The Effect of Voltage on Material Removal Rate in the ECM Process

Nagham Ghanim Ghazi
Construction and Projects Department, University of Technology, Baghdad, Iraq
nagham.g.ghazi@uotechnology.edu.iq (corresponding author)

Shukry Hammed Aghdeab
Nanotechnology and Advanced Materials Research Center, University of Technology, Baghdad, Iraq
shukry.h.aghdeab@uotechnology.edu.iq

Asmaa Omar Basheer
Construction and Projects Department, University of Technology, Baghdad, Iraq
asmaa.o.basheer@uotechnology.edu.iq

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ABSTRACT

The development of machining processes, such as Electrochemical Machining (ECM), has improved manufacturing complex shapes and complicated materials. This research investigates the enhancement of the ECM process to achieve the highest quality of materials. Specifically, Material Removal Rate (MRR) is utilized as a performance parameter to reduce machining time and increase productivity without influencing product quality. This is accomplished through machining a workpiece made of high-speed steel AISI M2, using a copper tool in a sodium chloride (NaCl) solution. Optimal voltage parameters are determined to address issues, such as surface defects, power consumption, and process instability. The primary goal of this research are to enhance surface quality and ensure precision machining. The experiment includes three parameters, each one at three levels: voltage (10 V, 20 V, and 30 V), electrolyte concentration (20 g/L, 40 g/L, and 60 g/L), and a gap width (0.1 mm, 0.2 mm, and 0.3 mm). The experimental work is carried out on Minitab, a statistical software with a general full factorial design. A mathematical model is developed to create a figure through which is determined how MRR performs with variation of the three experiment parameters. Analysis of variance is performed through the ANOVA test to study the influence of the input parameters. The results indicate that MRR is significantly affected by voltage, followed by electrolyte concentration, while the gap width demonstrated minimal effect. Increasing voltage and electrolyte concentration leads to an increase in MRR. Similarly, increasing the gap width initially leads to a decrease in MRR, which then reaches a plateau. The maximum and minimum MRR values are 0.0871 g/min and 0.0023 g/min, respectively, revealing that voltage is an effective parameter for ECM quality optimization.

Keywords-electrochemical machining; material removal rate; electrolyte; minitab; ANOVA

I. INTRODUCTION

ECM is a non-traditional machining method in which the tool cannot be harder than the workpiece. ECM depends on chemical reactions and is subsequently affected by electrical energy [1]. ECM depends on the anodic dissolution of the workpiece which is connected to the anode and the electrode tool which is connected to the cathode in an electrolytic solution [2]. ECM is utilized to cut composites, inconel, titanium alloy, and ceramics, which are considered complicated materials and are used in automotive, space, rail, and medical industries. These materials are difficult to manufacture through traditional processes due to their superior mechanical properties, high resistance to wear and corrosion, low thermal expansion coefficient, and low density [3, 4]. ECM provides less heat production due to less friction, no stress production due to the absence of direct contact between the electrodes, and superior surface finish attributed to material removal at atomic level [5]. The ECM process was introduced by Gusseff in 1929 [6]. In 1960, the US Anocut company invested in ECM technology building the first ECM machine [7]. ECM was later also applied to processes, such as drilling, grinding, polishing, die sinking, profiling and contouring, trepanning, deburring, and micro-machining [8].

Parameters of the ECM process, such as voltage, tool feed rate, electrolyte concentration, and cycle of duty, determine the workpiece surface quality. Output parameters, such as MRR and Overcut (OC), determine the machining performance of the

process [9]. Consequently, the output of the machining process is highly reliant on the input variables [10].

