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The influence of electrochemical machining parameters on power consumption and MRR

Lara A. Salman*, Abbas F. Ibrahim, Baraa M.H. Albaghdadi

Production Engineering and Metallurgy Dept., University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
*Corresponding author Email: laraa.salman@yahoo.com

HIGHLIGHTS

- The voltage, electrolyte concentration, workpiece material, and gap were analyzed for MRR and power consumption
- Power consumption decreased at low voltage, with the minimum power observed in Al6061 alloy
- Voltage and workpiece material are key for power, while gap and concentration are the least important for MRR and power

Keywords:

Electrochemical machining
Power consumptions
MRR
Taguchi technique
AMMCs

ABSTRACT

The electrochemical machining (ECM) process is a highly developed method of working with metal. This process can be used to machine objects that are difficult or impossible to create using conventional machining processes. In this context, monitoring power consumption in industrial companies makes the process more energy-efficient, cost-effective, and sustainable, lowers energy waste from machine tools, and, thus, reduces costs. Therefore, the primary objective of this research is to determine how the ECM impacts power consumption and the material removal rate (MRR). Specifically, the workpiece was made of aluminum 6061 alloys, Al-Sic, and Al-B_4C, using a stir casting process, while the tool was made of copper. The experiment is conducted by varying the input process parameters, including the electrolyte content (10,20,30) g/l, the voltage (10, 20, and 30) V, the gap (0.2, 0.5, and 0.8) mm, and the type of material. The Taguchi design of the experiment used orthogonal arrays, and the results were analyzed using the Minitab software. Four input variables, with three-factor level values for each variable, were examined in this experiment. The results showed that power consumption was decreased at a low voltage of 10 V to 104.6W, and at a high voltage of 30 V, the MRR increased to 0.074 (mm^3/min). Furthermore, the most important parameters for power are the voltage and the material, followed by the gap and then the concentration. At the same time, voltage and concentration are the most important variables for the MRR, followed by concentration and material.

1. Introduction

There is increasing pressure on the design of the manufacturing processes due to growing modification and efficiency requirements on components in the energy, industry, and medical technology sectors. In this regard, the electrochemical machining process offers many possibilities to meet these requirements. The properties of composite materials based on aluminum, such as increased hardness, excellent wear resistance, strong strength, and low thermal expansion coefficient, make them widely employed. Among the unconventional techniques, ECM is the most significant one that could be employed for machining hard or difficult-to-cut materials [1]. For instance, Sankar et al. [2], examined the ECM performance of AA7075-B_4C composites, optimized the MRR and SR responses using the response surface methodology, and performed an ANOVA analysis on the outcome. In this procedure, the electrolyte was $NaNO_3$. It was shown that process variables, including voltage and tool feed rate, significantly impacted the MRR and SR. Therefore, with 8 V applied voltage, 217 A current, and 0.3 mm/min tool feed rate, the maximum MRR and the lowest SR were reached. Raoi et al. [3], optimized the machining parameters with numerous features using the Taguchi technique. The L27 orthogonal array was selected for the study. The results show that the feed rate was the most important factor that simultaneously influences a number of machining properties. The best parametric combination is 16 V applied voltage, 1.0 mm/min feed rate, 30 g/l electrolyte concentration, and five-weight percent reinforcement content. This combination maximizes the material removal rate while simultaneously minimizing surface roughness and radial overcut. Kumar et al. [4], utilized ECM to machine Al-Sic composite to achieve excellent machining and product quality.

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Particularly, the Al-Sic composite reinforced with 10-15 wt.% of Sic was used as a workpiece material. Voltage, feed rate, and electrolyte concentration were used as the process limitations for conducting the experimental trials. The radial overcut (ROC), MRR, and SR were considered as output responses. The optimized parameters utilizing multi-parametric optimization showed considerable improvement in the process. In addition, Maniraj et al. [5], employed electrochemical machining to study the effects of the electrochemical process parameters on the ROC and the MRR to efficiently implement electrochemical machining for the copper manufactured by stir casting, which was used to create the test specimens of the copper alloy. According to the results, as the machining parameters are increased, the MRR increases. Moreover, Rajan et al. [6], manufactured metal matrix composites (MMCs) by reinforcing the aluminum alloy (7075) for two distinct weight percentages of B_4C, 5% and 10%. The AMMCs were made using the stir-casting technique. The output response was determined considering the overcut and machining speed. The results showed that when the electrolyte temperatures increased, the machining speed increased, and the overcut result of Al7075 with a 10% mass fraction of B_4C composite decreased. In another work, Abbas et al. [7], investigated the effect of ECM machining parameters on the ROC and the MRR. The workpiece material used was Al-7.5% B_4C. In particular, stir casting was used to create the metal matrix composites. The results indicated that the ROC increased when the electrolyte concentration, voltage, and IEG value increased. Additionally, the MRR decreased as the voltage and IEG value increased while the electrolyte concentration increased. Rajesh et al. [8], studied the effects of several electrochemical hole-digging process variables on the MRR of composite materials that are cast using the stir-casting method and consist of silicon carbide and the aluminum 7075 alloy. The study used the statistical tool Minitab'20 to create regression models. The results showed that an electrolyte concentration of 0.41 mol/lit and a voltage of 11 V produced the maximum MRR of 12.494 mg/min. In another research, Salman et al. [9], investigated the impact of the electrochemical drilling parameters on the metal matrix composite's manufactured MRR. The Taguchi method was used to produce the experiment. The results indicated that a concentration of 25 g/l, a gap of 0.5mm, and a voltage of 40 V would provide the optimal parametric combination for the MRR. Moreover, Sri et al. [10], studied the effects of the electrochemical machining parameters on the MRR and the SR output responses for Al hybrid composites, which were also analyzed by the preparation of the AA-6082/$ZrSiO_4$/TiC hybrid composite. The Taguchi method was used, and according to the ANOVA result, the electrode feed rate contributed the highest, followed by the electrolyte discharge rate and additional process variables for MRR and SR. On the other hand, energy consumption has been examined for several machining operations, including milling [11-13], turning, and grinding [14]. Other studies provided preliminary data about the effect of energy consumption on Electrical Discharge Machining (EDM). For example, Nieslony et al. [15], investigated how surface integrity and energy consumption relate to each other while cutting hot work die steel using EDM. Specifically, the energy consumption data was recorded online using current and voltage transducers to measure the energy consumption during the machining operation. After recording the data using the LabVIEW program, the energy consumption was computed. The results showed that there is a direct relationship between the energy and the surface integrity and that there is a linear relationship between the power and the MRR.

