International Journal of ChemTech Research
CODEN (USA): IJCRGG ISSN: 0974-4290
Vol.8, No.2, pp 508-518, 2015

Electrochemical Micro Machining on Hybrid Metal Matrix Composites

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Abstract: Micro Electro chemical machining (EMM) manufacturers and users are to achieve a better stability and high economical productivity of the manufacturing process is the main objectives of this investigation. This paper investigates the influence of the process parameters like machining voltage, electrolyte concentration, frequency on the over cut and Material Removal Rate (MRR). This paper discusses a methodology for the optimization of the machining parameters on drilling of Al- Al_2O_3 - B_4C Metal Matrix composites using EMM. The taguchi $\mathbf{L_{27}}$ orthogonal array and analysis of variance are employed to study the influence of machining parameters such as machining voltage, Electrolyte concentration, Frequency on the over cut and MRR. Based on the Taguchi analysis, optimum level of parameters is determined and the same to validate through the confirmation test. Experimental results are in close agreement with the developed model. It is observed that the machining performance can be effectively improved with respect to initial parametric setting.
Keywords: Metal Matrix Composite (MMCs), Material Removal Rate (MRR), Overcut, Electro chemical micromachining (EMM), Taguchi, ANOVA &Design of Experiment.

1. Introduction

EMM is a nontraditional non contact [tool and work piece] machining process in which material is removed by the mechanism of anodic dissolution during an electrolysis process. MMCs having outstanding properties like high modules, low ductility, high thermal conductivity and low thermal expansion, high strength-to-weight ratio, high toughness, high-impact strength, high wear resistance, low sensitivity to surface flaws, and high surface durability. As a result, many of the current applications for MMCs are in many industrial applications including electronics, bio medicine, optics, bio technology, home appliances, Fuel injection system components, ordnance components mechanical machine parts like turbine blades, engine castings, bearing cages, gears, dies and molds and all other major parts in automobile and aerospace industries. Electrochemical machining is widely recognized that has great potential and many applications in micromachining. The micro hole is the most demanding important basic element while fabricating the micro parts and micro devices which are best made through EMM.

2. Literature Review

Stir casting method is very popular due to its unique advantages[1]. Metal matrix composites fabricated by stir casting process, it could be considered as an excellent material in sectors where light weight, enhanced mechanical properties and wear resistance are prime consideration especially in automobile applications[2]. ECM technology and summarized that have been successfully adapted to produce macro, micro components with complex features and high aspect ratios for biomedical and other applications with the help of extensive research work needed in the area of machining parameter and tool design[3]. A very serious problem in machining MMCs because of the hard particles in the matrix present[4]. However, because of the poor machining properties of MMCs, drilling MMCs is a challenging task for manufacturing engineers. Most of the current literature presents experimental results in terms of tool life, quality of drilled hole, and induced force when drilling MMCs. Shorter pulse period machining voltage produces lower side gap and it also increases the unit removal [5]. Analysis of variance (ANOVA) was used for identifying the significant parameters affecting the responses[6-8]. In Taguchi's analysis method, the design parameters and noise parameters which influence the product quality are considered[9-14]. Electrochemical micromachining (ECMM) is an emerging nonconventional technology for producing micro/meso scale components[15]. Investigates the effect and parametric optimization process parameters of electro chemical micro machining of 304 stainless steel[16]. Experiments conducted with the developed setup by varying the machining voltage, electrolyte concentration, pulse-on time, and frequency on copper plate. In the study, they reported that a considerable amount of MRR at a moderate accuracy can be achieved with a machining voltage of 6–10 V, pulse-on time of 10–15 ms, and electrolyte concentration of 15–20 g/l[17]. The micro ECM process is complex, and it is not easy to decide the optimal machining parameters for improving the output quality. The optimization of process parameters is essential for the realization of a higher productivity, which is the preliminary basis for survival in today's dynamic market conditions. Optimal quality of the work piece in ECM can be generated through combinational control of various process parameters [18]. An attempt made to machine the A356/SiCp composite work material using the ECM process to study the effects of various parameters such as applied voltage, electrolyte concentration, feed rate, and percentage reinforcement on maximizing the MRR[19]. This process produces no tool wear, having shorter machining time and cost effective The ECMM is still in its initial stages of development and a lot of research needs to optimize the various process parameters[20-22]. Aluminum matrix composites are generally regarded as extremely difficult to machine, because of the abrasive characteristics of the reinforced particulates[23]. In the view of the above, an attempt has been made in this present investigation the influence of voltage, electrolyte concentration, frequency on MRR and overcut of the Aluminum matrix composites using Electro chemical micro machining through Taguchi method and Analysis of variance (ANOVA). Optimization of cutting parameters is important for achievement of high quality. Taguchi's method of experimental design is one of the widely accepted techniques for offline quality assurance of products and processes. Taguchi's robust design method is a unique statistical tool and it has potential for savings in experimental time and cost on product or process development and quality improvement.

