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Optimization of Machining Parameters in ECM of Al/B_4C Composites Using Taguchi Method

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Abstract: Aluminium metal matrix composites (AMMCs) are now gaining their usage in aerospace and automotive industries because of their inherent properties like high strength to weight ratio, low wear rate etc. Electrochemical Machining (ECM) allowed success in the production of newer materials, especially for the aerospace and biomedical applications. In this paper an attempt is made to machine the LM6 Al/B_4C_p composites using electrochemical machining process. Boron carbide particles of 30 micron size are reinforced in LM6 Al alloy matrix with 2.5%, 5% and 7.5% by weight. Taguchi's L_{27} orthogonal array is chosen to design the experiments and 27 tests are conducted to study the effect of various machining parameters like applied voltage, feed rate, electrolyte concentration and percentage of reinforcement on the material removal rate (MRR), surface roughness (SR) and radial over cut (ROC). Signal-to-noise (S/N), the analysis of variance (ANOVA) and regression analyses are employed to find the optimal levels and to analyze the effect of electrochemical machining parameters on MRR, SR and ROC. Confirmation tests with optimal levels of machining parameters are conducted to validate the test results. Experimental results have shown that the responses in ECM can be improved effectively through this approach.

Keywords: Electrochemical machining; taguchi method; Al/B_4C composites; ANOVA.

1. Introduction

ECM is the one of the non-conventional machining process used for machining high-strength, heat resistant, extremely hard materials into complex shapes. It is a process based on the controlled anodic dissolution process of the workpiece with the tool as cathode in an electrolytic cell. Its industrial applications have been extended to electrochemical drilling, grinding, deburring and polishing [1]. Senthilkumar et al. developed mathematical models for ECM based on response surface methodology (RSM) for Al/10%SiC composites [2]. They have taken electrolyte flow rate, applied voltage, electrolyte concentration and tool feed rate as process parameters and material removal rate and surface roughness as responses. Kao et al. optimized the electrochemical polishing of stainless steel using grey relational analysis by taking surface roughness and passivation strength of electrolyte as responses [3]. Munda et al. investigated the electrochemical micromachining through response surface methodology approach [4]. They have

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taken MRR and ROC as two different objective measures and developed the mathematical models. Asoken et al. [5] developed multiple regression and Artificial Neural Network (ANN) models for optimizing the electrochemical process parameters like voltage, current, gap and feed rate. Rao et. al. carried out modeling of the electrochemical machining process using fuzzy logics [6]. Evolutionary algorithms [7] were used for optimization of electrochemical machining process. Chakradhar et al. [8] developed the multi-objective optimization models for electrochemical machining of EN31 steel using grey relational analysis by considering electrolyte concentration, feed rate and voltage as process parameters.

In the present study LM6 Al/B_4C composites were machined by electrochemical machining process and optimization of the machining parameters was done using Taguchi's method.

2. Experimental work

Samples of 25 mm diameter and 20 mm length of LM6 Al/B_4C composites, with 2.5, 5 and 7.5 weight percentage of B_4C are fabricated by stir casting method. Experiments are conducted on METATECH ECM equipment based on Taguchi's design of experiments. In METATEC ECM equipment it is possible to vary the voltage from 0 to 20 V and feed rate from 0.2 mm/min to 2 mm/min. Low voltages leads to low material removal rate and high surface roughness in electrochemical machining process [2]. So the voltage is selected in the range of 12-20 V. It is observed that the frequency of short circuits is more at feed rate greater than 1 mm/min. Therefore, feed rate is selected in the range of 0.2-1 mm/min. Based on literature [2] electrolyte concentration is selected in the range of 10-30 g/lit. In ECM machining criteria also depends on the workpiece electrical conductivity and density. With increasing the percentage of reinforcement in the composites, the electrical conductivity and the density decrease. Therefore, to study the effect of percentage of reinforcement on machining criteria in ECM, B_4C is varied from 2.5% to 7.5% by weight in Al/B_4C composites. The factors to be studied and their levels are given in Table 1. 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. The process parameters like voltage and feed rate are changed by the control panel. The tool is made up of copper with a circular cross section with 2 mm internal hole. The tool is coated with a layer of 200 µm with epoxy powder resin, except for the base of the tool which will be participated in machining process. Electrolyte is fed axially to the machining zone through the central hole of the tool. NaCl solution is chosen as electrolyte, because it has no passivation effect on the surface of the job [9]. The observations (MRR, SR and ROC) are made by changing applied voltage, tool feed rate, electrolyte concentration and percentage of reinforcement. Table 2 lists Taguchi L_{27} orthogonal array, the measured values of responses and their S/N ratios. MRR is measured from weight loss. ROC is measured with digital vernier caliper. SR is measured with Talysurf tester. The responses MRR and ROC are calculated by following equations:

