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Optimization of Micro Electrochemical Machining of Inconel 625 using Taguchi based Grey Relational Analysis

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Abstract

Material removal rate (MRR) is an important feature of micro electrochemical machining (ECM). The process is based on chemical reactions. The rate of machining depends upon atomic weight, the current density, electrolyte and the time of machining. To know the effects of MRR on Inconel 625, experiments have been conducted by considering different parameters using of stainless steel electrodes. In this present investigation, optimization is based on Taguchi approach with a grey relational analysis (GRA). The experimental runs have been planned using Taguchi's principle with three input machining variables such as electrolyte concentration, voltage and feed rate. Besides the MRR, the surface roughness and overcut was included as performance measures in this investigation. ANOVA were involved to investigate the influence of process parameters on performance characteristics during machining. The outcome of this analysis shows that the voltage is the predominant factor for the desired performance characteristics and also optimum parameters are identified. The regression models are developed to be used as predictive tools. The confirmation test was conducted to validate the results achieved by GRA approach. This research work is help the industrialist for selecting parameters to attain desired outputs.

Keywords: Grey relation analysis; Micro electrochemical machining; Material removal rate; Overcut; Surface roughness.

INTRODUCTION

A harder and difficult to machine materials such as carbides, stainless steel, nickel based alloy and many other high strength-temperature resistant alloys find wide application in aerospace and nuclear engineering industries, owing to their high strength to weight ratio, hardness and heat resisting qualities. For such materials the conventional edged tool machining is highly uneconomical and the degree of accuracy and surface finish attainable are poor[1]. The accuracy and quality of machining is decided by machining parameters. So it requires one to find optimal conditions for attaining best process parameters. With regards to this, various investigations have carried out ECM of different materials and applied various optimization techniques to find optimal condition. Presented multi objective optimization of electrochemical drilling of Titanium alloy by using Taguchi based GRA method[2]. Proposed modeling, simulation and experimental investigation for generating 'I' shaped contour on Inconel 825 using electrochemical machining[3]. Investigated on electrochemical machining of contemporary titanium, nickel based alloys and analyzed about its application for machining the aero engine components ECM offers an effectual substitute method for producing various intricate shaped components like molds, turbine accessories, and micro dimensional components[4]. Explored about the ECM method with different electrolyte concentrations and surmised that the more accuracy is obtained with lower concentrations[5]. Explored about the ECM process for nickel based material and it is revealed that the achievement of quality product is possible by adopting the identical dissolution of electrochemical action[6]. Explicated the dominant variables in the ECM of Valve-Steels, utilizing various electrolytes and concluded that the electrode feed rate was the dominant parameter which influencing the Material Removal Rate (MRR)[7]. Examined the significant ECM process characteristics, namely electrode feed rate, voltage applied, discharge rate of electrolyte in determining the best possible process parameter for performance measures, namely MRR, life of tool, dimensional accuracy and cost of machining. Apposite choice of process parameters to ascertain the best possible machining performance is yet a complicated one[8]. Experimentally explored about EDM of various nickel based alloys namely Inconel 625 and Inconel 718 by using Taguchi's design approach for optimizing the performance characteristics[9]. Employed various multi criteria decision making tool GRA for electrical discharge machining of steels. The Taguchi based grey approach has been employed for multi objective optimization problems of WEDM process[10].

From that review, the optimization of ECM was carried out on various materials and the current study investigates on various output response parameters MRR, SR and overcut were found during micro ECM of Inconel 625. After that, these measures were explained and finally an optimal solution of process parameters was calculated using GRA.

Grey relational analysis:

The Grey system theory offers a proficient control on the uncertainty, multiple input and incomplete information. Method of GRA is an evaluation of the complete value of information variation among the sequences and furthermore employed to evaluate an almost accurate relationship among the sequences. It is an effectual approach to investigate the correlation among the sequences by means of less number of data and to examine several aspects.

