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Investigation and optimization of machining parameters in electrochemical machining of aluminium metal matrix composites

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ABSTRACT

Metal matrix composites (MMCs) have been increasingly used in industries, nuclear plant, and automobiles due to their superior properties compared to other alloys, and that is owing to the tough and abrasive hard reinforced particles. It's complicated to machine hard materials by traditional processes methods, therefore the present study focused on the investigation of parameters in electrochemical machining (ECM) like electrolyte concentration (EC), voltage(V), and Inter-electrode gap (IEG) on the radial over cut (ROC) and material removal rate (MRR) in the ECM of Al-7.5%B_4C. Stir casting method was used to fabricate metal matrix composites. Based on Taguchi design, the process parameters were optimized. A Multiple Regression Model (MRM) was employed as model for radial over cut and material removal rate. The mathematical model was examined using analysis of variance (ANOVA). The EC 10 g/L, V 10 v, and IEG 0.3 mm are the optimal parametric combination for ROC. Also, the EC 30 g/L, V 18 V, and IEG 0.2 mm are the optimal parametric combination for MRR.

Keywords: Electrochemical process, Metal matrix composites, radial over cut, material removal rate

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1. Introduction

The demand for composites materials has increased in various applications, such as automobile industries, aerospace, and biomedical. Aluminum-based composites materials are widely used because to their characteristics, like improved hardness, high wear resistance, good strength, low thermal expansion coefficient, etc. Because they possess a reinforcement strength and higher hardness, metal matrix composites are difficult to be machined by conventional machines [1-3]. High-hardness silicon and boron carbide, or aluminum oxide abrasive particles are used as reinforcing materials for aluminum alloys although their operating costs are high for machining these types of materials [4]. The machining of composite materials is receiving great attention due to the high tool wear associated with machining. Conventional operations, such as turning, shaping, planning, milling, and broaching of composite materials reinforced with carbon nanotubes or alumina abrasive particles are very hard due to their excessive abrasive characteristics [5, 6]. There are several processes of non-traditional processes, like chemical etching, ECM, abrasive flow machine, ultrasonic machine, and magnetic abrasive finishing which are widely used for the industrial processes. Electrochemical machining becomes a more applicable method for machining in advanced manufacturing processes due to their unique characteristics, like low cost, high machining efficiency,, hence the process of (ECM) [7]. According to Faraday's theory, and by the mechanism of anodic dissolution, MRR from the workpiece. The main benefits of using ECM, as shown in Fig. 1, are appropriate for operating difficult and complex materials, regardless of their strength and hardness. In addition, high MRR can be obtained, as well as a good surface quality and a high machining accuracy. No tool wear is in this operation because only the bubbles of hydrogen are released on the tool surface [9]. Electrochemical machining is used in mass production to reduce the cost.

Figure 1. The main benefits of using ECM

In addition, electrochemical machining also has some disadvantages. Manufacturing precision and operating stability are difficult to control since then. Applications of this process extend to electrochemical grinding (ECG), drilling and deburring. In modern researches, there have been three main areas of focus of electrochemical machining researchers. The first area is the operational precision of electrochemical machinery, which focuses on improving the surface quality and processing precision in the ECM. Such as parameter optimization and prediction, process calculation and simulation, the instrument shape design and flow field are the major objectives of the work. The objective is to enhance the conditions of electrolyte flow in the IEG and piece, maintain small and stable gaps to achieve the higher fabrication precision, and enhance the localization of anodic atomization, better process stability, and good surface finish. The second area is the fine electrochemical machines in which the surface structures and fine metallic parts can be achieved and by using an electrolyte solution and high-frequency pulsed energy to enhance the localization of the melt [10, 11]. Finally, a hybrid electrochemical treatment, in which the electrochemical machines are combined with each other with different types of energy, is to improve the advantages of electrochemical machining and other processes and reduce the potential drawbacks of a single technology. Electrochemical discharge machines (ECDMs) are a good example [12, 13]. J. Muda et al. focused on the electrochemical micromachining by using (RSM) approach with taking radial over cut and material removal rate as separate objective measures [14]. S. Rama Rao et al investigated a mathematical model depend on the MRR surface response methodology; on samples of Aluminium Casting Alloy (LM6) reinforcement by boron carbide (MMCs) produced using the stir casting process in the ECM process [15]. A Giribabu et al studied the parameters for electrochemical machining of Al/B_4C (MMCs) with orthogonal array in Taguchi method and genetic algorithms[16].G. Ganesan et al. used (RSM) to develop and enhance the mathematical models in ECM for LM25 Al -10% SiC composites materials [17]. D. Chakra and V. Gopal utilized the multi-objective optimization of the ECM examined by analyzing the gray relationship while using EN31 steel as workpiece with the EC, V, and feed rate as machining conditions [18]. T. Rajmohan conducted the enhancement in ECM of Al/SiC composites to reduce the surface roughness, thrust, tool wear and ledge height using Taguchi Gray Relationship Analysis (TGRA) taking into account multiple performance characteristics [19]. Rama Rao et al. used evolutionary algorithms and Taguchi technique to model the electrochemical machining by considering the electrolyte concentration, voltage, current, , gap and feed rate as dependent variables (surface roughness, radial over cut, and material removal rate) as independent variables for the process [20, 21]. Therefore, this paper deals with the fabrication of Al-7.5%B_4C composites. Process parameter optimization depends on the analysis methods with three input factors, such as the concentration of electrolyte, voltage, and gap (IEG) on the radial over cut and the material removal rate in electrochemical drilling (ECMD) on composite materials. ANOVA was used to develop an important model to examine the efficiency of the developed mathematical model.

