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Effect of process variables on metal removal rate in electrochemical machining of Al-B_4C composites

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ABSTRACT

Electrochemical machining (ECM) is an advanced machining process belonging to electrochemical category. It is now routinely used for the machining of aerospace components, critical deburring, fuel injection system components, dies and moulds etc. The important process variables of ECM process are feed rate, electrolyte flow rate, current, voltage, inter electrode gap, electrolyte concentration, type of electrolyte, etc. which affects the process responses like metal removal rate, radial over cut, surface finish, tool life, and production cost. The responses also depend largely on the workpiece material physical and electrical properties. In composites the physical and electrical properties depends on the percentage of reinforcement of particulates in the metal matrix.
The salient feature of the present research is that percentage of reinforcement is considered as one of the input parameter along with the voltage, feed rate and electrolyte concentration and varied within the selected range to study the metal removal rate (MRR) of ECM of LM6 Al-B_4C metal matrix composites produced through stir casting process. Mathematical model for MRR was developed based on response surface methodology (RSM). Surface plots are generated to study the effect of input parameters on MRR. The developed models are tested for their prediction accuracy using twenty experimental test cases and observed that the predicted values are closely related with the experimental values.

Key words: LM6 Al-B_4C composites, Electrochemical Machining, Metal removal rate, Percentage of reinforcement, Surface plots.

INTRODUCTION

In electrochemical machining, the metal is removed by the anodic dissolution in an electrolytic cell in which work piece is the anode and the tool is cathode. The electrolyte is pumped through the gap between the workpiece and the tool, while direct current is passed through the cell, to dissolve metal from the work piece. Ruszaj and Zybura-skrabalak developed a mathematical model for ECM utilizing a flat ended universal electrode [1]. It was observed that better material removal rates and low surface waviness can be achieved when compared with the ball ended electrodes. Later on, Hocheng et al. used the concept of redistribution of electric energy to erode a hole in the thin metal of sheet [2]. But it is very difficult to identify the optimal process parameters of ECM with this type of experimental study. Therefore, the establishment of the mathematical models is essential to correlate the input-output parameters using statistical regression analysis. Non-linear regression models for ECM were developed by

Ravikumar et al. with voltage, current, flow rate of electrolyte and gap between the electrode and workpiece as input parameters, and metal removal rate (MRR), surface roughness (SR) are treated as responses [3]. Later on, Senthilkumar et al. used response surface methodology (RSM) to study the characteristics of ECM of Al/SiC_P composites. Contour plots were constructed between the responses MRR and SR, and process parameters, namely applied voltage, electrolyte concentration, electrolyte flow rate and tool feed rate [4]. Ashokan et al. used multiple regression analysis and artificial neural networks (ANN) for the multi-objective optimization of ECM process [5]. Moreover, in [6] also the authors used ANN for the prediction of ECM process parameters. The output of the NN contains two outputs, such as MRR and SR, whereas the input layer is provided with three inputs, namely applied voltage, feed rate and electrolyte flow rate. Fuzzy logic had also been used by Ramarao et al. to model the ECM process with voltage, current, electrolyte flow rate and gap between the electrodes as inputs and MRR and SR as outputs [7]. It is also important to note that evolutionary algorithms, such as genetic algorithms [8, 9, 11], particle swarm optimization [10] and differential evolution [11] were also used for the parametric optimization of ECM process by different authors. More over, Non-dominated sorting genetic algorithm (NSGA-II) was also used by Senthil kumar at al. for parametric optimization of electrochemical machining of Al/15% SiC_p composites [12].

Most of the researchers concentrated only on the process parameters of ECM like, voltage, feed rate, electrolyte concentration, electrolyte flow rate, gap between electrodes etc. But incase of composites the quality of the machined surface is also depends on the electrical properties, further which depends on the percentage of reinforcement of ceramic particles. So, in this research percentage of reinforcement has been taken one of the input parameters along with voltage, feed rate and electrolyte concentration and the effect of these parameters on MRR was studied.

MATERIALS AND METHODS

The base material used in the present work is LM6 which is an aluminium-silicon alloy containing 11 to 13% of silicon. The details of the LM6 chemical composition is shown in Table 1. In order to obtain different composition, B_4C particles of 30microns size were added to the aluminium matrix in the proportion of 2.5%, 5% and 7.5% by weight.