At GRA, initially the data attained from the trials were normalized. By using normalized data the grey relational coefficient (GRC) is determined and the grey relational grade (GRG) is calculated. The procedure for GRA is explained as follows:

Step 1: Initially the raw data is preprocessed. The normalized values of the responses are calculated based on the following equations interrelating to the performance characteristics of a response variable. The desired quality characteristics for MRR are higher the better criterion; therefore, the normalization of the original sequence of this response was done by using Eq. (1):

$$Y_{pq} = \frac{Xpq - Min(Xpq)}{Max(Xpq) - Min(Xpq)} \quad (1)$$

The desired quality characteristics for SR and Overcut are smaller the better criterion; therefore the normalization of the original sequence of these performance variables was done by Eq. (2):

$$Y_{ij} = \frac{Max(Xpq) - Xpq}{Max(Xpq) - Min(Xpq)} \quad (2)$$

Where,

Xpq is the measured responses

Min (Xpq) is the minimum of Xpq

Max (Xpq) is the maximum of Xpq

p is the response variables and

q is the trial number

Fundamentally larger the normalized values, better the performance characteristics.

Step 2: The maximum of the normalized value, regardless of response variables, trials is computed by Eq. (3) Which is also known as reference value R.

$$R = Max\ (Y_{pq}) \quad (3)$$

Step 3: The absolute variance between the reference value R, and each normalized value is computed as follows in Eq. (4):

$$\Delta pq = |Ypq - R| \quad (4)$$

Where,

R is the expected sequence,

Y_{pq} is the comparability sequence and

Δpq is the deviation sequence of R and Y_{pq}.

Step 4: The grey relation coefficient ξpq for each of the normalized values is computed using the Eq. (5).

$$\xi pq = \frac{Min(\Delta pq) + \phi Max(\Delta pq)}{\Delta pq + \phi \max(\Delta pq)} \quad (5)$$

Where,

ϕ is the differentiating coefficient $\phi \epsilon$ [0,1] and 0.5 is the widely accepted value. The amount of relational degree between the actual and desired performance characteristics can be obtained through GRC values, ranging from 0 to 1. Higher the GRC values, the relational degree will be powerful.

Step 5: The grey relation grade for each trail is computed as follows in Eq. (6):

$$Vj = \frac{\sum_{i=1}^{n} \xi pq}{n} \quad (6)$$

Where,

n – Number of response variables.

The GRG 'Vj' symbolizes the level of relationship among the reference or ideal sequence and the comparative sequence. If larger GRG is obtained, then the equivalent set of process parameter is nearer to most favorable optimal setting.

EXPERIMENTAL DETAILS

The entire work has been carried out by micro electrochemical machining set up for Sivasakthy Electrical Services which is having,

Tool gap	-	0.025-0.75 mm
Current density amps/cm^3	-	200-800
Voltage	-	0-20 volts
Feed rate	-	0.01-1 mm/min
Electrolyte velocity	-	30-60 m/Sec
Electrolyte pressure	-	10-30 kgf/cm^2
Electrolyte Concentration mole/lit	-	0.23-0.49
Tool material	-	stainless steel

The setup consists of three main subsystems. They are machining cell, control panel and electrolyte circulation system.

Selection of work piece, tool material and electrolyte

Inconel 625 alloy was selected for experimental workpiece. Taguchi design (L_9 orthogonal array) is made for Inconel 625 specimen and the work piece is having dimension of length 40 mm, width 40 mm and thickness 0.4 mm. Compositions of the work piece materials are shown in Table 1. In micro ECM generally tool which is the cathode, is made up of conducting material such as stainless steel, copper. In this experiment stainless steel rod is taken as electrode material of length 55 mm and 1 $\pm$ 0.02 mm diameter. The electrolyte of this experiment was sodium chloride (NaCl).

