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The influence of magnetic field on the material removal rate in electrochemical machining process

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ABSTRACT

One of the most advanced techniques for dealing with metal is electrochemical machining (ECM). Objects that are hard or impossible to make with traditional machining techniques can be machined utilizing this method. However, in order to increase performance and economy, new ECM approaches must be developed because to the growing need for complex components in industries like aerospace, automotive, and medical devices. Thus, the main goal of this study is to ascertain how the ECM affects the material removal rate (MRR) in the presence of a magnetic field. In particular, the tool was composed of copper, and the workpiece was formed of aluminum 6061 alloy, Al-Sic, and Al-B4C using a stir casting technique. The voltage, gap, electrolyte concentration, and material type are among the input process factors that are changed during the experiment. The software used was Minitab to examine the results of the Taguchi design experiment, which employed orthogonal arrays. On the basis of the Taguchi design, the process parameters were improved. Specifically, four input variables were examined in this experiment, each having values at the three-factor level. According to the findings, the voltage was the most important factor. It contributed 50.12% for MRR without a magnetic field and 56.02% with one. The concentration came in second with 16.73% and 24.03% (without and with magnetic field), followed by the gap with 19.02 percent and 11.60% (without and with magnetic field), and the material type came in last with 1.35% and 0.57% (without and with magnetic field). Furthermore, the regression model's overall accuracy for the majority of experiments indicates that it is reasonably accurate with percent errors typically less than 1%.

Keywords: electrochemical machining; MRR, Taguchi technique, magnetic field, AMMCs.

INTRODUCTION

More demands on the functionality and efficiency of components have been placed on the industrial, energy, and medical technology sectors, which puts more pressure on the design of the associated manufacturing processes. Electrochemical machining provides many options to meet these needs. With regard to requirement-based removal localization, the process principles impose narrow limitations while maintaining high targeted removal rates. Current study indicates that the Magnetohydrodynamics effect (MHD) suggests that introducing a magnetic field to the surface of electrochemical processes can affect them. The field of research that combines fluid dynamics with electrodynamics is known as MHD. It deals with the situations when Lorentz forces, or the forces generated by magnetic field acting on a current-carrying conductor, influence the velocity of a fluid. As a result, the fluid needs to be capable of conducting current. This characteristic is present in varying degrees in ionized gases, salt water, and mercury [1]. A magnetic field was applied near the area being machined while electrochemical Ni deposition was taking place, according to

Bnud et al. [2]. Magneto hydrodynamic effects on electrochemical metal deposition are numerically simulated using three-dimensional geometry. The findings show that Lorentz forces in the electrolyte's bulk are the direct cause of the enhanced mass transfer, which has an immediate impact on electro crystallization. The accuracy of the machining process on S-03 special stainless steel in the presence of a magnetic field was examined by Tang et al. [3]. The experiments were conducted under the following magnetic field conditions: periodic, concentrated, and no magnetic field. The findings show that a strong magnetic field increases accuracy by 14.8% in comparison to a periodic magnet and 33.3% when compared to a circuit without a magnetic field. In order to examine the effects of a magnetic field, Yul et al. [4] changed an electrical process parameter. Without the use of chemical additives, cobalt thin films were formed from the electrolyte by combining magnetic fields with electric fields. The results of the investigation showed that when the intensity of the magnetic field increased, the mass of cobalt deposition and the steady state current decreased. A study by Bradley et al. [5] examined the effects of a magnetic field on the electrolyte's transit through the working gap and the machining outcomes. According to the study's findings, a magnetic field speeds up material removal and reduces surface roughness. Prasanna and colleagues [1] examined the impact of magnetic fields on electrochemical machining operations. It was discovered that the magneto hydrodynamic effect raises the machining rate while decreasing overcut. The commercial program COMSOL was utilized by Long et al. [6] to simulate the electrochemical reactions of ECM in the presence of a magnetic field. A magnetic field was applied to the aluminum alloy LY12's ECM. By aligning the magnetic field lines perpendicular to the water-based electrolyte flow field, the results showed that surface roughness decreases as the magnetic flux density increases. The effect of magnetic fields on the accuracy of micro-ECM machining was examined by Zhang et al. [7]. Different magnetic flux concentrations and magnetic field conditions are used for ECM. The findings demonstrated that micro electrochemical drilling's machining accuracy was increased by an external magnetic field oriented perpendicular to the feed direction. Liao et al. [8] used morphological observation and a range of electrochemical techniques to examine how electrochemical machining (ECM) affected the dissolving behavior of the Ti-48Al-2Cr-2Nb alloy both in the presence and absence of a magnetic field. Based on the findings, the use of a magnetic field increases the adsorption process's reaction rate, decreases the rate of dissolution, and inhibits the fluctuation of the current density during the electrochemical corrosion of alloy. This work focused on investigates the effect of magnetic field on the MRR for machining Al6061, Al-7.5%B4c, and Al-7.5%SIC in ECM. Taguchi designs were utilized to find the analytical procedure parameters, with four input factors: voltage, material type, electrolyte concentration, and gap (IEG).

