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RESEARCH ARTICLE - MECHANICAL ENGINEERING

Influence of Process Parameters on Machinability of Inconel 718 by Electrochemical Micromachining Process using TOPSIS Technique

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Abstract

Accurate and precise micromachining with intricate features is an essential requirement for various applications of engineering materials in the present scenario. This is effectively achieved by the enhancing the electrochemical machining process, since it is a new and promising technique offering distinct advantages in overall machining quality. The turbine performance depends on a turbine blade and many small apertures with varying diameters of 0.5–4 mm for reducing the heat produced during its operation for improving efficiency. The present study was carried out for investigating the effects of diverse input process factors on the machining accuracies in the electrochemical micromachining process under two different electrolytes such as sodium chloride and sodium nitrate. The sodium chloride was found to have a higher material removal rate compared to sodium nitrate as electrolyte. A better surface finish and radial overcut were achieved with sodium nitrate compared to sodium chloride electrolyte. The optimum combination of ECMM process parameters was determined using TOPSIS method and verified with a confirmation test.

Keywords Inconel 718 · NaCl · $NaNO_3$ · TOPSIS · Optimization

1 Introduction

Electrochemical machining process (ECMM) is a non-traditional machining technique specifically developed for hard-to-cut materials, such as nickel-based alloys like Inconel, Monel and Hastelloy. It is the suitable option for aerospace, automotive and marine applications. Geethapriyan et al. [1] studied the different process parameters such as ECMM voltage, concentration of electrolyte, micro-tool feed rate and duty ratio. The complications were analyzed during the investigation to correlate multiple characteristics of machining parameters. Alexandre and Atanas [2] studied about the recent developments and innovations in the field of electrochemical micromachining and also monitored the variable parameters governing electrochemical micromachining. It was particularly noted that the usage of sodium chloride increased the current efficiency when compared to sodium nitrate.

Tang and Guo [3] conducted electrochemical machining on special S-03 steel using sodium nitrate and sodium chlorate as electrolyte and studied the microstructure of the machined specimen. It has been observed that the nature of electrolyte can affect the machinability in ECMM process. Asokan et al. [4] investigated the influence of electrochemical micromachining process on machining of hardened steel using artificial neural network (ANN) optimization technique. It has been inferred that the adaptation of optimization approach can enhance the machinability in ECMM process. Munda and Bhattacharyya [5] chose the following input parameters to optimize the performance factors pulse-on and pulse-off time ratio, voltage, concentration of electrolyte, frequency and tool vibration for machining copper plates in ECMM process using response surface methodology (RSM). The surface performance measures can be analyzed in an efficient way by utilizing a scanning electron microscope (SEM). Kumar et al. [6] cited grey relational analysis (GRA) employed for optimizing the wire-EDM of Inconel X-750 material. However, the selection of the grey coefficient in GRA method is a tedious one. Franci and Joze [7] explained

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the genetic algorithm (GA) optimization technique for determining optimal solution in the machining process under various cutting conditions. Nevertheless, the utilization of GA method in MCDM technique is still limited owing to its adaptability.

Majid et al. [8] explained the importance of optimization method for solving decision problems using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) analysis method. It was inferred that it would be able to provide useful insights into the anatomy of the TOPSIS method. Prabhakaran et al. [9] suggested a new approach for deriving solution to multi-response problems involved in allocating weightage to the relative significance of output response criteria using TOPSIS model. The efficiency of the MCDM technique has been considerably enhanced with TOPSIS approach. Maity and Chakraborty [10] explained the grinding process with different types of abrasives for optimizing multiple surface finish parameters using TOPSIS along with Taguchi technique. The confirmation result is very important to evaluate the accuracy of TOPSIS method. Sakthivel et al. [11] analyzed the accuracy of various approaches such as FAHP-fuzzy TOPSIS and FAHP-fuzzy VIKOR in manufacturing industries. It has been found that TOPSIS approach can predict the optimal combination in a better efficient way. From the literature, it has been inferred that TOPSIS-based multi-objective optimization method can produce an optimum set of input process parameters and machining accuracy compared to other multi-criteria decision making (MCDM) methods such as artificial neural network optimization technique, response surface approach, grey relational approach and the genetic algorithm optimization technique. In this present study, an investigation has been done on the various influencing input process factors such as voltage, concentration of electrolyte, micro-tool feed rate and duty ratio on the machining accuracy of electrochemical micro-machining processes such as material removal rate, overcut and surface finish with multi-criteria decision making (MCDM) method using TOPSIS approach. The process parameters influencing the machining of difficult-to-cut materials such as Inconel 718 have been studied, and an effort has been made to understand the influence of stray current on machining accuracy.

2 Materials and Methods

Inconel 718 is a nickel-based superalloy having specific composition of nickel–iron–chromium alloys. It is an age-hardenable material having high tensile, yield and creep-rupture strength for operation up to a maximum temperature of about 1290 °F. Inconel alloy with higher oxidation- and corrosion-resistant properties is suitable for extremely harsh environments subjected to heat and pressure. The ECM tool should possess specific properties deemed necessary for the effective machining of the workpiece. The tool should have higher electrical conductivity, higher thermal conductivity, corrosion resistance and stiffness [12]. The copper tool electrode was selected for the machining process with the diameter of 500 μm by considering suitability factors for the aforesaid characteristics. The electrolytes used in electrochemical machining can be broadly classified into two categories such as passive electrolyte and non-passive electrolyte.

The passive and non-passive electrolytes selected for the machining of the workpiece are usually sodium chloride (NaCl) and sodium nitrate ($NaNO_3$). The concentration level of the electrolytes is determined by conducting preliminary experiments with each set of electrolytes by varying their concentration, keeping other parameters constant and vice versa. Since the ECMM process has considerable nonlinear nature during the machining process, the optimal selection of process parameters in ECMM process is highly essential to enhance the performance measures [13]. Voltage (V), concentration of electrolyte (EC), micro-tool feed rate (M-TFR) and duty cycle (DC) have been chosen as variable input process factors with the selected copper tool for machining Inconel-718 material in the present study. The process variables should be chosen under different levels such as lower, medium and higher levels of process variables [14]. The chosen voltage variations are 8 V, 9 V and 10 V with different concentrations of electrolytes such as 20 g/l, 30 g/l and 40 g/l. The micro-tool feed rate was fixed as 0.1, 0.5 and 1 μm/s. Finally, the duty ratio is selected as 33.3, 50 and 66. In the present study, the experiments were conducted under L_9 orthogonal array [15, 16]. The parametric design for the machining of Inconel 718 involves the monitoring of four parameters such as voltage, concentration of electrolyte, duty ratio and micro-tool feed rate. The preliminary determination of the range of values to be used in each level of the specific parameter can be identified by conducting experiments with the workpiece on the assumption of certain actual parameter values from previous research works.