3. Experimental Details

3.1 Preparation of the Hybrid Composites

Figure 1. Stir Casting Set up

The material used in this investigation consists of 2024 aluminum alloy as matrix and its chemical composition is shown in below Table 1. The aluminum matrix was reinforced with 10 % wt of Al_2O_3 / 10% wt of B_4C_p. It is well suitable for high temperature application due their high thermal conductivity. The average particle size Al_2O_3 was 50 microns and B_4Cp was 70 microns. The composites were prepared through stir casting route as shown in fig 1. The aluminum alloy was preheated in a resistance furnace at 450º C for 2 to 3 hour before melting. Al_2O_3 and B_4Cp were also preheated in a resistance furnace at 1100º C for 2 hour. The preheated aluminum were first heated above the liquidus temperature to melt them completely. This procedure has been adopted while stir casting aluminum composites[24-25]. The preheated reinforcements were added and mixed manually. Manual mixing was used because it was very difficult to mix using automatic device when the alloy was in a semisolid state. The composite slurry was then reheated to a fully liquid state, and mechanical mixing was carried out for about 20 min at an average mixing speed of 200–300 rpm. The final temperature was controlled to be within 750°C±20°C, and pouring temperature was controlled to be around 700°C. After thorough stirring, the melt was poured into steel molds of size 100x100x10 mm and allowed to cool to obtain cast sheet[26]. Then the thickness was reduced to 0.4 mm through rolling and the same was cut in to 50x50x0.4 mm to accommodate into the EMM.

Table 1 Chemical composition of Al 2024

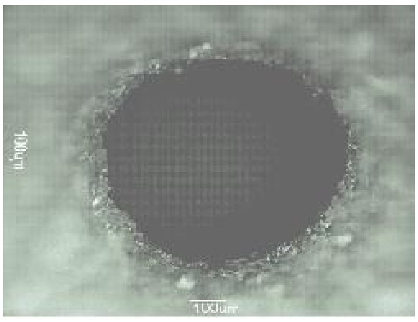
Component	Cr	Fe	Cu	Mn	Mg	Si	Ti	Zn	Al	others
Wt %	0.1	0.5	3.8-4.9	max 0.9	1.2-1.8	0.5	max 0.15	0.25	max 94.7	0.1 -0.2

3.2 Electrochemical Micro Machining (EMM)

EMM (Figure 2) is one of the nonconventional machining processes. It offers the unique advantage of better accuracy with high surface integrity of hard-machined components; also it has wider application because it produces good quality surfaces without affecting the metallurgical properties of the work material. During ECM, there will be reactions occurring at the electrodes i.e. at the anode or work-piece and at the cathode or the tool along with within the electrolyte. Ion and electrons crossing phase boundaries (the interface between two or more separate phases, such as liquid-solid) would result in electron transfer reaction carried out at both anode and cathode. It does not induce any deformation because no heat is generated while machining. Tool electrode feeding system, electrolyte supply system, mechanical machining system, inter electrode gap control system, pulse rectifier system are the major components of the EMM. The tool electrode feed mechanism, with resolution of 2 µm along Z – axis designed with stepper motor and 8051 micro controller. The electrolyte supply system consists of filter and pump arrangement. A pulsed power supply of 20 v and 30 A with capability for varying voltage, current, and pulse width was used[27-30]. The electrolyte of varying concentrations used in this study was sodium nitrate ($NANO_3$) and Al- Al_2O_3 - B_4C of thickness of 0.4 mm as work piece. Based on the literature review and preliminary experiments conducted, the initial process parameters and their corresponding levels are chosen. The work piece thickness 0.4 mm, machining current 0.8 A as fixed for entire experiment. Table 2 shows the machining parameters and their level indentified for this investigation. Electrochemical micro machining (EMM) characteristics (MRR and Overcut) as output responses for through micro – hole machining. MRR was derived as work piece removal weight over machining time. Overcut of the micro hole has been related with the machining accuracy, hence it is the difference between the diameters of the tool electrode and machined micro hole. With the support of optical microscope the diameter of the machined micro – hole was measured.

