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Effect of the hollow electrode on the material removal rate of titanium alloy (grade 1) in the electrochemical machining (ECM) process

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Abstract. This study examined the material removal rate (MRR) affected by the variables of the electrochemical process including electrode type, voltage, electrolyte type, electrolyte concentration, and gap. Titanium alloy was employed as the workpiece, while copper was utilized as the cylindrical electrode. The input parameters were established according to Taguchi's methodology. An analysis of variance (ANOVA) using a linear regression model was dependent on making sense of the experiment's findings. the solid electrode achieved the maximum material removal rate (MRR) value (0.0857) g/min, while the hollow electrode with (1500 l/hour) flow rate achieved the minimum material removal rate (MRR) value (0.00002) g/min. the material removal rate (MRR) was directly proportional to the voltage. Maximum material removal rate (MRR) occurred at a concentration of (75 g/l) for the (NH_4C) electrolyte, while minimum material removal rate (MRR) occurred at a concentration of (50 g/l) for the (NH_4Cl) electrolyte. It has been observed that the contributing factors in controlling material removal rate (MRR) were as follows; (66.67%) for the voltage, (5.89%) for the electrode, (5.72%) for the electrolyte concentration, (3.24%) for the type of electrolyte, and (3.07%) for the gap.

1 Introduction

One of the most well-known alternative production techniques is electrochemical machining (ECM). Between a cathode tool and an anode workpiece, an electrolyte solution conducts electricity [1][2]. Sparks will emerge due to low working temperature and must be avoided to prevent the tool wear rate [3] [4]. Since there is no physical contact between the tool and the workpiece material, neither mechanical nor thermal stresses will be created. The theory of anodic dissolution, upon which electrochemical machining (ECM) is based, was developed by Michael Faraday (1791-1867) in the nineteenth century. The aerospace, medical, automotive, gas turbine, electrical, and petroleum industries are only some of the commercial sectors that make use of the process [2] [5]. Defects like pitting and low surface roughness are often seen in the ECM of titanium alloy. Moreover, it is simple to create a passivation film during ECM [6] [8].

Milan Kumar, et al (2014), The effect of voltage, gap, electrolyte concentration rate, and tool feed rate on the material removal rate(MRR) was studied. AISI 202 was used as the workpiece and EN31 tool steel as the electrode. Through ANOVA analysis, it was concluded that the electrolyte concentration is the most effective factor in the material removal rate (MRR) [1]. Noor Abd Al-Hassan, et al (2016), The material removal rate (MRR) and the effects of current, electrolyte content, and gap size were investigated. The workpiece was constructed of stainless steel 316L, while the electrode was composed of copper. The conclusion is that The material removal rate (MRR) improves when the parameters (current, electrolyte concentration rate, and gap) are increased. [12]. Heba Saad Qasim, et al (2019) studied the effect of current, voltage, and concentration of electrolyte on the material removal rate (MRR) was studied. The workpiece that was used in the experiments was stainless steel 316 H, while the electrode was composed of copper. The paper focused on the effect of changing the electrolyte on the material removal rate (MRR). It was concluded that the use of (Na_2SO_4) as an electrolyte gives a higher material removal rate (MRR) than the use of (NaCl) as an electrolyte under similar conditions [7]. A. Parthiban, et al (2019), The researcher studied the impacts of voltage, gap, and concentration of electrolytes on the metal removal rate. In addition, three different compositions of substance (SiC) were used with different proportions and particle sizes. It was concluded that changing the composition of the material in terms of the proportion of materials and particle size is the most effective factor in the material removal rate (MRR) [10]. Bhiksha Gugulothu, et al (2021), experiment was done on Al5086/Flyash/Sic hybrid metal matrix composites workpiece to find out the effect of voltage, tool feed rate, and electrolyte concentration on the material removal rate (MRR). It was concluded that the feed rate of the tool is the most influencing factor on the metal removal rate (MRR) and the applied voltage is the least influencing factor[11]. In the past, various researchers have attempted process parameter optimization in ECM. M.V.A. Ramakrishna, et al (2021),

