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Application of Taguchi methods and ANOVA in optimization of process parameters for metal removal rate in electrochemical machining of Al/5%SiC composites

Rama Rao. S*, Padmanabhan. G**

*(Associate professor, Department of ME, NEC, Narasaropet, A.P, India)

**(Professor, Department of ME, S.V. University, Tirupathi, A.P, India)

ABSTRACT

Metal matrix composites (MMCs) are now gaining their usage in aerospace, automotive and biomedical industries because of their inherent properties like high strength to weight ratio, low wear rate etc. To machine these types of materials conventional machining methods are unsuitable because of high tool wear and tooling cost. Electrochemical Machining (ECM) is one of the important non-traditional machining processes, which is used for machining of electrically conducting, difficult-to-machine materials and intricate profiles. In the present work LM6 Al/5%SiC composites, which are fabricated by stir casting route, were machined by ECM process. The influence of the various process parameters, i.e. voltage, feed rate and electrolyte concentration on the predominant machining criteria, i.e. the metal removal rate (MRR) was studied. The settings of the process parameters were determined by using Taguchi's experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), and regression analyses are employed to find the optimal process parameter levels and to analyze the effect of these parameters on metal removal rate values. Confirmation test with the optimal levels of machining parameters was carried out in order to illustrate the effectiveness of the Taguchi optimization method.

***Keywords* – LM6 Al/ SiC composites, Stir casting, Electrochemical Machining, Material Removal Rate, Taguchi optimization methods, ANOVA.**

I. INTRODUCTION

ECM is the one of the non-conventional machining process used for machining high-strength, heat resistant, extremely hard materials into complex shapes. ECM is a process based on the controlled anodic dissolution process of the work piece as anode, with the tool as cathode in an electrolytic solution. Its industrial applications have been extended to electrochemical drilling, grinding, deburring and polishing [1]. Jagannath Munda et al. investigated the electrochemical micromachining through response surface methodology approach by taking MRR and ROC as separate objective measures, developed mathematical models and analyzed with reference to machining parameters [2]. P.S. Kao et al. investigated the electrochemical polishing of stainless steel by grey relational analysis by taking surface roughness and passivation strength of electrolyte as responses [3]. Modeling of the ECM has done by using fuzzy logics and evolutionary algorithms by taking current, voltage, gap and feed rate as process parameters and MRR and surface roughness as responses [4, 5]. P. Asoken et al. developed multiple regression and Artificial Neural Network (ANN) models for optimizing the electrochemical process parameters like voltage, current, gap and feed rate [6]. D. Chakradhar et al. developed the multi-objective optimization models for electrochemical machining by grey relational analysis while machining EN31 steel with electrolyte concentration, feed rate and voltage as process parameters [7]. C. senthilkumar et al. developed mathematical models for ECM based on Response Surface Methodology (RSM) for LM25 Al/10%SiC composites [8]. S. J. Ebeid et. al. developed mathematical models for correlating the inter relationships of various machining parameters such as voltage, feed rate, back pressure and vibration amplitude on over cut and conicity for achieving high controlled accuracy [9].

In this study, LM6 Al/5%SiC composites were fabricated by stir casting method and machined on ECM process. The settings of ECM process parameters were determined by using Taguchi's experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), and regression analyses are employed to find the optimal levels and to analyze the effect of the ECM process parameters on metal removal rate values. Confirmation test with the optimal levels of machining parameters was carried out in order to illustrate the effectiveness of Taguchi's optimization method.

II. Fabrication of Al/5%SiC Composites

The fabrication of LM6 Al/SiC composites, 5% of SiC by weight were carried out by stir casting technique. A measured amount of silicon carbide particles were preheated at around 800^{0}C for 2 hrs to make their surfaces oxidized. A measured amount of LM6 Aluminium alloy ingots were taken into a graphite crucible and melted in an electrical furnace. Pre-heated silicon carbide particles were added to the melt. After that, the melt was stirred around 20 min at an average mixing speed of 150-200 rpm to make a vortex in order to disperse the particles in the melt.

After through stirring the melt was poured into steel moulds of 25 mm diameter and 100 mm length and allowed to cool to obtain cast rods. The samples of 25mm diameter and 20 mm length were prepared from these cast rods. Stir casting equipment used for fabrication of composites is shown in Fig. 1.