2. Design of experimental (DOE)

Genichi Taguchi suggested a method is called Taguchi technique. The biggest advantage of this method is the reduction in the number of tests, therefore reducing the conducting experimental time and the cost of conducting

it. It's widely used in the statistical engineering analysis [20]. Experimental design is used with a combination of the concept of the quality loss function so as to obtain strong designs for processes conditions and product [21]. The results of experiment are modified into signal to noise (S/N) ratio, which works to determine the quality properties deviated or close to the required values. Analysis of the quality characteristics includes several classifications, nominal is the best, higher is the best, and smaller is the best [22].
The equation employed to determine the signal to noise to obtain the smallest ROC is:

$$S/N = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}(y^2)\right] \quad (1)$$

The equation employed to determine the signal to noise to obtain the highest removal rate is:

$$S/N = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}(1/y_i^2)\right]; i = 1,2, \dots \dots . n \quad (2)$$

Where, n represents the iterations number, and y_i is the observed response. Three factors were used in this paper to monitoring the degree of the effect of the processing parameters in electrochemical machines, machining parameters for experimental work is shown in Table 1.

Table1. Factors and their levels of electrochemical drilling

No.	Process parameters	Code	Level 1	Level 2	Level 3
1	EC (g/l)	A	10	20	30
2	V (v)	B	10	14	18
3	IEG (mm)	C	0.1	0.2	0.3

3. Experimental procedure

The tool used in the tests was brass tool with a circular cross section and the composition of electode is presented in Table 2. NaCl was used as the electrolye solution for experiment, due to the fact that the electrolyte sodium chloride is inexpensive, and available [23]. The tank of electrolyte was filled with the NaCl and supplied to the machining unit by pump with flow rate 10 L/min. The test specimens of aluminum alloy have the chemical composition shown in Table 3. The specimens reinforced with 7.5 weight percent of boron carbide were fabricated by stir casting technique Fig.2. In this paper, Al 6061 was used as a matrix and B_4C as a filler material.

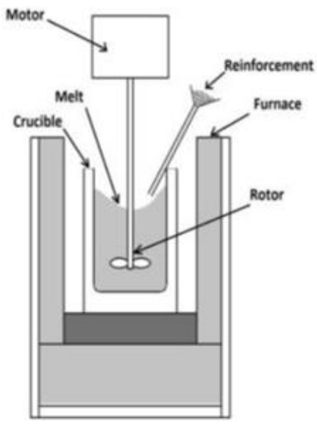

Figure 2. Stir casting principle

The aluminum alloy was melted, and B_4C powder mixture was preheated at 750°C for 1 hour to eject gases and moisture to escape from the particle surface. [24]. The preheated B_4Cparticle powder (7.5%) was added to the melted material. Stirring was continued for 10 min after the addition of B4C powder to get better distribution. The slag was removed and aluminum melt was poured in the graphite molds. By mechanical stirring an intermittent stiffener was whiskered into the molten metal which was allowed to solidify. Figure 3 shows the stir casting by portable drilling at 600 rpm. The properties of MMCs are strongly depends on the strength of the interfacial bonding of the reinforcement and the phase of the matrix [25]. The specimens of experiments have dimensions 40 mm, 20mm, 0.7mm length, breadth and thickness respectively.