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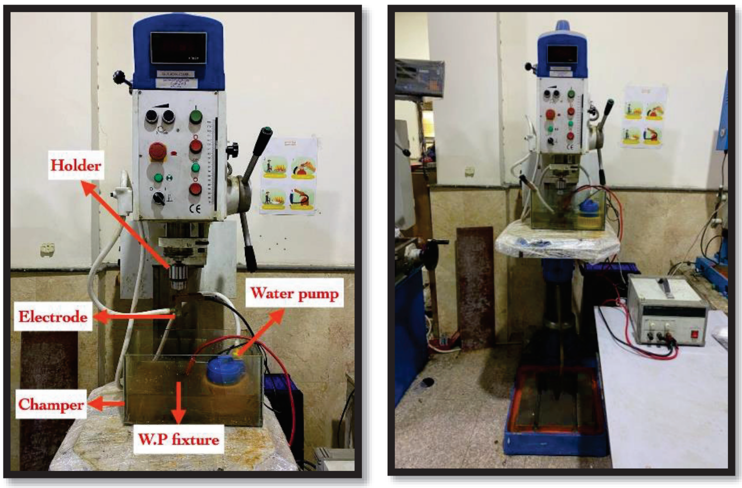
The effect of voltage, gap, tool feed rate, and electrolyte flow rate on metal removal rate was investigated. It was found that the most influencing factor on the metal removal rate is the voltage and feed rate. The workpiece used was (Al 5086 Alloy) and the copper was the electrode. The rate of metal removal increases with a linear increase with the increase in the applied voltage and increases with a non-linear increase with the increase in the tool feed rate [9].

Previous studies have included several researchers who have assessed the material removal rate (MRR) of various materials using diverse data. Several individuals used several electrodes composed of diverse materials to quantify the material removal rate (MRR) of distinct workpieces. As of now, no research has been conducted to examine the impact of hollow electrodes with different flow rates on the material removal rate (MRR) of titanium alloy during the ECM process. The originality in this study stems from the use of a hollow electrode with different flow rates in the electrochemical operation process. The use of titanium alloy in this study is also considered part of the originality of the research.

This work aims to examine the possibility of operating titanium alloys, which are considered to be materials that have weak electrical conductivity, on electrochemical machining using three different electrodes, and then Study the influence of five machining variables (electrode, voltage, type of electrolyte, concentration of electrolyte, and the gap) on the material removal rate (MRR) in the electrochemical machining (ECM) of titanium workpiece with the copper electrodes and finding the best results.



(a) ECM components.

(b) ECM machine.

Fig. 1. Electrochemical machines component

2 Experimental Work

2.1 Workpiece

Figure (2) displays a workpiece made of titanium alloy (grade 1) with dimensions of 500 × 350 × 20 mm and a thickness of 2 mm. The WJM method was used to divide it into 27 pieces, each measuring (20 × 20) mm. The chemical composition of the titanium alloy is presented in Table (1) as percentages. The table (2) presents the mechanical and physical characteristics of a titanium alloy plate (Grade 1). The mechanical and physical properties of the electrode and the workpiece were obtained through tests conducted at the Ministry of Science and Technology, Iraq, Baghdad.

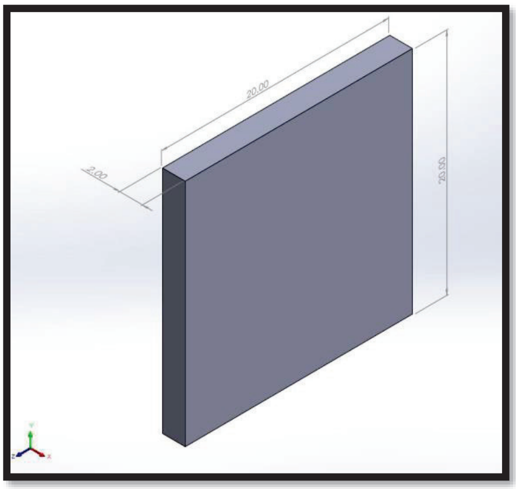


Fig. 2. Workpiece before cutting.

Table 1. Titanium alloy (grade 1) chemical composition.

Elements	Ti %	Fe %	C %	N %	H%	O %
Results	99.64	0.18	0.08	0.03	0.01	0.06

Table 2. The mechanical and physical properties of titanium alloy plate (Grade 1).

NO.	Property	value	NO.	Property	Value
1	Hardness (HRC)	65	5	Thermal conductivity (w/m.k)	21
2	Yield strength (MPa)	182	6	Electric resistivity (Ω.m)	41.7
3	Tensile strength (MPa)	539	7	Density (g/cm^3)	4.51
4	Elongation (%)	25	8	Melting point (℃)	1668±4

2.2 Tool

The experiment utilized three copper electrodes, a solid electrode, a hollow electrode (H1) with a flow rate of 1000 l/hour, and a hollow electrode (H2) with a flow rate of 1500 l/hour. A solid electrode with a diameter of 16mm and a length of 150mm was created shown in figure (3). The hollow electrode was fabricated with a 16 mm outer diameter, 8 mm inner diameter, and 150 mm length, as depicted in Figure (4).

