | 0.35 | 19 | 3.3 | 0.8 | 0.35 | 0.08 |

Throughout micro ECM usually, the cathode tool consists of conductive material like stainless steel and copper. Within that research, stainless steel rods are used as electrocatalysts with a span of 50 mm and a diameter of 1 ± 0.02 mm. The electrolyte used in this study was sodium chloride (NaCl). The experimental setup has illustrated in Figure 1. The effectiveness of machining varies depending mostly on processing variables. As from previous research, input variables such as voltage, feed rate and electrolyte concentration have selected for the present research because they've discovered to be had a massive effect on MRR, overcutting and SR. Table 2 gives the developed Taguchi model for this experimentation. Afterward, such interventions have stated as well as the optimization process of its input variables was eventually computed utilizing grey relational grades.
Table 2. Levels of selected input variables

| Input variables | Unit   | Level 1 | Level 2 | Level 3 |
|-----------------|--------|---------|---------|---------|
| Concentration   | Mole/lit | 0.25    | 0.34    | 0.43    |
| Voltage         | Volt   | 10      | 13      | 16      |
| Feed rate       | mm/min | 0.03    | 0.05    | 0.07    |

2.1 Grey relational technique

This approach provides an expert influence of uncertainty, various inputs and inaccurate data. The grey relational technique approach is an estimation of the full significance of the context difference between residues which is often used to determine the nearly consistent correlation between residues. It becomes an efficient method that explores the association between series through virtue of fewer statistics and to analyze a variety of influences[14]. At grey relational analysis, the results collected from its investigations are subsequently standardized. The grey relation coefficients are evaluated to use the datasets and the grey relation rank is measured. This protocol is explained in this section:

The source data becomes first pre-processed. The normalized response values are determined on the basis of the formula given (1) and (2), which refer to the output variables of the predictor variables[1]. The desirable performance parameters for MRR is higher the better criteria; The surface roughness and overcut are indeed the lower the better criteria. Inherently, the higher the normalized values, the stronger the output qualities.

Higher the better, $A_{pq} = \frac{B_{pq} - \min(B_{pq})}{\max(B_{pq}) - \min(B_{pq})}$ (1)

Lower the better, $A_{il} = \frac{\max(B_{pq}) - B_{pq}}{\max(B_{pq}) - \min(B_{pq})}$ (2)

The obvious variability in between highest possible normalized number and each normalized number is calculated using equation (3). Then, equations (4) and (5) used for calculation of grey relation grade and rank.

$\phi_{pq} = [A_{pq} - \max(A_{pq})]$ (3)

Grey relation grade, $\theta_{pq} = \frac{\phi_{pq} + (0.5 \times \max(\phi_{pq}))}{\phi_{pq} + (0.5 \times \max(\phi_{pq}))}$ (4)

Grey relation grade, $\gamma_j = \frac{\sum_{i=1}^{n}\theta_{pq}}{n}$ (5)
3 Results and discussion
The experiment was designed according to the 3-level L9 Taguchi orthogonal model. The model was compiled and analyzed utilizing the statistical tool Minitab 19. Throughout the experiment, three variables at three different levels have been perceived. Figure 2 shows the work material after machining.

![Figure 2. Work material after machining](image)

The MRR and overcut are being determined by the equations (6) and (7) given. The original and final weights of the work material are determined by an automated measuring system with a precision of 0.001 g. The roughness of machine workpieces is reported utilizing SRG4500 hardness test machine. The optical microscope is used for measuring the diameter of specimens. The measured results of MRR, SR and overcut are included in Table 3.