Therefore, it is challenging to estimate the process's overall energy consumption. In addition, Swat et al. [16], utilized the pulse electrochemical machining (PECM) process to analyze the energy consumption of a manufacturing process. In particular, two machine tool generations of the same manufacturer were used to compare PEM Center 8000 and PEM 600, and the result showed an improvement in energy consumption. By reviewing the previous research works, it became clear that the number of studies on power consumption in ECM is limited. Hence, there is a need for more investigation because monitoring power consumption in manufacturing organizations helps reduce machine tool energy waste and, as a result, saves costs. For this purpose, total transparency of energy usage across all industrial plants is necessary [17]. In this work, the power consumption during machining was measured using a DC multimeter device. A DC digital multimeter module, this device was designed to measure and show electrical parameters in direct current (DC) circuits in real-time. To this end, the present research studied the effects of machining parameters on power consumption and MRR in ECM to machine Al6061, Al-B_4C, and Al-Sic. Taguchi designs were employed to identify the parameters of the analytical techniques using four input factors, including voltage, material type, electrolyte concentration, and gap (IEG).

2. Experimental work

2.1 Materials

The machined workpiece was made of the Al6061 alloy. In this regard, the combination of excellent machinability, strength, corrosion resistance, and cost-effectiveness make Al6061 one of the most commonly used materials in machining for a wide range of industries. In addition to Al6061, Al-7.5%B_4C and Al-7.5%Sic workpiece materials were also used after fabricating them. Specifically, the workpiece's dimensions are 26 x 20 x 5 mm^3. In addition, the copper tool was used for the experiment due to the high electrical conductivity with a diameter of 12 mm and a length of 45 mm.

2.2 Preparation of the Materials

To prepare Al-7.5% Sic and Al-7.5% B_4C, aluminum alloy 6061 was melted in a furnace with a crucible inside to create Al-SIC and Al-B_4C as shown in Figure 1a. Next, using a stir-casting method at 750 °C, the molten material was combined with 7.5% Sic powder for Al-SIC and 7.5% B_4C powder for Al-B_4C, and stirring continued for 3 to 5 minutes after the addition of powder. Portable drilling was then used at 500 rpm for the stir-casting process, as shown in Figure 1b. In particular, the average particle size of Sic and B_4C powders was within the range of 25–38 μm.

(a) (b)