Figure 3. Stir casting process

Table 2. Composition of brass cathode

Element	Zin	Sn	Pb	S	As	Bi	Sb	Cu
Weight%	35.5	0.157	1.7	0.009	0.008	0.006	0.03	remain

Table3. Composition of Aluminum alloy

Metal	Zn%	Mg%	Cu%	Si%	Fe%	Mn%	Cr%	Ni%	AL%
Aluminum alloy	5.57	2.17	1.84	0.059	0.206	0.206	0.190	0.001	remain

By varying the predominant variables, the perceptions were made, such as concentration of electrolyte, applied voltage, and gap. By using vernier caliper, the diameter of drilled hole was measured, and the ROC was determined by this formula:

Radial Over Cut = (Dh – De) / 2 (3)

Where:

Dh: Diam. of the hole on the workpiece surface (mm)

De: Diameter of the brass tool electrode (mm)

MRR was measured from by the difference between the weights as:

Material removal rate = $(W_1 - W_2)/T$ (4)

Where, W_1,W_2 is the weight (gm) before and after machine respectively, and T is the process time (min)[26]. The electrochemical machining was used for the experimental work, as shown in Fig. 4.

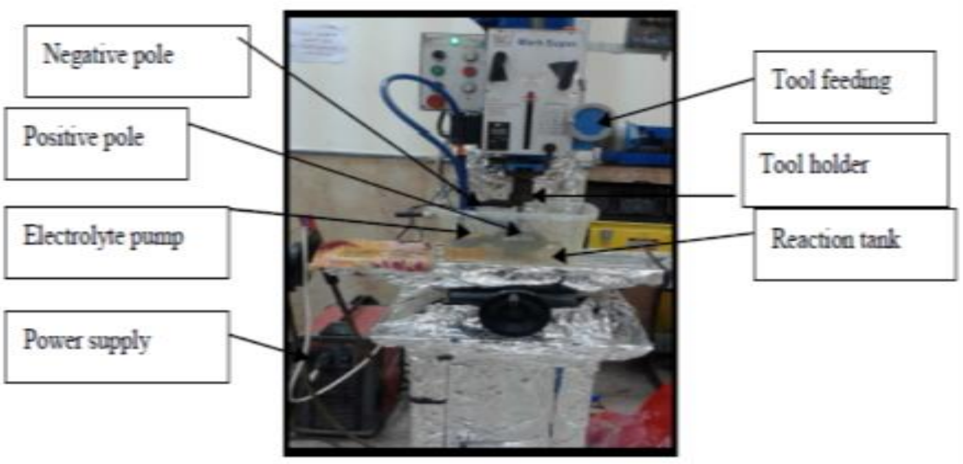

Figure 4. Electrochemical machining

By the digital weighing machine, the weights of the samples were measured by the weight losses after each experiment. Taguchi standard set orthogonal from L_9 (3^4) was used. This array was used with the machining conditions used in this paper and their levels set for each test, as listed in Table 4.

Table 4. Experimental results for response parameters

No.	Parameters Coded A	B	C	Parameters of ECM Electrolyte Con (g/L)	Voltage (volt)	IEG (mm)	ROC (mm)	MRR (gm/min)	S/N For ROC	S/N For MRR
1	1	1	1	10	10	0.1	0.841	0.517	1.50408	-5.73019
2	1	2	2	10	14	0.2	0.934	0.488	0.59306	-6.23160
3	1	3	3	10	18	0.3	0.997	0.421	0.02610	-7.51436
4	2	1	2	20	10	0.2	0.894	0.453	0.97325	-6.87804
5	2	2	3	20	14	0.3	0.922	0.449	0.70538	-6.95507
6	2	3	1	20	18	0.1	1.245	0.468	-1.90339	-6.59508
7	3	1	3	30	10	0.3	1.175	0.475	-1.40076	-6.46613
8	3	2	1	30	14	0.1	1.288	0.489	-2.19832	-6.21382
9	3	3	2	30	18	0.2	1.269	0.574	-2.06923	-4.82176

4. Analysis of variance (ANOVA)

Analysis of disparity is a tool utilized to calculate the influences of the various parameter level combinations through an analysis of their variability [27]. Tables 5 and 6 indicate the information of ANOVA for the ROC and removal rate of ECM. It's represented that the advanced paradigm is important, and their own mathematical paradigm is also indicated in the eq. 5 and 6. The value of F ratio represents the test statistic for each source. It is used to measure the statistical indication of a given factor for the experiment as a whole. The indication or no indication parameter on the responses is represented by P-value [28]. While the percent contribution for each machining parameters can be defined as the contribution rate on the radial over cut and the material removal rate.