\[
\text{Material removal rate} = \frac{\text{Original weight} - \text{Final weight}}{\text{Density} \times \text{Machining time}} \quad (6)
\]

\[
\text{overcut} = \text{Machined hole diameter} - \text{Initial diameter of hole} \quad (7)
\]

| Run | Electrolyte Conc (mole/lit) | Voltage (volts) | Feed rate (mm/min) | MRR (mm³/min) | SR (µm) | Overcut (mm) |
|-----|-----------------------------|-----------------|--------------------|---------------|--------|-------------|
| 1   | 0.25                        | 10              | 0.03               | 0.0371        | 0.5592 | 0.13543     |
| 2   | 0.25                        | 13              | 0.05               | 0.0397        | 0.4944 | 0.09862     |
| 3   | 0.25                        | 16              | 0.07               | 0.0890        | 0.3861 | 0.02261     |
| 4   | 0.34                        | 10              | 0.05               | 0.0403        | 0.6149 | 0.15223     |
| 5   | 0.34                        | 13              | 0.07               | 0.0794        | 0.5313 | 0.07552     |
| 6   | 0.34                        | 16              | 0.03               | 0.0801        | 0.4957 | 0.11263     |
| 7   | 0.43                        | 10              | 0.07               | 0.0746        | 0.6449 | 0.06852     |
| 8   | 0.43                        | 13              | 0.03               | 0.0574        | 0.6441 | 0.04072     |
| 9   | 0.43                        | 16              | 0.05               | 0.0913        | 0.5442 | 0.03231     |

3.1 Impact of the operating conditions on the calculated response
Taguchi’s model of the test requires lower tests to research the influence of the input variables. Taguchi is a simple, time-saving approach which could be extended closely towards any technical challenges[15], [16]. While its MRR is very weak relative to traditional tooling, it is really a favored choice for heavy metal contamination-to-cut products like nickel-based Inconel 718 alloys. The efficacy of the machining can be calculated by means of the material removal rate, so it is important to know the effect of the machining parameters throughout the micro ECM of Inconel 718 alloy. Table 4 gives the material removal rate responses; the voltage is the best response output variable compared to feed rate and electrolyte concentration. Figure 3 shows the MRR main effect plot. When the electrolyte concentration and voltage increase the MRR value also increases. But there is a deviation in feed rate versus MRR.
Table 4. Response Table for MRR

| Level | Electrolyte Concentration | Voltage | Feed Rate |
|-------|---------------------------|---------|-----------|
| 1     | -25.88                    | -26.35  | -25.12    |
| 2     | -23.94                    | -24.95  | -25.57    |
| 3     | -22.72                    | -21.24  | -21.85    |
| Delta | 3.16                      | 5.11    | 3.72      |
| Rank  |                           |         | 2         |

A surface roughness including its machining process can indeed be calculated from its textured surfaces. That surface texture achieved during the machining process has been of high caliber that neither additional finishing procedure is needed again for the workpiece. From the response table 5 explains the voltage being the prominent parameter affecting the SR. Figure 4 shows the main effect plot for surface roughness. The electrolyte concentration increases from 0.25 to 0.43 mole/lit, the SR value gets reduced. But the SR increases during the voltage and feed rate increases.

Table 5. Response Table for SR

| Level | Electrolyte Concentration | Voltage | Feed Rate |
|-------|---------------------------|---------|-----------|
| 1     | 6.478                     | 4.361   | 4.988     |
| 2     | 5.271                     | 5.144   | 5.209     |
| 3     | 4.305                     | 6.549   | 5.856     |
| Delta | 2.172                     | 2.188   | 0.868     |
| Rank  |                           |         | 3         |
Figure 4. Main effect plot for SR

Tests are performed from an inverted optical microscope. The main impact graph for overcut as seen in Fig. 5, it is shown that while the chloride concentration rises from 0.25 to 0.34 mole/liter, the overcut rises, but perhaps the overcut reduces when the chloride content increase. A drop in the overcut with an improvement in feed rate and voltage also observed.