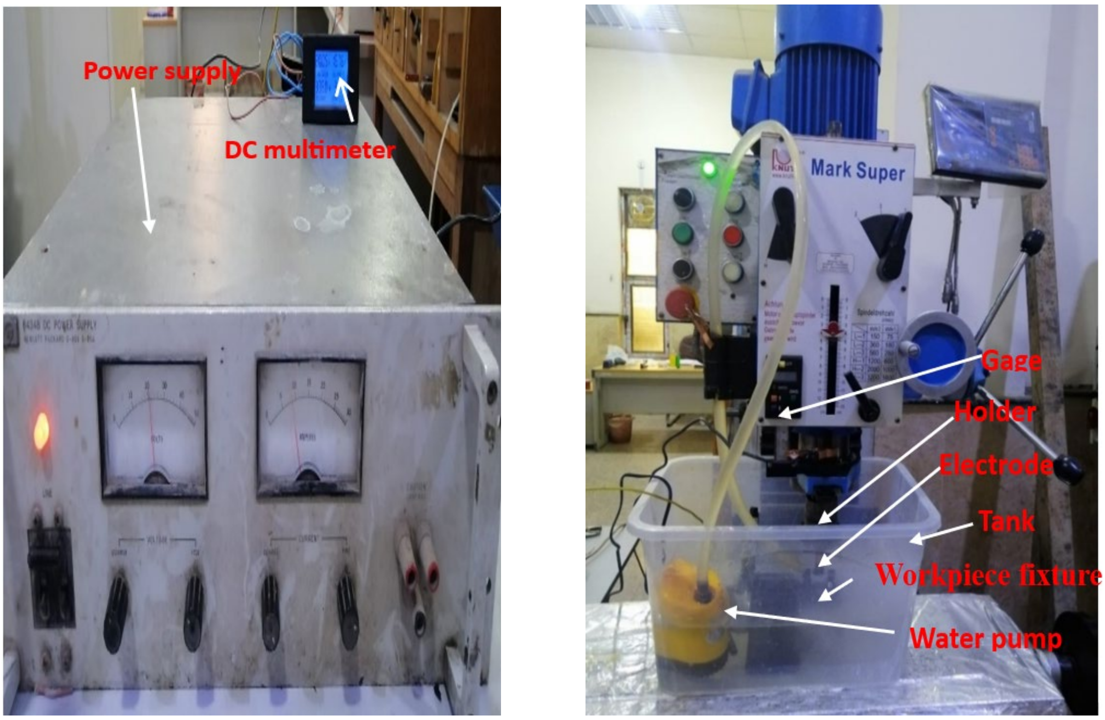
Figure 1: (a) Melting the aluminum alloy with powder (b) The stir casting using portable drilling

2.3 The used electrolyte

The electrolyte solution used in this experimental work was NaCl at three different concentrations: 10, 20, and 30 g/l.

2.4 Experimental setup

The practical experiments were implemented using Mark Super S TV1000 Drill operation with table dimensions 800 x 240 mm^2. This machine was turned into an electrochemical machine, which involves several key adaptations. Specifically, the process was achieved by adding several components, including a power supply and DC multimeter device as shown in Figure 2a, a tool holder for securing the electrode above the workpiece, a work table for mounting the workpiece, a tank for containing the dielectric fluid, a water pump for recycling the dielectric fluid, a workpiece fixture to fix the workpiece. These electrochemical machining components utilized in the experiment are shown in Figure 2b.



(a) (b)

Figure 2: (a) Power supply and DC multimeter device (b) Electrochemical machining components

2.5 Process parameters

The practical experiments were designed by the Minitab 17 software using the multi-level approach. The input parameters with different levels were voltage (V), concentration (g/l), workpiece material, and gap. In this experiment, the L9 orthogonal array was exploited to investigate the effects of four independent variables, each of which has three-factor level values, as shown in Table 1. Particularly, these parameters were analyzed to determine their impact on the responses of the power consumption and the MRR. The utilized machining input parameters and the experimental results are shown in Table 2, where each experiment in this table was conducted for five minutes.

Table 1: The input parameters and their levels

No	Process parameters	Code	Level 1	Level 2	Level 3
1	Volt (v)	A	10	20	30
2	Concentration (g/l)	B	10	20	30
3	Workpiece material	C	1	2	3
4	Gap (mm)	D	0.2	0.5	0.8

Table 2: The ECM input parameters

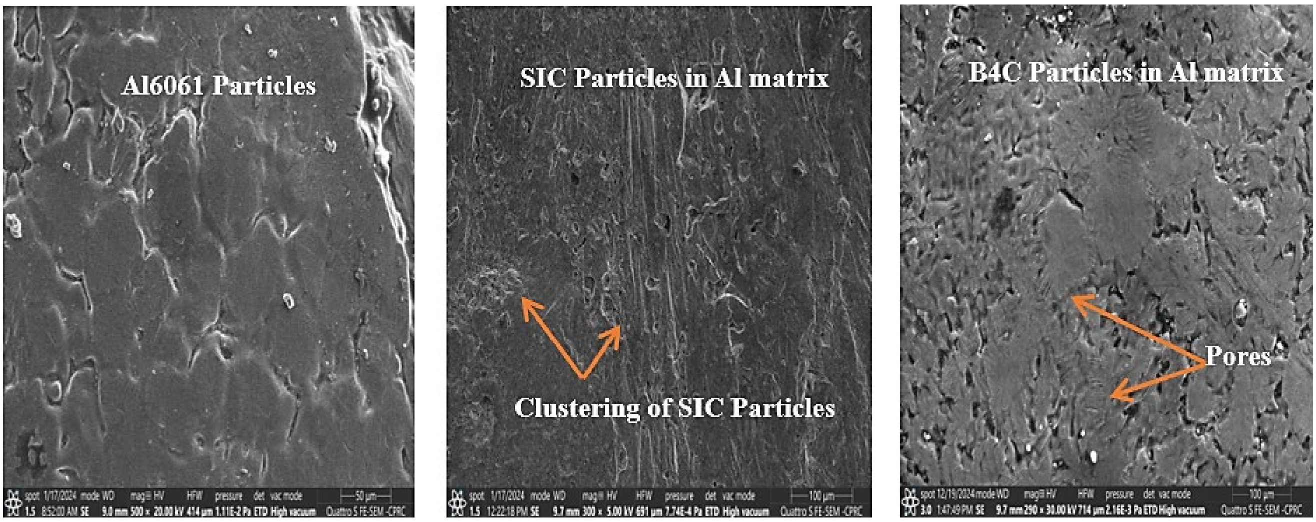
Run Order	Volt (v)	Concentration (g/l)	Workpiece material	Gap (mm)
1	10	10	1	0.2
2	10	20	2	0.5
3	10	30	3	0.8
4	20	10	2	0.8
5	20	20	3	0.2
6	20	30	1	0.5
7	30	10	3	0.5
8	30	20	1	0.8
9	30	30	2	0.2