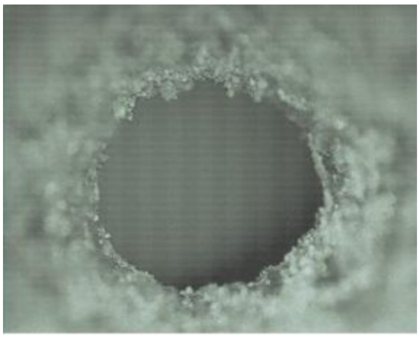
Table 2 Machining process parameters and their corresponding levels

Symbol	Factors	Level 1	Level 2	Level 3
A	Machining Voltage (V)	4	7	10
B	Elect.concenton (g/l)	20	30	40
C	Frequency (Hz)	25	40	55



4V/ 30g/l/55 Hz

Figure 2. EMM Set up



12V / 25 g/l / 30 Hz

Figure 3.optical image for Micro hole

3.3 Methodology

The optimization of process parameters is the key step in the Taguchi method. Twenty seven experimental runs (L_{27}) based on the Orthogonal Array (OA) of Taguchi methods have been carried out. The multi-response optimization of the process parameters viz. MRR, Over cut has been performed for making a micro hole in the process of micro-ECM of hybrid Al- Al_2O_3 - B_4C metal matrix composites, each experiment was replicated twice. Machining time, over cut, MRR noted for every trial.

There are three categories of quality characteristic in the analysis of the S/N ratio:

1. Larger is better
2. Nominal is best
3. Smaller is best

Larger is better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the larger-is-better S/N ratio using base 10 log is: $S/N = -10\log[\text{sum}(1/Y^2)/n)]$

where Y = responses for the given factor level combination and n = number of responses in the factor level combination.

Nominal is best (I)

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the nominal-is-best I S/N ratio using base 10 log is: $S/N = -10\log(10\, s^2)$

where s = standard deviation of the responses for all noise factors for the given factor level combination.

Nominal is best (II)

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the nominal-is-best II S/N ratio using base 10 log is: $S/N = 10\log((Y^2)/s^2)$

where Y = mean of responses for the given factor level combination, s = standard deviation of the responses for the given factor level combination, and n = number of responses in the factor level combination.

Smaller is better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the smaller-is-better S/N ratio using base 10 log is: $S/N = -10\log[\text{sum}(Y^2)/n)]$

where Y = responses for the given factor level combination and n = number of responses in the factor level combination. In this study higher MRR and Lower over cut are desired. Therefore MRR is Larger is better and

Overcut is Smaller is better chosen for this study. Table 3 shows the experimental results for L_{27} orthogonal array.

Table 3 Experimental results for L_{27} orthogonal array

Trial No.	A	B	C	MRR mg/min	Over Cut (μ m)	S/N Ratio for MRR	S/N Ratio for Overcut
1	4	20	25	0.59	242.5	-4.583	-47.6942
2	4	20	40	0.53	194.36	-5.5145	-45.7721
3	4	20	55	0.43	168.44	-7.3306	-44.5289
4	4	30	25	0.29	183.28	-10.752	-45.2623
5	4	30	40	0.51	152	-5.8486	-43.6369
6	4	30	55	0.49	169.8	-6.1961	-44.5988
7	4	40	25	0.55	222.46	-5.1927	-46.945
8	4	40	40	0.39	200.36	-8.1787	-46.0362
9	4	40	55	0.46	96.42	-6.7448	-39.6833
10	8	20	25	0.32	156.48	-9.897	-43.8892
11	8	20	40	0.47	197.64	-6.558	-45.9175
12	8	20	55	0.49	165.3	-6.1961	-44.3655
13	8	30	25	0.5	148.34	-6.0206	-43.4252
14	8	30	40	0.21	212.28	13.5556	-46.5382
15	8	30	55	0.28	188.6	11.0568	-45.5108
16	8	40	25	0.53	123.44	-5.5145	-41.8291
17	8	40	40	0.44	186.46	-7.1309	-45.4117
18	8	40	55	0.38	110.2	-8.4043	-40.8436
19	12	20	25	0.54	196.4	-5.3521	-45.8628
20	12	20	40	0.4	220.88	-7.9588	-46.8831
21	12	20	55	0.29	195.42	-10.752	-45.8194
22	12	30	25	0.47	183.44	-6.558	-45.2699
23	12	30	40	0.53	142.68	-5.5145	-43.0873
24	12	30	55	0.49	170.26	-6.1961	-44.6223
25	12	40	25	0.45	111.64	-6.9357	-40.9564
26	12	40	40	0.37	192.4	-8.636	-45.6841
27	12	40	55	0.46	180.12	-6.7448	-45.1112

4. Major Results and Inferences

Minitab 16 statistical software has been used for the analysis of the experimental work. The software studies the experimental data and then provides the calculated results of signal-to-noise ratio. This analysis is carried out for significance level of $\alpha = 0.05$, i.e., for a confidence level of 95%.