Fig. 1 stir casting equipment

The details of the LM6 alloy composition was shown in Table 1.

Table 1 Composition of LM6 by weight (%)

Al	Cu	Mg	Si	Fe	Mn
87.81	0.08	0.1	11.24	0.46	0.14
Ni	Zn	Lead	Tin	Ti	Others
0.01	0.01	0.01	0.01	0.16	0.1

III. Taguchi Experiment: Design and Analysis

Essentially, traditional experimental design procedures are too complicated and not easy to use. A large number of experimental works have to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments [10].

Taguchi methods [11] have been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process. The greatest advantage of this method is the saving of effort in conducting experiments; saving experimental time, reducing the cost, and discovering significant factors quickly. Taguchi's robust design method is a powerful tool for the design of a high-quality system. In addition to the S/N ratio, a statistical analysis of variance (ANOVA) can be employed to indicate the impact of process parameters on metal removal rate values. The steps applied for Taguchi optimization in this study are as follows.

- Select noise and control factors
- Select Taguchi orthogonal array
- Conduct Experiments
- Metal Removal Rate measurement
- Analyze results; (Signal-to-noise ratio)
- Predict optimum performance
- Confirmation experiment

IV. Experimental Procedure

A. Plan of Experiments

Taguchi methods which combine the experiment design theory and the quality loss function concept have been used in developing robust designs of products and processes and in solving some taxing problems of manufacturing [12]. The degrees of freedom for three parameters in each of three levels were calculated as follows [13].

Degree of Freedom (DOF) = number of levels -1 (1)
For each factor, DOF equal to:
For (A); DOF = 3 – 1 = 2
For (B); DOF = 3 – 1 = 2
For (C); DOF = 3 – 1 = 2

In this research nine experiments were conducted at different parameters. For this Taguchi L_9 orthogonal array was used, which has nine rows corresponding to the number of tests, with three columns at three levels. L_9 OA has eight DOF, in which 6 were assigned to three factors (each one 2 DOF) and 2 DOF was assigned to the error. For the purpose of observing the degree of influence of the process parameters in ECM, three factors, each at three levels, are taken into account, as shown in Tables 2. The MRR values corresponding to each experiment were shown in Table 3.

Table 2 ECM Process parameters

Parameter	code	Levels		
		1	2	3
Voltage (V)	A	12	16	20
Feed Rate mm/min)	B	0.1	0.2	0.3
Electrolyte Concentration (g/lit)	C	10	20	30

Table 3 Taguchi L_9 OA for MRR

Expt. No	A	B	C	MRR (g/min)
1	1	1	1	0.0559
2	1	2	2	0.0789
3	1	3	3	0.1023
4	2	1	2	0.0765
5	2	2	3	0.0987
6	2	3	1	0.1012
7	3	1	3	0.0923
8	3	2	1	0.1005
9	3	3	2	0.1200

B. Experimental Details

The experiments were conducted on METATECH ECM equipment which is shown in Fig 2. The ECM setup consists of control panel, machining chamber, electrolyte circulation system. The workpiece is fixed inside the chamber and tool is attached to the main screw which is driven by a stepper motor. For avoiding short-circuits, a current sensing circuit is interfaced between the tool and the steeper motor controller circuit. If the current exceeds an acceptable limit, a signal is sent to the stepper motor controller circuit which immediately reverses the downward motion of the tool. The process parameters like current, voltage and feed rate are varied by the control panel. The electrolyte is pneumatically pumped. The tool was made up of copper with a circular cross section of 12mm diameter with 2mm internal hole. The tool was coated with a layer of 200µm epoxy powder resin, except for the base of the tool which will be the machining area. Electrolyte was axially fed to the machining zone through the central hole of the tool. NaCl solution was chosen as electrolyte, as it has no passivation effect on the surface of the job [9]. An electrolyte flow rate of 8 liters per min., and an inter electrode gap of 0.3 mm was maintained constant for all the experiments. The machining has been carried out for fixed time interval and MRR was measured from weight loss.