Authors in [11] utilized the Electrochemical Micromachining (EMM) process on a nickel plate in sulphuric acid (H_2SO_4) electrolyte. The results suggest that low voltage, small pulse on time, and small diameter of electrode are the variables that improve machining accuracy. Authors in [12] investigated the Pulse Electrochemical Machining (PECM) process in an electrolyte of sodium nitrate ($NaNO_3$) to cut a workpiece of lamellar cast iron by a tool of stainless steel. The findings indicated that the pressure of the electrolyte has minimal effect on MRR. In addition, the voltage and the feed rate significantly affected MRR. Furthermore, increasing the vibration frequency and pulse on time leads to an increase in MRR. The impact of employing an acidified electrolyte, which includes adding 0.05 m/L of H_2SO_4 to sodium nitrate $NaNO_3$, on the EMM of stainless steel was investigated in [13]. Authors observed that increasing voltage leads to an increase in MRR and OC. The acidified $NaNO_3$ electrolyte yielded superior results compared to the $NaNO_3$ electrolyte containing higher MRR concentrations. Voltage variation, electrolyte concentration, and tool feed rate were investigated with respect to radial OC for machining aluminum-silicon alloy, reinforced with boron carbide (Al/B_4C_p) metal matrix composite in NaCl electrolyte, using a copper tool [14]. The voltage influenced the radial OC by 65.44%, followed by feed rate and electrolyte concentration with 30.22% and 4.31%, respectively. Authors in [15] utilized the artificial bee colony optimization algorithm of Response Surface Methodology (RSM) to discover the optimum parameter combinations of a workpiece of EN 31 steel in potassium chloride (KCl) electrolyte, using a tool coated with epoxy powder resin. The 3D surface plots revealed that the concentrations of electrolyte, tool feed rate, and voltage increase MRR, while in contrast gap width leads to their decrease. The ECM process was investigated in [16] to determine better input parameters on stainless steel 316 and copper electrode. The results indicated that increasing the voltage initially causes an increase in MRR, followed by a decrease. The maximum value of MRR and the minimum value of surface roughness are acquired at a voltage of 13.5 V. Moreover, authors in [17] investigated the influence of voltage at four different levels (10 V, 15 V, 20 V, and 25 V) for aluminum hybrid matrix composites. The experiments were performed on Taguchi L16 orthogonal array. The maximum MRR value was 0.00953 mg/min, which is attained by a voltage of 25 V. Micro holes on titanium alloys in glycerol ($C_3H_8O_3$) and C_8O_7 as electrolytes with different levels for an applied voltage of (8 V,10 V,12 V, and 14 V) were studied [18], achieving the maximum MRR value at a voltage of 14 V. Finally, authors in [19] utilized COMSOL Multiphysics software to create a model for MRR. Aluminum, nickel, stainless steel, and tungsten were selected and compared as materials for the workpiece to identify the optimum one, utilizing a copper tool. The findings revealed that stainless steel workpieces exhibited the maximum MRR. An increase in voltage and electrolyte conductivity led to an increase in MRR.

The present study aims to improve the control in ECM process by determining the best voltage values to achieve the highest accuracy in dimensions with fewer errors, and increase the repeatability and reliability of industrial production. Further research is needed to address certain limitations, including the behavior of various advanced and composite materials under voltage variation, the application of artificial intelligence or numerical modeling for optimized predictive outcomes, and methods for minimizing electrolyte consumption while extending tool lifespan.

II. WORKING PRINCIPLE OF ECM PROCESS

Faraday's and Ohm's laws serve as the foundation for ECM process, which removes metal by an anodic dissolution of the workpiece. Electrodes (the tool and the workpiece) exist in a medium of a flowing electrolyte that forms an electrolytic cell. Current flows in the electrolyte when electrodes are connected to an electric source of about 20 V because of the attraction of positive ions toward the cathode and negative ions toward the anode. The rate of ions arrival to the workpiece and tool determines current density, and current is directly proportional to the voltage, concentration of electrolyte, gap width, and feed rate. During the electrolysis process at the cathode, release of hydroxyl ions occurs. Then, hydroxyl ions are combined with the workpiece ions and form insoluble metal hydroxides. In this way, the metal is removed as sludges and precipitates by electrochemical and chemical reactions [20].