Table 6. Response Table for overcut

| Level | Electrolyte Concentration | Voltage | Feed Rate |
|-------|---------------------------|---------|-----------|
| 1     | 23.47                     | 19.00   | 21.38     |
| 2     | 19.25                     | 23.45   | 22.09     |
| 3     | 26.97                     | 27.23   | 26.21     |
| Delta | 7.72                      | 8.23    | 4.83      |
| Rank  | 2                         | 1       | 3         |

Figure 5. Main effect plot for Overcut
3.2 Multi objective optimization

The grey relation grades are calculated for each run and presented in Table 7. The maximum value of grey relation grade noted as rank 1. The optimum value found in run 3 at electrolyte concentration is 0.25 mole/lit, voltage is 13 volts and feed rate is 0.07 mm/min.

Table 7. Grey relation grade and the experimental runs rank

| Run | Electrolyte Conc (mole/lit) | Voltage (volts) | Feed rate (mm/min) | Grey Relational Grade |
|-----|----------------------------|-----------------|--------------------|----------------------|
| 1   | 0.25                       | 10              | 0.03               | 0.6245               |
| 2   | 0.25                       | 13              | 0.05               | 0.7456               |
| 3   | 0.25                       | 16              | 0.07               | 0.5794               |
| 4   | 0.34                       | 10              | 0.05               | 0.5409               |
| 5   | 0.34                       | 13              | 0.07               | 0.5957               |
| 6   | 0.34                       | 16              | 0.03               | 0.7070               |
| 7   | 0.43                       | 10              | 0.07               | 0.4618               |
| 8   | 0.43                       | 13              | 0.03               | 0.4488               |
| 9   | 0.43                       | 16              | 0.05               | 0.6227               |

3.3 Confirmatory examination

The best result for a control parameter influencing the effects is being calculated by using the overall grey relation grade. The confirmative test has performed out once the optimum state became determined as well as the measurement was confirmed and the related MRR, SR and overcut are reported. The relation between the actual and optimal value of the input variables is seen in Table 8. From this comparison, it would be claimed that there is an increase in the grey ratio of 0.1180 between the actual run number 1 and the optimal run number 2.

Table 8. Confirmatory examination result

| Responses/ Level | Actual (Run 1) | Optimum (Run 2) | % of improvement |
|------------------|---------------|-----------------|-----------------|
| MRR              | 0.0371        | 0.0398          | 7.8%            |
| SR               | 0.5592        | 0.4939          | 11.7%           |
| Overcut          | 0.13543       | 0.09858         | 27.2%           |
| Grey relation grade | 0.6245        | 0.7425          | 18.9%           |
| Improvement on grey relation grade | 0.1180 |

4 Conclusions

This research worked towards multi-objective optimization of Inconel 718 alloy microelectrochemical machining utilizing Grey Relational Assessment dependent on Taguchi. The research outcomes were taken from its relevant study analysis and testing:

- The voltage is the primary aspect for all the necessary output parameters.
- When the electrolyte concentration and voltage increase the MRR value also increases. But there is a deviation in feed rate versus MRR.
- The electrolyte concentration increases from 0.25 to 0.43 mole/lit, the SR value gets reduced. But the SR increases during the voltage and feed rate increases.
- While the chloride concentration rises from 0.25 to 0.34 mole/liter, the overcut rises, but perhaps the overcut reduces when the chloride content increase. A drop in the overcut with an improvement in feed rate and voltage also observed.
- The optimum grey relation was identified to be 0.25 mole/liter electrolyte concentration, 13 V voltage and 0.07 mm/min feed rate.
The confirmatory examination was performed to verify the findings obtained by the grey relational method. From this examination, it would be claimed that there is an increase in the grey ratio of 0.1180 between the actual run number 1 and the optimal run number 2.

Its result of such a current study also highlighted a key for the manufacturers to improve productive capacity as well as quality in the handling of Inconel 718 alloy using a micro-electrochemical machining.

Acknowledgments
This work was supported by the Sri Krishna College of Engineering and Technology, India - 641008 as part of the motivation towards research and development of modern technologies.

