Journal of Scientific & Industrial Research
Vol. 79, May 2020, pp. 424-429

Investigations on Electrochemical Micro Drilling of Nickel Alloy using Taguchi based Grey Approach

K Rajendiran[1], D Saravanan[2], P Parthiban[3]* and V Anandakrishnan[3]

[1]Department of Mechanical Engineering, Jayaram College of Engineering and Technology, Thuraiyur, Tiruchirappalli – 621 014

[2]Department of Mechanical Engineering, MIET Engineering College, Tiruchirappalli-620 007

[3]Department of Production Engineering, National Institute of Technology, Tiruchirappalli- 620 015, Tamil Nadu, India

Received 25 June 2019; revised 22 January 2020; accepted 26 March 2020

Inconel 600 is the nickel based super alloy which is employed in numerous engineering applications like gas turbine blades, turbochargers and heat exchangers etc. However, it is very difficult to machine due to its high strength and poor thermal diffusion. Conventional machining methods of these materials may result in decreased life time. An electrochemical machining is an advanced non-traditional technique which is suitable for machining hard material, strenuous materials and Intricate shapes. In this paper, electrochemical micro drilling (ECMD) on Inconel 600 material is investigated. The experiments are devised and analyzed using Taguchi's L_{18} orthogonal array and Grey relational analysis (GRA). Analysis of variance (ANOVA) has been implemented to find out the significance of electrochemical micro drilling parameters on the performance characteristics.

Keywords: ECMD, Inconel 600, Taguchi method, GRA, ANOVA

Introduction

Inconel 600 alloys are high strength and highly corrosion resistant materials, well suited for chemical Industries, airframe components etc.[1] ECM is one of the advanced unconventional material removal process which is used to machine hard materials and the micro ECM process is the effective machining process for the development of MEMS and widely used in aerospace, electronics and micro-mechanics Industries.[2] In ECMM, optimized process parameters are used to find the best combination of set of machining variable for attaining the better machining characteristics.

Investigations for ECMM

Fabrication of a 500 μm-deep microgroove in stainless steel and the impact of the EMM parameters on the MRR have been discussed in this paper.[3] In this paper, Taguchi L27 based orthogonal array and ANOVA methods are applied for the optimization of machining parameters on drilling of Al606 1- 6% Gr.[4] The vital parameters influencing the machining accuracy, MRR and the process suitability of micromachining is discussed in this article.[5,7] The classification of sequential micro-machining process is discussed in this paper.[6] The effect of material removal rate (MRR), machining time and overcut in the micro drilling process is studied, which determines the machining and geometric characteristics of the drill bit.[8] The influence of almost all the machining process input values such as Voltage, Inter Electrode Gap (IEG), Duty Ratio, Electrolyte Temperature, Type of electrolyte, Frequency of Pulse, etc., which are in R&D and industrial applications oriented are reviewed in this article.[9,10]

The ECM process monitoring and controlling system is introduced where the parameter is modified based on tool electrode kinematics and the designed criteria is considered for the parameter modification.[11] A good combination of process parameter using GRA with Taguchi method is attempted. The most affecting parameter for NaCl and $NaNO_3$ are found to be micro-tool feed rate and applied voltage respectively.[12] The latest micro drilling techniques were discussed to fulfill the future requirements namely twisted, spade, D-shaped micro drilling.[13] Multi response optimization of ECMM parameters on SS304 alloy with polymer graphite electrode employing $NaNO_3$ is experimented[14]. The micro-hole machining is done using copper inorganic work piece. Ultraviolet rays are used for heating the electrolyte

*Author for Correspondence
E-mail: parthee_p@yahoo.com

while machining. L_{18} orthogonal array is considered in this experimental work.[15] The optimization on electrochemical drilling process of Inconel 718 and Inconel 625 is done by investigating on Taguchi's approach and regression model. The significance of input variables is found using ANOVA and Design of Experiments are used for the trails conducted in this experiment. Finally the regression models were developed.[16,17] A constant electrolyte flow in ECD method have been applied on machining of Inconel 718 to achieve stability in removing insoluble waste products from machining gap.[18,19] The process of particle transport in inter-electrode gap is verified experimentally by considering low frequency vibration for understanding flushing of by-products in ECM method.[20]

In this paper, an attempt has been made to ascertain the influence of various micro ECM input variables on desired performance responses are MRR and dimensional deviation for ECMD of said material. The effective and efficient measurement and assessment of these output characteristics needs attention. Therefore, Taguchi’s experimental design approach is applied to determine the possible combination of input variables for ECMD. Single objective optimization has been achieved by Taguchi’s approach. To optimize multi performance characteristics of Micro ECD process, GRA have been applied. To test the significance of input process variables on desired output performance measures ANOVA have been employed. The influence of process parameters is analyzed using Minitab 16.0 statistical software.