C. Measurement of MRR

MRR was measured as;

MRR= (Initial Weight-Final Weight)/Time. (2)

Fig. 2 Experimental setup of ECM

V. Results and Analysis of Experiments

A. Regression Analysis

The applied voltage, feed rate and electrolyte concentration were considered in the development of mathematical models for the metal removal rate. The correlation between factors (applied voltage, feed rate and electrolyte concentration) and metal removal rate on the LM6 Al/5%SiC composite were obtained by multiple linear regressions.

The standard commercial statistical software package MINITAB was used to derive the models of the form:

Metal removal rate (MRR) = -0.00349 + 0.00315*A + 0.165*B + 0.000595*C (3)

R^2=0.996

In multiple linear regression analysis, R^2 is the regression coefficient (R^2 >0.90) for the models, which indicate that the fit of the experimental data is satisfactory.

B. Analysis of the S/N Ratio

Taguchi method stresses the importance of studying the response variation using the signal – to – noise (S/N) ratio, resulting in minimization of quality characteristic variation due to uncontrollable parameter. The metal removal rate was considered as the quality characteristic with the concept of "the larger-the-better". The S/N ratio used for this type response is given by [13]:

The S/N ratio for the larger-the-better is:
S/N = -10*log (mean square deviation)

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \quad (4)$$

Where n is the number of measurements in a trial/row, in this case, n=1 and y is the measured value in a run/row. The S/N ratio values are calculated by taking into consideration Eqn. 4. The MRR values measured from the experiments and their corresponding S/N ratio values are listed in Table 4. The MRR response table for the voltage, feed rate and electrolyte concentration was created in the integrated manner and the results are given in Table 5.

Regardless of the category of the performance characteristics, a greater S/N value corresponds to a better performance. Therefore, the optimal level of the machining parameters is the level with the greatest S/N value. Based on the analysis of the S/N ratio, the optimal machining performance for the metal removal rate was obtained at 20 volts voltage (level 3), 0.3 mm/min feed rate (level 3) and 30 g/lit electrolyte concentration (level 3). Fig. 5 shows the effect of the process parameters on the metal removal rate values.

Table 4 MRR values and S/N ratio values for experiments

Exp. No.	MRR value (g/min)	S/N ratio (dB)
1	0.0559	25.0518
2	0.0789	22.0585
3	0.1023	19.8025
4	0.0765	22.3268
5	0.0987	20.1137
6	0.1012	19.8964
7	0.0923	20.6960
8	0.1005	19.9567
9	0.1200	18.4164

Table 5 S/N ratio values for MRR by factor level

Level	Voltage	feed rate	Electrolyte Concentration
1	-22.30	-22.69	-21.63
2	-20.78	-20.71	-20.93
3	-19.69[a]	-19.37[a]	-20.20[a]
Delta	2.61	3.32	1.43
Rank	2	1	3

[a] Optimum level

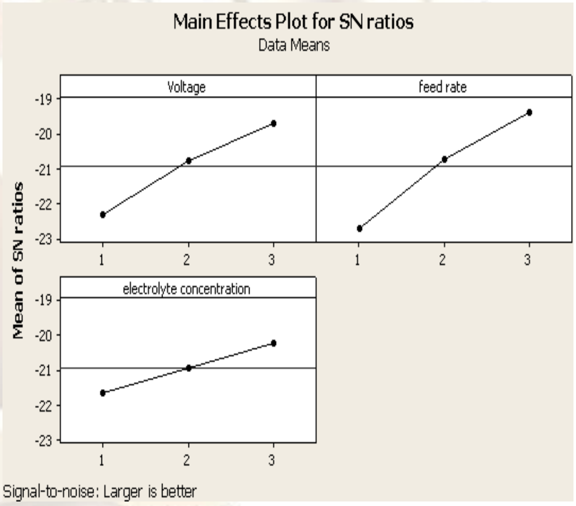

Fig. 5 Effect of process parameters on MRR

The effect of process parameters on the metal removal rate values was shown in Fig. 5. The MRR increases with increasing in voltage, feed rate and electrolyte concentration. According to the Faraday's law MRR is proportional to the machining current. The increase in machining voltage causes a greater machining current in the electrode gap, thereby causing the enhancement of the MRR. With the increase in electrolyte concentration, the larger number of ions associated with the machining processes, increases the machining current and thus results in higher MRR. An increase in feed rate also increases the metal removal rate. This happens due to the reduction in gap between electrodes that increases the current density in the gap with the consequent rapid anodic dissolution.