Table 5. Analysis for radial over cut

Source	DF	Seq. SS	SS	MS	F	P
Concentration%	2	10.6504	10.6504	5.3252	7.85	0.113
Volt	2	4.2689	4.2689	2.1344	3.15	0.241
Gap	2	0.9038	0.9038	0.4519	0.67	0.600
Residual Error	2	1.3567	1.3567	0.6783	/	/
Total	8	17.1797	/	/	/	/

ROC = 0.392 + 0.01600 Electrolyte concentration (g/l) + 0.02504 Applied voltage (v) (5)

Table 6. Analysis for removal rate

Source	DF	Seq. SS	SS	MS	F	P
Concentration%	2	1.48545	1.48545	0.74273	0.92	0.521
Volt	2	0.03857	0.03857	0.01928	0.02	0.977
Gap	2	1.68192	1.68192	0.84096	1.04	0.490
Residual Error	2	1.61323	1.61323	0.80661	/	/
Total	8	4.81917	/	/	/	/

MRR = 0.8151 - 0.030292 Electrolyte concentration (g/l) - 0.01496 Applied voltage(v)+ 0.2058 IEG(mm) + 0.000373 [Electrolyte concentration(g/l)]^2 - 1.675 [IEG(mm]^2+ 0.000921 Electrolyte concentration(g/l)*Applied voltage(v)+ 0.02167 Electrolyte concentration(g/l)*IEG(mm) (6)

SS is the variation, and MS is the variance.
The best performance occurs when S/N ratio was high. Thus, the higher level (S/N) indicate to the optimum level for a parameter and it permanently indicate the best characteristics quality with low variance [29]. The response table for the means of ROC obtained for the varying processing levels of parameter as shown in Table 7, and it can be seen that $A_1B_1C_1$ represents the best level combination of low ROC, and the (V) has larger influence on the ROC followed by the (EC) and (IEG). As well, it can be observed in Table 8 that $A_3B_1C_1$ is the optimal level combination to maximum MRR, and the gap has the greater influence on the MRR than the electrolyte concentration and voltage.

Table 7. Response for means of ROC

Level	Concentration%	Volt	Gap
1	0.9240	0.9700	1.1247
2	1.0203	1.0480	1.0323
3	1.2440	1.1703	1.0313
Delta	0.3200	0.2003	0.0933
Rank	1	2	3

Table 8. Response for means of MRR

Level	Concentration%	Volt	Gap
1	0.4753	0.4817	0.4913
2	0.4567	0.4753	0.5050
3	0.5127	0.4877	0.4483
Delta	0.0560	0.0123	0.0567
Rank	2	3	1

5. Analysis and discussion the results

The obtained results from experimental work are shown in the Tables 4. ROC and MRR were analyzed in accordance with the input factors, i.e. concentration of electrolyte, voltage and gap. Nine experiments were conducted according to the Taguchi design.

5.1 Analysis of ECM parameters on radial over cut

The influence of different machining factors on the ROC in the ECMD of Al-7.5%B_4C composites is shown in Figure 5. And, depending on the mathematical model in equation (5), the effects of different processing parameters were performed on the radial over cut for the purpose of achieving the control of it.