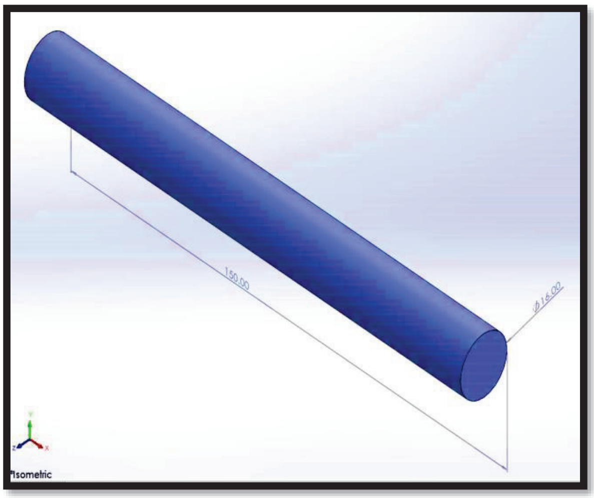


Fig. 3. Solid electrode copper.

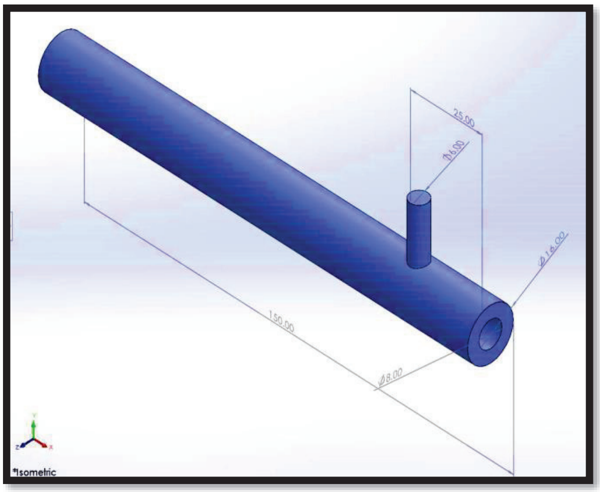


Fig. 4. Hollow electrode copper.

3 Design Of Experiments

The Taguchi technique is one of the most important tools used to study engineering analysis. To get to the data and do the process, the information must first be assembled logically. The focus is on its benefits since this technique saves time, cost, and effort when it comes to experimenting. With the help of the quality loss function hierarchy and Taguchi's techniques, great organizational designs can be made. Taguchi's technique was used with the statistical analysis software Minitab 20. For this purpose, table (5-1) shows the ECM variables with five factors and three levels and the results of material removal rate (MRR). In this work, the experiments were done with the L27 orthogonal array (OA). Analysis of the variance (ANOVA) was used to find out how the most important levels 1,2, and 3 variables affect the performance variable.

Table 3. Experimental impact of the variables on MRR that was designed in the Taguchi technique.

NO. of EXP.	Electrode	Voltage (V)	Electrolyte Type	Electrolyte weight (g)	Gap (mm)
1	S	10	NaCl	25	0.1
2	S	10	NaCl	25	0.3
3	S	10	NaCl	25	0.5
4	S	20	KCl	50	0.1
5	S	20	KCl	50	0.3
6	S	20	KCl	50	0.5
7	S	30	NH_4Cl	75	0.1
8	S	30	NH_4Cl	75	0.3
9	S	30	NH_4Cl	75	0.5
10	H1	10	KCl	75	0.5
11	H1	10	KCl	75	0.1
12	H1	10	KCl	75	0.3
13	H1	20	NH_4Cl	25	0.5
14	H1	20	NH_4Cl	25	0.1
15	H1	20	NH_4Cl	25	0.3
16	H1	30	NaCl	50	0.5
17	H1	30	NaCl	50	0.1
18	H1	30	NaCl	50	0.3
19	H2	10	NH_4Cl	50	0.3
20	H2	10	NH_4Cl	50	0.5
21	H2	10	NH_4Cl	50	0.1
22	H2	20	NaCl	75	0.3
23	H2	20	NaCl	75	0.5
24	H2	20	NaCl	75	0.1
25	H2	30	KCl	25	0.3
26	H2	30	KCl	25	0.5
27	H2	30	KCl	25	0.1