3 Results and Discussion

The performance analysis on machinability of Inconel 718 material has been investigated to study the influence of process factors on material removal rate (MRR), overcut (OC) and surface roughness (R_a) in the electrochemical micromachining process. The determined experimental results have been discussed with the optimization of the process parameters using TOPSIS method. Figure 1a–c shows the predicted effect of process parameters on the various response characteristics of the machining processes.

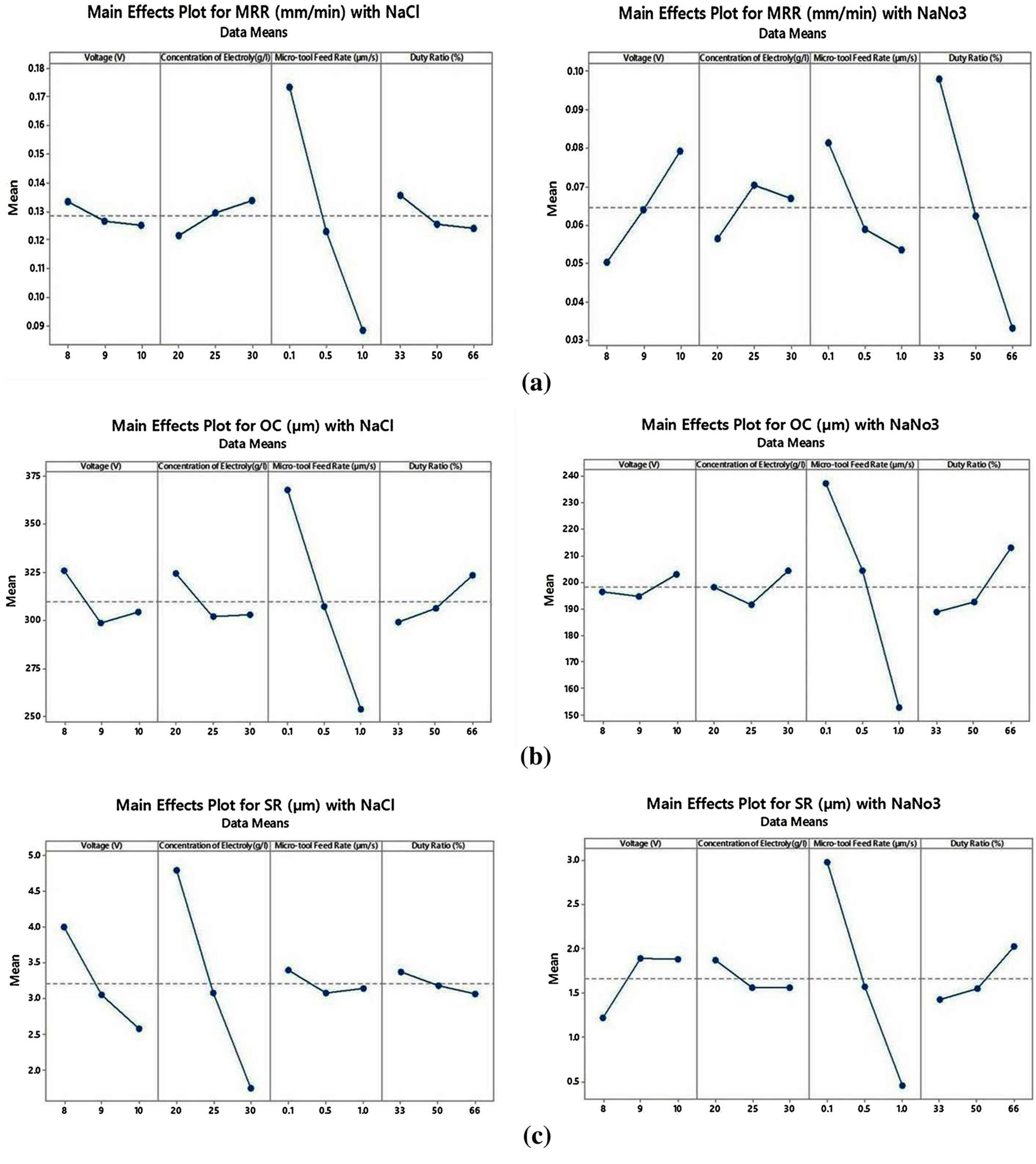


Fig. 1 Effect of process parameters on **a** MRR, **b** OC, **c** R_a

MRR represents to improve the mass production approach in industries. The maximum material removal rate is obtained in sodium chloride electrolyte compared to sodium nitrate because it produces aggressive ions during the electrical current supply. The maximum MRR is obtained in 8 V, 20 g/l, 0.1 µm/s and 33.3% in NaCl due to high flushing time to take out sludge particles from the machining surface. Figure 1a shows the effect of process parameters on material removal rate during machining of Inconel 718 nickel-based superalloy in ECMM process. Since the micro-tool feed rate has influence on MRR in NaCl at higher feed rate, it produces micro-spark on tool tough workpiece surface. According to the specific electrolyte, higher material removal rate of about 0.1 mm is achieved with lower tool feed rate. From the graph, it has been seen that the lower micro-tool feed rate (0.1 µm/s) and lower duty cycle (33.3%) resulted in higher MRR of sludge particles removed from the machined surface. It has higher flushing time during the machining process for sodium chloride and micro-spark not being generated.

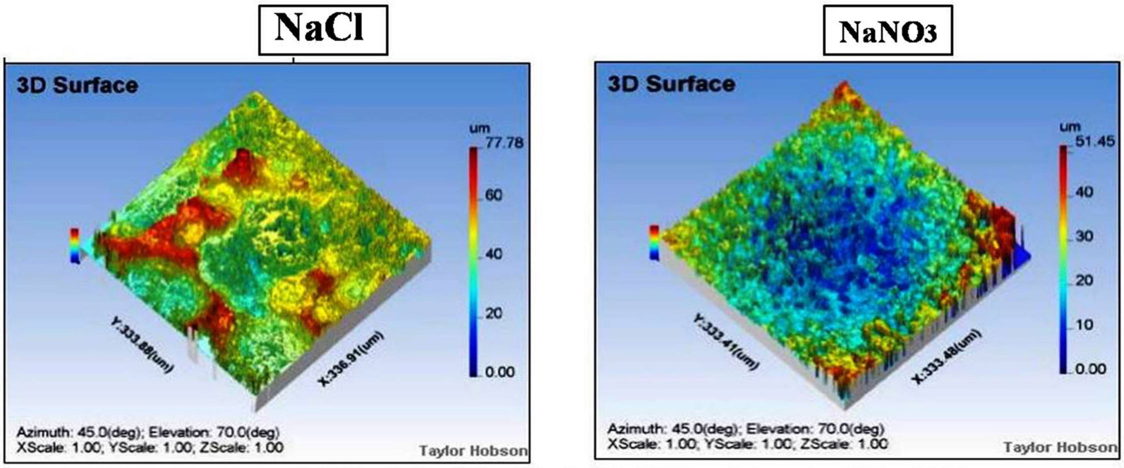
However, sodium nitrate as electrolyte provides consistent average lower overcut readings in all the experiments compared to sodium chloride. Figure 1b shows that higher micro-tool feed rate and lower duty cycle yield minimum overcut in sodium nitrate electrolyte due to the protective oxide layer produced over the machined surface. This helps to get a better and more accurate machined surface due to its higher localization effect. Therefore, overall poor overcut has been generated in the range of lower micro-tool feed rate and higher duty cycle (66.6%). Due to lower flushing time, the metal particles getting stuck up in the machined surface and stray current has been increased producing large overcut.