4.1 Analysis For MRR

Figure 4 shows the main effects at each level. Interpreting the main effects table, it can be seen that the optimal values for maximum MRR were machining voltage of 8 V, electrolyte concentration of 30 g/l, and frequency of 55 Hz.

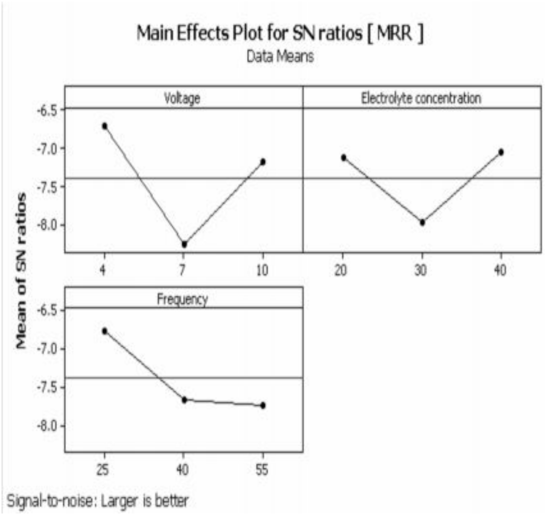


Figure 4 S/N ratio graph for MRR

Table 4 Taguchi Analyses: MRR Response Table for Signal to Noise Ratios (Larger is better)

Level	Voltage	Electrolyte concentration	Frequency
1	-6.705	-7.127	-6.756
2	-8.259	-7.966	-7.655
3	-7.183	-7.054	-7.736
Delta	1.555	0.913	0.98
Rank	1	3	2

The MRR increases with an increase in pulse frequency then the dissolution efficiency increases rapidly, causing a rapid increment of MRR in the machining zone. Response Table for Signal to Noise Ratios (Larger is better) shown in Table 4. Figure 5 show the residual graph for MRR.

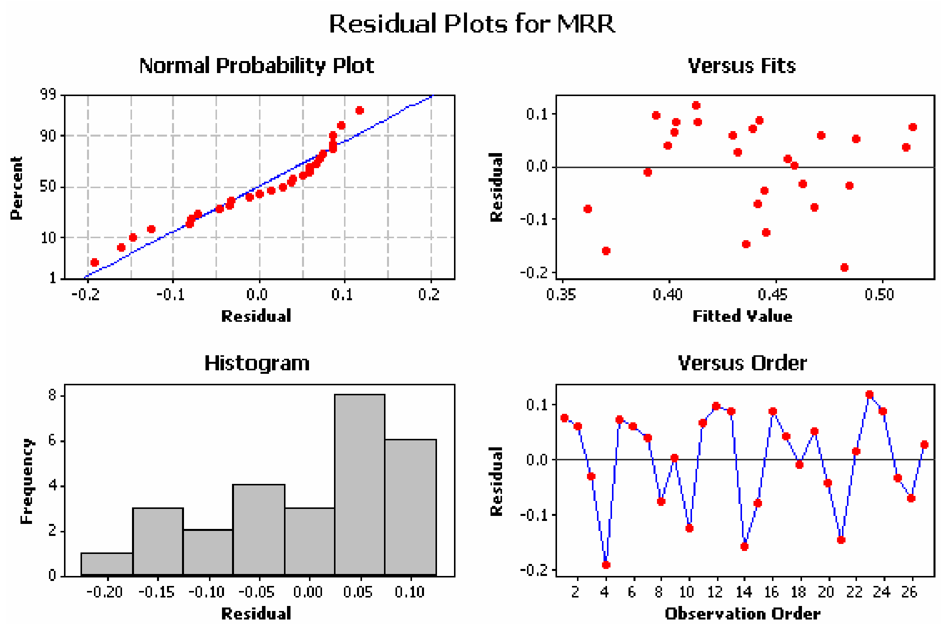


Figure 5 Residual graph for MRR

4.2 Analysis for Over Cut

The response table shows the average of selected characteristics for each level of the factor. This table includes the ranks based on the delta statistics, which compare the relative value of the effects. It is the difference between the highest and lowest averages for the factor chosen. Rank starting from 1 is assigned in the descending order of the delta values. Response Table for

Signal to Noise Ratios (Smaller is better) shown in Table 5. From Figure 6, it can be conclude that the optimal values for minimum overcut were machining voltage of 8 V,electrolyte concentration of 40 g/l, frequency of 55 Hz.