4 Result And Discussion

As shown in Table (3), five variables were used in this investigation at three levels: the concentration of electrolyte (25, 50, and 75 g/l), the type of electrolyte (NaCl, KCl, and NH_4Cl), the gap (0.1, 0.2, and 0.3)mm, and the electrodes (solid electrode, hollow electrode (H1) with flow rate 1000 l/hour, and hollow electrode (H2) with flow rate 1500 l/hour). The variables displayed in Table (3) were created using the Taguchi Technique. Table (4) displays the experimental and predicted results for a titanium alloy (grade 1) workpiece under the given conditions. Software called Minitab 20 was utilized for the MRR analysis. To evaluate the precision of the previously mentioned equations, The equations (1) were utilized to determine the predicted values of MRR. The developed model has demonstrated satisfactory prediction accuracy. As well as Figures (5) display the comparison between the observed and predicted.

Table 4. Input variables and their levels.

NO.	Variables	Units	Level 1	Level 2	Level 3
1	Electrode	_	S	H1	H2

2	Voltage	V	10	20	30
3	Concentration	g/l	25	50	75
4	Electrolyte type	_	NaCl	KCl	NH_4Cl
5	Gap	mm	0.1	0.3	0.5

Table 5. Experimental and predicted impact of the variables on MRR that was designed in the Taguchi technique.

NO.	Electrode	Voltage (V)	Electrolyte Type	Electrolyte weight(g/l)	Gap (mm)	EXP. MRR (g/min)	Pred. MRR (g/min)
1	S	10	NaCl	25	0.1	0.00004	0.0032
2	S	10	NaCl	25	0.3	0.00003	0.0012
3	S	10	NaCl	25	0.5	0.000023	0.0018
4	S	20	KCl	50	0.1	0.01264	0.0131
5	S	20	KCl	50	0.3	0.009	0.0086
6	S	20	KCl	50	0.5	0.0083	0.0081
7	S	30	NH_4Cl	75	0.1	0.0857	0.0599
8	S	30	NH_4Cl	75	0.3	0.0546	0.0554
9	S	30	NH_4Cl	75	0.5	0.03	0.0549
10	H1	10	KCl	75	0.5	0.000027	0.0032
11	H1	10	KCl	75	0.1	0.00003	0.0012
12	H1	10-	KCl	75	0.3	0.000021	0.0018
13	H1	20	NH_4Cl	25	0.5	0.0055	0.0072
14	H1	20	NH_4Cl	25	0.1	0.0043	0.0027
15	H1	20	NH_4Cl	25	0.3	0.00223	0.0021
16	H1	30	NaCl	50	0.5	0.0449	0.0408
17	H1	30	NaCl	50	0.1	0.0348	0.0363
18	H1	30	NaCl	50	0.3	0.0331	0.0357
19	H2	10	NH_4Cl	50	0.3	0.000013	0.0032
20	H2	10	NH_4Cl	50	0.5	0.00002	0.0012
21	H2	10	NH_4Cl	50	0.1	0.000066	0.0018
22	H2	20	NaCl	75	0.3	0.0086	0.0103
23	H2	20	NaCl	75	0.5	0.00346	0.0058
24	H2	20	NaCl	75	0.1	0.0092	0.0052
25	H2	30	KCl	25	0.3	0.01	0.0263
26	H2	30	KCl	25	0.5	0.0207	0.0218
27	H2	30	KCl	25	0.1	0.03866	0.0212

