

# The effects of the process parameters in electrochemical machining on the surface quality

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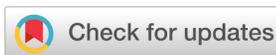
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## ABSTRACT

Based on the number of previous studies, this study aims to investigate the effects of process parameters of an Electrochemical Machining process which are electrolyte concentration, voltage applied to the machine, feed rate of the electrode and Inter-Electrode Gap between tool and work - piece. Aluminum samples of 25 mm diameter x 25 mm height and 30mm diameter x 25mm height of the tool is made up of copper with a circular cross section with 2 mm internal hole. The design of the system is based on the Taguchi method. Here, the signal-to-noise (S/N) model, the analysis of variance (ANOVA) and regression analyses are applied to determine optimal levels and to investigate the effects of these parameters on surface quality. Finally, the experiments that use the optimal levels of machining parameters are conducted to verify the effects of the process parameters to the surface quality of the products. The results pointed a set of optimal parameters of the ECM process. The Inter-Electrode Gap between tool and work - piece has extremely effected on these Material Removal Rate and surface roughness. The Material Removal Rate increases with decreases in Inter-Electrode Gap, and Ra decreases with decreases in Inter-Electrode Gap. The experimental results show that maximum Material Removal Rate have obtained with electrolyte concentration at 100 g/l, feed rate at 0.0375 mm/min, voltage at 15V, and Inter-Electrode Gap at 0.5mm. The minimum Ra have obtained with electrolyte concentration at 80 g/l, feed rate at 0.0468 mm/min, voltage at 10V, and Inter-Electrode Gap at 0.5mm. This results has led to need studies on these parameters in Electrochemical Machining which are improving productivities and surface roughness of the products.

**Key words:** Electrochemical machining (ECM), Taguchi method, ANOVA, surface quality

## INTRODUCTION

In recent years there are a large of advanced new materials and alloys which have been discovered but they are difficult to machine such as super alloys, alloys steel, tool steel, and stainless steel with conventional machining methods<sup>1</sup>. This demands leads to several problems, and some feasible solutions would be solved in the future. Thus, new machine methods must be taken to mitigate the problems of urgent demands that they are beneficial methods called Non - Traditional Manufacturing (NTMPs). And, Electrochemical Machining (ECM) is one of the widely used Non - Traditional Machining processes. ECM principle is based on the phenomenon of electrolysis, whose laws were established by Faraday in 1833. “Faraday believes that if two conductive poles are placed in a conductive electrolyte bath and energized by a current, metal may be depleted from the positive pole (anode) and plated onto the negative pole (cathode)”<sup>1</sup>. The first law states that the amount of electrochemical dissolution or deposition is proportional to amount of charge passed through the electrochemical

cell, which may be described as in (1):

$$m \sim Q \quad (1)$$

Where:

m – Mass of material dissolved or deposition;

Q – Amount of charge passed

And, the second of Faraday law states that the amount of material deposited or dissolved further depends on Electrochemical Equivalence of the materials that is again the ratio of the atomic weight and valency, which may be showed as in (2):

$$m = \frac{It\varepsilon}{F} \quad (2)$$

Where:

m = weight of a material (g).

I = Current (A).

t = machining time (sec).

$\varepsilon$  = gram equivalent weight of the material.

F = constant of proportionality – Faraday (96,500 coulombs).

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ECM equipment consists of three sub – equipment: machining setup, control unit and electrolyte circulation system. ECM process is performed without physical contact between the tool and the work - piece in contrast to the mechanical machining, and without strong heating in the machining zones in distinction to the methods like Electrical Discharge Machining - EDM. Therefore, no surface metal layer with mechanical distortion, comprehensive stresses, cracks, and thermal distortion forms in ECM. Besides, the numbers of these advantages of this process which are its applicability regardless of material hardness, no tool wear, high material removal rate and production of components of complex geometry. Despite these advantages it has been developed and applied in aerospace, aeronautics, defence, medical industries and other industries<sup>1-3</sup>.