EXPERIMENTAL WORK

Preparation of the materials

The alloy used to make the machined workpiece was Al6061. In this regard, Al6061 is among the most widely used materials in machining for a variety of sectors due to its exceptional machinability, strength, resistance to corrosion, and affordability. After they are produced, Al-7.5 %B4C and Al-7.5 %Sic workpiece material are also utilized together with Al-6061. In order to generate Al-7.5%Sic and Al-7.5%B4C, aluminum alloy 6061 was melted in a furnace that contained a crucible. The molten material was then mixed with 7.5% Sic powder for Al-SIC and 7.5% B4C powder for Al-B4C using a stir-casting technique at 750 °C. Stirring was maintained for three to five minutes following the addition of the powder. Next, as illustrated in Figure 1, 500 rpm portable drilling was employed for the stir-casting procedure. Specifically, Sic and B4c powders had typical particle sizes between 25 and 38 µm. The workpiece is specifically 26 × 20 × 5 mm in size. Furthermore, the experiment was conducted using a copper tool, which has a diameter of 12 mm and a length of 45 mm, because of its high electrical conductivity.

The used electrolyte

In this experiment, three different concentrations of NaCl electrolyte solution (10, 20, and 30 g/l) were utilized.

The used magnets

Neodymium magnets with a diameter of Ø50 were employed in this experiment. A digital gauss

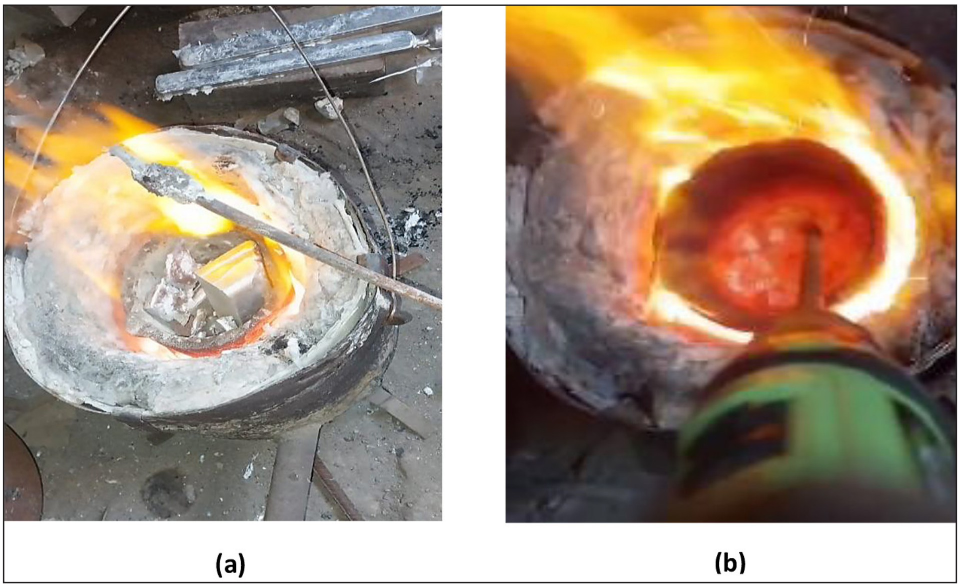

Figure 1. (a) Melting the aluminum alloy with powder (b) The stir casting using portable drilling