Table 5 Taguchi Analysis: Over cut Response Table for Signal to Noise Ratios (Smaller is better)

Level	Voltage	Electrolyte concentration	Frequency
1	-44.91	-45.64	-44.57
2	-44.19	44.66	45.44
3	44.81	43.61	43.9
Delta	0.71	2.03	1.54
Rank	2	3	1

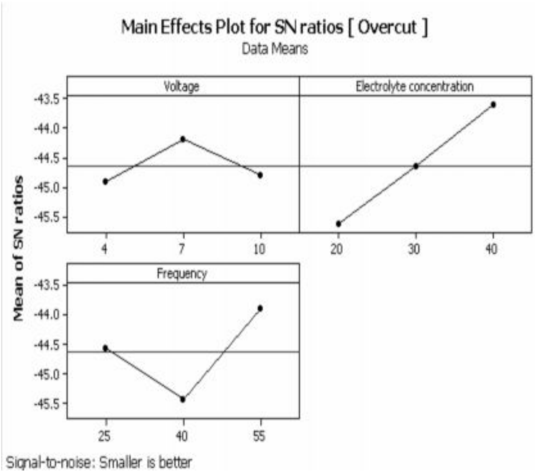


Figure 6 S/N ratio graph for Over cut

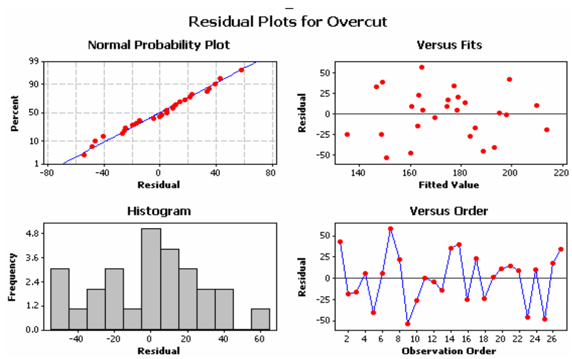
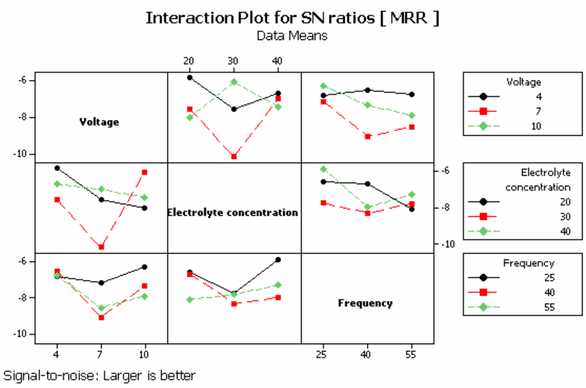


Figure 7 Residual graph for Over cut



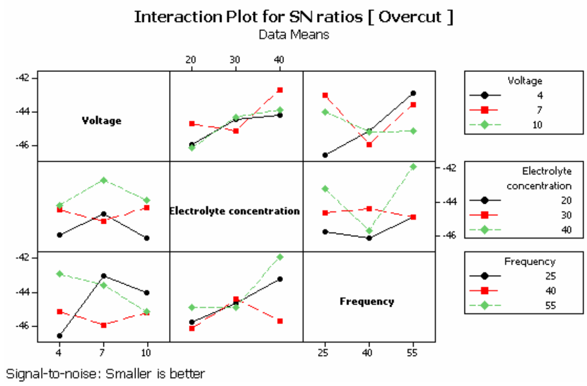


Figure 8 Interaction Plot for MRR

Figure 9 Interaction Plot for Overcut

Figure 7 show the residual graph for Overcut. Figures 8 & 9 shows the interaction between the Voltages, Electrolyte concentration, Frequency to MRR & Overcut Respectively.