Table 1. The chemical composition of Al-Si alloy

Al	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti
87.77	0.08	0.1	11.25	0.46	0.14	0.01	0.01	0.01	0.01	0.16

In this study an attempt is made to establish the input-output relationship of electro chemical machining (ECM) of aluminum metal matrix composites. It is important to note that selection of the range of operating parameters is an important consideration. A pilot study has been conducted to determine the appropriate working ranges of the parameters. The levels of the process parameters selected are given in Table 2.

Table 2. The process parameters and their levels

Level	Voltage A (Volt)	Feed Rate B (mm/min)	Electrolyte concentration C (g/L)	%of reinforcement D (wt%)
-1	12	0.2	10	2.5
0	16	0.6	20	5.0
1	20	1.0	30	7.5

For the four variables the design required 27experiments with 16 factorial points, eight axial points to form central composite design with $\alpha=1$ and three center points for replication to estimate the experimental error. The design was generated and analyzed using MINITAB14 statistical package. The levels of each factor were chosen as −1, 0, 1 in coded form to have a central composite design as shown in Table 3.

Response surface methodology (RSM) is used for establishing the mathematical relationship between the response (Y_u) and various input process parameters [13]. In order to study the effect of the ECM input process parameters on the metal removal rate, a second-order polynomial response can be fitted into the following equation:

$$Y_u = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i<j=2}^{2} b_{ij} X_i X_j \quad (1)$$

Where Y_u is response and $x_{i\,(1,2,\,\ldots\,,k)}$ are coded levels of k quantitative variables. The coefficient b_0 is the constant term; the coefficients b_i, b_{ii}, and b_{ij} are the linear, quadratic, and interaction terms. To establish the prediction model, a software package MINITAB14 was used to determine the coefficients of mathematical modeling based on the response surface regression model.

Experimental Work

The fabrication of LM6 Al-B_4C metal matrix composites (MMC) were carried out by stir casting process. The preheated B_4C particles are added to the aluminium melt and stirred mechanically for uniform mixing and then poured into the steel moulds. 25mm diameter and 20mm length specimens were prepared from these castings. The experiments were conducted on the METATECH ECM. The circular cross section tool made up of copper is used in this study. The electrolyte used for experiment was fresh NaCl solution with different concentrations, because of the fact that NaCl electrolyte has no passivation effect on the surface of the job [14]. Electrolyte was axially fed to the cutting zone through the central hole of the tool. The MRR was measured from the mass loss and shown in Table 3.

Table 3. Design matrix and response values

S. No.	A	B	C	D	MRR (g/min)
1	-1	-1	-1	-1	0.268
2	+1	-1	-1	-1	0.398
3	-1	+1	-1	-1	0.689
4	+1	+1	-1	-1	0.892
5	-1	-1	+1	-1	0.447
6	+1	-1	+1	-1	0.684
7	-1	+1	+1	-1	0.932
8	+1	+1	+1	-1	0.988
9	-1	-1	-1	+1	0.130
10	+1	-1	-1	+1	0.282
11	-1	+1	-1	+1	0.498
12	+1	+1	-1	+1	0.688
13	-1	-1	+1	+1	0.227
14	+1	-1	+1	+1	0.492
15	-1	+1	+1	+1	0.703
16	+1	+1	+1	+1	0.805
17	-1	0	0	0	0.448
18	+1	0	0	0	0.564
19	0	-1	0	0	0.381
20	0	+1	0	0	0.771
21	0	0	-1	0	0.379
22	0	0	+1	0	0.491
23	0	0	0	-1	0.553
24	0	0	0	+1	0.302
25	0	0	0	0	0.504
26	0	0	0	0	0.466
27	0	0	0	0	0.489

Mathematical Modeling

Experiments have been carried out using the ECM set up on LM6 Al-B_4C composites to study the influence of some of the predominant process parameters such as voltage, feed rate, electrolyte concentration, and %wt. of B_4C on metal removal rate. The mathematical relationship for correlating the metal removal rate and the considered input process variables has been obtained as follows:

$$MRR = 0.469654 + 0.080574A + 0.203185B + 0.085778C - 0.095796D + 0.044463A^2 + 0.114963B^2 - 0.026037C^2 - 0.03387D^2 - 0.0145AB - 0.000875AC + 0.005208AD - 0.006917BC - 0.00875BD - 0.011125CD \quad (2)$$

The analysis of variance (ANOVA) and the F-ratio test have been performed to justify the goodness of fit of the developed mathematical models and are presented in Table 4.