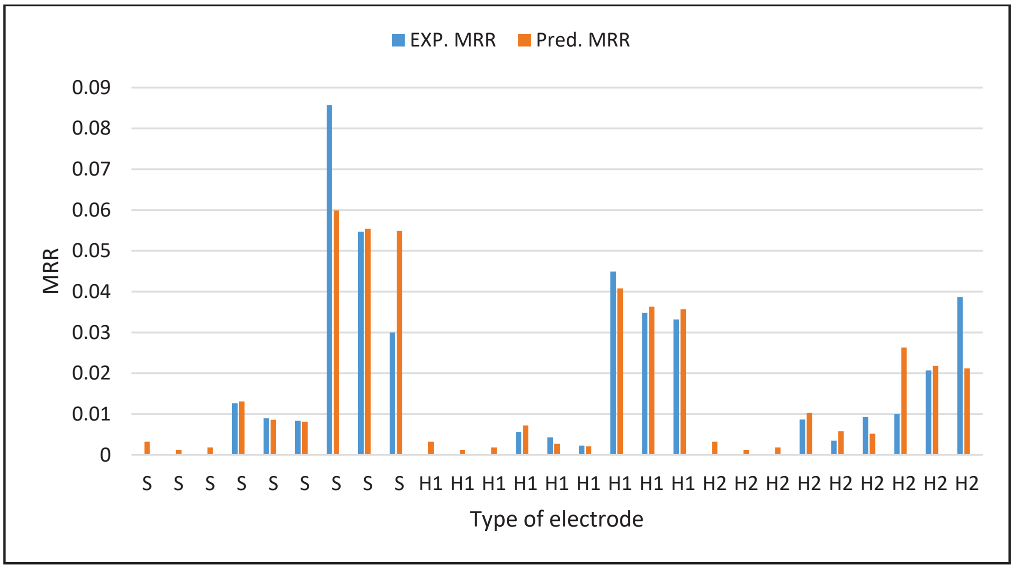


Fig. 5. Experimental and Predicted values of MRR for ECM process.

5 Measurement Of Material Removal Rate (Mrr)

The material removal rate (MRR) can be described as the ratio of the change in weight of the machined item before and after machining to the material and machining time. The weight of the workpiece was determined using a high-accuracy weight balance that has a range of (0.01-220) g and the accuracy of this device is (±0.0003) as shown in Figure 6. Equation 1 shows the calculation of the (MRR).

MRR = (wb-wa)/MT (g/min) …… (1)
MRR = material removal rate.
Wb = weight of the workpiece before machining (g).
Wa = weight of the workpiece after machining (g).
MT =machining time (min).

Fig. 6. Balance device.

6 The Effect Of Machining Parameters On Material Removal Rate (Mrr):

The results of surface roughness at different electrodes, voltage, the weight of electrolyte, type of electrolyte, and gap values are given in Table (4).

Figure (6), the material removal rate (MRR) in a solid electrode rises between (0.00002 -0.0857) g/min, with a mean MRR of (0.02227) g/min. Additionally, the MRR increases (0.00002-0.0449) g/min with the mean of MRR (0.0138) g/min in a hollow electrode with a flow rate of 1000 l/hour. Additionally, the MRR increases (0.00001-0.0386) g/min with the mean of MRR (0.01) g/min in a hollow electrode with a flow rate of 1500 l/hour. It can be explained that increasing the flow rate may lead to a turbulent flow of electrolytes and may cause damage to the (MRR).

Also, it can be seen that the voltage is directly proportional to (MRR). Regarding the electrolyte, the material removal rate increase occurred with ammonia chloride compared to sodium chloride and potassium chloride. Also, the increase in electrolyte concentration (25-75) g/l leads to a rise in the material removal rate (MRR). This can be explained because ammonia chloride achieves the maximum dissolution rate for the workpiece, and the increase in electrolyte concentration leads to faster chip removal due to increased electrical conductivity.

As shown in Figure (6), the gap is inversely proportional to the MRR, as the MRR decreases as the gap increases from (0.1-0.5) mm.

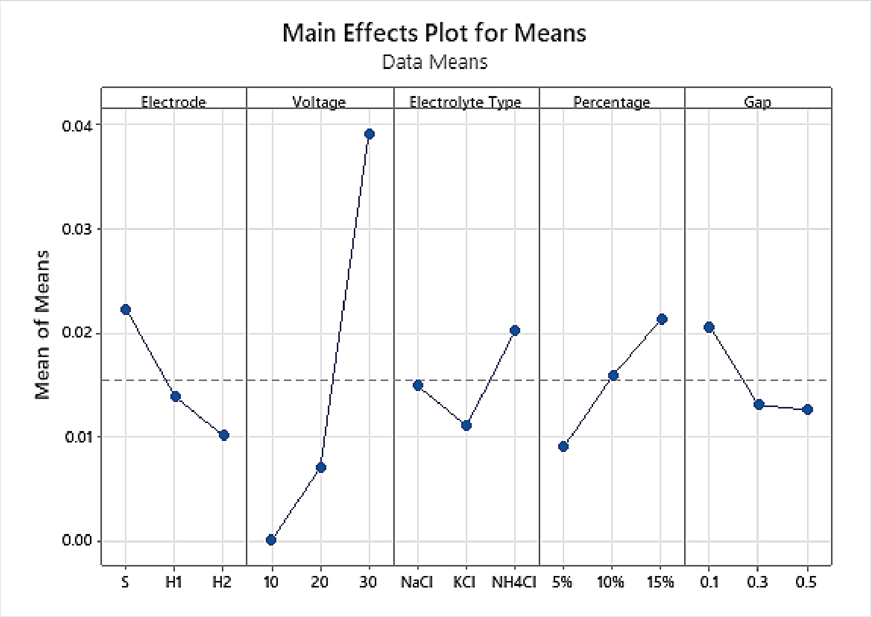


Fig. 7. Main effects plot for material removal rate (MRR).