Experimental Procedure for ECMM

The machining chamber / electrolyte tank was made up of acrylic material. The entire work holding platform was placed inside the chamber. The chamber was filled with electrolyte, according to need. During the machining process both were immersed in electrolyte. The tool (electrode), the work piece is connected to negative and positive terminals of pulsed power supply via the tool holder to act as cathode and anode. Since, the stepper motor rotation is bidirectional; the tool can be moved forward and backward direction. Sodium nitrate ($NaNO_3$) was used as an electrolyte and pumped into the machining zone with velocity to flush out the removed particles of material during machining. In this ECMM experiments stainless steel wire of 250 microns diameter was used.

A well planned and executed experimental run may detail great information related to the effects on desired performance measures due to one or more factors. The preparation for experimental work includes defining the problem by selecting the proper variables, defining the objectives and developing an appropriate experimental plan. The selection of input variables and interactions between the variables is based on their influence over the output characteristics. In this experiment there were five factors (A,B,C,D,E) and three levels were considered.[17] The process parameters for electrochemical micro drilling were A: Electrolyte Concentration (mol/lit) 0.40, 0.45 & 0.50; B: Voltage(V) 8, 9 & 10; C: Current (A) 0.6, 0.8 & 1.0; D: Duty Cycle(%) 33.33, 50.00 & 66.66; E: Frequency (Hz) 30, 40 & 50.

In accordance with the total degree of freedom (17), the possible combination of the input process variables was obtained from Taguchi’s L_{18} orthogonal array. The experiments were conducted twice in each combination of Input parameters and the average MRR was calculated from trail 1 & 2 experiments and tabulated as shown in Table 1. The experimental layout and observations to be performed in micro ECMD are exposed in Table 1.

Results and Discussion

The output attainment of machining is assessed by MRR and dimensional deviation. The dimensions of the drilled micro holes were measured by an optical microscope. Time taken for machining is noted for each and every run. The lower the dimensional deviation the better the machining responses were found. Higher the MRR, better the machining output performance. Therefore, the dimensional deviation should be the lower- the- better and the MRR should be the higher- the- better performance characteristics**.**

Influence of process variables on MRR

In Fig. 1 the response graph of MRR during electrochemical micro drilling of Inconel 600 is illustrated. From the graph, it is observed that the maximum MRR is attained at the highest level of duty cycle (66.66%) and the MRR is increased linearly with duty cycle. Machining voltage is the second major significant variable influencing MRR, followed by electrolyte concentration and frequency.

Since the disbanding of metal is directly linked to the pulse ON time and debris removal has been achieved in a short span of time (pulse OFF time).

Table 1 — Experimental layout and observation for micro ECMD

Experimental layout for micro ECMD						Observation for micro ECMD		
Exp. No	A (mol/lit)	B (Volts)	C (Amps)	D (%)	E (Hz)	Machining time (min)	MRR (mm^3/min.)	Dimensional Deviation (microns)
1	0.40	8	0.6	33.33	30	32.5	0.0003606	10
2	0.40	9	0.8	50.00	40	23.5	0.0008293	32
3	0.40	10	1.0	66.66	50	15.0	0.0010358	35
4	0.45	8	0.6	50.00	40	30.0	0.0006629	18
5	0.45	9	0.8	66.66	50	22.0	0.0007723	29
6	0.45	10	1.0	33.33	30	19.0	0.001068	36
7	0.50	8	0.8	33.33	50	31.5	0.0003672	16
8	0.50	9	1.0	50.00	30	26.0	0.0004046	18
9	0.50	10	0.6	66.66	40	20.0	0.0007331	22
10	0.40	8	1.0	66.66	40	22.0	0.0007638	24
11	0.40	9	0.6	33.33	50	29.0	0.0006052	19
12	0.40	10	0.8	50.00	30	25.0	0.0007172	19
13	0.45	8	0.8	66.66	30	20.0	0.0008402	31
14	0.45	9	1.0	33.33	40	29.0	0.0006183	18
15	0.45	10	0.6	50.00	50	23.5	0.0007549	20
16	0.50	8	1.0	50.00	50	27.5	0.0006044	22
17	0.50	9	0.6	66.66	30	13.0	0.0012926	30
18	0.50	10	0.8	33.33	40	26.0	0.0004046	16