Table 4. Analysis of Variance for MRR

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F value	P value
Regression	14	1.23908	0.088505	48.10	0.000
Linear	4	1.15768	0.289420	157.30	0.000
Square	4	0.07363	0.018408	10.00	0.001
Interaction	6	0.00776	0.001294	0.70	0.653
Lack-of-Fit	10	0.02135	0.002135	5.83	0.155
Pure Error	2	0.00073	0.000366		
Total	26	1.26115			

The value of the R^2 is over 98.2%, which indicates that the developed model shows the good relationship between the input parameters and output response (MRR) at a 95 % confidence level. The P value of the model is lower than 0.05(i.e. level of significance α=0.05, or 95% confidence), which indicates that the developed model is statistically significant. The results prove that all the input parameters, i.e. voltage, feed rate, electrolyte concentration and percentage of reinforcement have their influence on the metal removal rate.

RESULTS AND DISCUSSION

A mathematical model was developed through experimental observations and response surface methodology. Based on this mathematical model studies have been made to analyze the effect of various input parameters on the metal removal rate (MRR). The surface plots for the response of MRR were drawn. Figure 1 shows that functional dependence of MRR on the voltage and feed rate for the invariable electrolyte concentration value of 20 g/lit and B_4C value of 5 wt%. From figure 1, the MRR increases with increase in voltage and feed rate. With increase in applied voltage, the machining current in the inter electrode gap (IEG) increases, which leads to the enhancement of MRR. It is also interesting to note that increased feed rate reduces the IEG that leads to increase in the current density in the gap. This effect causes rapid anodic dissolution which increases the MRR [15].

Figure 2 shows that functional dependence of MRR on the electrolyte concentration and percentage of reinforcement for the invariable voltage value of 16 volts and feed rate value of 0.6 mm/min. From Fig 2, it is observed that increase in electrolyte concentration increases the MRR. With increasing the electrolyte concentration the electrical conductivity of the electrolyte increases and also that releases large number of ions in IEG, which results in higher machining current in IEG and causes higher MRR. Moreover, from Fig 3 the MRR decreases with an increase in percentage of reinforcement. This may be due to the fact that by increasing the percentage of reinforcement, the electrical conductivity of the work piece decreases, because the reinforced particles are poor conductors than the base material. Thus increase in the percentage of reinforcement leads to lower metal removal rate.