Since the applied energy influences the machining accuracy over the machined surface, it is important to analyse the different effects of the input process parameters on determining the surface roughness. Figure 1c provides the basic understanding that higher electrolyte concentration produces low roughness during the machining process. The higher electrolyte concentration increases the current density value in the machining zone. Hence, the surface roughness of the machined surface is inversely proportional to current density while machining workpiece using sodium chloride solution. When sodium nitrate is used, surface roughness decreases with increasing micro-tool feed rate in a linear fashion because it has higher flushing time that indicates increase in the localization effect in the machining zone while attaining machining accuracy. Since the duty cycle has influenced the surface roughness, it has produced lowest value during its minimum value.

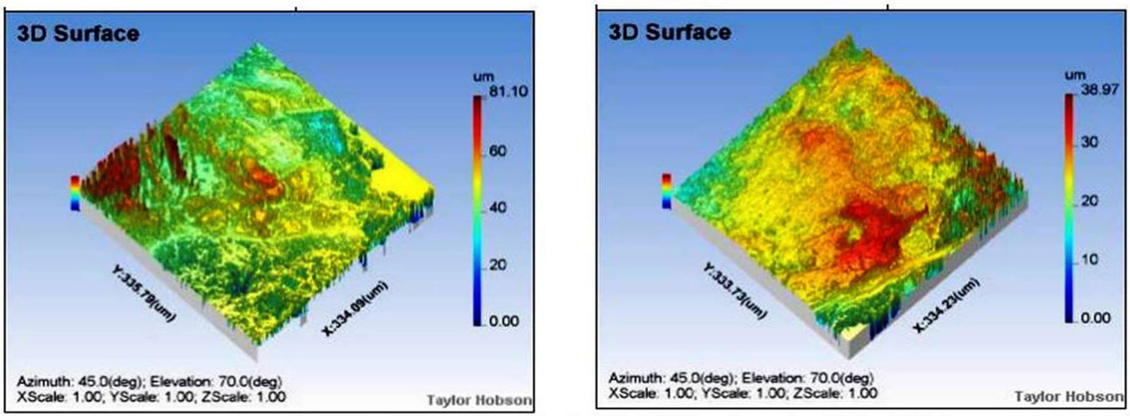
Figures 2, 3 and 4 show that three-dimensional surface roughness profile under different process parameters combination. The higher surface roughness has been observed with an increase in voltage, concentration of electrolyte, micro-tool feed rate and duty ratio for sodium chloride electrolyte compared with sodium nitrate. However, the surface roughness comparatively decreases with the lower voltage, duty cycle and higher electrolyte concentration, micro-tool feed rate. The duty cycle indicates the duration at which energy is being applied across the machining zone. The energy is directly proportional to electrolyte concentration. Since higher spark energy is developed during high duty cycle and electrolyte concentration, higher surface roughness has been observed with such parameter. The surface roughness value is also primarily due to the chemical dissolution developed during the machining process. The passive layer of electrolyte concentration is developed by the current density and the duration of applied electrical energy while using sodium nitrate as electrolyte. Hence, it has produced lower surface roughness compared with sodium chloride as electrolyte. The higher current density and pulse duration produce larger surface roughness coupled which can produces lower machining accuracy. It is vice versa for lower pulse on time and duty cycle for generating lower surface roughness which develops high machining accuracy [17–19].

Scanning electron microscopy (SEM) image is used for investigating the influence of input process parameters on surface topography and overcut in the ECMM process as shown in Fig. 5. The higher pulse on time with high duty cycle has produced larger crater and poor surface roughness, since it has smaller flushing time for generating micro-spark between the specimen and the tool electrode. The pulse duration has the largest influence on determining of the current density. A higher duty cycle has produced poor overcut. This has resulted in random material removal over the machined surface which leads to large circularity in the drilled hole. It has been observed that lower pulse on time coupled with lower duty cycle has produced lower surface roughness and overcut with better accuracy, since it has more flushing time for removing the sludge particles from the machining surface. The sodium chloride electrolyte can produce lesser machining accuracy compared to sodium nitrate due to ability of having aggressive ions for removing material in larger quantity from the workpiece surface. It becomes an irreversible ECMM process for sodium nitrate because it produces passive layer or protective oxide layer for reducing the overcut. The smaller surface roughness helps in achieving higher machining accuracy [20–22]. The process optimization is mainly influenced by the duration and the magnitude of the applied electrical energy in ECMM process.

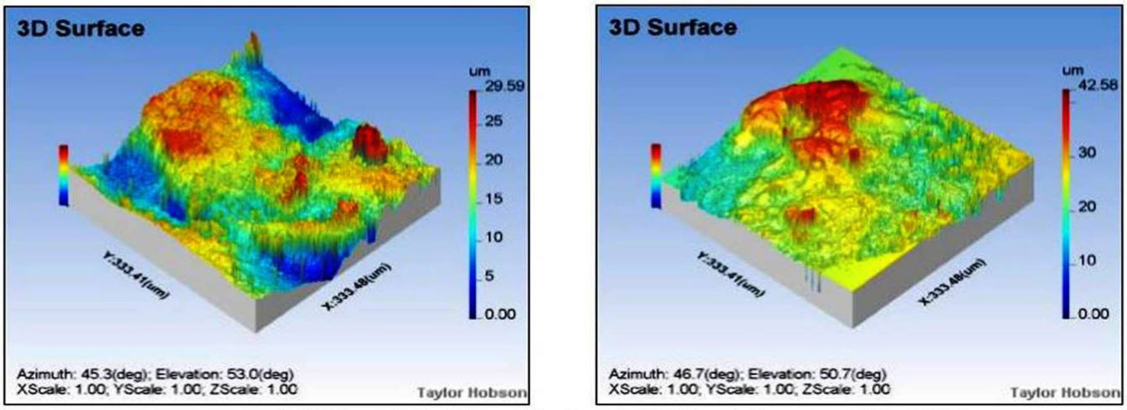
The selection of optimum machining parameters in ECMM process involves the adopting multi-criteria decision making methodology (MCDM) for finding solutions to the multiple performances [23]. The TOPSIS approach has been found to be the most effective for solving the MCDM problems considering the simplicity of its calculation method [24]. The advantage of the values is being close to the best or the ideal solution and ease of repeatability. TOPSIS technique needs input process parameters for solving the multi-objective problems for allocating the weight for each response. The weighting procedure has been carried out for ranges of response parameters from least to the most important to enable calculation of the stages of Simos [25]. This procedure is used for calculating the normalized weights and to minimize the errors with the objective of improving response values. The effect of the weighted input parameters on the output parameters has been determined by using Simos procedures [26]. In this present work, this decision maker is used for finding out the response parameters from the least to the most important ones such as OC, SR and MRR.