Table 1. Chemical composition of Inconel 625 alloy

	Cr	Mo	Co	Nb+Ta	Al	Ti	C	Fe	Mn	Si	P	S	Ni
Min	20	8	--	3.15	--	--	--	--	--	--	--	--	Balance
Max	23	10	1	4.15	.4	.4	.1	5	.5	.5	.015	.015	Balance

Machining parameters and responses

The efficiency of machining depends largely on machining parameters. From the literature review the process parameters like voltage, tool feed rate and concentration of electrolyte have chosen for the current study since they were found to have significant influence on MRR, overcut and SR. The MRR can be defined as the rate of dissolution of material from the workpiece. Initial and final weights of the workpiece were measured by electronic weighing balance machine of accuracy of 0.001 g. MRR of Inconel 625 has been considered as one of the performance measures was calculated by following expression:

$$MRR = \frac{Wi-Wf}{\rho * t} \quad (7)$$

Where,

Wi - Weight final

Wf - Weight initial

ρ - Density of the material

t - Machining time

Similarly, overcut for the work piece specimen was also measured along the radius of the circular shaped tool.

$$overcut = Lf - Li \quad (8)$$

Where,

Lf =Final length of machined surface

Li =Initial length of machined surface

Surface roughness values for all the specimens were also recorded using SRG 4500 surface roughness tester equipment. Surface roughness were measured along numerous positions using surface profile and averaged out over the entire surface from the edges to central portion.

Design of experiment

The experiment was planned as per 3 levels L_9 Taguchi orthogonal array. The design was generated and analyzed by using MINITAB 16 statistical software. Three factors at three levels were considered for the experimentation. The levels of the individual process parameters are given in Table 2. The experimental values of MRR, surface roughness and overcut are given in Table 3.

Table 2. Process parameters and their values

Machining parameters (Notation)	Unit	Level 1	Level 2	Level 3
Concentration(C)	Mole/lit	0.23	0.32	0.41
Voltage (V)	Volt	9	12	15
Feed rate (F)	mm/min	0.02	0.04	0.06

Table 3. Experimental results showing MRR, SR and overcut

S.No	Electrolyte Conc (mole/lit)	Voltage (volts)	Feed rate (mm/min)	MRR (mm^3/min)	SR (µm)	Overcut (mm)
1	0.23	9	0.02	0.0366	0.5583	0.13443
2	0.23	12	0.04	0.0395	0.4933	0.09962
3	0.23	15	0.06	0.0884	0.3853	0.02161
4	0.32	9	0.04	0.0396	0.6150	0.15123
5	0.32	12	0.06	0.0787	0.5300	0.07562
6	0.32	15	0.02	0.0795	0.4960	0.11163
7	0.41	9	0.06	0.0735	0.6450	0.06842
8	0.41	12	0.02	0.0565	0.6433	0.04082
9	0.41	15	0.04	0.0908	0.5447	0.03241

Influence of cutting parameters on responses measured:

Taguchi design of experiment uses a less number of runs to study the effect of process parameters. Taguchi is easy, time saving method and can be directly applied to any engineering problems.

Material removal rate (MRR):

Although the material removal rate in micro ECM is very low as compared to that of conventional machining, but it's still a preferable option for machining of difficult-to-cut materials such as Nickel-based super alloy, Inconel 625. The productivity of micro ECM can be determined through MRR, so it is necessary to know the influence of the machining parameters on the MRR during ECM of Inconel 625.

The main effect plot for SN ratios of the MRR depicting the effect of various machining parameters on MRR are shown in Fig. 1.