meter device was used to determine the magnetic flux density (T) of the magnet. This magnet's maximum observed flux density was 0.05 Tesla (T). The magnetic field is applied in the experiment parallel to the tool's axis of motion and perpendicular to the electrolyte flow. Two magnets are placed vertically and parallel to the work material, as shown in Figure 2. In each experiment, electrolyte is allowed to flow over the workpiece material, which is positioned between the gaps of two magnets facing one another. Next, the material is machined both with and without the use of a magnetic field.

Experimental setup

The Mark Super S TV1000 Drill was used to carry out the actual experiments. This machine had a number of significant modifications to become an electrochemical machine. In particular, the process was accomplished by adding a number of parts, such as a workpiece fixture to secure the workpiece, a DC multimeter device, a tank to contain the dielectric fluid, a water pump to recycle the dielectric fluid, a work table to mount the workpiece, and a tool holder to secure the electrode above the workpiece. Figure 3 displays the electrochemical machining parts used in the experiment.

Figure 2. Neodymium magnet

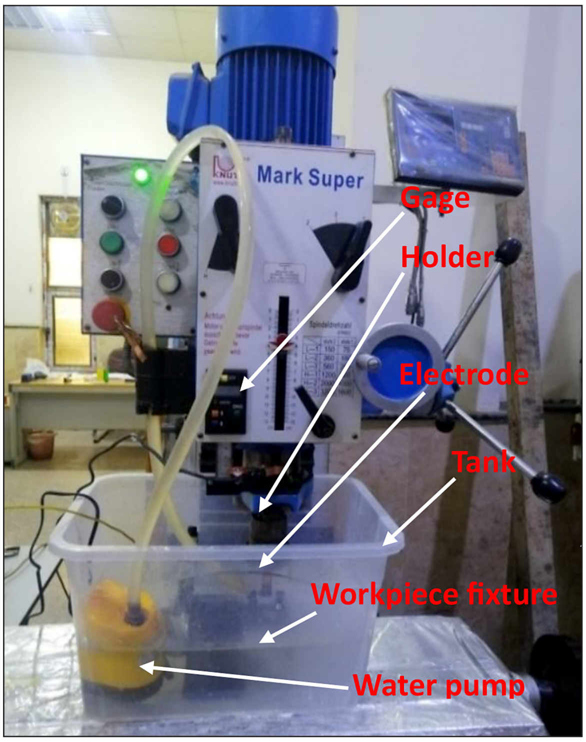

Figure 3. Electrochemical machining

Process parameters

The Minitab 17 program used a multi-level strategy to design the practical trials. The workpiece material, gap, concentration (g/l), and voltage (v) were the input factors with varying levels. Four independent variables, each with three-factor level values, were used in this experiment to examine their impacts using the L9 orthogonal array, as indicated in Table 1. These parameters were specifically examined to ascertain how they affected the MRR's responses. Table 2 displays the experimental findings and the machining input settings that were used. Each experiment in this table lasted five minutes to make sure the surface was machined.