3. Results and discussion

3.1 The microstructure of Al6061, Al7.5% B_4C, and Al7.5% SiC

The microstructure of the aluminum specimens (Al6061, Al-B_4C, and Al-Sic) was analyzed using the Scanning Electron Microscope (SEM). Figure 3 (a, b, and c) shows optical images of Al6061, 7.5% Sic, and 7.5% B_4C mixed with Al6061 at different magnifications from x200 to x500. According to Figure 3a, it is clear that Al6061 is a solid solution alloy with a fine, homogeneous grain structure that has a relatively smooth surface. Figure 3b represents the micrographs of the workpiece material after adding 7.5%SiC for the aluminum alloy and the aluminum matrixes dispersed visible silicon carbide (SiC) particles. These SiC particles may have an uneven or angular shape and will appear as hard, distinct phases that are difficult to deform. The mechanical properties of the composite are improved by these particles, which provide a rough surface. In particular, some clustering or agglomeration of SiC particles can be observed based on the casting process. Figure 3c demonstrates the micrographs of Al7.5% B_4C, and the SEM image shows how the boron carbide (B_4C) particles are dispersed within the aluminum (Al) matrix.

In this context, the uniform distribution of B4C is ideal for improved mechanical properties. However, the clustering or agglomeration of particles may occur, leading to localized stress concentrations. In addition, the pores that appear in the figure depend on the fabrication process.



(a) **(b)** **(c)**

Figure 3: Surface morphology of (a) Al 6063, (b) 7.5% SiC, (c) Al7.5% B_4C

3.2 The effect of machining parameters on the power consumption

In this work, power consumption was determined during machining using a DC multimeter device. More precisely, two terminals, one for the DC power source and the other for the ECM machine were used to link the device to the machine. In this regard, the main effect plot for the variables influencing the power consumption is displayed in Figure 4 and Table 3. The results indicate that there is a direct relationship between voltage and power consumption. In more detail, when the voltage was increased from 10 to 30 volts, the power consumption increased. This increase is due to higher current flow and faster reaction rates at elevated voltages [18]. Therefore, the minimum power consumption was achieved at 10 volts. In addition to the voltage, the effect of the electrolyte concentration on power was measured, as illustrated in Figure 4, in which the results showed that the lower electrolyte concentration results in fewer ions available for conduction, leading to higher electrical resistance. According to Ohm's Law, this higher resistance can cause an increase in the voltage needed to maintain the same current, which can lead to higher power consumption. While high electrolyte concentration can initially reduce power consumption through improved conductivity, it can also lead to increased viscosity, flow issues, gas evolution, and other factors that may ultimately raise power consumption [19]. Consequently, the minimum power consumption was obtained at 20 (g/l).

In this context, when machining different materials like Al6061, Al-SiC, and Al-B_4C in ECM, the choice of material significantly impacts power consumption due to variations in conductivity, MRR, and interaction with the electrolyte. Generally, Al6061 shows moderate and efficient power consumption due to its good conductivity and electrochemical properties. On the other hand, for Al-SiC and Al-B_4C, power consumption may increase due to the lower conductivity and the potential for reduced MRR [20]. However, the ultimate power consumption will also depend on specific machining parameters and conditions. According to Figure 4 and Table 1, it is clear that when the gap is small, 0.5 mm, the electrical resistance is lower because the ions travel a shorter distance, resulting in more efficient ion transportation, which reduces the amount of power needed to sustain the desired current. However, when applying a smaller value of the gap, 0.2 mm, high power consumption was generated because of the generation of excessive heat and localized reactions, which may cause short-circuiting or damage to the tool and the workpiece. In contrast, a larger gap decreases the current density, which can reduce the MRR and lead to higher overall power consumption due to longer processing times [21]. Therefore, the minimum power consumption was obtained at a 0.5 mm gap.