It is true that surface quality has become significant because of increased quality demands. Moreover, surface roughness is one of major quality attributes of ECM products beside material removal rates, accuracy and performance of machining. Hence, a lots of investigations have attempted the study of the effects of multiple machining parameters on surface roughness. The effects of a pulsating electrolyte during the electrochemical machining process on surface roughness and material removal rate have been successfully studied through experimentations, and obtained lower surface roughness and higher material removal rate on Ti6Al4V sample machined by ECM. The minimum surface roughness  $R_a$  of  $0.53\mu\text{m}$  and maximum MRR of  $0.39\text{ g/min}$  are observed by using a pulsating electrolyte<sup>2</sup>. Weidong Liu *et al.*<sup>4</sup> focused to study the effects of main parameters like the composition and concentration of electrolyte, machining voltage, electrolyte flow rate, and Inter – Electrode Gap (IEG) on machining performance in Jet electrochemical machining of TB6 titanium alloy. From experiment results, 24V voltage, 0.6mm IEG, 2.1l/min flow rate and 15% sodium chloride electrolyte are selected as control parameters. Material removal rate of  $10.062\text{g/min}$ , surface roughness of  $0.231\mu\text{m}$  and average overcut of  $1.01\text{mm}$  are observed when the optimum parameters are used. Milan Kumar *et al.*<sup>5</sup> presented the effects of process parameters on MRR and surface roughness characteristics (centre line average roughness:  $R_a$ , root mean square roughness:  $R_q$ , skewness:  $R_{sk}$ , kurtosis:  $R_{ku}$  and mean line peak spacing:  $R_{sm}$ ), and parametric optimization of process parameters in ECM of EN31 tool steel using grey relation analysis. The experimental results show that maximum MRR and minimum surface roughness have obtained with electrolyte concentration 10%, voltage 10V, feed rate  $0.25\text{mm/min}$  and

IEG  $0.2\text{mm}$ . Jerzy Kozak and Maria Zybura - Skrabalak<sup>6</sup> presents some features of ECM processes, such as the effect of heterogeneous structure of material work - piece and the influence hydrodynamic instability of anode boundary layer on the surface roughness. A mathematical model was developed to simulate the evolution of surface profiles during electrochemical machining of alloys with the heterogeneous structure. Results of computer simulation and an analysis of the effects of various ECM factors and the structure of the work - piece material, on surface roughness and its parameters is done. The experimental investigations confirmed the effect of hydrodynamic instability of boundary layer on micro topography of machined surface done. H.M.Osman and M.Abdel-Rahman<sup>7</sup> investigates integrity of surfaces produced by electrochemical machining. M.Sankar *et al.*<sup>8</sup> conducted to optimize main parameters such as voltage, feed rate, and current, were optimized based on multiple responses. The results show that feed rate and applied voltage are the most significant parameters which affect multiple machining responses simultaneously. Optimization of machining parameters in ECM of Al/B4C composites using Taguchi Method was reported by S. R. Rao<sup>9</sup>. There are 27 tests to study the effects of various parameters like applied voltage, feed rate, electrolyte concentration and percentage of reinforcement on Material Removal Rate (MRR), surface roughness ( $R_a$ ) and radial overcut (ROC). A Rotary U Shaped Tool is applied to investigate the MRR, overcut diameter and overcut depth of AISI P20 work – piece. Four parameters were chosen as process variables: feed rate, voltage, electrolyte concentration and tool diameter. From these results, MRR increase with increasing the feed rate, voltage and electrolyte concentration but decreases with increasing the tool diameter. Both overcut and over depth which are increasing with increasing feed, voltage, and electrode diameter but decreases with increasing electrolyte concentration<sup>10</sup>.

This paper deals with the effects of these parameters and optimization of the ECM process based on Taguchi techniques. From previously literatures, in this work two contradicting response parameters Material Removal Rate (MRR) and surface roughness ( $R_a$ ) were considered for analysis (MRR is to be maximized and  $R_a$  is to be minimized). There are consists of four input parameters which are electrolyte concentration, feed rate, voltage and Inter-Electrode Gap as process variables and Aluminium (Al) were machined by electrochemical machining process.

### EXPERIMENTAL PROCEDURES

Experiments are conducted on ECM equipment as in Figure 1 and based on Taguchi’s design of experiments.



Figure 1: ECM Machine

Electrolyte to be able to through the central hole of 2mm of the tool and into machining zones. Figure 3 shown experiment setup.

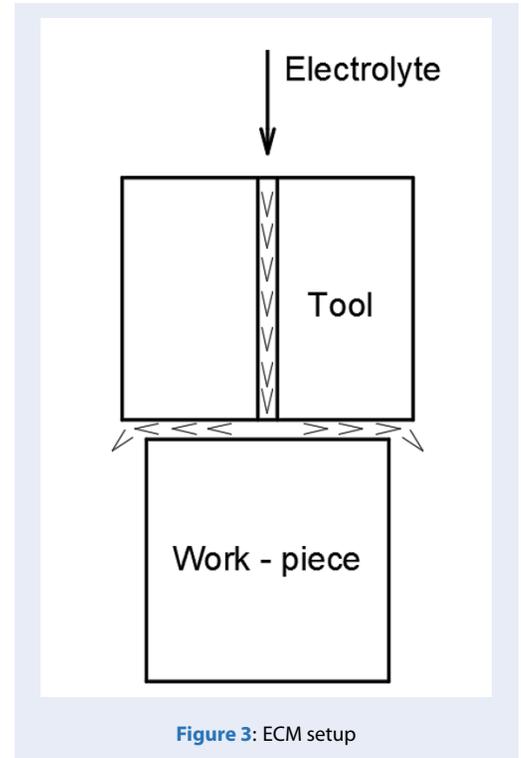


Figure 3: ECM setup

As above introduction tab, ECM setup in experiment consists of control panel, machining chamber, and electrolyte system. The work-piece is located in a safety box and to be fixed inside the chamber and a tool is attracted to the main crew which driven by a stepper motor. Applied voltage and feed rate which are controlled by control panel. And, Aluminum samples of 25 mm diameter x 25 mm height and 30mm diameter x 25mm height of the tool is made up of copper with a circular cross section with 2 mm internal hole. Figure 2 shown dimensions of a tool and work – piece.