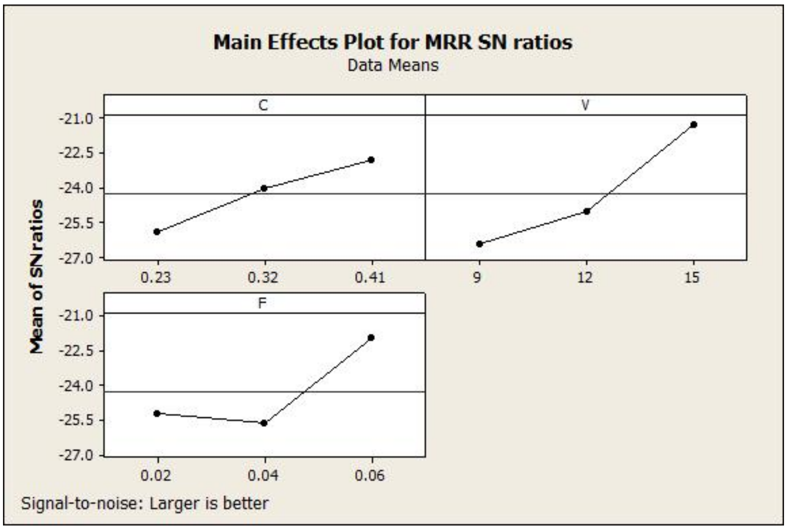

Figure 1. Main effect plots for MRR

As seen from the above graph obtained, the MRR increased with an increase in both voltage and electrolyte concentration. This is due to the fact that to increase in voltage the current increases in the inter electrode gap thus increasing the MRR. The feed rate is another important parameter. Increase in feed rate results in a decrease of the conducting path between the workpiece and the tool, hence resulting in high current density thus enhancing the rapid anodic dissolution. A Feed rate increase from 0.04 to 0.06 there is an increase in the MRR but at low feed rate there is a reduction in the MRR.

Surface roughness (SR)

The quality of the machined surface can be determined by its surface texture. During the micro ECM process the surface quality obtained is of such high order that no further finishing operation is required for the micro electrochemical machined surface.

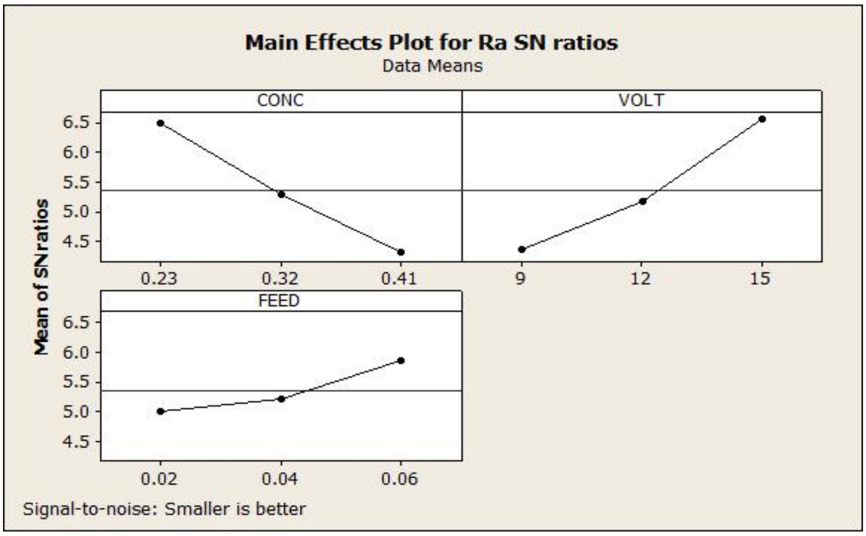

Figure 2. Main effect plots for SR

From the main effect plot of the Ra shown in Fig. 2. it can be seen that when concentration of electrolyte increase from 0.23 moles/lit to 0.41 moles/lit there is an increase in the surface roughness. Also noted was a decrease in the surface roughness with an increase in the voltage and feed rate. The non-uniform removal of material during ECM of Inconel 625 at low voltage leads to high surface roughness, but as the voltage increases uniform dissolution of material takes place resulting in lowering of surface roughness.

Overcut (OC)

The measurements were taken from the upright metallurgical microscope with CMOS camera equipment. The main effect plot of the overcut is shown in Fig. 3, it can be seen that when concentration of electrolyte increase from 0.23 mole/lit to 0.32 moles/lit there is an increase in the overcut but the overcut is decreases when increased the electrolyte concentration. Also noted was a decrease in the overcut with an increase in the voltage and feed rate. The non-uniform removal of material during ECM of Inconel 625 at low voltage leads to high overcut but as the voltage and feed rate increases the uniform dissolution of material takes place resulting in lowering of overcut.