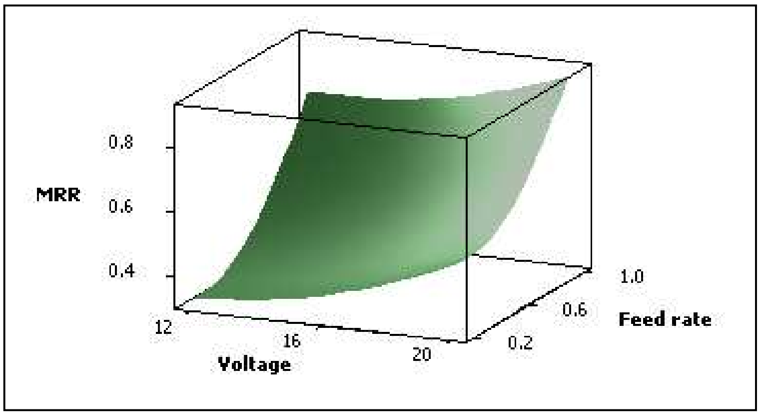

Fig. 1: Effect of Feed rate and applied voltage on MRR

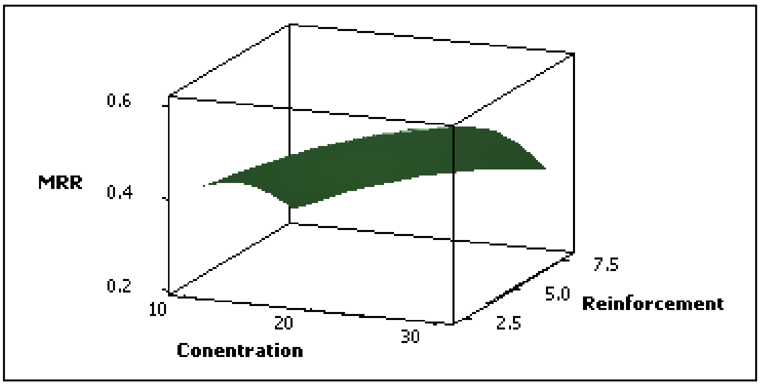

Fig. 2: Effect of electrolyte concentration and % of reinforcement on MRR

TESTING OF THE MODELS

The prediction accuracy of the developed models is tested with the help of twenty test cases as given in Table 5.

Table 5. Input-Output data of the test cases

Test No	Voltage (A)	Feed rate (B)	Electrolyte concentration (C)	Percentage of reinforcement (D)	MRR(g/min)
1	15	0.5	15	5	0.413
2	12	0.8	25	7.5	0.567
3	16	0.8	20	2.5	0.798
4	20	0.9	25	5	0.801
5	18	1	30	7.5	0.96
6	13	0.2	15	2.5	0.286
7	14	0.7	20	5	0.521
8	17	0.6	30	7.5	0.512
9	19	0.4	10	7.5	0.311
10	14	1	25	2.5	0.952
11	15	0.8	10	2.5	0.546
12	18	0.5	30	5	0.601
13	13	0.3	25	7.5	0.321
14	12	0.2	15	5	0.254
15	20	1	30	5	0.966
16	18	0.9	15	7.5	0.662
17	17	0.7	10	2.5	0.601
18	16	0.6	30	5	0.599
19	19	0.3	25	7.5	0.389
20	15	0.4	30	2.5	0.574

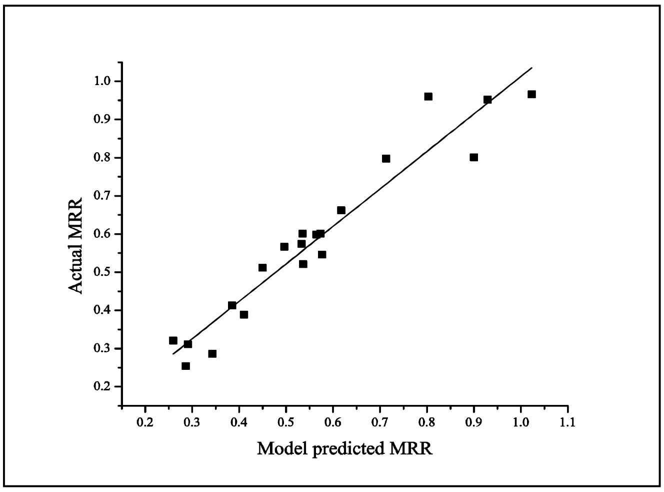

Fig. 3 Actual MRR Vs model predicted MRR for test cases

Figure 3 show the scatter plots for the prediction of MRR for the non-linear statistical model. From Fig. 3, it can be observed that the predicted values for MRR are seen to be very close with the experimental values. It is clear from the fact that the points are scattered very close to the best fit line.

CONCLUSION

In the present study, aluminum MMC was fabricated with the help of stir casting method. It is interesting to note that percentage of reinforcement has been considered as one of the process parameter that influences the quality of the parts produced using ECM. Later on, the electrochemical machining of aluminum MMC has been modeled with the help of non-linear regression model. The performance characteristic viz. MRR is considered as response and various machining parameters, namely voltage, feed rate, electrolyte concentration and percentage of reinforcement are treated as inputs of the model. Mathematical model was developed for the response MRR using response surface methodology and the model was analyzed using ANOVA. In the present study, surface plots are constructed to study the influence of input process parameters on the response of non-linear models. MRR decreases with the increase in percentage of reinforcement and increases with increase in voltage, feed rate and electrolyte concentration. It is to be noted that the findings of the experimentation are matching with the results available in the literature. Further, the developed models are tested for their prediction accuracy using twenty experimental test cases. The predicted values are closely related with the experimental values.

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