RESULTS AND DISCUSSION

Machining parameters effect on the MRR

The MRR is a crucial performance indicator in ECM, influencing the machining efficiency, productivity, and quality of the machined components. MRR was measured without and with magnetic field as depicted in Figure 4 and 5. The results show that, significantly impacts the MRR in ECM. The voltage was measured 0.0390 at 10 V and increased to 0.0746 at 30 V. This higher MRR results from faster material dissolution at the anode (workpiece) and increased accure due to increased ion migration and electrochemical reaction rates [9]. When magnetic field was applied the MRR increased to 0.0449 at 10 V and increased to 0.097 at 30 V as show in Figure 5. The results indicated that, the effect of voltage on the MRR is influenced by the MHD effect, which enhances the ion transport and improves the overall machining efficiency at all voltage levels [10]. As shown in the same Figure, the electrolyte concentration has also affected the MRR without magnetic field. Specifically, it can be seen that the increase in the electrolyte concentration led to an increase in the MRR 0.053 at 10 g/l increased to 0.0737 at 30 g/l. This is due to the fact that the electrolyte concentration directly affects the ion transfer mechanism inside the machining gap. More specifically, raising the electrolyte concentration usually improves the solution's electrical conductivity, which in turn reduces the electrical resistance in the machining gap and increases the anodic dissolution's efficiency [7]. When magnetic field was applied the results show that the MRR was increased from 0.0554 at 10 g/l to 0.09 at 30 g/l as seen in Figure 5. The results indicated that, the MHD improved electrolyte dynamics and ion mobility when a magnetic field is applied. Conductivity and reaction efficiency are enhanced by the interaction between the magnetic field's Lorentz force and ion flow [11]. In essence, the MRR is significantly impacted by the type of material utilized in the ECM process, such as Al-6061,

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

Al-SiC, and Al-B4C. As the Figure 4 illustrates, the larger MRR was achieved for the Al6061 alloy at 0.0608 (mm^3/min) without magnetic field, because Al-6061 is a softer alloy and has a lower resistance to ion dissolution than composites like Al-SiC and Al-B4C, it usually exhibits a higher MRR. However, because of their slower anodic dissolution and higher surface resistance, Al-SiC and Al-B4C, which contain harder reinforcements (SiC and B4C), may have lower MRR under comparable machining conditions [12]. When magnetic field was applied this led to improved ion transport and electrolyte flow. From the Figure 5 the results show that the MRR was measured 0.0692 (mm^3/min) in Al6061 and increased to 0.0772 (mm^3/min) in Al-SiC then decreased to 0.0639 (mm^3/min) in Al-B4C, this indicated that Al6061 dissolved electrochemically with ease, but the magnetic field's ability to improve electrolyte flow and debris flushing is less significant due to the absence of strong reinforcements like SiC or B4C [13]. In comparison to Al6061, the hardness of the material was increased and electrical conductivity was decreased when SiC reinforcements are present, this is due to the Lorentz force that improved the removal of SiC particles and byproducts from the machining gap when it was subjected to a magnetic field, therefore because of its improved conductivity and modest resistance to dissolving, Al-SiC increases MRR.also because of B4C have a great hardness, minimal electrical conductivity, and low chemical reactivity, the removal of material was less efficient even with the magnetic field therefore it reduced MRR. [14]. So as show from the results, the influence of the magnetic field appeared in all tested materials and because of the composition of Al-SiC, the MRR was increased because Lorentz force that improved the removal of SiC. Additionally, Figure 4 displays the mean MRR with regard to the gap without a magnetic field. The results indicate that the MRR decreased as the gap size increased. In particular, because the electric field intensity is more concentrated and allows more effective