(a) V= 8V; CE= 20g/l; M-TFR= 0.1μm/s; DR=33%



(b) V= 9V; CE= 25g/l; M-TFR= 1μm/s; DR=33%



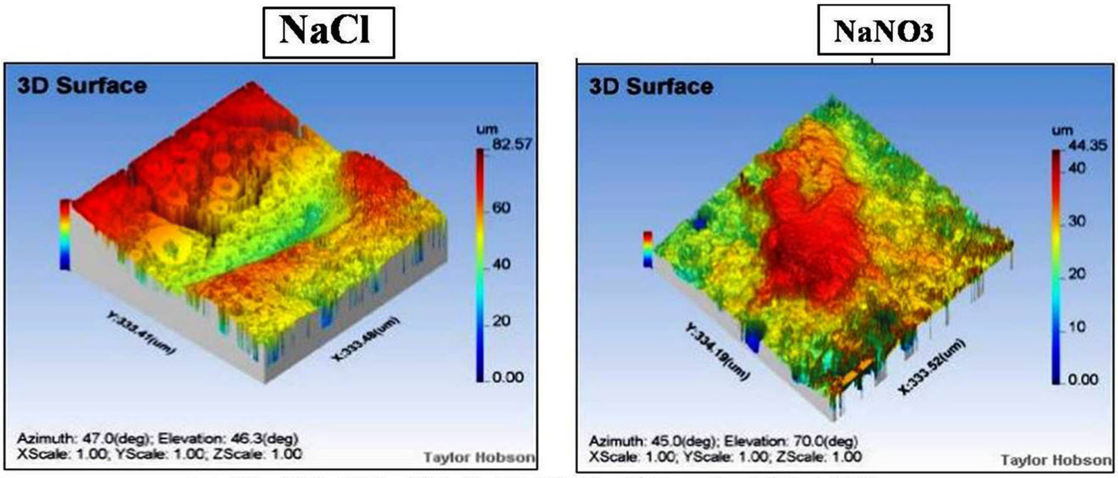
(c) V= 10V; CE= 30g/l; M-TFR= 0.5μm/s; DR=33%

Fig. 2 Three-dimensional surface roughness measurements of machined specimen with duty ratio of 33%

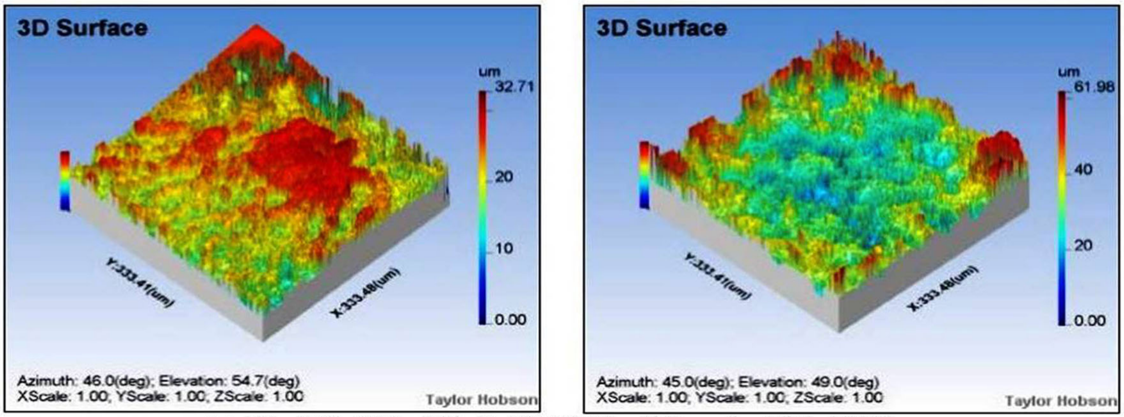
The material removal rate is chosen as the most important response because it is used to increase the mass production in various industries for that reason the distinct white cards are placed between two response parameters for increasing the weights of the responses. The following steps have been used for selecting the most important weighted values to the response parameter [27, 28].

Step 1 Calculation of normalized values of output response parameters

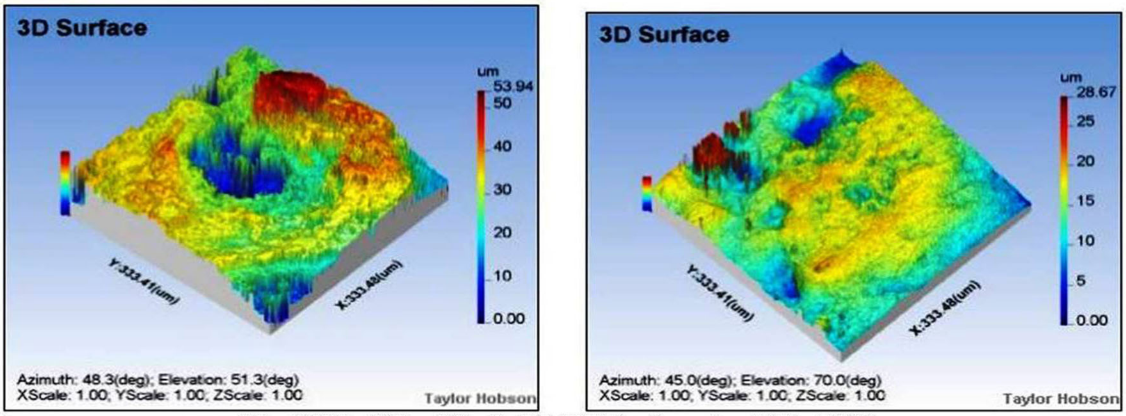
The output response is converted into normalized values for eliminating the units from all the responses using Eq. 1, and the normalized values (V_{ab}) for each output response parameter are shown in Table 1.