$$MRR=(m_b-m_a)/t \quad (1)$$

$$ROC=(d_h-d_t)/2 \quad (2)$$

Where m_b and m_a are mass in grams of the workpiece before and after machining and t is the machining time in minutes; d_h is the diameter of the hole produced in the workpiece and d_t is diameter of the tool.

Table 1. Factors and their levels

Symbol	Factors	Level 1	Level 2	Level 3
A	Voltage (V)	12	16	20
B	Feed Rate (mm/min)	0.2	0.6	1.0
C	Electrolyte Concentration (g/lit)	10	20	30
D	Percentage of Reinforcement (Wt %)	2.5	5.0	7.5

Table 2. Taguchi L_{27} orthogonal array and responses

Exp. No.	Factors				Responses			S/N ratios		
	A	B	C	D	MRR	SR	ROC	MRR	SR	ROC
1	1	1	1	1	0.268	4.948	0.96	-11.4373	-13.8886	0.35458
2	1	1	2	2	0.335	5.002	0.94	-9.4991	-13.9829	0.53744
3	1	1	3	3	0.227	4.591	0.79	-12.8795	-13.2381	2.04746
4	1	2	1	1	0.353	4.92	0.75	-9.0445	-13.8393	2.49877
5	1	2	2	2	0.448	4.498	0.65	-6.9744	-13.0604	3.74173
6	1	2	3	3	0.42	4.725	0.8	-7.535	-13.488	1.9382
7	1	3	1	1	0.689	4.555	0.67	-3.2356	-13.1698	3.4785
8	1	3	2	2	0.545	4.356	0.64	-5.2721	-12.7818	3.8764
9	1	3	3	3	0.703	4.232	0.65	-3.0609	-12.5309	3.74173
10	2	1	1	2	0.321	4.882	0.91	-9.8699	-13.772	0.81917
11	2	1	2	3	0.329	4.823	0.94	-9.6561	-13.6663	0.53744
12	2	1	3	1	0.488	4.254	1.05	-6.2316	-12.5759	-0.42379
13	2	2	1	2	0.379	4.54	0.76	-8.4272	-13.1411	2.38373
14	2	2	2	3	0.302	4.431	0.69	-10.3999	-12.93	3.22302
15	2	2	3	1	0.583	3.998	0.99	-4.6866	-12.0369	0.0873
16	2	3	1	2	0.615	4.274	0.75	-4.2225	-12.6167	2.49877
17	2	3	2	3	0.619	4.346	0.7	-4.1662	-12.7618	3.09804
18	2	3	3	1	0.812	3.598	0.93	-1.8089	-11.1212	0.63034
19	3	1	1	3	0.282	5.472	0.91	-10.995	-14.7629	0.81917
20	3	1	2	1	0.599	4.797	1.1	-4.4515	-13.6194	-0.82785
21	3	1	3	2	0.603	4.64	1.16	-4.3937	-13.3304	-1.28916
22	3	2	1	3	0.526	5.214	0.85	-5.5803	-14.3434	1.41162
23	3	2	2	1	0.688	4.897	1.03	-3.2482	-13.7986	-0.25674
24	3	2	3	2	0.732	4.531	1.08	-2.7098	-13.1239	-0.66848
25	3	3	1	3	0.688	5.002	0.64	-3.2482	-13.9829	3.8764
26	3	3	2	1	0.887	4.389	0.99	-1.0415	-12.8473	0.0873
27	3	3	3	2	0.944	3.989	1	-0.5006	-12.0173	0.0000

3. Methodology

In this study, the settings of electrochemical machining parameters are 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 electrochemical machining parameters on material removal rate, surface roughness and radial over cut values.