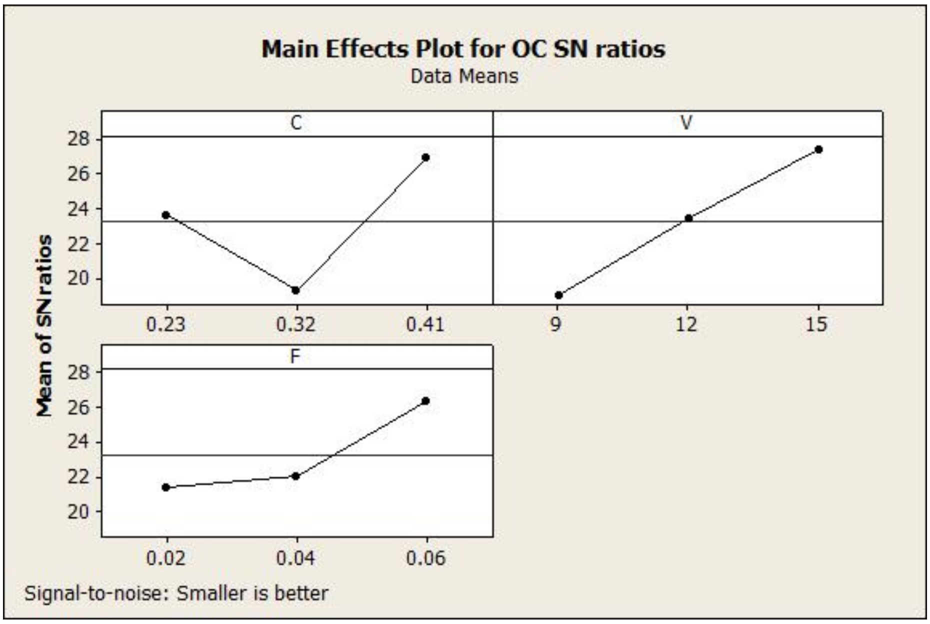

Figure 3. Main effect plots for overcut

Analysis Of Variance (ANOVA)

ANOVA developed by Sir Ronald Fisher is a very powerful statistical tool to determine the significance of the process parameters on the responses measured. The F-test in the table assesses which process factors are significant and insignificant. Generally a large F-value signifies the higher significance of the process parameters on the performance characteristics.

Percentage of contribution of each factor can also be deducted from the ANOVA table which is calculated by following expression:

$$\% \, contribution = \frac{Sum\ of\ square\ of\ variation}{Total\ sum\ of\ square\ of\ variation} * 100 \quad (9)$$

Table 4 here presents combined ANOVA table for all the response MRR. From the table it can be observed that the most significant factor contributing towards the MRR is voltage and feed with percentage contribution of 51.34 % and 29.58 % respectively. In case of Surface roughness it was voltage and concentration of electrolyte with percentage contribution of 46.36 % and 45.55 % respectively as given in Table 5.

Table 4. ANOVA table for MRR

Source of variation	DOF	Sum of squares	F-value	% contribution
Concentration	2	14.937	14.99	17.88
Voltage	2	42.895	43.06	51.34
Feed Rate	2	24.716	24.81	29.58
Error	2	0.996		1.19
Total	8	83.545		

Table 5 ANOVA table for Surface Roughness

Source of variation	DOF	Sum of squares	F-value	% contribution
Concentration	2	7.2143	181.87	45.55
Voltage	2	7.3427	185.11	46.36
Feed Rate	2	1.2427	31.33	7.85
Error	2	0.0397		2.51
Total	8	15.8395		

Table 6 here presents combined ANOVA table for all the response overcut. From the table it can be observed that the most significant factor contributing towards the MRR is voltage and electrolyte concentration with percentage contribution of 38.08 % and 32.32 % respectively.

Table 6. ANOVA table for overcut

Source of variation	DOF	Sum of squares	F-value	% contribution
Concentration	2	88.50	2.32	32.32
Voltage	2	104.28	2.73	38.08
Feed Rate	2	42.90	1.12	15.67
Error	2	38.14		13.93
Total	8	273.81		

Response Table for Outputs:

Response table can also indicate which process parameters has greater influence on the responses measured by giving the process parameter a rank. Also one can infer the optimal condition from the response table. The highest value corresponding to the particular level in the response table is the optimal one for the MRR and it's the lower value for the surface roughness and overcut. From the response table of MRR (Table 7) it can be also inferred that the voltage is most influencing process parameter. The optimal condition was found at 0.41 mole/lit concentration of electrolyte (level 3), 15v voltage (level 3) and 0.06 mm/min feed rate (level 3).