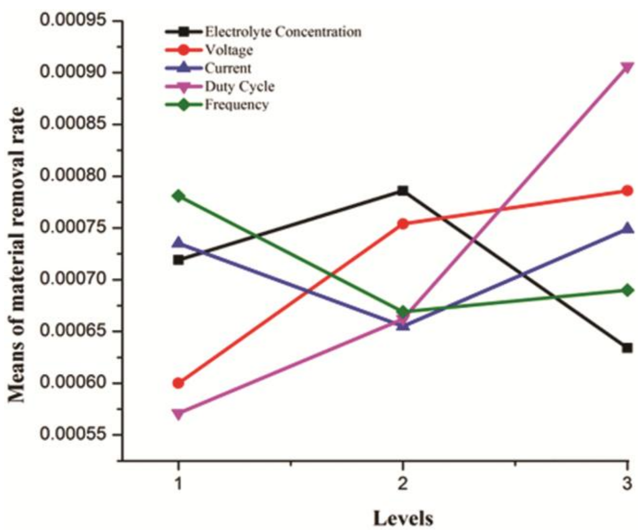

Fig. 1 — Response graph for MRR

Duty Cycle is emerging as a predominant variable which influences the rate of material removal for these materials.

Taguchi's response analysis for MRR is conducted using S/N ratio which is presented in Fig. 1. The optimum input process parameter set is A2B3C3D3E1, which means that A2 = 0.45 mol/lit, B3=10V, C3= 1A, D3= 66.66% and E1=30 Hz.

Influence of process parameters on Dimensional Deviation

The dimensional deviation during ECMD of said material Graph is shown in Fig. 2. From the graph, it is observed that the maximum MRR is obtained at the highest level of duty cycle (66.66%). Applied Current is the next significant process variable which is influencing the dimensional deviation and it is followed my machining voltage, electrolyte concentration and frequency. Duty Cycle is a predominant variable which influences the dimensional deviation for these materials.

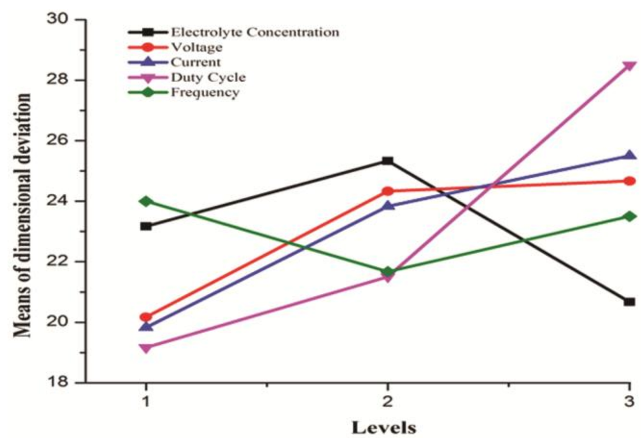

Fig. 2 — Response graph for dimensional deviation

Taguchi's response graph analysis for dimensional deviation are presented in Fig. 2 and from analysis the best possible process parameter set is A3B1C1D1E2 which means that A3= 0.50 mol/lit, B1= 8V, C1= 0.6 A, D1=33.33% and E2= 40 Hz. In this case the most influencing parameter is Duty cycle and which is followed by current, voltage, electrolyte concentration and frequency respectively.

Multi objective optimization by GRA Analysis

The three steps in GRA (Grey Relational Analysis) are Data-pre-processing, Grey Relational Coefficient (GRC) and Grey Relational Grade (GRG). Data pre-processing method is a transfer of original data sequence to a comparable sequence. So the normalized data are required.[21] The three data normalization methods are Lower-the-better (LB), Higher-the-Better (HB) and Nominal the Best (NB).