4.3 Anova for MRR and Over Cut

ANOVA is performed to identify the process parameters that influence the MRR and Over cut of this investigation. Table 6 and Table 7 shows the ANOVA result for the material removal rate and over cut of Al-Al_2O_3 - B_4C under electrochemical micro machining. The F-ratio, which is used to measure the significance of factor at the desired significance level, is the ratio between variance due to the effect of a factor and variance due to error term. From Table 6 & 7 results it is obvious that all the selected factors have statistical and physical significances on the material removal rate and over cut during machining of composite at 95% confidence level. The results of ANOVA, the Voltage and Electrolyte concentration are the significant machining parameters for affecting the MRR. Based on the F value (1.10), Voltage is the most significant factor that influences the MRR with 9.12 % contribution.The second ranking factor is Frequency,which contributes 5.99%. Similarly the Electrolyte concentration were the significant machining parameters for affecting the Over cut with 16.61 % contribution.The second ranking factor is Frequency which contributes 10.79 %. With the increase in electrolyte concentration, ions associated with the machining operation in the machining zone also increase. A higher concentration of ions reduces the localization effect of electrochemical material removal reactions. This leads to the higher overcut and thus reduces the machining accuracy [18].

Table 6 ANOVA table for MRR

Factors	DOF	Sumof squares	Mean square	F value	$F_{0.05}$	% of contribution
Voltage	2	0.021719	0.010859	1.10	0.351	9.12
Electrolyte Concentration	2	0.005652	0.002826	0.29	0.753	2.37
Frquency	2	0.014052	0.007026	0.71	0.502	5.99
Error	20	0.196763	0.009838			
Total	26	0.238185				

S = 0.0991874 R-Sq = 17.39% R-Sq(adj) = 0.00%

Table 7 ANOVA table for Over cut

Factors	DOF	Sum of squares	Mean square	F value	$F_{0.05}$	% of contribution
Voltage	2	1189	594	0.52	0.604	3.57
Electrolyte Concentration	2	5540	2770	2.41	0.116	16.61
Frquency	2	3599	1800	1.56	0.234	10.79
Error	20	23020	1151			
Total	26	33348				

S = 33.9261 R-Sq = 30.97% R-Sq(adj) = 10.26%

4.5 Confirmation Test

Confirmation test is carried out to verify the accuracy of the model developed. The experimental data obtained are compared with the values predicted by the developed model and presented in Table 8 and Table 9 .It is observed that the model close to agreeable degree of approximation. The errors were minimal and therefore the regression models can be effectively employed to predict the MRR and over cut during the EMM of hybrid composites. Table 8 shows the S/N ratio of the predicted MRR and the actual MRR. Based on the confirmation test, the MRR is improved by 57.32 %. Therefore, the parameter combination suggested for the higher MRR is machining voltage of 8 V, Electrolyte concentration of 30 g/l, and frequency of 55 Hz. Table 9 shows the comparison of the S/N ratio of the predicted overcut with the actual overcut.. Based on the confirmation test, the Over cut is improved by 12.06 %.The parameter combination suggested for the lesser overcut is machining voltage of 8 V ,electrolyte concentration of 40 g/l, and frequency of 55 Hz.

Table 8 Conformation test table for MRR

	Initial levels of machining parameters	Optimal combination levels of machining parameters	
		Prediction	Experiment
Level	A1B1C1	A3B3C1	A3B3C1
S/N ratio of MRR value (dB)	-4.583	-11.0568	-10.74

Table 9 Conformation test table for Over cut

	Initial levels of machining parameters	Optimal combination levels of machining parameters	
		Prediction	Experiment
Level	A1B1C1	A3B2C3	A3B2C3
S/N ratio of Overcut value (dB)	-47.6942	-40.8436	-41.94

5 Conclusions

The Present investigation is focused on optimization and analysis electrochemical micro machining of Al-2024 /10 % wt of Al_2O_3 / 10% wt of B_4C metal matrix composites machining parameters. From the study of result in EMM was using Taguchi's techniques and ANOVA. The following can be concluded from the present study.

1. Based on the confirmation test, the improvements of the MRR from the initial machining parameters to the optimal machining parameters are about 57.32 %.
2. The optimal values for maximum MRR were machining Voltage of 8 V, Electrolyte concentration of 30 g/l, and Frequency of 55 Hz.
3. Based on the confirmation test, the improvements of the Overcut from the initial machining parameters to the optimal machining parameters are about 12.06 %.
4. The optimal values for minimum Overcut were machining Voltage of 8 V, Electrolyte concentration of 40 g/l, and Frequency of 55 Hz.
5. The results of ANOVA, the Voltage and Frequency are the significant machining parameters for affecting the MRR. Similarly the electrolyte concentration and Frequency are the significant machining parameters for affecting the Over cut.

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