III. EXPERIMENTAL SETUP

The ECM machine utilized in this study is shown in Figure 1. The electrodes are immersed in a solution of NaCl and water as electrolyte, with concentrations of 20 g/L, 40 g/L, and 60 g/L.

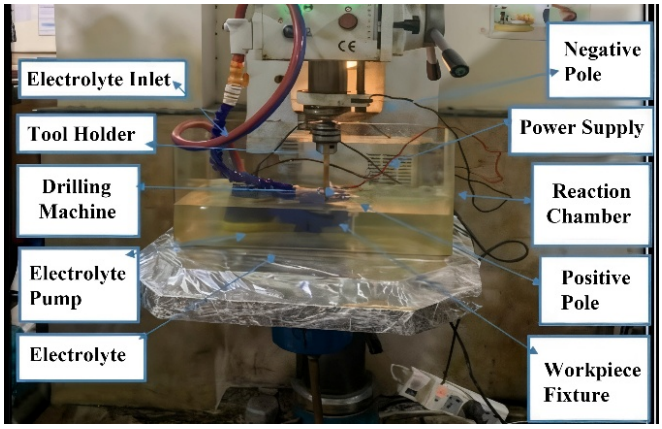

Fig. 1. ECM machine.

The components of NaCl are listed in Table I. Electrolyte temperature, set at 25 °C at the beginning of machining, increased to 45 °C during the process. The tool was as close as possible to the workpiece with three different levels of gap width, including 0.1 mm, 0.2 mm, and 0.3 mm. Sinking the tool into the workpiece allows it to duplicate its shape. When the applied voltage rises to 20 V, the ions of the electrolyte begin to migrate toward the workpiece and tool [21].

TABLE I. NaCl COMPONENTS

Metal	Content (%)
Magnesium	< 0.19
Sulfur	0.0549
Calcium	0.2485
Copper	0.00165
Cadmium	< 0.00054
Iron	0.01
Lead	0.00025
Chlorine	11.9
Sodium	1.4

A. Workpiece

The dimensions of the workpiece specimens are 60×45×3 mm, as illustrated in Figure 2.

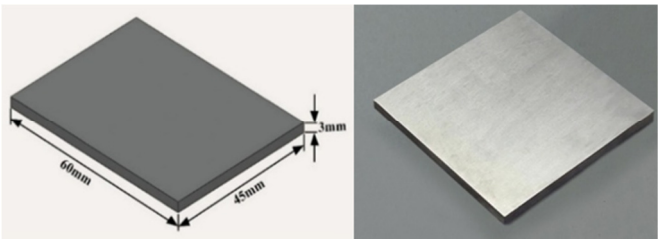

Fig. 2. Dimensions and shape of the workpiece before machining.

High-speed steel AISI M2 is selected as the workpiece due to elements of chromium and vanadium content that resist corrosion. This behavior reduces the random removal of metal, providing high accuracy, as presented in in Table II. In addition, the workpiece preserves its hardness and toughness even after the machining process. This process does not affect the mechanical properties shown in Table II.

TABLE II. CHEMICAL COMPOSITION AND MECHANICAL/ PHYSICAL PROPERTIES OF HIGH-SPEED STEEL AISI M2

Material	Weight (%)	Properties	Values
Carbon	0.855	**Flexural strength**	4700 MPa
Silicon	0.305	**Elastic modulus**	190-210 GPa
Manganese	0.28	**Specific heat**	17.2×10^{-6} J/g×°C
Molybdenum	5.43	**Thermal conductivity**	19 W/m×K
Nickel	0.14	**Electrical conductivity**	2.5×10^{6} S/m
Copper	0.715	**Melting point**	4680 °C
Phosphorus	0.001	**Electrical resistivity**	54×10^{-6} Ω×cm
Sulfur	0.001	**Density**	8.138 g/m^3
Chromium	4.71	**Hardness**	65 HRC
Vanadium	1.88	**Machinability**	65% of a 1% carbon steel
Tungsten	5.73	**Charpy impact**	36 J
Iron	Balance	**Poisson's ratio**	0.27-0.30