From Table 8 it was found the optimal condition for surface roughness to be at 0.41 g/lit concentration of electrolyte (level 3), 9v voltage (level 1) and 0.02 mm/min feed rate (level 1). From the response table of overcut (Table 9) it can be also inferred that the voltage is most influencing process parameter. The optimal condition was found at 0.32 mole/lit concentration of electrolyte (level 2), 9v voltage (level 1) and 0.02 mm/min feed rate (level 1).

Table 7. Response Table for MRR

Level	Concentration	Voltage	Feed Rate
1	-25.95	-26.48	-25.23
2	-24.04	-25.03	-25.65
3	-22.82	-21.30	-21.94
Delta	3.13	5.18	3.71
Rank	3	1	2

Table 8. Response Table for Surface Roughness

Level	Concentration	Voltage	Feed Rate
1	6.494	4.634	4.995
2	5.276	5.161	5.212
3	4.306	6.550	5.869
Delta	2.188	2.186	0.874
Rank	1	2	3

Table 9. Response table for Overcut

Level	Concentration	Voltage	Feed Rate
1	23.59	19.04	21.42
2	19.29	23.41	22.08
3	26.96	27.38	26.34
Delta	7.66	8.33	4.92
Rank	2	1	3

Multiple Regression Analysis:

The mathematical relationship among the electrochemical machining process parameters and desired performance measures are derived based on the values obtained from the experimentation. The empirical relations which are simulating the electrochemical drilling process are developed by multiple regression analysis. The dependency of material removal rate, surface roughness and overcut to feed rate, voltage and concentration of electrolyte is established using multiple regression equations. The regression equations for various desired performance measures are developed and shown in below equations.

$$MRR\ (mm^3/min) = 0.106759 + (0.239144*C) - (0.0200965*V) - (1.87707*F) - (0.210808*C^2) + (0.00108967*V^2) + (30.5483*F^2) \quad (10)$$

$$Ra\ (\mu m) = 0.340272 + (0.891358*C) + (0.0177593*V) + (0.455556*F) - (0.246914*C^2) - (0.00164815*V^2) - (20*F^2) \quad (11)$$

$$\text{Overcut (mm)} = -0.0822388 + (3.4715*C) - (0.0494061*V) + (2.78942*F) - (5.75412*C^2) + (0.00162241*V^2) - (47.4958*F^2) \quad (12)$$

Where,

'F' is feed rate of the electrode (mm/min),

'V' is voltage (volts) and 'C' is electrolyte concentration (mole/lit). The R^2 values of developing regression models are given in Table 10 and the values are proving that the developed models are fit for further prediction.

Table 10. R^2 values of developed regression model

Regression	R^2 values		
Model	MRR	Surface Roughness	Overcut
Linear + square	97.92%	99.96%	95.64%

Grey Relational Analysis:

The optimum process parameters, grey relational grades were calculated and presented in Table 11. After, GRG values were calculated the runs were arranged as per their subsequent grades with the highest grade given to first rank shown in Table 11. Fig. 4 depicts the variation of GRG with experimental trial numbers. It has been found that the experimental run no. 3 that is the test carried out with 0.23 moles/lit electrolyte concentration, 12 V and 0.06 feed rate provided the best results.