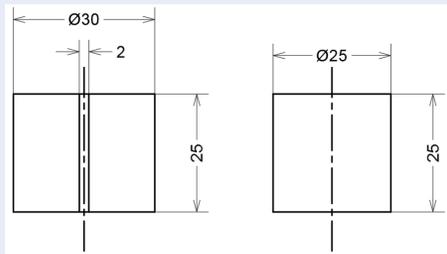
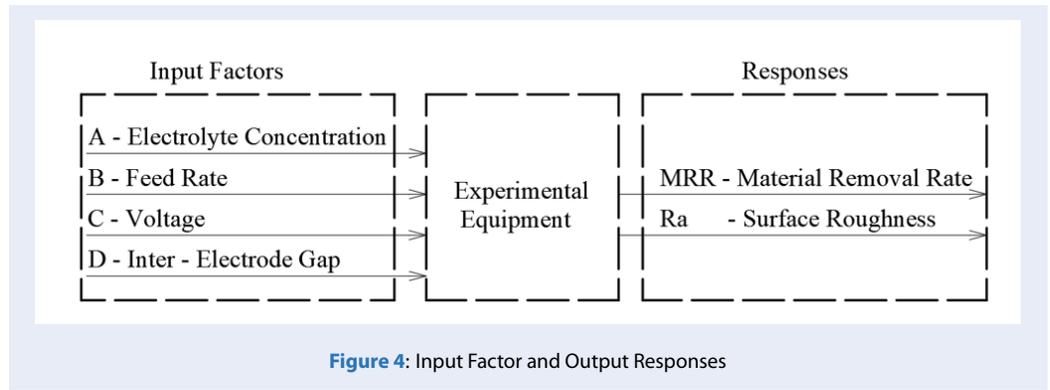


Figure 2: Dimensions of Tool and Work – Piece

Figure 4 is showed input factors and these responses. Based on Rebecca and Ivanov (2016)<sup>11</sup> NaCl solution is chosen as electrolyte, because it has no passivation effect on the surface of the job. Reference<sup>1</sup> electrolyte concentration is selected in the range of 80- 100g/lit. Because low voltages lead to low material removal rate and high surface roughness in electrochemical machining process<sup>9</sup>. Thus, applied voltage in ECM process it is possible to vary range of from 5 to 30 V and feed rate from 0.2 mm/min to 2 mm/min<sup>9</sup>. But, they depend on experiments conditions, applied voltage the range of 10-20V and the range of feed rate from 0.0375-0.0562mm. The smaller the inter- electrode gap, the smaller the applied potential has to be reach the machining potential as the ohmic drop caused by the electrolyte resistance is reduced<sup>11</sup>. Thus, IEGs are selected in the range of 0.5-1.5mm<sup>5,12</sup>.

Tables 1 and 2 are showed input levels of factors and these responses, L27 Taguchi Orthogonal Arrays.

MRR is measured from weight loss. And, surface roughness ( $R_a$ ) is measured with Mitutoyo SJ-210



**Table 1: Four input factors and their levels.**

Symbol	Level 1	Level 2	Level 3
A	80	90	100
B	0.0375	0.0468	0.0562
C	10	15	20
D	0.5	1	1.5

A: Electrolyte concentration (g/l); B: Feed rate (mm/min); C: Voltage (V); D: Inter - Electrode Gap (mm)

Surface Roughness (ISO 1997,  $\lambda = 0.8, \mu\text{m}$ ). The responses MRR calculated by following (3):

$$MRR = \frac{m_b - m_a}{t} \tag{3}$$

$m_a$ : mass of Work - piece before machining (gram)

$m_b$ : mass of Work - piece after machining (gram)

$t$ : machining time (min)

### 3. METHODOLOGYS

#### Regression analysis

Regression analysis is a statistical tool for estimating the relationships among variables. Regression analysis helps one understand how the typical value of the dependent variable changes when any one of the independent variables is varied. It is also used to understand which among the independent variables are related to the dependent variable and to explore the forms of these relationships<sup>11,13</sup>. The general form of a multiple regression model is as follows:

$$\begin{aligned} \text{Dependent variable} \\ = b_0 + b_1 + b_2 (\text{Independent variable 2}) \\ + b_3 (\text{Independent variable 3}) \end{aligned} \tag{4}$$

Where  $b_1, b_2, b_3, \dots$  are estimates of the independent variables 1, 2, 3, ... and  $\epsilon$  is the error.