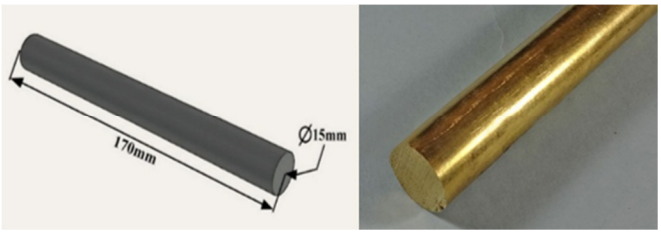

Fig. 3. Dimensions and shape of the solid tool.

B. Tool

Figure 3 presents the solid copper tool utilized in this study, with dimensions of 15 mm diameter and 170 mm length. The tool has a high electrical conductivity of 59.6×10^{6} S/m.

C. Experimental Design

Minitab is utilized to analyze the results, with a general full factorial design yielding 27 experimental runs, as detailed in Table III.

TABLE III. VARIABLE AND MEASURED PARAMETERS

Experiment number	Voltage (V)	Concentration of electrolyte (g/L)	Gap width (mm)	MRR (g/min)
1	10	20	0.1	0.0041
2	10	20	0.2	0.0025
3	10	20	0.3	0.0023
4	20	40	0.1	0.0231
5	20	40	0.2	0.0097
6	20	40	0.3	0.0123
7	30	60	0.1	0.0871
8	30	60	0.2	0.0753
9	30	60	0.3	0.0745
10	10	60	0.3	0.0028
11	10	60	0.1	0.0047
12	10	60	0.2	0.0031
13	20	20	0.3	0.0095
14	20	20	0.1	0.0037
15	20	20	0.2	0.0033
16	30	40	0.3	0.0612
17	30	40	0.1	0.0572
18	30	40	0.2	0.0541
19	10	40	0.2	0.0027
20	10	40	0.3	0.0024
21	10	40	0.1	0.0042
22	20	60	0.2	0.0214
23	20	60	0.3	0.0128
24	20	60	0.1	0.0282
25	30	20	0.2	0.0465
26	30	20	0.3	0.0419
27	30	20	0.1	0.0405

IV. RESULTS AND DISCUSSION

A. Voltage Influence on Material Removal Rate

Voltage at levels of 10 V, 20 V, and 30 V on MRR is studied for different electrolyte concentrations of 20 g/L, 40 g/L, and 60 g/L, and at a stable gap width of 0.1 mm, 0.2 mm, and 0.3 mm, as shown in Figure 4. Increasing voltage results in an increase in MRR and electric field generation. This behavior leads to a larger reaction zone for a faster decomposition of metal to ions, causing more material to be removed from the workpiece. However, at an electrolyte concentration of 20 g/L with gap widths of 0.1 and 0.2 mm, a decrease is followed by an increase in MRR, despite a concurrent increase in voltage. This phenomenon can be attributed to the reduction in ion availability at lower electrolyte concentrations, which elevates the electrolyte's electrical resistivity, and consequently diminishes current generation, as described by Ohm's law [22]:

$$I = \frac{V}{R} \quad (1)$$

where I indicates the current, V the voltage, and R the resistivity.