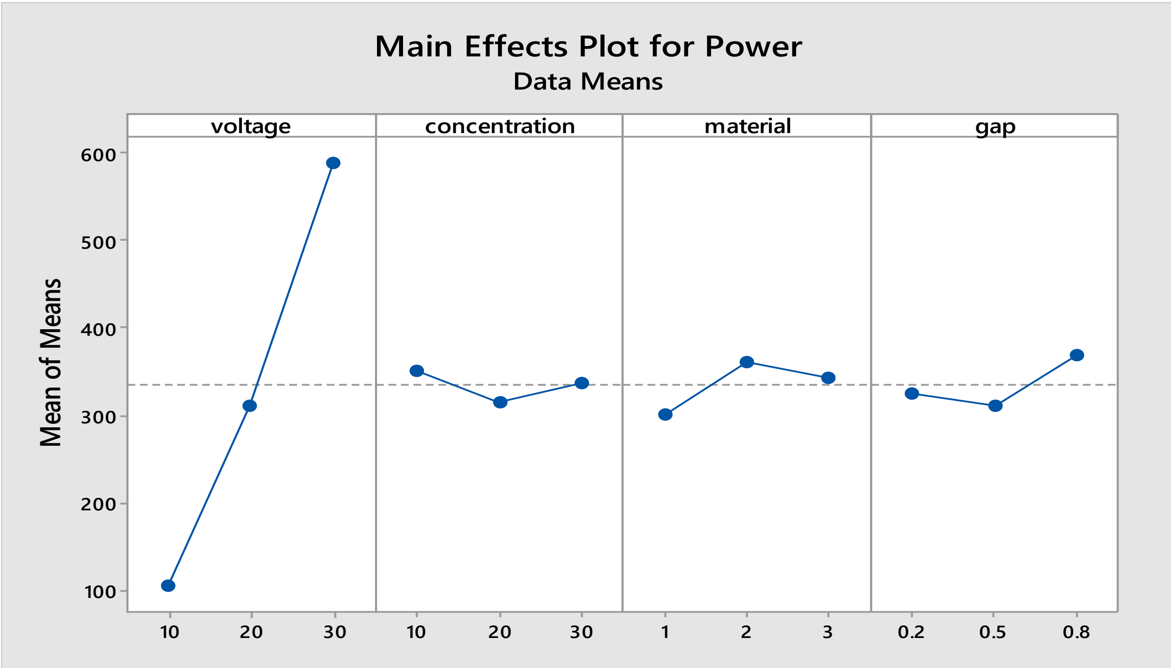


Figure 4: Main effects plot for power consumption in the ECM

3.3 The effect of the machining parameters on the MRR

The MRR is a crucial performance indicator in ECM, influencing the machining efficiency, productivity, and quality of the machined components. As depicted in Figure 5, the voltage significantly impacts the MRR in ECM. In particular, when the voltage was increased from 10 to 30V, the MRR also increased because when the voltage increases, the rate of ion migration and the electrochemical reactions also increases, leading to a higher MRR, which is due to faster material dissolution at the anode (workpiece) [22]. As shown in the same figure, the electrolyte concentration has also affected the MRR. Specifically, it can be seen that the increase in the electrolyte concentration led to an increase in the MRR [9]. This is because the electrolyte concentration directly influences the ion transfer mechanism within the machining gap. Particularly, increasing the electrolyte concentration typically enhances the electrical conductivity of the solution, which lowers the electrical resistance in the machining gap and improves the efficiency of the anodic dissolution, and this outcome has a substantial impact on the MRR in ECM. In essence, the MRR is significantly impacted by the type of material utilized in the ECM process, such as Al-6061, Al-Sic, and Al-B_4C. As the figure illustrates, the larger MRR was achieved for the Al6061 alloy at 0.0608 (mm^3/min). Because

Al-6061 is a softer alloy and has a lower resistance to ion dissolution than composites like Al-Sic and Al-B_4C, it usually exhibits a higher MRR. However, because of their slower anodic dissolution and higher surface resistance, Al-Sic and Al-B_4C, which contain harder reinforcements (Sic and B_4C), may have lower MRR under comparable machining conditions [23].

Furthermore, the mean MRR with respect to the gap was measured as shown in Figure 5, and the result shows that when the gap was increased, the MRR decreased. Particularly, a smaller gap typically results in a higher MRR [9] because the electric field strength is more concentrated, allowing for more efficient electrochemical reactions. As the gap increases to 0.8 mm, the MRR generally decreases. This outcome is due to the reduced electric field strength, which diminishes the efficiency of the anodic dissolution process. Therefore, as demonstrated in the figure, the maximum MRR was at a gap of 0.2 mm.