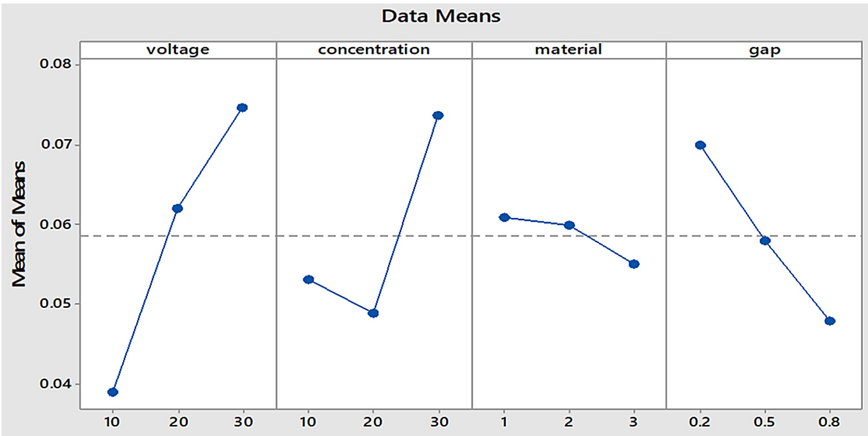

Figure 4. Main effects plot for MRR without magnetic field in ECM

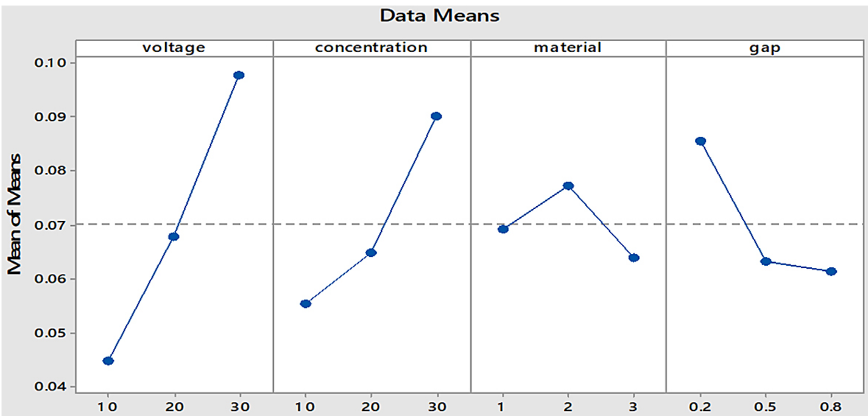

Figure 5. Main effects plot for MRR with magnetic field in ECM

electrochemical processes, a smaller gap usually produces a greater MRR [7]. The MRR typically falls when the gap increases to 0.8 mm. This result is caused by a reduced electric field, which makes the anodic dissolving process less effective. Consequently, the greatest MRR was at a gap of 0.2 mm, as seen in the Figure. When magnetic field was applied the MRR increased at all gap values compared to the condition without a magnetic field. This indicated that the magnetic field enhanced ion transport through the Lorentz force, improving conductivity and increasing the electrochemical reaction rate. At 0.2 mm, the MRR increased slightly because the ion transport is already efficient in a narrow gap. At 0.5 mm, the increased in MRR is more significant since the magnetic field helps counteract the electrolyte resistance due to the wider gap. At 0.8 mm, the MRR improves the most with the magnetic field since it compensates for the otherwise poor ion mobility in a large gap.

The Table 3 demonstrates that higher voltage, electrolyte concentration, and smaller gap size improved MRR in ECM for both with and without the magnetic field. as show from the table, the magnetic field generally raised MRR, which indicated that it could improve the efficiency of material removal, possibly through better heat distribution or enhanced movement or behavior of charged particles. As show from the results there was a higher MRR across all conditions, because the magnetic field enhances ion transport and debris removal so the best conditions (Run 9: 30 V, 30 g/L, 0.2 mm gap, Al-SiC) result in the highest MRR (0.1400 mm³/min) with a magnetic field. Figure 6 shows the MRR with and without magnetic field of the experiments (1 to 9) and the results showed that, in every experiment, the orange line is consistently above the blue line, indicating that the magnetic field increases the MRR. Lorentz forces are produced by a magnetic field, and they improve electrolyte flow. As a result, machining efficiency is improved by removing reaction by-products including hydrogen bubbles and metal hydroxides.

Analysis of variance (ANOVA)

The data on the analysis of variance (ANOVA) for the MRR of ECM with and without a magnetic

Table 3. The ECM parameters' results

Run order	Volt (V)	Concentration (g/l)	Workpiece material	Gap (mm)	MRR without magnetic field (mm³/min)	MRR with magnetic field (mm³/min)
1	10	10	1	0.2	0.0472	0.0491
2	10	20	2	0.5	0.0300	0.0400
3	10	30	3	0.8	0.0400	0.0500
4	20	10	2	0.8	0.0472	0.0516
5	20	20	3	0.2	0.0600	0.0718
6	20	30	1	0.5	0.0787	0.0800
7	30	10	3	0.5	0.0650	0.0700
8	30	20	1	0.8	0.0566	0.0830
9	30	30	2	0.2	0.1024	0.1400