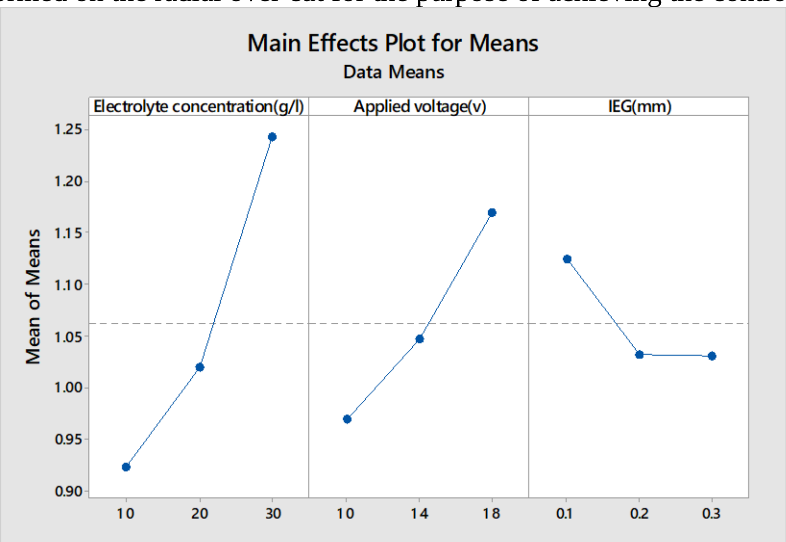

Figure 5. Influence of electrolyte concentration, voltage, and IEG on the ROC

The increase in concentration of electrolyte causes increasing in ROC. Also, the increases in electrolyte concentration lead to precipitation at a higher concentration electrolyte and lead to forming the bubbles of oxygen, hydrogen, etc. These influences result in the increasing flow of current to the cutting zone of machining process therefore raises the radial over cut. Elevations in (V) increase the current of electrolytic in the gap and increase the stray density of current, which results in higher ROC. A rises in the (V) value due to a rises in the electrolytic current in the IEG and a rises in the intensity of the stray current, resulting in higher radial over cut. A great number of the IEG leads to decrease the current in the cutting zone and thus causes a decrease in ROC.Figure6 manifests the relationship between electrolyte concentration and voltage on the radial over cut. ROC is increasing with increasing electrolyte concentration and voltage. The minimum value of ROC occurred at 10 g/l of electrolyte concentration and 10volt, while the maximum value occurred at 30 g/l and 14 volt. From figure 7, the influence of EC and IEG on the ROC indicates the minimum value of ROC at 10 gm/l and 0.1 mm IEG, while the maximum value is at 30 gm/l and 0.1 mm.

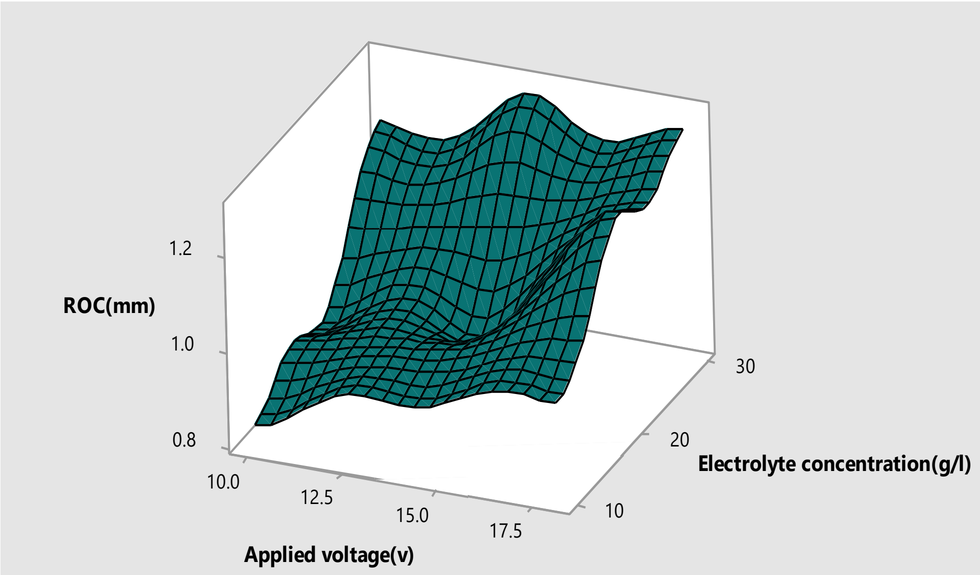

Figure 6. Relationship among radial over cut, electrolyte concentration, and voltage