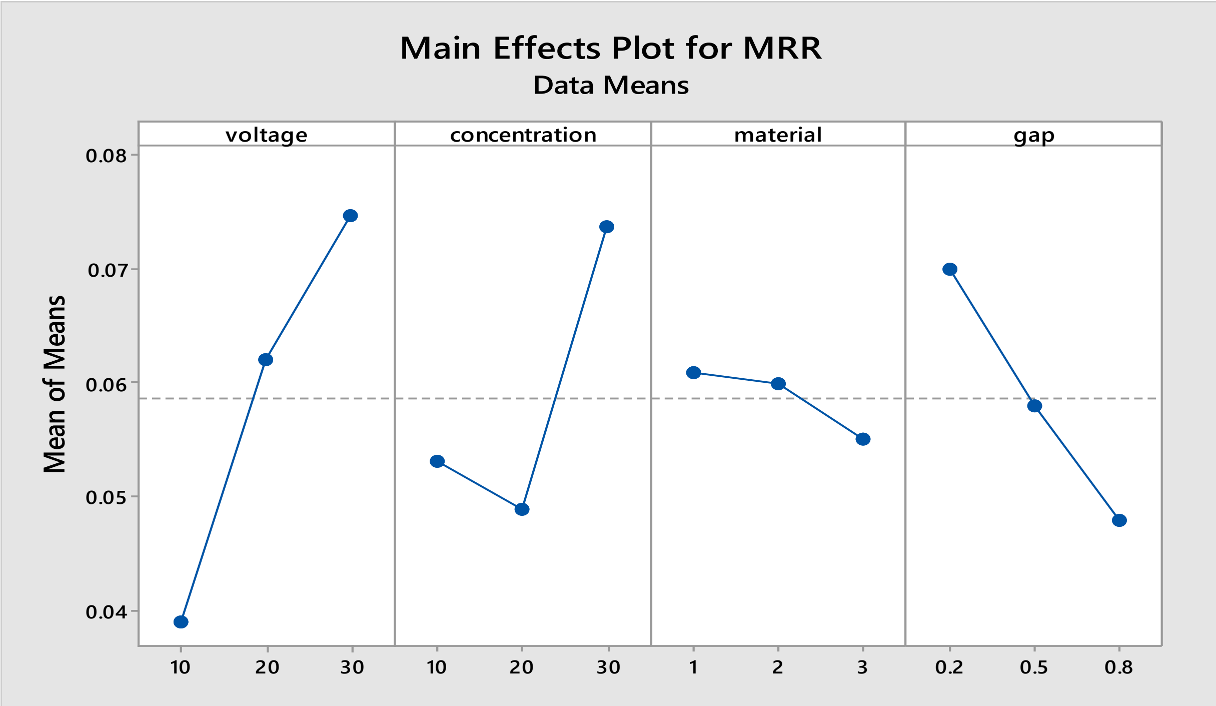


Figure 5: Main effects plot for MRR in ECM

Table 3: The ECM parameters' results

Run Order	Volt (v)	Concentration (g/l)	Workpiece material	Gap (mm)	MRR (mm^3/min)	Power (W)
1	10	10	1	0.2	0.0472	76.8
2	10	20	2	0.5	0.0300	88.3
3	10	30	3	0.8	0.0400	148.7
4	20	10	2	0.8	0.0472	390.0
5	20	20	3	0.2	0.0600	290.0
6	20	30	1	0.5	0.0787	255.0
7	30	10	3	0.5	0.0650	589.0
8	30	20	1	0.8	0.0566	570.0
9	30	30	2	0.2	0.1024	609.0

3.4 Analysis of variance (ANOVA)

Tables 4 and 5 indicate the information on the analysis of variance (ANOVA) for the power consumption and the MRR of ECM. Based on these tables, when analyzing the regression model used for the results by Minitab, the analysis of variance results for the measured power and the MRR showed that voltage is the dominant factor in determining the response. More precisely, the results indicate that the voltage has the highest contribution of 95.64% for power consumption and 50.12% for MRR.

Table 4: The ANOVA table for the measured power

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	358345	89586	35.28	0.002
Voltage	1	352450	352450	138.79	0.000
Concentration	1	310	310	0.12	0.745
Material	1	2642	2642	1.04	0.365
Gap	1	2944	2944	1.16	0.342
Error	4	10158	2539		
Total	8	36850			

Table 5: The ANOVA table for the measured MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	0.003308	0.000827	6.82	0.045
Voltage	1	0.001901	0.001901	15.68	0.017
Concentration	1	0.000634	0.000634	5.23	0.084
Material	1	0.000051	0.000051	0.42	0.552
Gap	1	0.000722	0.000722	5.95	0.071
Error	4	0.000485	0.000121		
Total	8	0.003793			

Tables 6 and 7 display the power and MRR response tables for means. These tables show the most important parameter and the least important parameter for the power and the MRR. The tables clearly illustrate that the voltage and the workpiece material are the most important power-related characteristics, whereas the gap and the concentration are the least important parameters. As for the MRR, the voltage and the concentration are the most important parameters, while the gap and the workpiece material are the least important parameters. To this end, using the previously provided data, the following machining factors might be employed to predict the ideal power consumption and the MRR performance:

Table 6: Response table of means for power consumption

Level	Voltage A	Concentration B	Material C	Gap D
1	104.6	351.9	300.6	325.3
2	311.7	316.1	362.4	310.8
3	589.3	337.6	342.6	369.6
Delta	484.7	35.8	61.8	58.8
Rank	1	4	2	3

Table 7: Response table of means for MRR

Level	Voltage A	Concentration B	Material C	Gap D
1	0.03907	0.05313	0.06083	0.06987
2	0.06197	0.04887	0.05987	0.05790
3	0.07467	0.07370	0.05500	0.04793
Delta	0.03560	0.02483	0.00583	0.02193
Rank	1	2	4	3

3.5 Predicting the optimum value of each response

The optimality search model for the various process variable conditions to maximize the MRR and minimize the power consumption value of various machined workpieces was formulated based on the methodology, as described below. The regression analysis was used to determine and examine the relationship between the machining process's results and the parameters of the input variables. Specifically, Equations (1) and (2) can be obtained to correlate the various process variable effects on the power consumption and MRR to determine the optimal combination of the machining parameters and their combined effects on the desired response criteria.