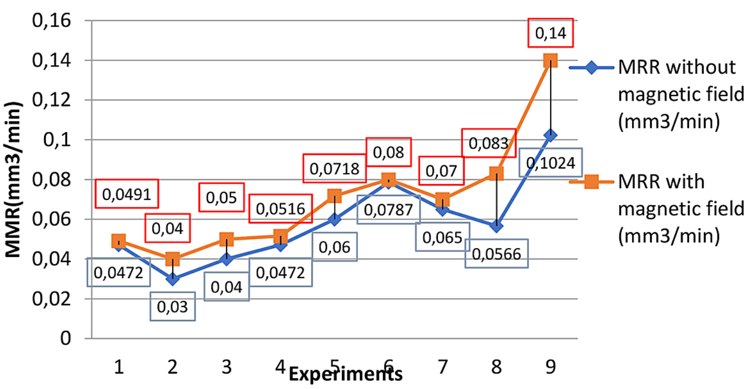

Figure 6. MRR results with and without magnetic field

Table 4. The ANOVA table for the measured MRR without magnetic field

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			

field are shown in Tables 4 and 5. Based on these tables, Minitab's analysis of variance results for the observed MRR revealed that the voltage is the primary factor influencing the response when examining the regression model of the data. More specifically, the findings show that the voltage contributes the most to MRR without a magnetic field (50.12%) and with a magnetic field (56.02%). The MRR response for means is shown in Tables 6 and 7. The most and least significant parameters for the MRR are displayed in these tables. It is evident that the most important factor influencing MRR is voltage, and that this influence grows considerably as the magnetic field increases. The second most important factor is electrolyte concentration, which enhances electrochemical reactions and ion conductivity. Gap size has a moderate impact; higher MRR is produced by smaller gaps. Al-SiC gains the most from the magnetic field, while workpiece material is least affected. So, the magnetic field enhanced the overall effect of the input parameters, leading to improved MRR. Therefore, the following machining parameters in Table 6 might be used to forecast the optimal MRR performance with magnetic field using the data previously provided.

Predicting the optimum value of MRR response

Based on the methods outlined below, the optimality search model was developed for the different process variable settings in order to optimize the MRR value of different machined workpieces. The relationship between the parameters of the input variables and the results of the machining process was determined and investigated using regression analysis. The best combination of machining parameters and their combined impacts on the desired response criteria can be found by using Equations 1 and 2 to correlate

Table 5. The ANOVA table for the measured MRR with magnetic field

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	4	0.006867	0.001717	11.86	0.017
Voltage	1	0.004171	0.004171	28.82	0.006
Concentration	1	0.001789	0.001789	12.36	0.025
Material	1	0.000043	0.000043	0.29	0.616
Gap	1	0.000864	0.000864	5.97	0.071
Error	4	0.000579	0.000145		
Total	8				

Table 6. Response table of means for MRR without magnetic field

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

Table 7. Response table of means for MRR with magnetic field

Level	Voltage A	Concentration B	Material C	Gap D
1	0.04493	0.05547	0.06927	0.08553
2	0.06780	0.06493	0.07720	0.06333
3	0.09767	0.09000	0.06393	0.06153
Delta	0.05273	0.03453	0.01327	0.02400
Rank	1	2	4	3

the effects of the various process variables on the MRR without and with magnetic field. The mathematical correlation between the MRR without magnetic field and the process variables under consideration has been obtained as follows:

$$MRR(mm^3/min) = 0.1082 - 0.00465\,X1 - 0.00068\,X2 - 0.0490\,X3 + 0.0184\,X4 + 0.000107\,X1 \times X2 + 0.00223\,X1 \times X3 + 0.00034\,X2 \times X3 \quad (1)$$

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

$$MRR(mm^3/min) = 0.10962 - 0.004362\,X1 - 0.003208\,X2 - 0.037438\,X3 + 0.021333\,X4 + 0.000213\,X1 \times X2 + 0.001549\,X1 \times X3 + 0.000723\,X2 \times X3 \quad (2)$$

where: $X1$ – voltage (V), $X2$ – concentration (g/l), $X3$ – material, $X4$ – gap (mm).