The normalized data for Higher-the-Better (HB) is given as $y_i^*(k) = \frac{y_{i(k)-} min\ y_i(k)}{max\ y_i(k) - min\ y_{i\ (k)}}$ ... (1)

The normalized data for Lower-the-better (LB) is given as $y_i^*(k) = \frac{max\ y_{i(k)-} y_i(k)}{max\ y_i(k) - min\ y_{i\ (k)}}$ ... (2)

Where

$y_i^*(k)$ is a normalized data sequenc eafter processing,

$y_i(k)$ is original sequence,

$min\, y_i\,(k)$ and $max\, y_i\,(k)$ are the smallest and largest value of $y_i(k)$ for the k^{th} response.

Grey Relational Coefficient

The GRC was calculated as follows

$\varepsilon_i\,(k) = \frac{\Delta \min + \omega \Delta max}{\Delta_{oi}\,(k) + \omega \Delta max}$ ... (3)

Where

$\varepsilon_i\,(k)$ is the grey relation coefficient of the i^{th} experiment for the k^{th} response,

$\Delta_{oi}(k) = \|y_o^*(k) - y_i^*(k)\|$ i.e., absolute of the difference between $y_o^*(k)$ and $y_i^*(k)$,

$y_o^*(k)$ is the reference sequence,

Δmax and Δmin are the largest and smallest value of $\Delta_{oi}\,(k)$.

Grey Relational Grade

The GRG Γi is obtained by averaging the GRC corresponding to each experiment as follows

$\Gamma_i = \frac{1}{n}\sum_{k=1}^{Q} i(k).$ ... (4)

Where the total number of responses is ***Q*** and the number of output responses is ***n***.

The level of correlation between the reference sequence and the comparability sequence is ***n***. If grey relational grade is high then the corresponding parameter combination is closer to the optimal value. The estimated and ranked GRC & GRG values are shown in Table 2.

From the outcomes of GRA, it is observed that the larger GRG value shows the better multi characteristics machining performance, which means that the corresponding set of machining parameters is considered as the optimum machining process parameters. From Table 2, the trial No. 17 having maximum GRG value. It shows that the analogous process value has the better multi performance.

Optimum level selection for multi performance characteristics

The response graph in Fig. 3 is for the multiple performance characteristics optimization for ECMD

Table 2 — Calculated GRC and GRG values for micro ECMD

Order	Normalized Values		Grey relational coefficient		Grey Relational grade	Rank
	Material Removal Rate	Dimensional Deviation	Material Removal Rate	Dimensional Deviation		
1	0	1	0.333333	1	0.6667	2
2	0.502897	0.153846	0.501453	0.371429	0.4364	18
3	0.724464	0.038462	0.644715	0.342105	0.4934	11
4	0.324356	0.692308	0.425299	0.619048	0.5222	3
5	0.441738	0.269231	0.472473	0.40625	0.4394	17
6	0.759013	0	0.674776	0.333333	0.5041	9
7	0.007082	0.769231	0.334914	0.684211	0.5096	8
8	0.04721	0.692308	0.344165	0.619048	0.4816	13
9	0.399678	0.538462	0.454412	0.52	0.4872	12
10	0.432618	0.461538	0.468436	0.481481	0.4750	14
11	0.262446	0.653846	0.404023	0.590909	0.4975	10
12	0.382618	0.653846	0.447475	0.590909	0.5192	4
13	0.514592	0.192308	0.507404	0.382353	0.4449	16
14	0.276502	0.692308	0.408664	0.619048	0.5139	7
15	0.423069	0.615385	0.464282	0.565217	0.5147	5
16	0.261588	0.538462	0.403743	0.52	0.4619	15
17	1	0.230769	1	0.393939	0.6970	1
18	0.04721	0.769231	0.344165	0.684211	0.5142	6

of Inconel 600. Also it is observed that the current is the significant variable for influencing the multiple machining performance characteristics. From Illustration the set of process parameters is A3B1C1D1E1, which means that A3=0.50 mol/lit, B1= 8V, C1= 0.6A, D1=33.33% and E1= 30Hz. Hence, Current is the most influencing parameter and then frequency, duty cycle, Electrolyte concentration and machining voltage respectively.