#### Taguchi Method

One of the advantages of the Taguchi method is that it uses a special design of orthogonal arrays to study the scope of a research project or the entire parameter space with a small number of experiments<sup>11</sup>. From results, Taguchi method allows for the analysis of many different parameters without a prohibitively high amount of experimentation.

The S/N ratio for the Larger - to - better is given Taguchi as (5):

$$\frac{S}{N} = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^n y_i^2 \right] \tag{5}$$

Where:

$y$  - observed data.

$n$  - number of observations.

The S/N ratio for the Smaller - to - better is given Taguchi as (6):

$$\frac{S}{N} = -10 \log_{10} \left[ \sum_{i=1}^n \frac{y_i^2}{n} \right] \tag{6}$$

#### Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a potential technique used to study the significance of the all parameters and their interactions by comparing the mean square with an estimate of the experimental error at a specific confidence level<sup>5,9</sup>. In present paper, ANOVA is performed using Minitab 18. The relative influence of the parameters is measured by total sum of square value (SST) by following (7):

$$\frac{S}{N} = -10 \log_{10} \left[ \sum_{i=1}^n \frac{y_i^2}{n} \right] \tag{7}$$

Where  $n$  is the number of experiments in the orthogonal array,  $n_i$  is the mean S/N ratio for the  $i_{th}$  experiment and  $n_m$  is the total mean S/N ratio of all

**Table 2: 27 Taguchi Orthogonal Arrays**

A	B	C	D	MRR	Ra
1	1	1	1	1.552	4.428
1	2	2	1	1.454	5.604
1	3	3	1	1.371	4.17
2	1	2	2	1.425	4.768
2	2	3	2	1.336	4.885
2	3	1	2	1.543	4.236
3	1	3	3	1.314	6.275
3	2	1	3	1.563	6.222
3	3	2	3	1.435	6.494
3	1	1	3	1.544	4.248
3	2	2	3	1.472	6.523
3	3	3	3	1.322	6.543
1	1	2	1	1.416	4.848
1	2	3	1	1.365	6.807
1	3	1	1	1.523	5.28
2	1	3	2	1.346	6.838
2	2	1	2	1.551	4.434
2	3	2	2	1.42	4.534
2	1	1	2	1.561	5.737
2	2	2	2	1.428	4.967
2	3	3	2	1.396	5.305
3	1	2	3	1.429	6.836
3	2	3	3	1.314	5.032
3	3	1	3	1.525	4.728
1	1	3	1	1.324	6.34
1	2	1	1	1.596	5.939
1	3	2	1	1.427	6.682

MRR (g), Ra (μm)

experiments. The percentage contribution P can be calculated as:

$$P = \frac{SS_d}{SS_T} \tag{8}$$

Where,  $SS_d$  is the sum of squared deviations. Further, the Fisher’s  $F$ -ratio, the ratio between the regression mean square and the mean square error, is used to identify the most significant factor on the performance characteristic.

The  $P$ -value reports the significance level (suitable and unsuitable). Percent (%) represents the significance

rate of the machining parameters on the response.

## RESULTS ANALYSIS AND DISCUSSION

### Effects on MRR

From experiment results, the machinability of ECM depends on electrolyte concentration, feed rate, voltage and IEG. The influence of various machining parameters on MRR is shown in Figure 5. The Inter-Electrode Gap between tool and work - piece has ex-

tremely effect on MRR and it increases with decreases in IEG. And then voltage, and then feed rate, and then feed rate. And, regression models for MRR are decried by (9):

$$MRR=1.6562+0.00039A-0.00611B+0.00283C \\ 0.10389D \quad (9)$$

In Table 3, ANOVA of MRR is presented with all the terms. After eliminating interaction of process parameter like B\*C, B\*D, and C\*D. It can be proving that electrolyte concentration NaCl, feed rate, voltage, and Inter-Electrode Gap effects on MRR by 0.039%, 0.4%, 0.75% and 93.56%, respectively.

In Table 4 showed the optimal machining performance for the Electrolyte concentration level 100g/l (level 3), Feed rate 0.0375mm/min (level 1), Voltage 15V (level 2), IEG 0.5mm (level 1). In which there IEG is important and then voltage, and then feed rate and then electrolyte concentration.

The estimated model coefficients for SN ratios are shown in Table 5. Parameter results are standard deviation of error  $S = 0.0682$ , amount of variation  $R^2 = 99.63\%$  and  $R^2(\text{adj.}) = 98.40\%$ . And comparing the P value is less than or equal to 0.05 it can be concluded that the effect is significant, otherwise is not significant.

The residual plots of MRR is showed in Figure 6.

The residual plot in the graph for normal probability plot indicate the data are normally distributed and variables are influencing the response. Standardized residues are between 0.08 and 0.08.

The residuals versus fitted value indicate the variation is constant.