(a) V= 8V; CE= 25g/l; M-TFR= 0.5µm/s; DR=50%



(b) V= 9V; CE= 30g/l; M-TFR= 0.1µm/s; DR=50%



(c) V= 10V; CE= 20g/l; M-TFR= 1µm/s; DR=50%

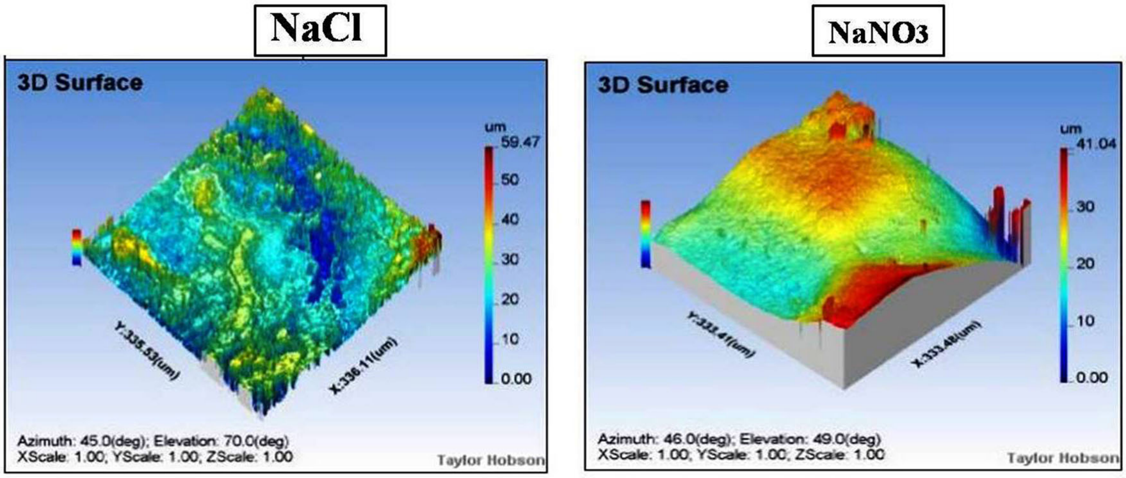
Fig. 3 Three-dimensional surface roughness measurements of machined specimen with duty ratio of 50%

$$V_{ab} = \frac{Y_{ab}}{\sqrt{\sum_{a=0}^{n} Y_{ab}^2}} \quad a = 1, 2, \ldots 9; \quad b = 1, 2, 3 \tag{1}$$

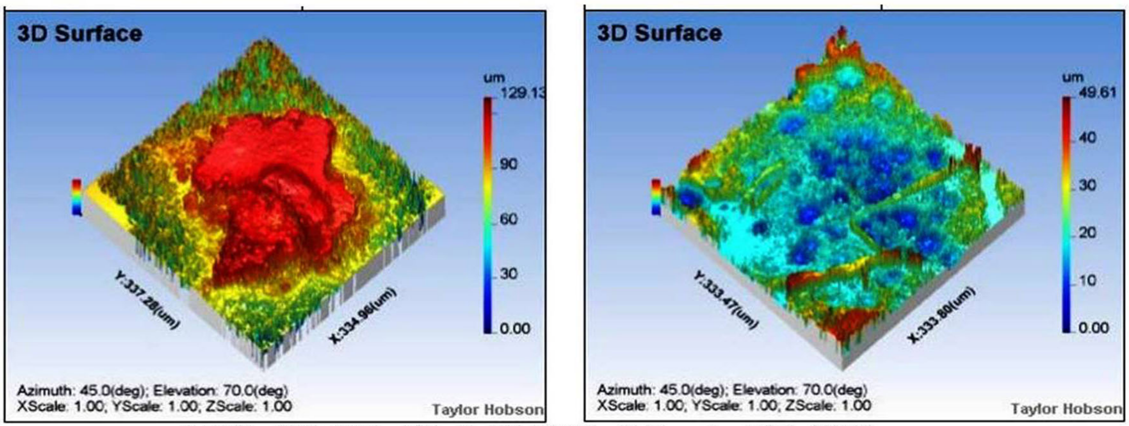
where a is the number of experimentations; b, the number of responses; Y_{ab}, normalized value of ath alternative run related to bth response.

Step 2 Compute the weight normalization matrix

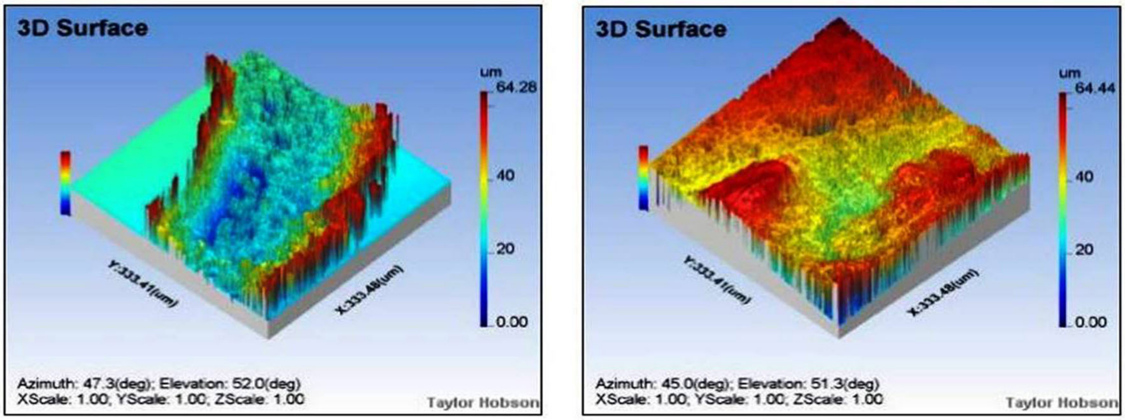
The weight normalization matrix (W_{ab}) is attained by the weighted value (S_b) and normalized value (V_{ab}) using Eq. 2.