The mathematical relationship for correlating the power consumption and the considered process variables has been obtained as follows:

$$\text{Power (W)} = 220 - 1.35\,X1 - 19.74\,X2 - 174.2\,X3 + 305.5\,X4 + 0.685\,X1\times X2 + 7.05\,X1\times X3 + 4.42\,X2\times X3 \quad (1)$$

The mathematical correlation between the MRR and the process variables under consideration has been obtained as follows:

$$\text{MRR (mm}^3\text{/min)} = 0.1082 - 0.00465\,X1 - 0.00068\,X2 - 0.0490\,X3 + 0.0184\,X4 + 0.000107\,X1\times X2 + 0.00223\,X1\times X3 + 0.00034\,X2\times X3 \quad (2)$$

where: X1= Voltage (V), X2= Concentration (g/l), X3= Material, X4= Gap (mm)

In the model summary, some numbers show how well different models fit the data. In this regard, the coefficient of determination, namely the R-Square (R-Sq), can be used to evaluate the effectiveness of the regression model. The adjusted R-square R-sq (adj) is the number of terms in the model multiplied by the adjusted R. Generally, a higher R-square value indicates a better fit of the model to the data. Tables 8 and 9 list the R-sq values and the R-sq (adj) for the developed mathematical models.

To evaluate the accuracy of the equations mentioned above, the expected values of the MRR and the power consumption were calculated using Equations (1) and (2). Accordingly, the predictive accuracy of the generated model has been shown to be adequate. Tables 10 and 11 show how the predicted and the observed values compare for the power consumption and the MRR.

Table 8: Response table of means for MRR

S	R-sq	R-sq (adj)	R-sq (pred)
24.6682	99.83%	98.68%	38.55%

Table 9: Model summary of MRR for the machining variables

S	R-sq	R-sq (adj)	R-sq (pred)
0.0110117	87.21%	74.43%	40.88%

Table 10: Prediction accuracy of power consumption

Run Order	Volt (v)	Concentration (g/l)	Workpiece material	Gap (mm)	Power (W) Exp.	Power (W) Pred.	Percent Error (%)
1	10	10	1	0.2	76.8	79.20	3.03
2	10	20	2	0.5	88.3	70.85	19.76
3	10	30	3	0.8	148.7	150.90	1.47
4	20	10	2	0.8	390.0	399.00	2.30
5	20	20	3	0.2	290.0	298.90	3.06
6	20	30	1	0.5	255.0	263.95	3.50
7	30	10	3	0.5	589.0	584.85	0.70
8	30	20	1	0.8	570.0	565.80	0.73
9	30	30	2	0.2	609.0	604.70	0.70

Table 11: Prediction accuracy of MRR

Run Order	Volt (v)	Concentration (g/l)	Workpiece material	Gap (mm)	MRR(mm^3/min) Exp.	MRR (mm^3/min) Pred.	Percent Error (%)
1	10	10	1	0.2	0.0472	0.04598	2.58
2	10	20	2	0.5	0.0300	0.03890	22.88
3	10	30	3	0.8	0.0400	0.03862	3.45
4	20	10	2	0.8	0.0472	0.04252	9.91
5	20	20	3	0.2	0.0600	0.05528	7.87
6	20	30	1	0.5	0.0787	0.07400	5.97
7	30	10	3	0.5	0.0650	0.06710	3.23
8	30	20	1	0.8	0.0566	0.05872	3.74
9	30	30	2	0.2	0.1024	0.10448	2.03

As can be observed in Figures (6 and 7) the normal probability plots were created for each mathematical model (power consumption and MRR) that was created. These charts evaluate the normal distribution of errors and the normality assumption. When the plot nearly approaches a red straight line, and the error distribution exhibits a normal pattern, there is a strong connection between the observed and the predicted values. As can be seen in the figures, there is a strong linear correlation because all of the data points are grouped along the upward regression line, with a small scatter around the line. Concerning MRR and power consumption, this result shows a positive correlation between the experimental and the projected values.