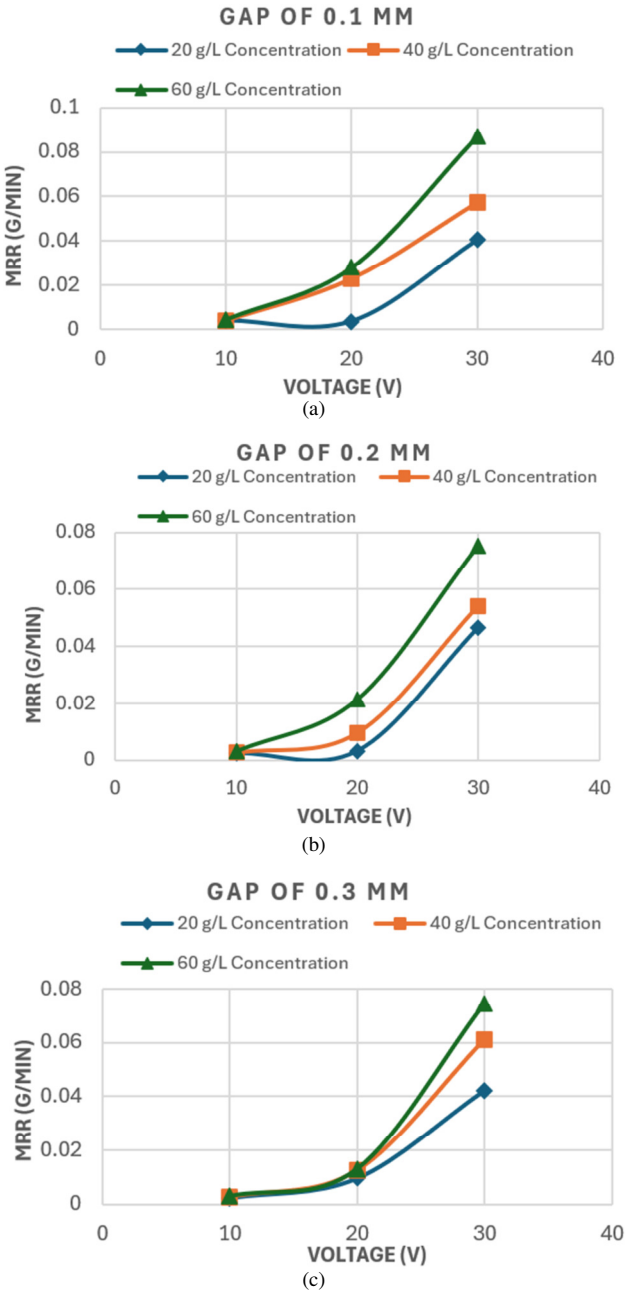

Fig. 4. Influence of voltage on MRR for: (a) 0.1 mm, (b) 0.2 mm, and (c) 0.3 mm.

B. Input Parameters Influence on Material Removal Rate

MRR results during voltage variation, electrolyte concentration, and gap width are displayed in Figure 5. There is a clear relation between voltage and MRR. When the voltage increases, MRR increases and a sharp increase is obvious at a high voltage value of 30V. This relation emerges because of the increasing current that makes the electrochemical removal process faster.

There is regularity and rise in the relation between electrolyte concentration and MRR. This refers to a rise in the number of electrolyte ions, which improves electrical conductivity and electrochemical reaction rate.

The gap width has a weak impact on MRR. When the gap increases, MRR decreases and then stabilizes because of the reduction in current density, which slows the removal process, but at a certain level when the gap width is 0.3 mm, there are no changes in MRR despite the voltage increases.

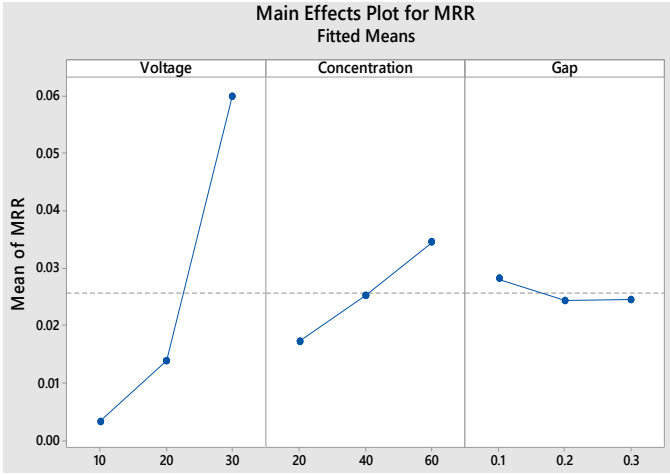

Fig. 5. Variable parameter influence on MRR.