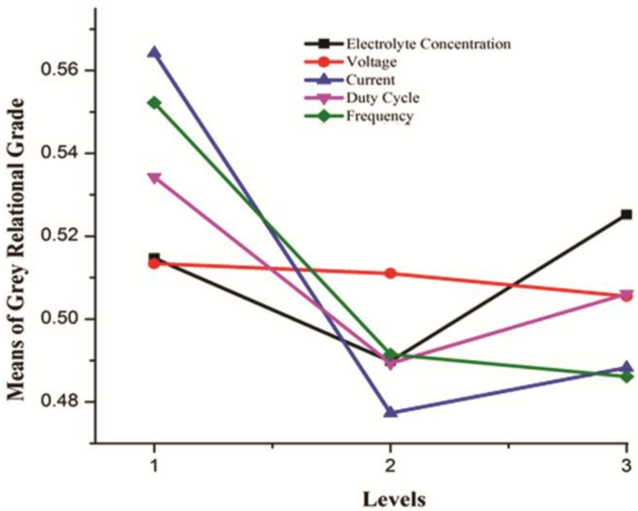

Fig. 3 — Response graph for grey relational grade (GRG)

Analysis of variance MRR, dimensional deviation (DD) and GRG

The outcomes of ANOVA analysis for MRR and dimensional deviation are shown in Table 3. From the 'F' value, it is observed that the duty cycle is the best process variable for MRR and dimensional deviation in the proposed process for the given material. Also, the ANOVA analysis confirms that the results are closely connected with outcomes of Figs 1 & 2 Taguchi's response analysis.

The outcomes of ANOVA for multi performance machining characteristics are shown in Table 3. From the 'F' value, it is clear that the current is the most significant process parameter for multi performance machining characteristics in ECMD of selected material and it is followed by frequency, duty cycle, electrolyte concentration, machining voltage, respectively. The results obtained through ANOVA analysis are closely connected to outcomes of Fig. 3 Taguchi's response analysis.

Confirmation test for micro ECMD

The final step of conformation test to affirm the results based on Taguchi Grey approach. In this investigation, a confirmation test was performed by applying the best set of input parameters

Table 3 — ANOVA for MRR, Dimensional deviation (DD) and GRG in micro ECMD

Source		DF	Seq SS	Adj SS	Adj MS	F	P
A	MRR	2	21.305	10.652	10.652	1.17	0.364
	DD	2	8.539	8.539	4.27	0.56	0.597
	GRG	2	0.9238	0.9238	0.4619	0.51	0.622
B	MRR	2	19.061	9.531	9.531	1.05	0.399
	DD	2	13.788	13.788	6.894	0.9	0.45
	GRG	2	0.0178	0.0178	0.0089	0.01	0.99
C	MRR	2	4.337	2.169	2.169	0.24	0.794
	DD	2	16.39	16.39	8.195	1.07	0.394
	GRG	2	6.6805	6.6805	3.3402	3.68	0.081
D	MRR	2	62.28	31.14	31.14	3.43	0.092
	DD	2	49.061	49.061	24.531	3.19	0.104
	GRG	2	1.7319	1.7319	0.8659	0.95	0.43
E	MRR	2	1.56	0.78	0.78	0.09	0.919
	DD	2	1.228	1.228	0.614	0.08	0.924
	GRG	2	3.6556	3.6556	1.8278	2.02	0.204
Error	MRR	7	63.592	9.085	9.085	—	—
	DD	7	53.834	53.834	7.691	—	—
	GRG	7	6.349	6.349	0.907	—	—
Total DF	MRR	17	172.135	—	—	—	—
	DD	17	142.84	—	—	—	—
	GRG	17	19.3586	—	—	—	—

(A3B1C1D1E1) for ECMD of said material. The predicted and Experimented optimum machining parameters (A3B1C1D1E1) for GRG is (0.001145,13).

Conclusions

The application of Inconel 600 has increased in various engineering industries such as aerospace and high temperature equipment. The experimental results confirm that the duty cycle is one of the most influencing input parameter for MRR and the dimensional deviation. Also the ANOVA analysis confirmed that the results obtained are closer to Taguchi's analysis. Optimum process parameters are obtained using GRA to achieve better machining characteristics. Therefore, the proposed Taguchi based Grey Approach is a suitable method to establish the optimum process parameters of multiresponse characteristics.

References

1 Salcedo A T, Arbizu I P & Pérez C J L, Analytical modelling of energy density and optimization of the EDM machining parameters of Inconel 600, *Metals*, **7** (2017) 166.