(a) V= 8V; CE= 30g/l; M-TFR= 1μm/s; DR=66%



(b) V= 9V; CE= 20g/l; M-TFR= 0.5μm/s; DR=66%



(c) V= 10V; CE= 25g/l; M-TFR= 0.1μm/s; DR=66%

Fig. 4 Three-dimensional surface roughness measurements of machined specimen with duty ratio of 66%

To compute the weighted value (S_b), first calculate the Simos weighting procedure as shown in Table 2.

$$W_{ab} = S_b \, * \, V_{ab} \tag{2}$$

Step 3 Selection of the best and the worst alternatives

The best and the worst alternatives are recognized on the basis of each output response, and the *b*th response is determined to have the best performance by Eq. 3

$$Q^{+} = \left\{ [\max(Q_{ab}) | b \in B] \text{ or } \left[\min(Q_{ab}) | b \in B^{l} \right] \quad a = 1, 2, \ldots 9 \right\} \tag{3}$$

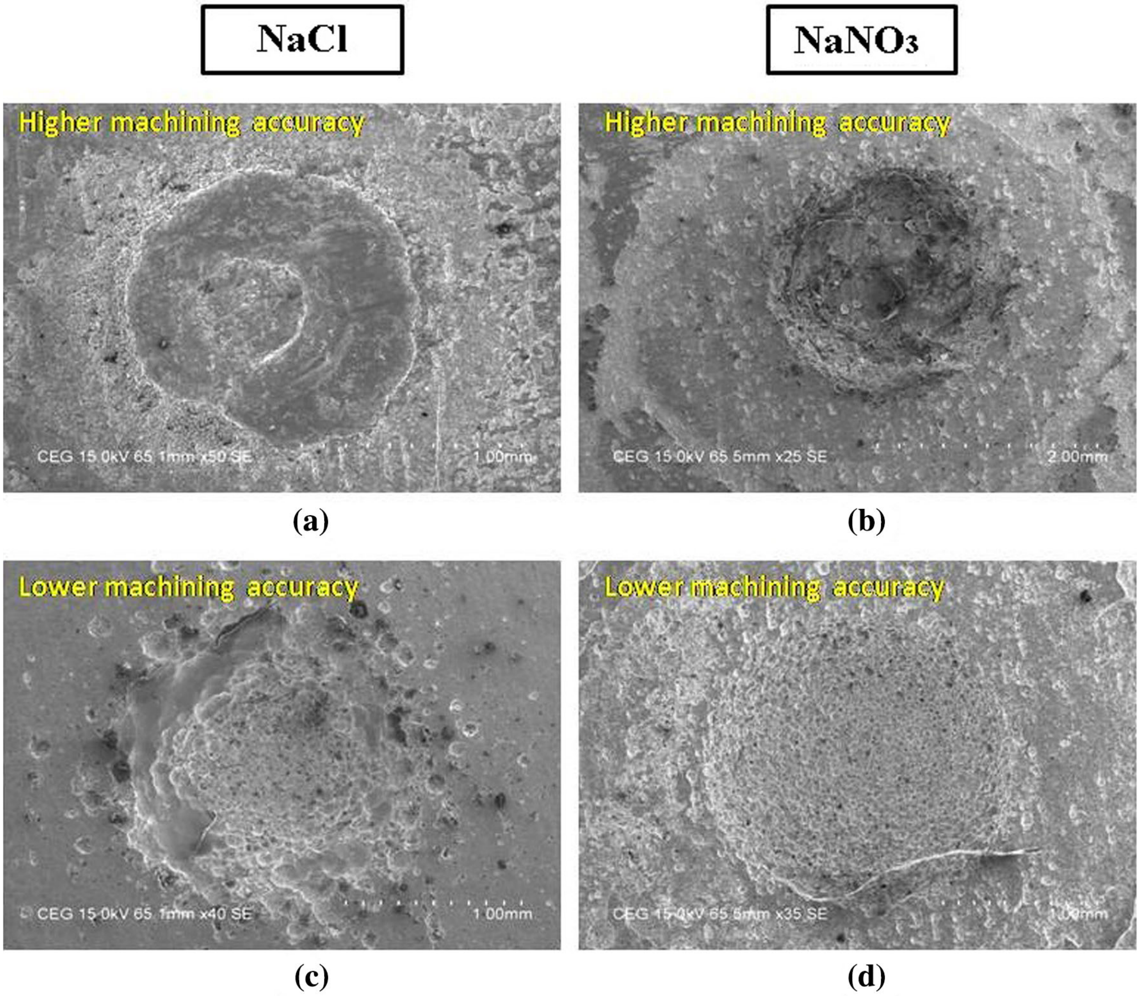


Fig. 5 SEM image of Inconel 718 nickel-based superalloy machined surface: **a** $V = 9$ V; EC = 20 g/l; M-TFR = 0.5 µm/s; DC = 66%; **b** $V = 10$ V; EC = 25 g/l; M-TFR = 0.1 µm/s; DC = 66%; **c** $V = 10$ V; EC = 30 g/l; M-TFR = 0.5 µm/s; DC = 33%; **d** V = 9 V; EC = 25 g/l; M-TFR = 1 µm/s; DC = 33%

where Q^+ indicates a positive ideal solution [0.25547, 0.03203, 0.03340] for sodium chloride and [0.28828, 0.01294, 0.03088] for sodium nitrate.

On calculating the Q^- values, the *b*th response is noted to show the worst performance [0.10842, 0.16433, 0.05777] for sodium chloride and [0.02713, 0.16648, 0.05798] for sodium nitrate.

Where Q^- indicates a negative ideal solution.

Step 4: Compute the best (E_i^+) and worst alternative distance (E_i^-)

The machining characteristics of the response are calculated as the excellent alternative distance (E_a^+) from the Q^+ values and the poor alternative distance (E_a^-) from the Q^- values. Therefore, the E_a^+ and E_a^- values are found with the use of Eqs. 4 and 5. The performance of each and every experiment for best and worst setting is shown in Table 3.

$$E_\mathrm{a}^+ = E_\mathrm{a}^+\sqrt{\sum_{a=1}^{9}\left(W_{ab} - Q_b^+\right)^2} \tag{4}$$

$$E_\mathrm{a}^- = \sqrt{\sum_{a=1}^{9}\left(W_{ab} - Q_b^-\right)^2} \tag{5}$$

where $a = 1, 2, 3, \ldots 9$.

Step 5 Determine the closeness coefficient values (K_i)

The closeness coefficient values are calculated on the basis of Eq. 6.

$$K_a = \frac{E_\mathrm{a}^-}{E_\mathrm{a}^- + E_\mathrm{a}^+} \quad a = 1, 2, \ldots 9; \quad 0 \le K_a \le 1 \tag{6}$$

Finally, the ranking is given on the basis of the order of best value, which is close to the ideal solution from the K_a value.