The histogram proved the data are not normally distributed it may be due to the fact that the number of points are very less.

Residual versus order of the data indicates that there are systematic effects in the data due to data collection order.

### Effects on Ra

From experiment results, the machinability of ECM depends on electrolyte concentration, feed rate, voltage and IEG. The influence of various machining parameters on the surface roughness ( $R_a$ ) is shown in Figure 7. The Inter-Electrode Gap between tool and work - piece has extremely effect on  $R_a$  and it increases with decreases in IEG. And then voltage, and then feed rate, and then feed rate. And, regression models for Ra are decried by (10):

$$Ra = 4.437+0.417A+0.39511B+0.084C-0.303D \quad (10)$$

In Table 6, ANOVA of Ra is presented with all the terms. After eliminating interaction of process parameter like B\*C, B\*D, and C\*D. It can be proving that

electrolyte concentration NaCl, feed rate, voltage, and Inter-Electrode Gap effect the Surface Roughness by 0.15%, 16%, 0.42% and 39.31%, respectively.

In Table 7 showed the optimal machining performance for the Electrolyte concentration level 80g/l (level 1), Feed rate 0.0468mm/min (level 2), Voltage 10V (level 1), IEG 0.5mm (level 1). In which there IEG is important and then feed rate, and then voltage and then electrolyte concentration.

The estimated model coefficients for SN ratios are shown in Table 8. Parameter results are standard deviation of error  $S = 0.4297$ , amount of variation  $R^2 = 94.02\%$  and  $R^2(\text{adj.}) = 74.11\%$ . And comparing the P value is less than or equal to 0.05 it can be concluded that the effect is significant, otherwise is not significant.

The residual plots of MRR is showed in Figure 8. The residual plot in the graph for normal probability plot indicate the data are normally distributed and variables are influencing the response.

The residuals versus fitted value indicate the variation is constant.

The histogram proved the data are not normally distributed it may be due to the fact that the number of points are very less.

Residual versus order of the data indicates that there are systematic effects in the data due to data collection order.

## CONCLUSIONS

In the present study, four factors are considered electrolyte concentration, feed rate, voltage and Inter-Electrode Gap . Aluminium as a Work - piece and 27 experiments conducted to obtain an optimum level in achieving high material removal rate and minimum surface roughness. And, to determine effect levels on two outputs.

The IEG between tool and workpiece has extremely effect on MRR and it increase with diseases in Inter-Electrode Gap. And then voltage, and then Feed rate, and then electrolyte concentration.

Among the four process parameters, The IEG between tool and workpiece influences highly on surface roughness and it diseases with diseases in Inter-Electrode Gap. Followed by feed rate, and then electrolyte concentration, and then voltage

Form results:

1. Maximum MRR at Electrolyte concentration level 100g/l (level 3), Feed rate 0.0375mm/min (level 1), Voltage 15V (level 2), IEG 0.5mm (level 1).

**Table 3: Analysis of Variance for SN ratios of MRR**

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.00297	0.00297	0.00149	0.32	0.738
	2	0.03061	0.03061	0.01531	3.29	0.108
C	2	0.05664	0.05664	0.02832	6.09	0.036
D	2	7.05368	7.05368	3.52684	758.55	0
Error	18	0.39517	0.39517	0.09647		
Total	26	7.53908				

**Table 4: Taguchi analysis response for MRR: Large is better**

Level	A	B	C	D
1	3.173	3.197*	3.116	3.811*
2	3.153	3.184	3.227*	3.130
3	3.176*	3.120	3.158	2.560
Delta	0.024	0.077	0.111	1.250
Rank	4	3	2	1

**Table 5: Estimated model coefficients for SN ratios of MRR**

Term	Coef	SE Coef	T	P
Constant	3.16724	0.01312	241.358	0.000
Electrol 2	-0.01473	0.01856	-0.794	0.057
Feed Rat 1	0.02995	0.01856	1.614	0.058
Voltage 2	0.06018	0.01856	3.243	0.018
Inter 1	0.64361	0.01856	34.681	0.000

S = 0.0682 R-Sq = 99.63% R-Sq(adj) = 98.40%

**Table 6: Analysis of Variance for SN ratios of  $R_a$**

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.0282	0.02818	0.01409	0.08	0.927
	2	2.9649	2.96495	1.48247	8.03	0.02
C	2	0.0771	0.07706	0.03853	0.21	0.817
D	2	7.2898	7.28977	3.64488	19.74	0.002
Error	6	8.1822	8.1822	1.9532		
Total	26	18.5422				

A: Electrolyte concentration (g/l); B: Feed rate (mm/min); C: Voltage (V); D: Inter – Electrode Gap (mm)