Table 11. Grey relation grade and corresponding rank

S. No	GMRR	GSR	GOC	GRG	Rank
1	0.33333	0.42873	0.3649	0.37564	8
2	0.34580	0.54590	0.4538	0.44850	7
3	0.91751	1	1	0.97250	1
4	0.34598	0.36115	0.3333	0.34682	9
5	0.69152	0.47298	0.5454	0.56998	3
6	0.70516	0.53985	0.4186	0.55453	4
7	0.61011	0.33333	0.5806	0.50803	6
8	0.44126	0.33477	0.7714	0.51580	5
9	1	0.44899	0.8572	0.76872	2

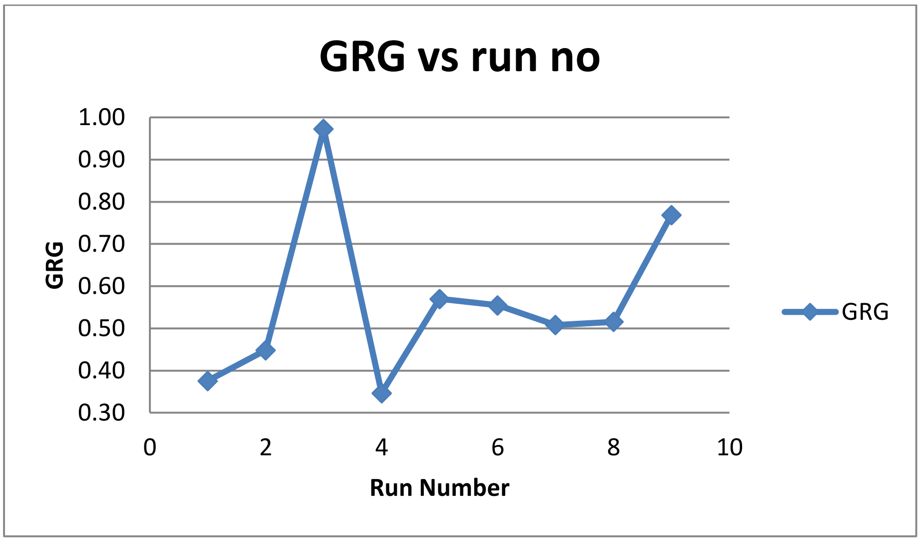

Figure 4. Plot of GRG versus Run Number

Table 12. Response table for average grey relational grade

Level	Concentration	Voltage	Feed Rate
1	0.5989	0.4102	0.4820
2	0.4904	0.5114	0.5213
3	0.5975	0.7652	0.6835
Delta	0.1084	0.3551	0.2015
Rank	3	1	2

The dominant input factors responsible for higher MRR and low surface roughness and overcut were found out from response table for grey relational grade is given in Table 12. It has been found that the difference (delta) was maximum for Voltage, followed by feed rate signifying they have substantial influence over ECM performance characteristics. Concentration of electrolyte on the other hand, has the least impact. The optimal condition was found at 0.23 mole/lit concentration of electrolyte (level 1), 15v voltage (level 3) and 0.06 mm/min feed rate (level 3).

Table 13 here presents combined ANOVA table for all the response overcut. From the table it can be observed that the most significant factor contributing towards the GRG optimum value is voltage and feed rate with percentage contribution of 68.02 % and 22.09 % respectively.

Table 13. ANOVA table for GRG

Source of variation	DOF	Sum of squares	F-value	% contribution
Concentration	2	4.815	3.28	7.58
Voltage	2	43.200	29.40	68.02
Feed Rate	2	14.029	9.55	22.09
Error	2	1.469		2.31
Total	8	63.514		

Confirmation test:

The optimal condition for a process parameter affecting the outcomes can be found out using average GRG. In order to determine average GRG, the GRG values for a particular level of the parameters were added and their average was taken. Then, for every process parameter the highest value of a particular level will have the maximum effect on experimental outcomes. The optimal condition for machining parameters turns out to be 0.23 mole/lit concentration, 0.06 mm/min feed rate and 15 V. From the main effect plot of the GRG (Fig. 5) it can be seen that when concentration of electrolyte decrease from 0.23 mole/lit to 0.32 moles/lit there is a decrease in the GRG but the GRG is increased when increased the electrolyte concentration. Also noted was increased in the GRG with an increase in the voltage and feed rate.