2 Pandey A, Goyal A & Meghvanshi R, Experimental Investigation and Optimization of Machining Parameters of Aerospace Material Using Taguchi's DOE Approach, *Mater Today: Proc*, **4** (2017) 7246–7251.

3 Rathod V, Doloi B & Bhattacharyya B, Influence of electrochemical micromachining parameters during generation of microgrooves, *Int J Adv Manuf Tech*, **76** (2015) 51–60.

4 Satishkumar P, Dharmalingam S, Raja K, Lingadurai K & Padmanaban G, Investigation on Electrochemical Micro Machining of Al 606 1–6% wt Gr based on Taguchi design of experiments, *Int J Chem Tech Res*, **7** (2015) 203–211.

5 Leese R & Ivanov A, Electrochemical micromachining: review of factors affecting the process applicability in micro-manufacturing, *Proc Inst Mech Eng, Part B: J Eng Manuf*, **232** (2018) 195–207.

6 Chavoshi S Z, Goel S & Morantz P, Current trends and future of sequential micro-machining processes on a single machine tool. *Mater & Des*, **127** (2017) 37–53.

7 Palani S, Iruthayaraj R, Vijayakumar D, Selvam M & Paul L P R, Analysis of Electro Chemical Micro Machining Process Parameters by Taguchi Orthogonal Array, *Int J Innov Technol Explor Eng*, **8** (2019) 2278–3075.

8 Sathish T, Experimental investigation of machined hole and optimization of machining parameters using electrochemical machining, *J Mater Res Technol*, **8** (2019) 4354–4363.

9 Geethapriyan T, Kalaichelvan K, Rajadurai A, Muthuramalingam T & Naveen S, A review on investigating the effects of process parameters in electrochemical machining, *Int J Appl Eng Res*, **10** (2015) 1743–1748.

10 Unare A J & Attar P R, Optimization of process parameter of electrochemical machining of aluminium alloy 7075 by using gray taguchi method, *Int Res J Eng Technol*, **3** (2016) 120–123.

11 Paczkowski T & Zdrojewski J, Monitoring and control of the electrochemical machining process under the conditions of a vibrating tool electrode, *J Mater Process Technol*, **244** (2017) 204–214.

12 Geethapriyan T, Kalaichelvan K & Muthuramalingam T, Multi performance optimization of electrochemical micro-machining process surface related parameters on machining Inconel 718 using Taguchi-grey relational analysis, *MetallItal*, **4** (2016) 13–19.

13 Hasan M, Zhao J & Jiang Z, A review of modern advancements in micro drilling techniques, *J Manuf Process*, **29** (2017) 343–375.

14 Pradeep N, Sundaram K S & Kumar M P, Multi-response optimization of electrochemical micromachining parameters for SS304 using polymer graphite electrode with $NaNO_3$ electrolyte based on TOPSIS technique, *J Braz Soc Mech Sci Eng*, **41** (2019) 323.

15 Soundarrajan M & Thanigaivelan R, Investigation on electrochemical micromachining (ECMM) of copper inorganic material using UV heated electrolyte, *Russ J Appl Chem*, **91** (2018) 1805–1813.

16 Manikandan N, Kumanan S & SathiyanarayananC, Optimization of Electrochemical drilling process using Taguchi method and regression analysis, *Int J Mach Mach Mater*, **19** (2017) 136–159.

17 Manikandan N, Kumanan S & Sathiyanarayanan C, Multi response optimization of electrochemical drilling of titanium Ti6Al4V alloy using Taguchi based grey relational analysis, *Indian J Eng Mater Sci*, **22** (2015) 153–160.

18 Wang X, Qu N, Fang X & Li H, Electrochemical drilling with constant electrolyte flow, *J Mater Process Technol*, **238** (2016) 1–7.

19 Anasane S S & Bhattacharyya B, Experimental investigation into fabrication of microfeatures on titanium by electrochemical micromachining, *Adv Manuf*, **4** (2016) 167–177.

20 Feng Z, Orona-Hinojos J M, Villanueva P P, Lomeli P & Hung W N, Flushing enhancement with vibration and pulsed current in electrochemical machining, *Int J Eng Mater Manuf*, **2** (2017) 67–85.

21 Manikandan N, Kumanan S & Sathiyanarayanan C, Multiple performance optimization of electrochemical drilling of Inconel 625 using Taguchi based Grey Relational Analysis, *Int J Eng Sci Technol*, **20** (2017) 662–671.