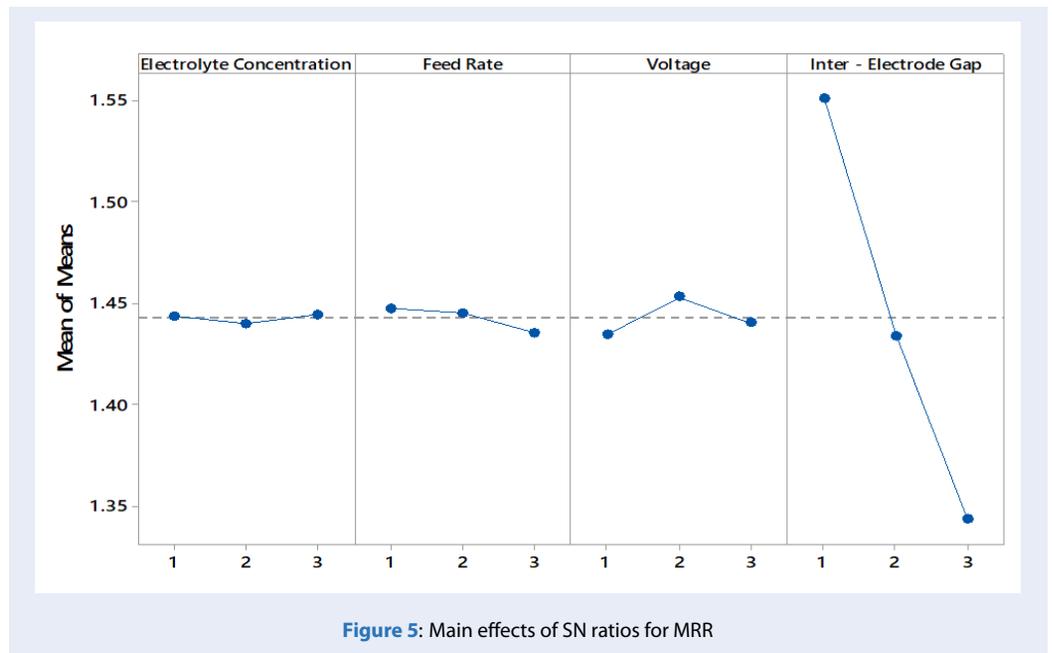


Figure 5: Main effects of SN ratios for MRR