Table 6 ANOVA results for metal removal rate for the ECM of LM6 Al/5%SiC composites

Source of variation	Degrees of freedom (DOF)	Sum of squares (S)	Variance (V)	F-ratio (F)	P-value (P)	Percentage (%)
A	2	0.0009555	0.0004778	115.37	0.009	34.04%
B	2	0.0016305	0.0008152	196.86	0.005	58.09%
C	2	0.0002124	0.0001062	25.65	0.038	7.57%
Error	2	0.0000083	0.0000041			0.30%
Total	8	0.0028067				100%

C. Analysis of Variance (ANOVA)

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested. ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. First, the total sum of squared deviations SS_T from the total mean S/N ratio n_m can be calculated as [14]:

$$SS_T = \sum_{i=1}^{n} (n_i - n_m)^2 \qquad (3)$$

where n is the number of experiments in the orthogonal array and η_i is the mean S/N ratio for the ith experiment.

The percentage contribution P can be calculated as:

$$P = \frac{SS_d}{SS_T} \qquad (4)$$

where SS_d is the sum of the squared deviations. The ANOVA results are illustrated in Table 6.

Statistically, there is a tool called an F test, named after Fisher [15], to see which design parameters have a significant effect on the quality characteristic. In the analysis, the F-ratio is a ratio of the mean square error to the residual error, and is traditionally used to determine the significance of a factor.

The P-value reports the significance level (suitable and unsuitable) in Table 6. Percent (%) is defined as the significance rate of the process parameters on the metal removal rate. The percent numbers depict that the applied voltage, feed rate and electrolyte concentration have significant effects on the metal removal rate. It can observed from Table 6 that the applied voltage (A), feed rate (B) and electrolyte concentration (C) affect the metal removal rate by 34.04%, 58.09% and 7.57% in the electrochemical machining of LM6 Al/5%SiC composites, respectively. A confirmation of the experimental design was necessary in order to verify the optimum cutting conditions.

VI. CONFIRMATION TEST

The experimental confirmation test is the final step in verifying the results drawn based on Taguchi's design approach. The optimal conditions are set for the significant factors (the insignificant factors are set at economic levels) and a selected number of experiments are run under specified cutting conditions. The average of the results from the confirmation experiment is compared with the predicted average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental results [15]. In this study, a confirmation experiment was conducted by utilizing the levels of the optimal process parameters

(A3B3C3) for metal removal rate value in the electrochemical machining of LM6 Al/5%SiC composites and obtained as 0.131 g/min.

VII. CONCLUSION

This study has discussed an application of the Taguchi method for investigating the effects of process parameters on the metal removal rate value in the electrochemical machining of LM6 Al/5%SiC composites. In the ECM process, the parameters were selected taking into consideration of manufacturer and industrial requirements.

From the analysis of the results in the ECM process using the conceptual signal-to-noise (S/N) ratio approach, regression analysis, analysis of variance (ANOVA), and Taguchi's optimization method, the following can be concluded from the present study:

- Statistically designed experiments based on Taguchi methods were performed using L_9 orthogonal arrays to analyze the metal removal rate as response variable. Conceptual S/N ratio and ANOVA approaches for data analysis drew similar conclusions.
- Statistical results (at a 95% confidence level) show that the voltage (A), feed rate (B), and electrolyte concentration (C) affects the metal removal rate by 34.04%, 58.09% and 7.57% in the electrochemical machining of LM6 Al/5%SiC composites, respectively.
- The maximum metal removal rate is calculated as 0.131 g/min by Taguchi's optimization method.
- In this study, the analysis of the confirmation experiment for metal removal rate has shown that Taguchi parameter design can successfully verify the optimum cutting parameters (A3B3C3), which are voltage=20 V (A3) feed rate= 0.3 mm/rev (B3) and electrolyte concentration=30 g/lit (C3).
- Metal removal rate increases with voltage, feed rate and electrolyte concentration in electrochemical machining of LM6 Al/5%SiC composites.

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