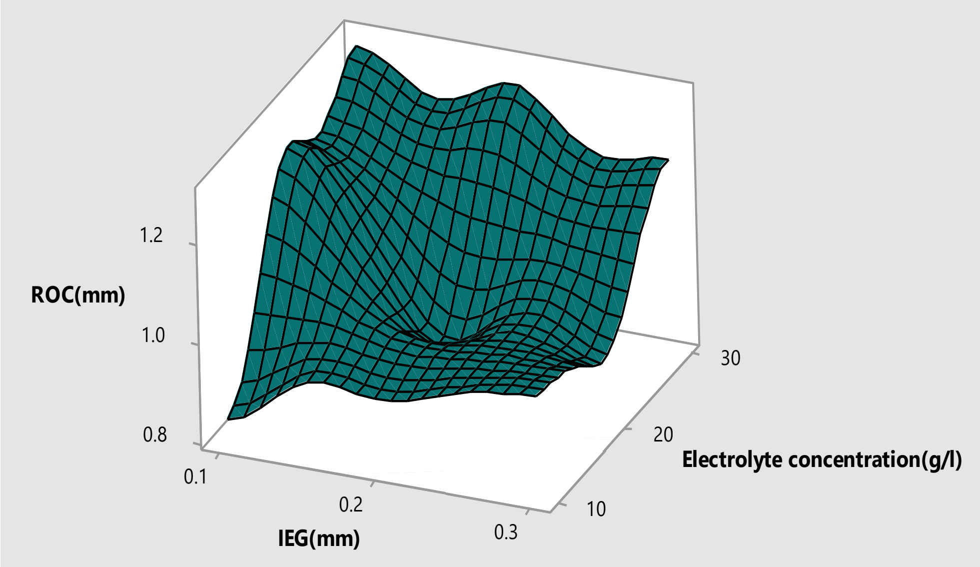

Figure 7. Relationship among radial over cut, concentration and gap

The minimum ROC value occurred at the lowest value of IEG and voltage, while the maximum ROC value occurred at 0.1 mm of IEG and 14 volt, Figure 8.

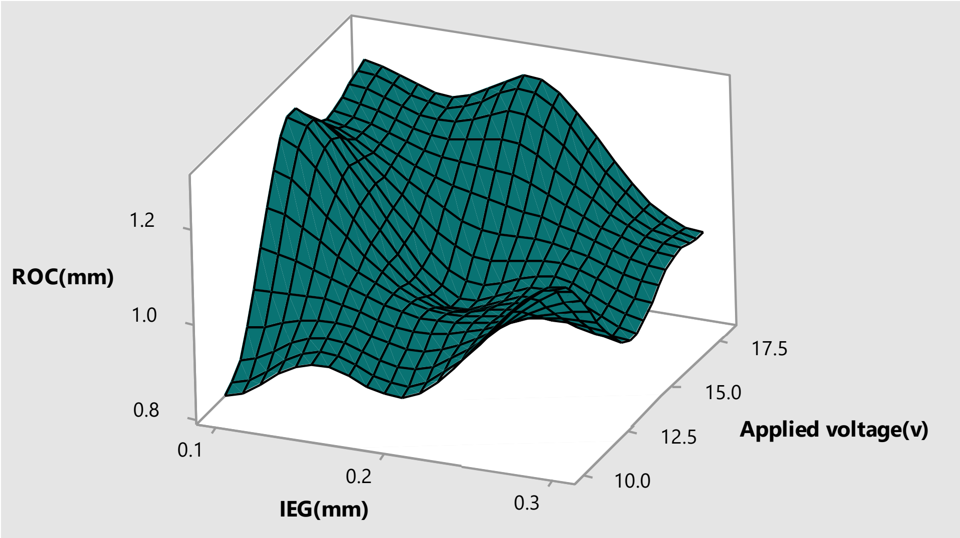

Figure 8. Relationship among radial over cut, inter electrode gap and voltage

5.2 Analysis of ECM factors on material removal rate

Figure 9 evinces the influence of various factors on the removal rate, and depends on the mathematical model in equation (6) in order to control MRR, the influences of different machining variables on the MRR took place. It can be seen that a rises in the EC lead to a rises in the MRR. This result could indicate an augmentation in the conductivity of the electrolyte solution as the concentration was increased due to the augmentation in the machining current in IEG. Any rises in the voltage value results in the stability of the process at a high voltage and the decrease in the MRR in the lateral direction of the hole. As well, the increase in IEG causes a decrease in MRR, due to the stabilization of the process on increased IEG and reduced removal rate in the lateral direction of the hole.