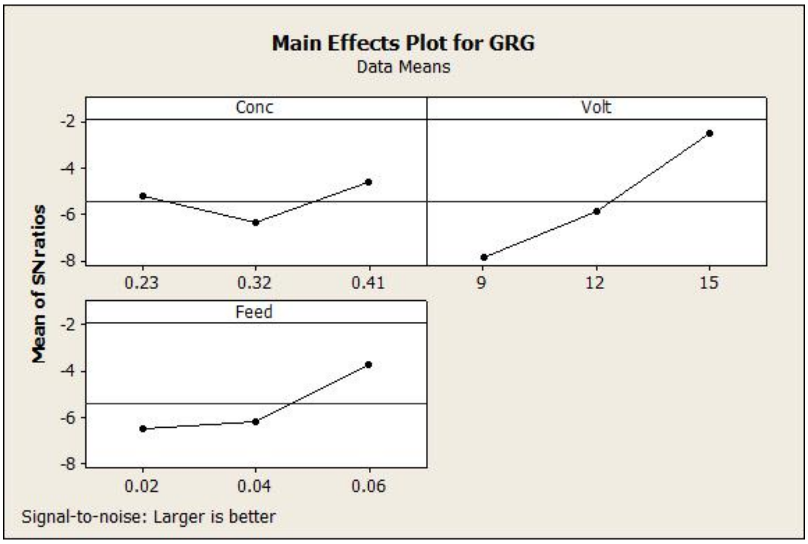

Figure 5. Main effect plots for GRG

Table 14. Confirmation test results

Setting level	Initial setting (0.23 mole/lit, 9 V and 0.02 mm/min)	Optimum machining parameters (0.23 mole/lit, 15 V and 0.06 mm/min)
MRR (mm^3/min)	0.0366	0.0884
Ra (μm)	0.5583	0.3853
Overcut (mm)	0.1344	0.02161
Grey Relational Grade	0.3756	0.9725
Enhancement on GRG		0.5969

Confirmatory tests were carried out after determining the optimal condition and experiment was carried out to validate the analysis and the corresponding MRR, surface roughness and overcut were recorded. The comparison between the initial and the optimum level of process parameters are shown in Table 14. It is observed from the analysis that the optimum parameter shows the considerable improvement in machining performance.

CONCLUSION

The current study focused on multi objective optimization of micro electrochemical machining on Inconel 625 using Taguchi based Grey Relational Analysis. The following conclusions were drawn from this experimental results and analysis:

The voltage is the predominant variable for all the desired performance characteristics. The R^2 value of the developed regression model shows that the developed regression models can be used for reliable prediction. The optimal condition for GRG was found to be at 0.23 mole/lit concentration of electrolyte, 15 V voltage and 0.06 feed rate mm/min. Confirmatory test results revealed that there is a considerable improvement in the multi performance index GRG as 0.5969 for experimental values. The outcome of this present investigation will be an extensive support to the industries for enhancement of productivity and product quality in the processing of Inconel 625 using a micro electrochemical machining process.

REFERENCES

[1] Senthil S. *Unconventional machining processes* (10th ed. Nagapattinam, India) 2013.

[2] Manikandan N, Kumanan S & Sathiyanarayanan C, *Indian J Eng Mater Sci*, 22 (2015) 153–160.

[3] Nayak A A, Gangopadhyay S & Sahoo D K, *J manuf proc*, 23 (2016) 269–277.

[4] Klocke F, Zeis M, Klink A & Veselovac D, *The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM) Procedia CIRP*, 6 (2013) 369–373.

[5] De Silva A K M, Altena H S J & McGeough J A. *CIRP Ann Manuf Technol*, 52 (2003) 165–168.

[6] Burger M, Koll L, Werner E A & Platz A, *J Manuf Proc*, 14 (2012) 62–70.

[7] Joao Cirilo da Silva Neto, Evaldo Malaquias da Silva & Marcio Bacci da Silva, *J Mater Proc Technol*, 179 (2006) 92–96.

[8] Rao R V, Pawar P J & Shankar R, *Proc Inst Mech Eng B J Eng Manuf*, 22 (2008) 949–958.

[9] Dhanabalan S, Sivakumar K & Sathiya Narayanan C, *Mater Manuf Proc*, 29 (2014) 253–259.

[10] Tripathy S & Tripathy D K, *Eng. Sci. Technol. An Int. J*, 19 (2016) 62–70.