C. Variance Analysis

ANOVA is a statistical test that compares multiple machining parameters to determine the most influential one on MRR response, and the level of its influence. As depicted in Table IV, voltage and concentration have a p-value smaller than 0.05, significantly affecting MRR. Simultaneously, the gap width p-value is greater than 0.05, meaning that any changes do not affect MRR.

TABLE IV. ANOVA TEST RESULTS FOR MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Voltage	2	0.016307	0.008154	126.37	0.000
Concentration	2	0.001347	0.000674	10.44	0.001
Gap	2	0.000084	0.000042	0.65	0.532
Error	20	0.001290	0.000065	-	-

Every parameter has a percentage contribution to MRR, calculated from the ANOVA test and (2). The results reveal that voltage presented the highest percentage contribution of 85.7%, followed by concentration with a value of 7.1%, and gap width with a value of 0.44%:

$$Percentage\ Contribution = \frac{Adj\ SS}{Total\ Adj\ SS} \times 100\% \quad (2)$$

D. Model Summary

As observed in Table V, the very small value of 0.008 for S indicates that the model is quite precise in data estimation. The model explains the percentage of variation in MRR, which is 93.22%. R-sq (adj) value is close to the value of R-sq, which means that the model is not complicated and works well, even with the correction of the number of variables. Also, R-sq

(pred) value is close to that of R-sq, meaning that the model can be used to predict future values.

TABLE V. MODEL SUMMARY FOR MRR

S	R-sq	R-sq (adj.)	R-sq (pred.)
0.0080326	93.22%	91.18%	87.64%

The assumptions of the statistical model were verified using a normal probability plot, which indicated that the residuals values were very close to the normal distribution, with some slight deviations at the high values, as shown in Figure 6.

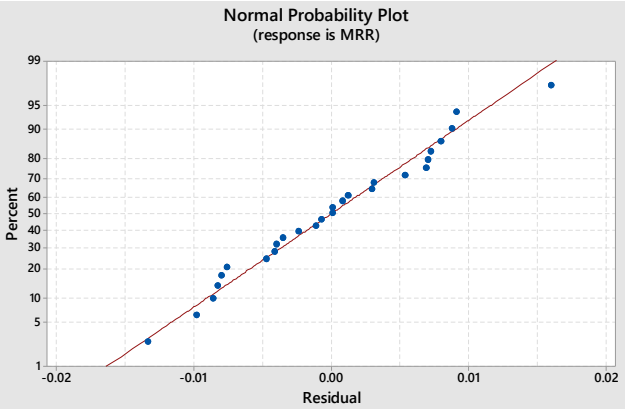

Fig. 6. Normal probability plot.

V. CONCLUSION

The machining performance of the Electrochemical Machining (ECM) process is investigated on a high-speed steel AISI M2 workpiece and a copper tool. Material Removal Rate (MMR) is employed as a performance metric. Different values of voltage, concentration of electrolyte, and gap width are utilized. The input parameters are analyzed based on the full factorial design in Minitab software. The results of this research lead to the following observations:

- An increase in voltage leads to an increase in MRR.
- During all experiments, MRR presents the highest value of 0.0871 g/min, reducing machining time, increasing productivity speed, and reducing the overall machining cost of ECM process.
- Achieving the lowest MRR value of 0.0023 g/min leads to the production of highly precise parts that need high accuracy and smooth surface.
- The highest MRR values are obtained for a voltage value of 30 V, electrolyte concentration of 60 g/L, and a gap width of 0.1 mm.
- An increase in electrolyte concentration leads to an increase in MRR. In contrast, an increase in gap width initially leads to a decrease in the value of MRR, and eventually stabilizes.
- Voltage and electrolyte concentration have significant effects on MRR, with a contribution percentage of 85.7% and 7.1%, respectively. On the other hand, gap width does not have a significant effect.

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