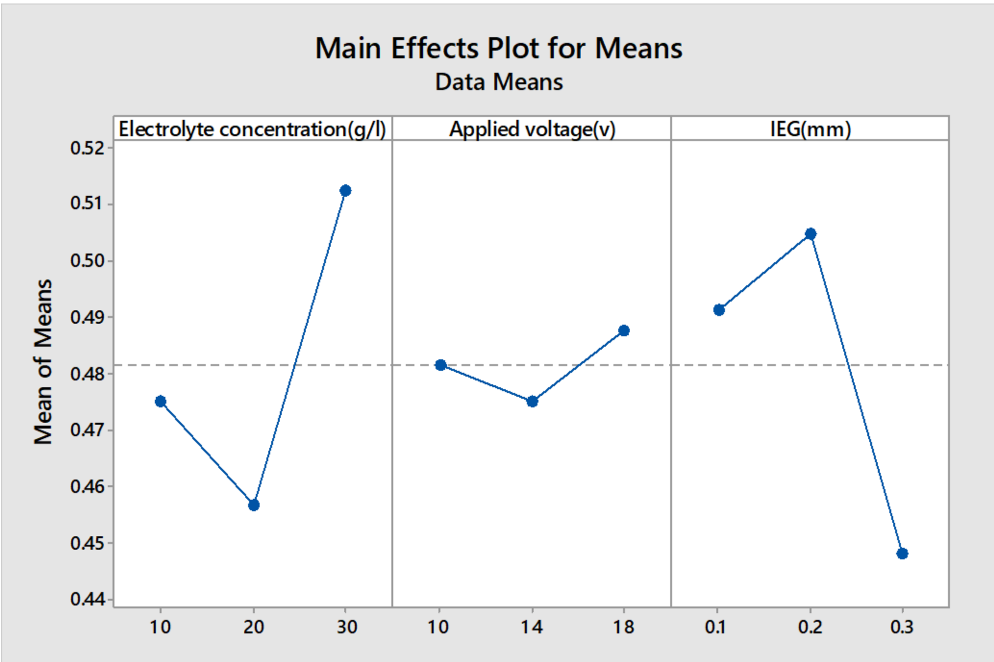

Figure 9. Influence of EC, V, and IEG on the removal rate

The effect of the V and the EC on the removal rate is shown in figure 10. With increasing the voltage, the value of the MRR decreases, while when increasing the concentration of electrolyte. The value of the MRR increases and the highest MRR is at the highest voltage value (18 volt) and the highest electrolyte concentration (30 g/l), while the lowest value of the MRR is at the highest voltage value (18 volt) and the lowest electrolyte concentration (10 g/l).

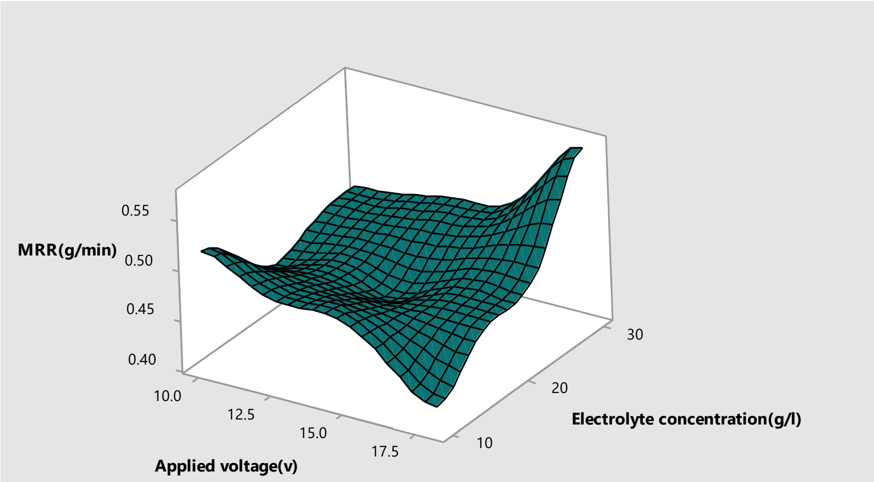

Figure 10. Relationship among material removal rate, Voltage and EC

From Figure 11, when the IEG value increases, the MRR decreases, and that the highest value of the MRR occurred at the gap value (0.2 mm) and the EC (30 g/l), and the lowest value for the MRR is at the highest gap (0.3 mm) and the lowest electrolyte concentration (10 g/l).

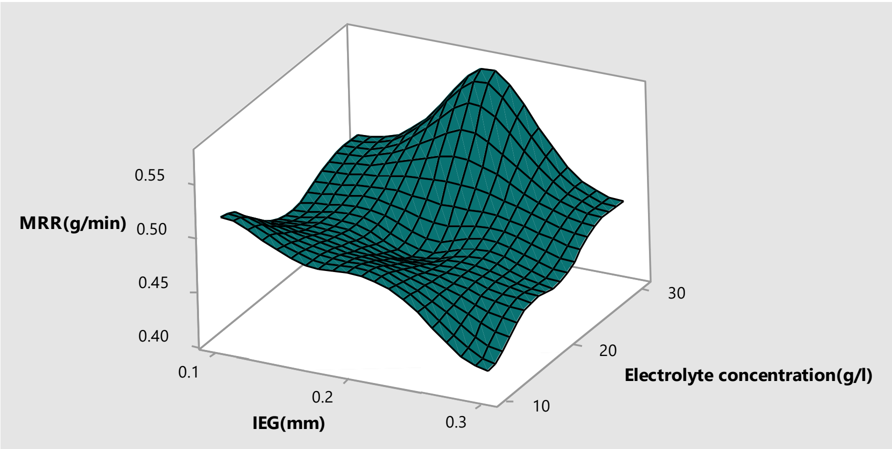

Figure 11. Relationship among material removal rate, inter electrode gap and electrolyte concentration.