References
[1] Madhankumar S, Manonmani K, Rajesh S, Balamurugan R and Harikrishnan M 2018 Optimization of Micro Electrochemical Machining of Inconel 625 using Taguchi based Grey Relational Analysis Int. J. Appl. Eng. Res. 13 6771–9
[2] Manikandan N, Kumanan S and Sathiyanarayanan C 2015 Multi response optimization of electrochemical drilling of titanium Ti6Al4V alloy using Taguchi based grey relational analysis Indian J. Eng. Mater. Sci. 22 153–60
[3] Sharma P, Chakradhar D and Narendra Nath S 2016 Effect of wire diameter on surface integrity of wire electrical discharge machined Inconel 706 for gas turbine application J. Manuf. Process. 24 170–8
[4] Geethapriyan T, Kalaichelvan K and Muthuramalingam T 2016 Influence of Coated Tool Electrode on Drilling Inconel Alloy 718 in Electrochemical Micro Machining Procedia CIRP 46 127–30
[5] Jeykrisnan J, Vijaya Ramnath B, Chenbhaga Ram N, Nikhil K, Naveen Babu R and Naveen D 2018 Investigation on the Influence of Performance Characteristics on Machining Inconel 625 alloy in Electro-Discharge Machining (EDM) Mater. Today Proc. 5 20449–54
[6] Nayak A A, Gangopadhyay S and Sahoo D K 2016 Modelling, simulation and experimental investigation for generating ‘I’ shaped contour on Inconel 825 using electro chemical machining J. Manuf. Process. 23 269–77
[7] Zeng Z, Wang Y, Wang Z, Shan D and He X 2012 A study of micro-EDM and micro-ECM combined milling for 3D metallic micro-structures Precis. Eng. 36 500–9
[8] Madhankumar S, Balamurugan R and Rajesh S 2019 Investigations on austenitic nickel-chromium based super alloys - Inconel 625 and Inconel 718 from material removal rate in micro electrochemical machining AIP conference Proceeding vol 2128 (AIP Publishing) p 040009
[9] Rajurkar K P, Sundaram M M and Malsh A P 2013 Review of Electrochemical and Electrodischarge Machining Procedia CIRP 6 13–26
[10] Kumar M, Vaishya R O, Oza A D and Suri N M 2020 Experimental Investigation of Wire-Electrochemical Discharge Machining (WECMD) Performance Characteristics for Quartz Material Silicori 12 2211–20
[11] Hosseini E and Popovich V A 2019 A review of mechanical properties of additively manufactured Inconel 718 Addit. Manuf. 30 100877
[12] Selvan T A, Madhankumar S and Manonmani K 2018 Optimization of Material Removal Rate and overcut in Micro Electrochemical Machining of Inconel 718 using Taguchi Analysis Int. J. Pure Appl. Math. 119 869–77
[13] Qu N S, Zhang Q L, Fang X L, Ye E K and Zhu D 2015 Experimental Investigation on Electrochemical Grinding of Inconel 718 Procedia CIRP 35 16–9
[14] Manikandan N, Kumanan S and Sathiyanarayanan C 2017 Multiple performance optimization of electrochemical drilling of Inconel 625 using Taguchi based Grey Relational Analysis Eng. Sci. Technol. an Int. J. 20 662–71
[15] Madhankumar S, Balamurugan R, Rajesh S and Senthilkumar K M 2020 Fabrication of Al6063 alloy, silicon carboide and boron glass powder metal matrix composites in stir casting process and analysis the impact of process variables on mechanical properties Mater. Today Proc.
[16] S. Rajesh, S. Madhankumar, M. Harikrishnan T V 2018 Effect of Processing Parameters on Metal Matrix Composites in Stir Casting Process Using Taguchi Technique *Int. J. Res. Appl. Sci. Eng. Technol.* **6** 1610–5