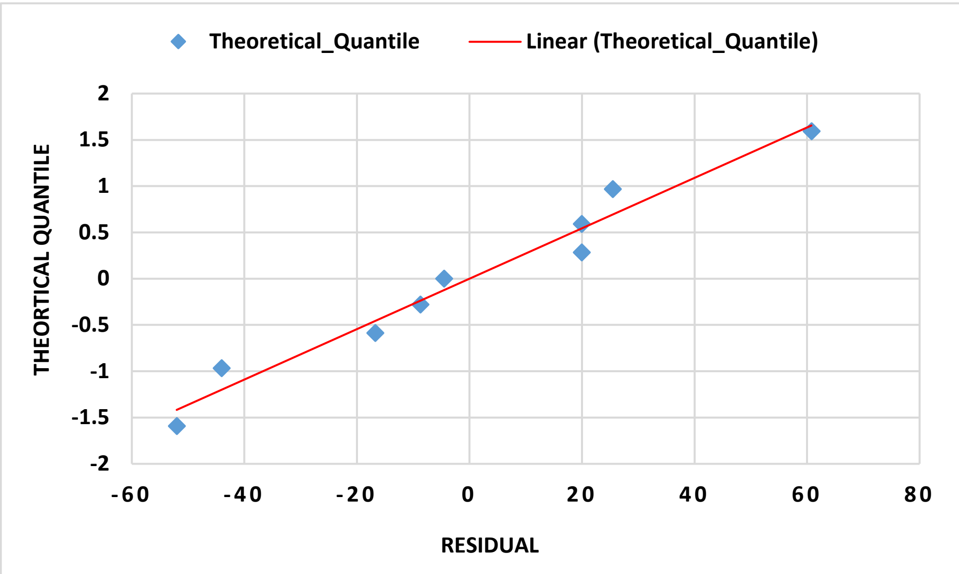


Figure 6: Normal probability for power

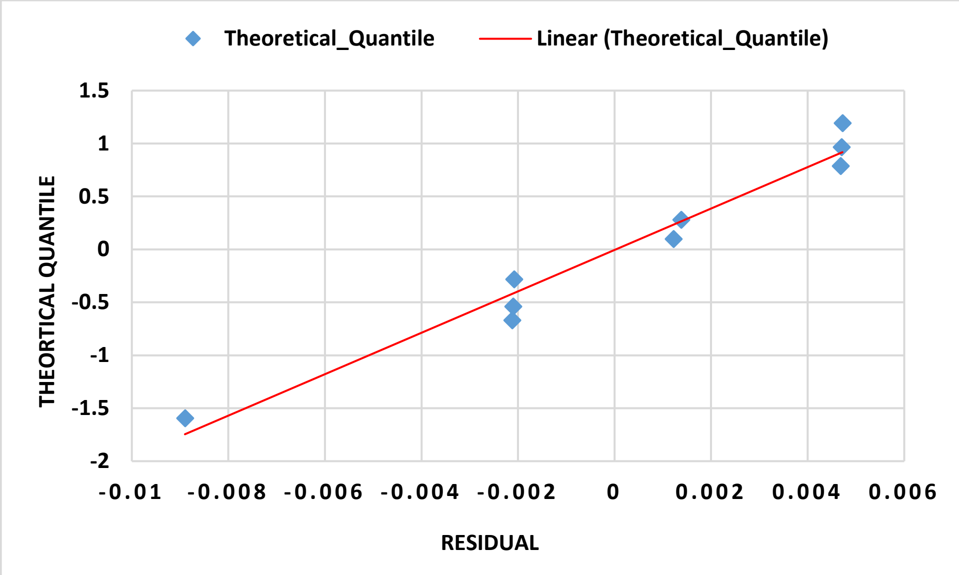


Figure 7: Normal probability for MRR

4. Conclusion

In this work, the conditions in the ECM process performance characteristics for every experiment were compared to analyze the impact of the machining parameters on the MRR and the power consumption. More specifically, the results from the tables and figures presented above indicate that:

1) Power consumption decreased at low voltage, and the minimum power was obtained in the Al6061 alloy at a voltage of 10 V, a concentration of 20 g/l, and a 0.5 mm gap.
2) The MRR increased in all experiments, and the maximum MRR was obtained in the Al6061 alloy at a high voltage of 30 V, a high concentration of 30 g/l, and a low gap of 0.2 mm.
3) The voltage and the workpiece material are the most important power-related parameters, whereas the gap and the concentration are the least important.
4) For the MRR, voltage and concentration are the most important parameters, while the gap and the workpiece material are the least important.

Since monitoring power consumption in manufacturing organizations helps reduce machine tool energy waste and, consequently, save costs, future research is needed to understand better how to reduce power consumption by changing machining parameters or adding additional factors during the process that contribute to reducing the amount of energy consumed, such as adding a magnetic field.

Author contributions

Conceptualization, **L. Salman, A. Ibrahim** and **B. Albaghdadi**; data curation, **L. Salman**.; formal analysis, **L. Salman**; investigation, **L. Salman**; methodology, **L. Salman, A. Ibrahim** and **B. Albaghdadi**; project administration, **L. Salman, A. Ibrahim** and **B. Albaghdadi**; resources, **L. Salman**.; software, **L. Salman**.; supervision, **A. Ibrahim** and **B. Albaghdadi**; validation, **L. Salman, A. Ibrahim** and **B. Albaghdadi**; visualization, **L. Salman, A. Ibrahim** and **B. Albaghdadi**; writing—original draft preparation, **L. Salman**; writing—review and editing, **L. Salman**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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