Table 1 Normalized value for output responses parameters

S. No.	Voltage (V)	Concentration of electrolyte (g/l)	Micro-tool feed rate (µm/s)	Duty ratio (%)	Normalized matrix value (n_{ij})					
					Sodium chloride (NaCl))			Sodium nitrate ($NaNO_3$)		
					MRR	R_a	OC	MRR	R_a	OC
1	8	20	0.1	33	0.44819	0.56666	0.41270	0.42795	0.41480	0.37460
2	8	25	0.5	50	0.31566	0.35333	0.33177	0.22416	0.15032	0.31562
3	8	30	1.0	66	0.23698	0.22285	0.29452	0.04760	0.04463	0.28517
4	9	20	0.5	66	0.27564	0.41619	0.34518	0.08706	0.39157	0.35721
5	9	25	1.0	33	0.23772	0.28762	0.23863	0.42720	0.05492	0.22057
6	9	30	0.1	50	0.43632	0.16761	0.36805	0.37408	0.49444	0.38877
7	10	20	1.0	50	0.19021	0.38857	0.27656	0.26850	0.12593	0.25197
8	10	25	0.1	66	0.41779	0.23904	0.39156	0.32623	0.57408	0.41420
9	10	30	0.5	33	0.33121	0.11047	0.30246	0.50576	0.23892	0.34098

Table 2 Calculation of Simos weighting procedure

Subject response	Number of responses	Number of positions	Non-normalized weighted matrix	Total
OC	1	1	(1/7)*100 = 14.28–14	14
SR	1	2	(2/7)*100 = 28.57–29	29
White cards	1	(3)		
MRR	1	4	(4/7)*100 = 57.14–57	57
Total	4	7		100

Table 3 Closeness coefficient values and their ranks

S. No.	Closeness coefficient values						Rank	
	NaCl			$NaNO_3$			NaCl	$NaNO_3$
	E_i^+	E_i^-	K_i	E_i^+	E_i^-	K_i		
1	0.13452	0.14705	0.52224	0.11813	0.22173	0.65241	4	3
2	0.10410	0.09523	0.47774	0.16395	0.15944	0.49302	5	6
3	0.12497	0.10452	0.45545	0.26130	0.15460	0.37171	6	8
4	0.13325	0.06606	0.33146	0.25970	0.05806	0.18271	8	9
5	0.13050	0.08874	0.40477	0.04487	0.26498	0.85516	7	1
6	0.02547	0.18196	0.87721	0.15233	0.18755	0.55181	1	5
7	0.16779	0.05505	0.24703	0.13734	0.18237	0.57041	9	4
8	0.04635	0.16082	0.77624	0.18649	0.15881	0.45991	2	7
9	0.06727	0.15556	0.69808	0.05881	0.27884	0.82581	3	2

Table 4 Average closeness coefficient for each input parameter

Factor notation	Control factor	Average closeness coefficient						Max–Min	
		Sodium chloride (NaCl)			Sodium nitrate ($NaNO_3$)			NaCl	$NaNO_3$
		Level 1	Level 2	Level 3	Level 1	Level 2	Level 3		
P	Voltage (V)	0.4851	0.5378	0.5737	0.5057	0.5299	0.6187	0.0886	0.1129
Q	Concentration of electrolyte (g/l)	0.3669	0.5529	0.6769	0.4685	0.6027	0.5831	0.3100	0.1341
R	Micro-tool feed rate (µm/min)	0.7252	0.5024	0.3690	0.5547	0.5005	0.5991	0.3561	0.0985
S	Duty ratio (%)	0.5417	0.5339	0.5210	0.7777	0.5384	0.3381	0.0206	0.4396

Total mean closeness coefficient value (NaCl) = 0.5323
Total mean closeness coefficient value ($NaNO_3$) = 0.5514

Table 5 Initial and predicted value results

Conditions	Setting level		Response parameters							
	NaCl	$NaNO_3$	NaCl			$NaNO_3$			NaCl	$NaNO_3$
			MRR (mm^3/min)	SR (μm)	OC (μm)	MRR (mm^3/min)	SR (μm)	OC (μm)		
Initial setting parameters	P3Q3R2S1	P1Q1R1S1	0.1324	1.16	284.69	0.0926	2.5	226.57	0.6980	0.6524
Optimal process parameters										
Predicted	P3Q3R1S1	P3Q2R3S1							0.9207	0.9441
Experimental	P3Q3R1S1	P3Q2R3S1	0.1794	1.18	316.43	0.1044	0.231	123.41	0.9347	0.9570

Enhancement in closeness coefficient value using TOPSIS method for sodium chloride = 0.2367
Enhancement in closeness coefficient value using TOPSIS method for sodium nitrate = 0.3046

The average closeness coefficient for each of the input process parameters with levels is determined for L_9 orthogonal array. The optimal process factor combination has been found for each factor as shown in Table 4. The optimal process factor combination has been obtained as the V (10 V), EC (30 g/l), M-TFR (0.1 μm/s) and DC (33%) for NaCl and V (10 V), EC (25 g/l), M-TFR (1 μm/s), DC (33%) for $NaNO_3$ from closeness coefficient values. The micro-tool feed rate has the higher significant input parameter since it has higher maximum–minimum value compared to other process parameters with NaCl electrolyte. However, duty cycle is the most influential input parameters for $NaNO_3$. The maximum MRR and the minimum R_a, OC have been obtained in micro-tool feed rate for NaCl as that of duty cycle for $NaNO_3$. The optimal input process parameters are determined on the basis of predicted closeness coefficient value. The confirmation test has been performed for evaluating the accuracy of optimal process parameters on machining Inconel 718 using the ECMM process shown in Table 5. The predicated closeness coefficient value (C_p) with optimal level can be calculated from Eq. 7.

$$C_p = C_m + \sum_{b=1}^{n} (C_o - C_m) \tag{7}$$

where C_m is the overall mean closeness coefficient value, C_o is the optimal closeness coefficient value for each level of factors, and n is the number of input process factors.

The predicted value has been found as 0.9207 for NaCl electrolyte as that of 0.9441 for $NaNO_3$ electrolyte. The values of the attained response parameters are 0.1794 (MRR), 1.18 (R_a) and 316.43 (OC) for NaCl electrolyte and 0.1044 (MRR), 0.231 (R_a) and 123.41 (OC) for $NaNO_3$ electrolyte from the optimal setting parameters. The closeness coefficient value has been computed as 0.9347 for NaCl electrolyte and 0.9570 for $NaNO_3$ electrolyte. The confirmation experiment indicates the closeness of the predicated closeness coefficient value to the experimental closeness coefficient value. The optimal process parameter has been found as P3Q3R1S1 for NaCl electrolyte and P3Q2R3S1 for $NaNO_3$ electrolyte. Since the anodic dissolution depends on electrolyte concentration, higher electrolyte concentration can give better machinability. The higher duty ratio can produce higher removal energy in ECMM process. Owing to the importance of micro-tool feed rate and duty ratio on determining crater size, those parameters have considerable influence on performance measures of ECMM process.

4 Conclusion

In the present study, the influence of process factors on machining Inconel 718 in ECMM process using TOPSIS method has been computed and analyzed. The following conclusions have been made from the experimental results.

