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

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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.<sup>1</sup> 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.<sup>2</sup> 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  $\mu\text{m}$ -deep microgroove in stainless steel and the impact of the EMM parameters on the MRR have been discussed in this paper.<sup>3</sup> In this paper, Taguchi  $L_{27}$  based orthogonal array and ANOVA methods are applied for the optimization of machining parameters on drilling of Al606 1- 6% Gr.<sup>4</sup> The vital parameters influencing the machining accuracy, MRR and the process suitability of micromachining is discussed in this article.<sup>5,7</sup> The

classification of sequential micro-machining process is discussed in this paper.<sup>6</sup> 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.<sup>8</sup> 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.<sup>9,10</sup>

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.<sup>11</sup> A good combination of process parameter using GRA with Taguchi method is attempted. The most affecting parameter for NaCl and NaNO<sub>3</sub> are found to be micro-tool feed rate and applied voltage respectively.<sup>12</sup> The latest micro drilling techniques were discussed to fulfill the future requirements namely twisted, spade, D-shaped micro drilling.<sup>13</sup> Multi response optimization of ECMM parameters on SS304 alloy with polymer graphite electrode employing NaNO<sub>3</sub> is experimented<sup>14</sup>. The micro-hole machining is done using copper inorganic work piece. Ultraviolet rays are used for heating the electrolyte

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while machining.  $L_{18}$  orthogonal array is considered in this experimental work.<sup>15</sup> 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.<sup>16,17</sup> 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.<sup>18,19</sup> 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.<sup>20</sup>

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 ( $\text{NaNO}_3$ ) 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.<sup>17</sup> 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

Exp. No	Experimental layout for micro ECMD					Observation for micro ECMD		
	A (mol/lit)	B (Volts)	C (Amps)	D (%)	E (Hz)	Machining time (min)	MRR (mm <sup>3</sup> /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

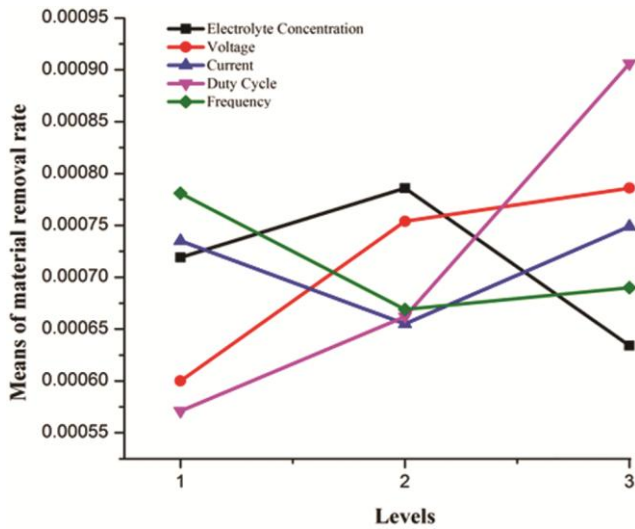


Fig. 1 — Response graph for MRR

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

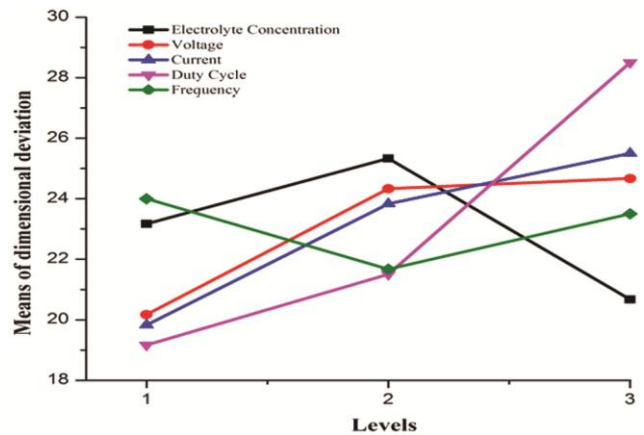


Fig. 2 — Response graph for dimensional deviation

variable which is influencing the dimensional deviation and it is followed by machining voltage, electrolyte concentration and frequency. Duty Cycle is a predominant variable which influences the dimensional deviation for these materials.

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.<sup>21</sup> 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 sequence after 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  $k^{\text{th}}$  response.

**Grey Relational Coefficient**

The GRC was calculated as follows

$$\varepsilon_i(k) = \frac{\Delta_{\min} + \omega \Delta_{\max}}{\Delta_{oi}(k) + \omega \Delta_{\max}} \quad \dots (3)$$

Where

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

$\Delta_{\max}$  and  $\Delta_{\min}$  are the largest and smallest value of  $\Delta_{oi}(k)$ .

**Grey Relational Grade**

The GRG  $\Gamma_i$  is obtained by averaging the GRC corresponding to each experiment as follows

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

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.

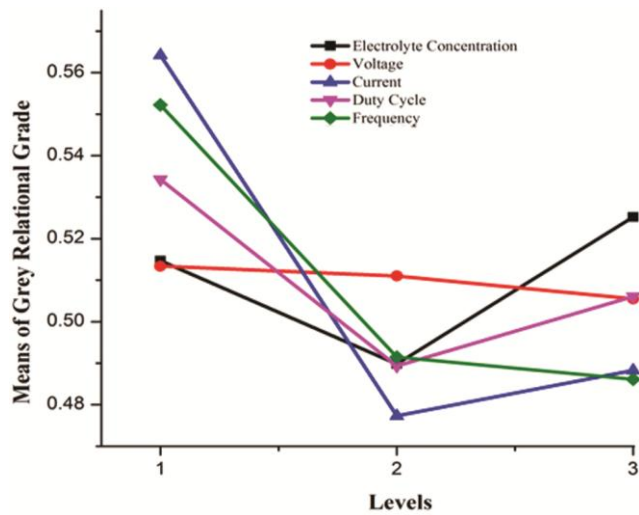


Fig. 3 — Response graph for grey relational grade (GRG)

**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.

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