7 Analysis Of Variance (Anova)

The analysis of variance (ANOVA) results are shown in Table (5) along with the sources of the variation, degree of freedom (DF), total sum of the squares (Adj SS), average square (Adj MS), F-value, which shows which variables contribute to the output, P-values that are below 0.05, which are considered to be significant, and P-values that are more than 0.05, which are not important. The material removal rate was the subject of an analysis of variance (ANOVA), which took into consideration the details listed in the table.

Table 6. ANOVA table for MRR for machining variables.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Electrode	2	0.000699	0.000349	2.86	0.087
Voltage	2	0.007844	0.003922	32.08	0.000
Electrolyte type	2	0.000388	0.000194	1.59	0.235
Weight of electrolyte	2	0.000679	0.000339	2.78	0.092
Gap	2	0.000140	0.000070	0.57	0.576
Error	16	0.001956	0.000122		
Total	26	0.011704			

8 Regression Model

Coefficients were employed to build the mathematical model, and then regression equations for process variables were used to create a mathematical connection between the input variables and material removal rate to correlate MRR. This enabled us to assess the Surface Roughness Model's level of regression. This was done to evaluate the level of regression in the material removal rate Model. According to the equations for regression, equation (1) presents the regression formula of MRR of process parameters.

$$MRR= 03.601+0.498\,S-0.754\,H1+0.256\,H2 - 2.970\,V10+1.129\,V20 + 1.840\,V30 - 0.168\,NaCl-0.172\,KCl+0.340\,NH_4Cl-0.286\,W25-0.603\,W50 +0.889\,W75-0.081\,G0.1+0.107\,G0.3-0.026\,G0.5 \quad ... (1)$$

9 Model Summary

The statistics that compare the different models in terms of how well they fit the data are shown in the model summary that shows in Table (6). The R-Square (R-Sq) value is the amount of variation in the observed outputs that can be assigned to the model. An R-square that has been altered to take into account the number of terms in the model is referred to as "adjusted R-square" (R-Sq (adj)). The ability of the model to predict brand-new data is shown by the R-square that was predicted, also known as R-sq (pred). R-square (R-sq) and adjusted R-square (R-sq (adj)) values that are higher than those that are lower indicate a better match. The table gives information on the models for material removal rate.

Table 7. Definition of model MRR.

S	R-sq	R-sq(adj)	R-sq(pred)
0.0110566	83.29%	72.84%	52.41%

10 Conclusion

This study investigated the impact of material removal rate (MRR) on various input variables of the electrochemical process, such as electrode type, voltage, electrolyte type, electrolyte concentration, and gap. The workpiece in this process was made of titanium alloy, while copper was used as the electrode. The input parameters were determined based on Taguchi's methodology. The experiment's findings were interpreted using both analysis of variance (ANOVA) and a linear regression model. Decisions can be made based on the aforementioned experimental findings that have been evaluated.

1- The maximum value of the material removal rate is (0.0857) g/min, while the minimum material removal rate value was (0.00002) g/min.
2- The maximum material removal rate (MRR) value was obtained when using a solid electrode and the minimum material removal rate (MRR) value was obtained when using a hollow electrode (H2) with a flow ratio of 1500 l/hour.
3- Increasing the voltage leads to an increase in material removal rate (MRR).
4- Maximum material removal rate (MRR) occurs at a (75) g/l concentration of (NH_4Cl) electrolyte, and minimal surface roughness is achieved at a (50) g/l concentration of (NH_4Cl) electrolyte.
5- It has been observed that voltage is the most effective or contributing factor in controlling MRR, with a percentage contribution of (66.67%). While the electrode (having a percentage contribution of 5.89%), the type of electrolyte (having a percentage contribution of 3.24%), and the electrolyte concentration (having a percentage contribution of 5.72%). While the gap has a minimum percentage contribution of 3.07%

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