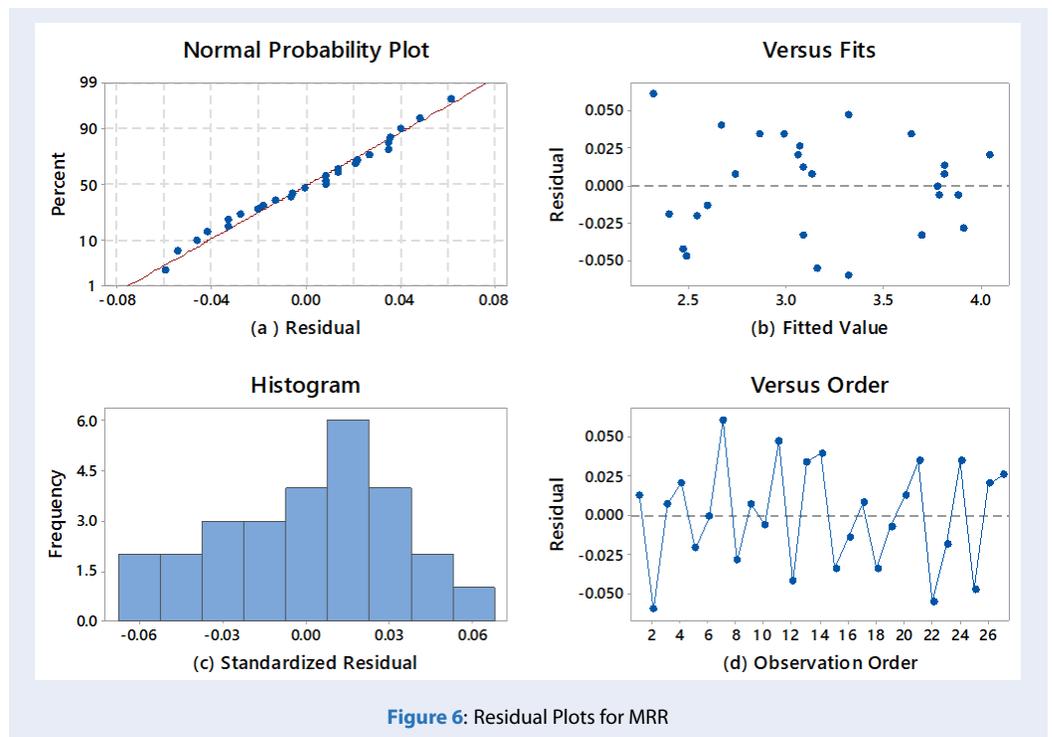
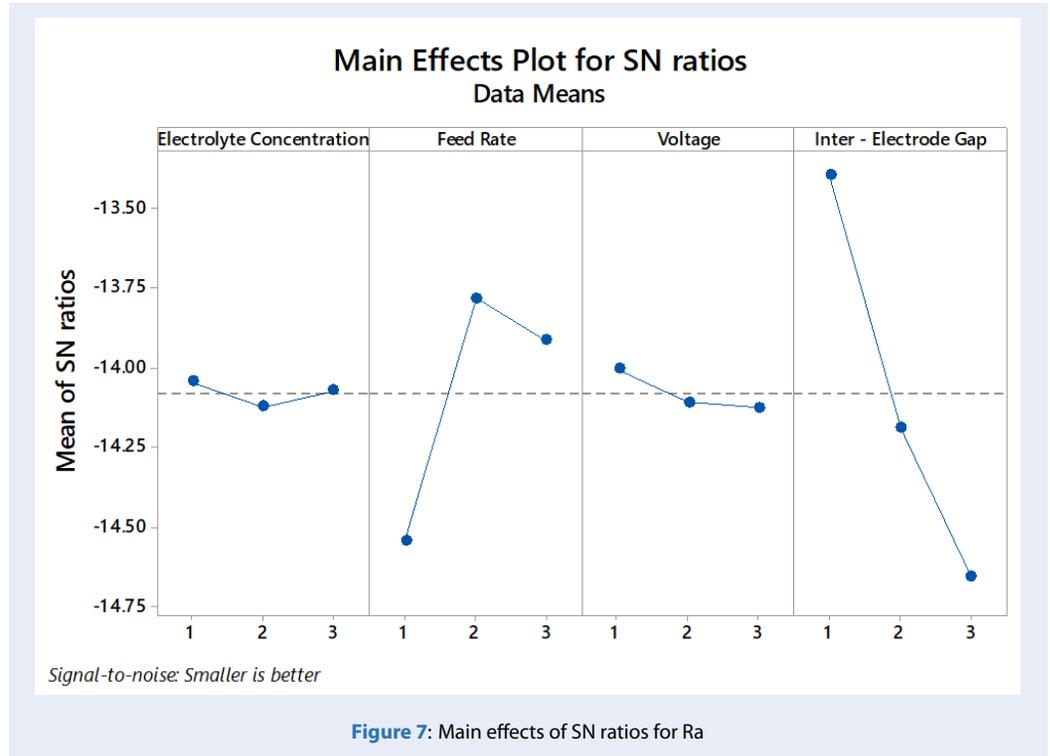