From Figure 12, the highest MRR is at the highest voltage value (18 volt) and at a gap value (0.2 mm), and the lowest MRR is at the highest voltage value (10 volt) and the highest gap value (0.2 mm).

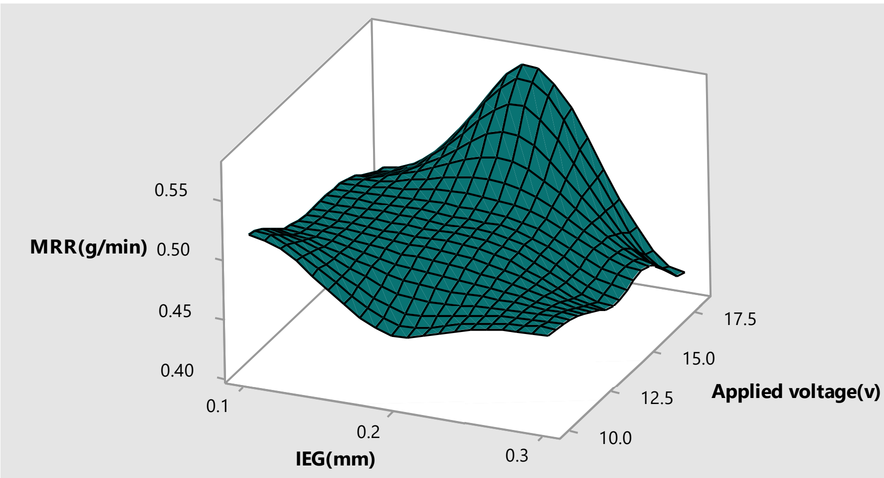

Figure 12. Relationship among material removal rate, inter electrode gap and electrolyte concentration.

5.3. Estimation of the optimum response characteristics for (ROC)

From Figure 5 and Table 5, it is clear that the optimal parameters collection for min. ROC is $A_1B_1C_3$, i.e. at (10 g/L) EC, (10 V) voltage, and (0.3 mm) IEG. It is suggested that the combination of parameters within the studied range as mentioned above gives the lowest level ROC. By the aforementioned data, one could predict the optimum ROC performance using machining factors as:

Predicted mean (ROC) = A1+B1+C3-2 (average mean) (7)

From Table 7,

Predicted mean (ROC) =0.9240+0.9700+1.0313-2(1.063) = 0.799 mm

5.4 Estimation of the optimum response characteristics for (MRR)

From Fig. 9 and Table 6, it is clear that the optimal parameters collection for max. MRR is A3B3C2, i.e. at (30 g/L) EC, (18 V) voltage, and (0.2 mm) IEG.

Predicted mean (MRR) = A3+B3+C2-2 (average mean) (8)

From Table 8,

Predicted mean (MRR) = 0.5127+0.4877 +0.5050-2(0.482) = 0.5414 g/min

6. Conclusions

The aluminum workpieces is manufactured and reinforced by boron carbide powder using the stir-casting method. A mathematical model of the response has been developed ROC and MRR using Taguchi method and model was analyzed utilize ANOVA for investigating the impact of factors on the MRR, and ROC values in the ECM of Al/B_4C composites, the following can be concluded:

1. Development of a mathematical model to predict ROC and MRR in the electrochemical etching of Al-7.5% B_4C composite.
2. Based on the Taguchi model, the experiments were designed to analyze the optimum processing conditions of the radial over cut and the material removal rate in the ECM. It is obtained that the (EC) 10 g/L, (V) 10 v, and (IEG) 0.3 mm are the optimal parametric combination for ROC. Also, the (EC) 30 g/L, (V) 18 v, and (IEG) 0.2 mm are the optimal parametric combination for MRR.
3. The ROC increased with increasing the electrolyte concentration, voltage and IEG value. The rate of material removal increased with raising the concentration of electrolyte and decreased with increasing the voltage and IEG value.
4. The models of the radial cut and removal rate in this paper may be used to improve the quality of the hole as the processing conditions are improved.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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