- The micro-tool feed rate and concentration of electrolyte have a higher influence on machining characteristics with NaCl as electrolyte owing to its aggressive ions produced in the ECMM process.
- The duty cycle and concentration of electrolyte have a strong influence on machining characteristics with $NaNO_3$ as electrolyte owing to its ability to produce a passive layer over the surface for preventing larger overcut in ECMM process.
- The optimal process parameter setting has been obtained as voltage 10 V, concentration of electrolyte 30 g/l, micro-tool feed rate 0.1 μm/s, duty ratio 33% for sodium chloride; voltage 10 V, concentration of electrolyte 25 g/l, micro-tool feed rate 1 μm/s, duty ratio 33% for sodium nitrate.

References

1. Geethapriyan, T.; Kalaichelvan, K.; Muthuramalingam, T.: Multi performance optimization of electrochemical micromachining pro-

cess parameters on machining Inconel 718 using Taguchi-grey relational analysis. La Metallurgia Italiana **4**, 13–19 (2016)

2. Alexandre, S.; Atanas, I.: Recent developments and research challenges in electrochemical micromachining. Int. J. Adv. Manuf. Technol. **69**, 563–581 (2013)
3. Tang, L.; Guo, Y.-F.: Experimental study of special purpose stainless steel on electrochemical machining of electrolyte composition. Mater. Manuf. Process. **28**, 457–462 (2013)
4. Asokan, P.; Ravi, K.R.; Jeyapaul, R.; Santhi, M.: Development of multi-objective optimization models for electrochemical machining process. Int. J. Adv. Manuf. Technol. **39**(1), 55–63 (2008)
5. Munda, J.; Bhattacharyya, B.: Investigation into electrochemical micromachining through response surface methodology based approach. Int. J. Adv. Manuf. Technol. **35**(7), 821–832 (2008)
6. Kumar, M.; Sing, H.; Zude, Z.: Multi response optimization in wire electrical discharge machining of Inconel X-750 using Taguchi's technique and grey relational analysis. Mater. Manuf. Process. **3**, 1–14 (2016)
7. Franci, C.; Joze, B.: Optimization of cutting process by GA approach. Robot. Comput. Integr. Manuf. **19**, 113–121 (2003)
8. Majid, B.; Khanmohammadi, O.S.; Morteza, Y.; Joshua, I.: A state-of the-art survey of TOPSIS applications. Expert Syst. Appl. **39**, 13051–13069 (2012)
9. Prabhakaran, R.T.D.; Babu, B.J.C.; Agrawal, V.P.: Optimum selection of a composite product system using MADM approach. Mater. Manuf. Process. **21**, 883–891 (2006)
10. Maity, S.R.; Chakraborty, S.: Grinding wheel abrasive material selection using fuzzy TOPSIS method. Mater. Manuf. Process. **28**, 408–417 (2013)
11. Sakthivel, G.; Saravanakumar, D.; Muthuramalingam, T.: Application of failure mode and effect analysis in manufacturing industry-an integrated approach with FAHP-fuzzy TOPSIS and FAHP-fuzzy VIKOR. Int. J. Prod. Qual. Manag. **24**, 398–423 (2018)
12. Swain, A.K.; Sundaram, M.M.; Rajurkar, K.P.: Use of coated micro tools in advanced manufacturing: an exploratory study in electrochemical machining (ECM) context. J. Manuf. Process. **14**, 150–159 (2015)
13. Geethapriyan, T.; Kalaichelvan, K.; Muthuramalingam, T.: Influence of coated tool electrode on machining Inconel alloy 718 in electrochemical micro machining. Procedia CIRP **46**, 127–130 (2016)
14. Vasanth, S.; Muthuramalingam, T.; Vinothkumar, P.; Geethapriyan, T.; Murali, G.: Performance analysis of process parameters on machining titanium (Ti–6Al–4V) alloy using abrasive water jet machining process. Procedia CIRP **46**, 139–142 (2016)
15. Muthuramalingam, T.; Mohan, B.: Application of Taguchi-grey multi response optimization on process parameters in electro erosion. Measurement **58**, 495–502 (2014)
16. Muthuramalingam, T.; Mohan, B.: Influence of tool electrode properties on machinability in spark erosion machining. Mater. Manuf. Process. **28**, 939–943 (2013)
17. Geethapriyan, T.; Kalaichelvan, K.; Muthuramalingam, T.; Rajadurai, A.: Performance analysis of process parameters on machining α–β titanium alloy in electrochemical micromachining process. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. **232**, 1577–1589 (2018)
18. Huang, S.F.; Liu, Y.: Electrochemical micromachining of complex shapes on nickel and nickel-based superalloys. Mater. Manuf. Process. **29**, 1483–1487 (2014)
19. Malapati, M.; Bhattacharyya, B.: Investigation into electrochemical micromachining process during micro-channel generation. Mater. Manuf. Process. **26**, 1019–1027 (2011)
20. Lohrengel, M.M.: Pulsed electrochemical machining of iron in $NaNO_3$: fundamentals and new aspects. Mater. Manuf. Process. **20**, 1–8 (2005)
21. Thanigaivelan, R.; Arunachalam, R.M.: Experimental study on the influence of tool electrode tip shape on electrochemical micromachining of 304 stainless steel. Mater. Manuf. Process. **25**, 1181–1185 (2010)
22. Rathod, V.; Doloi, B.; Bhattacharyya, B.: Sidewall insulation of microtool for electrochemical micromachining to enhance the machining accuracy. Mater. Manuf. Process. **29**, 305–313 (2014)
23. Muthuramalingam, T.; Mohan, B.; Rajadurai, A.; Saravanakumar, D.: Monitoring and fuzzy control approach for efficient electrical discharge machining process. Mater. Manuf. Process. **29**, 281–286 (2014)
24. Huo, J.; Liu, S.; Wang, Y.; Muthuramalingam, T.; Pi, V.N.: Influence of process factors on surface measures on electrical discharge machined stainless steel using TOPSIS. Mater. Res. Express **6**(8), 086507 (2019)
25. Yuvaraj, N.; Kumar, M.P.: Multi response optimization of abrasive water jet cutting process parameters using TOPSIS approach. Mater. Manuf. Process. **30**, 882–889 (2015)
26. Yaxin, T.: Laser enhanced electrochemical machining process. Mater. Manuf. Process. **17**, 789–796 (2006)
27. Shuangqing, Q.; Feng, J.; Ningsong, Q.; Hansong, L.: Improving the localization of surface texture by electrochemical machining with auxiliary anode. Mater. Manuf. Process. **29**, 1488–1493 (2014)
28. Hai-Ping, T.; Jung-Chou, H.; Jyun-Cin, Y.; Biing-Hwa, Y.: Improvement of electrochemical micro drilling accuracy using helical tool. Mater. Manuf. Process. **23**, 499–505 (2008)