Figure 6: Residual Plots for MRR



**Table 7: Taguchi analysis response for  $R_a$ : Smaller is better**

Level	A	B	C	D
1	-14.05*	-14.54	-14.01*	-13.40*
2	-14.12	-13.78*	-14.11	-14.19
3	-14.07	-13.92	-14.13	-14.66
Delta	0.08	0.76	0.12	1.26
Rank	4	2	3	1

A: Electrolyte concentration (g/l); B: Feed rate (mm/min); C: Voltage (V); D: Inter – Electrode Gap (mm)

**Table 8: Estimated model coefficients for SN ratios of  $R_a$**

Term	Coef	SE Coef	T	
Constant	-14.081	0.0827	-170.269	0
A (1)	0.035	0.11695	0.299	0.775
B(2)	0.2981	0.11695	2.549	0.044
C(1)	0.0749	0.11695	0.641	0.545
D(1)	0.6843	0.11695	5.851	0.001

S = 0.4297; R2 = 94.02% and R2(adj.) = 74.11%.

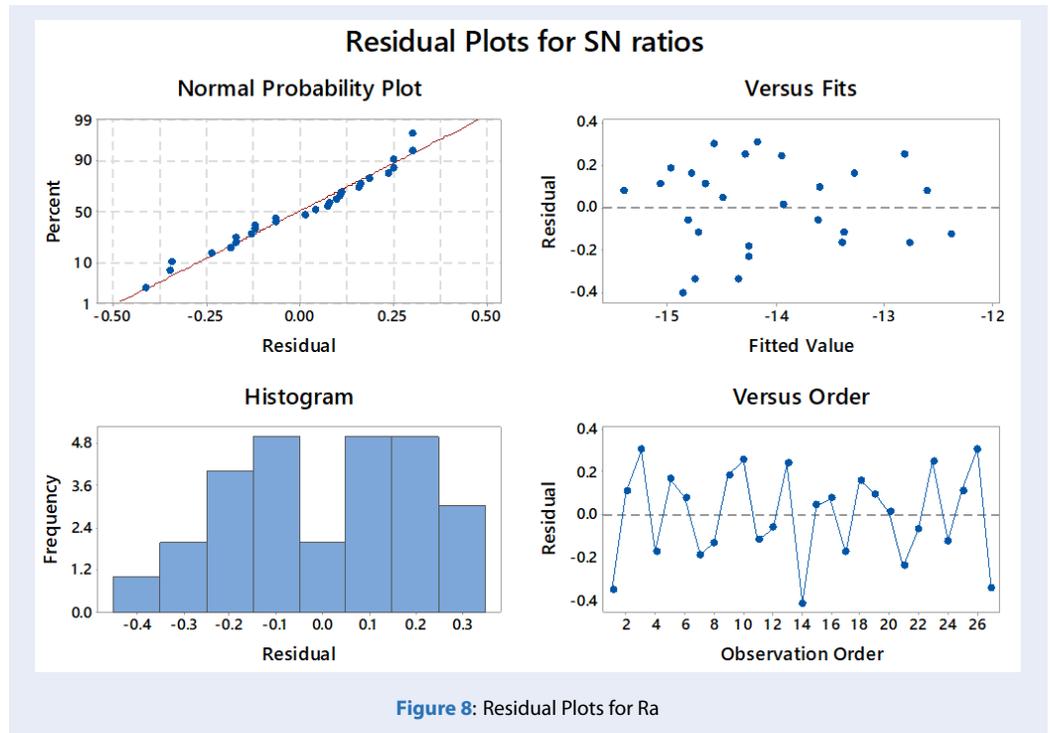


Figure 8: Residual Plots for Ra

2. Minimum  $R_a$  at the Electrolyte concentration level 80g/l (level 1), Feed rate 0.0468mm/min (level 2), Voltage 10V (level 1), IEG 0.5mm (level 1).

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## ABBREVIATIONS

NTMPs: Non – Traditional Manufacturing

ECM: Electrochemical Machining

S/N: Signal-To-Noise

ANOVA: The Analysis of Variance

EDM: Electrical Discharge Machining

MRR: Material Removal Rate

IEG: Inter – Electrode Gap

$R_a$ : Surface Roughness

ROC: Radial overcut

## CONFLICT OF INTEREST

The authors hereby warrant that this paper is no conflict of interest with any publication.

## AUTHOR’S CONTRIBUTION

Ms. Nguyen Thi Bich Nhung played a role as an executor, collected the experimental data, analyzed the

statistic and

wrote the paper.

Dr. Dao Thanh Liem contributed for writing orient paper.

Dr. Truong Quoc Thanh played a role as a corresponding author.

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# Ảnh hưởng thông số công nghệ trong gia công điện hóa đến chất lượng bề mặt

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## TÓM TẮT

Dựa vào những nghiên cứu liên quan đến lĩnh vực gia công điện hóa từ các nghiên cứu trên thế giới. Nhóm tác giả lựa chọn nghiên cứu ảnh hưởng của những thông số công nghệ quá trình gia công điện hoá (ECM) là nội dung chính của bài báo, những thông số công nghệ được đưa vào nghiên cứu đó là nồng độ chất điện phân, hiệu điện thế giữa hai điện cực, tốc độ tiến dụng cụ và khe hở giữa hai điện cực. Dụng cụ điện cực sử dụng là đồng có kích thước  $\Phi 30$  mm x 25 mm, đường kính lỗ 2 mm và vật liệu phôi sử dụng là đồng. Nhôm tròn có kích thước  $\Phi 25$  mm x 25 mm. Thiết kế thực nghiệm dựa vào phương pháp Taguchi. Các bước bao gồm phân tích tỉ số nhiều, phân tích ANOVA và phân tích hồi quy được áp dụng để xác định những mức độ tối ưu và nghiên cứu ảnh hưởng các thông số gia công lên chất lượng bề mặt. Cuối cùng các thực nghiệm đã được sử dụng để so sánh mức độ tối ưu của thí nghiệm thực tế và dựa vào phần mềm Taguchi. Kết quả thực nghiệm cho thấy khe hở giữa hai điện cực là thông số ảnh hưởng lớn nhất đến tốc độ ăn mòn vật liệu, và đồng thời đó cũng là thông số ảnh hưởng mạnh đến độ nhám bề mặt. Với nồng độ chất điện phân 100 gam/lít, Tốc độ tiến dụng cụ là 0,0375 mm/phút, hiệu điện thế giữa dụng cụ và phôi là 15 Vol, Khe hở giữa hai điện cực là 0,5 mm thì tốc độ ăn mòn vật liệu đạt tối ưu. Độ nhám bề mặt nhỏ nhất tại nồng độ chất điện phân 80 gam/lít, tốc độ tiến dụng cụ 0.0468 mm/phút, hiệu điện thế 10 vol, và khe hở giữa hai điện cực là 0.5 mm. Từ đó có thể kết luận việc tối ưu các thông số công nghệ của quá trình gia công điện hóa là điều kiện tiên quyết nâng cao năng suất cũng như chất lượng bề mặt của sản phẩm.

**Từ khoá:** Gia công điện hóa, phương pháp Taguchi, Phân tích ANOVA, Chất lượng bề mặt

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