There are Figures in the model summary that illustrate how well various models fit the data. Accordingly, the R-Square (R-Sq), the coefficient of determination, can be used to assess the regression model's efficacy. In the model, the number of terms is multiplied by the adjusted R to get the adjusted R-squared R-sq(adj). In general, the model fits the data better when the R-Square value is higher. Tables 8 and 9 provide the $R2$ values and $R2adj$ for the mathematical models that were created for MRR with magnetic field. From the models the results show that, the machining model was significantly improved by the magnetic field, which makes it more capable of explaining and forecasting MRR changes. The most significant finding was the rise in R-sq(pred) from 40.88% to 57.11%, demonstrating that the magnetic field produced a more stable and dependable material removal process.

Table 8. Model summary of MRR without magnetic field for the machining variables

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

Table 9. Model summary of MRR with magnetic field for the machining variables

S	R-sq	R-sq (adj)	R-sq (pred)
0.0120310	92.22%	84.45%	57.11%

Table 10. Prediction accuracy of MMR with magnetic field

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	0.0491	0.0448	8.75
2	10	20	2	0.5	0.0400	0.0401	0.25
3	10	30	3	0.8	0.0500	0.0500	0.00
4	20	10	2	0.8	0.0516	0.0515	0.19
5	20	20	3	0.2	0.0718	0.0717	0.14
6	20	30	1	0.5	0.0800	0.0798	0.25
7	30	10	3	0.5	0.0700	0.0710	1.43
8	30	20	1	0.8	0.0830	0.0841	1.33
9	30	30	2	0.2	0.1400	0.1399	0.07

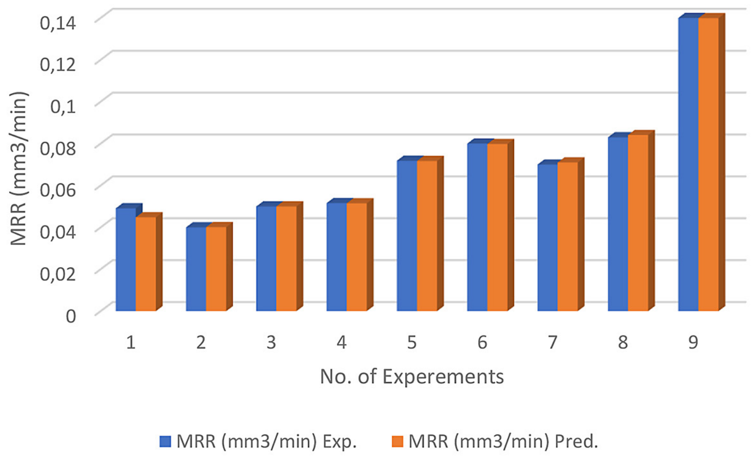

Figure 7. Experimental and predicted value of MRR with magnetic field

Since the results improved when using a magnetic field, so the accuracy of the Equation 2 mentioned above was evaluated and also the expected values of the MRR by applied magnetic field were calculated. Accordingly, the predictive accuracy of the generated model has been shown to be adequate. Table 10 show how the predicted and the observed values compare for the MRR. the table indicated that, With percent errors typically less than 1%, the regression model's overall accuracy for the majority of experiments (except for from Experiment 1) indicates that it is reasonably accurate. The experimental and predicted value of MRR with magnetic field show in Figure 7, which indicated that there is a greater agreement in points between the two bars of experimental and predicted values.

CONCLUSION

The impact of the machining settings on the MRR with and without magnetic was analyzed in this work by comparing the conditions in the ECM process performance characteristics for each experiment. The experiment's findings demonstrate that applying a magnetic field using a permanent neodymium magnet has a significant impact on the electrochemical processes that occur between the charged work material and the electrolyte. The flow of positive ions (cations) from the work material and electrons from the tool is accelerated by the induced current created by the electrolyte's interaction with the magnetic field. Metal ions, in this case aluminum Al6061, deposit onto the tool more quickly as a result of the increased ion mobility. This phenomenon, which is typified by the magnetohydrodynamic effect, demonstrates that the magnetic field can successfully change the rate at which ions flow and, as a result, the electrochemical deposition process's efficiency. In a variety of commercial and scientific applications, the results highlight the possibility of using magnetic fields to optimize the MRR and regulate electrochemical processes.

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