3.1. Regression analysis

Regression analysis is a statistical tool for estimating the relationships among variables. Regression analysis helps one understand how the typical value of the dependent variable changes when any one of the independent variables is varied. It is also used to understand which among the independent variables are related to the dependent variable and to explore the forms of these relationships. The general form of a multiple regression model is as follows:

$$\begin{aligned} \text{dependent variable} = {} & b_0 + b_1 \text{ (Independent variable 1)} \\ & + b_2 \text{ (Independent variable 2)} \\ & + b_3 \text{ (Independent variable 3)} \\ & + \ldots + \varepsilon \end{aligned} \tag{3}$$

where b_1, b_2, b_3, … are estimates of the independent variables 1, 2, 3, … and ε is the error.

3.2. Taguchi method

In traditional experimental design procedures, a large number of experimental works have to be carried out when the number of process parameters increases. This problem is solved by the Taguchi method, which uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. 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. The steps applied for Taguchi optimization in this study are presented in Figure 1. In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value (standard deviation, SD) for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the SD. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available, depending on the type of characteristic; lower the better (LB), nominal the best (NB) or higher the better (HB). The S/N ratio for the higher-the-better criterion is given by Taguchi as:

$$S/N = -10\log_{10}\left[\frac{1}{n}\sum\frac{1}{y^2}\right] \tag{4}$$

where 'y' is the observed data and 'n' is the number of observations.

The S/N ratio for the lower-the-better criterion is given by Taguchi as:

$$S/N = -10\log_{10}\left[\frac{\sum y^2}{n}\right] \tag{5}$$

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 [10]. Finally, confirmation experiments are conducted using optimal levels of process parameters.

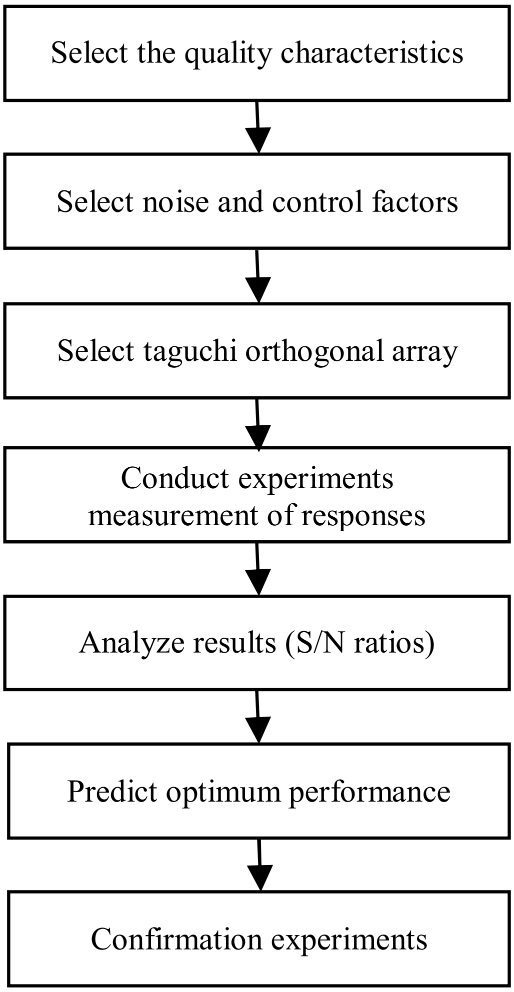

Figure 1. Steps applied in taguchi's optimization method

3.3. Analysis of variance

Analysis of variance (ANOVA) is a statistical tool used to investigate the significance of the all parameters and their interactions by comparing the mean square with an estimate of the experimental error at a specific confidence level. The relative influence of the parameters is measured by total sum of square value (SS_T) and is given by:

$$SS_T = \sum_{i=1}^{n} \left(n_i - n_m\right)^2 \tag{6}$$

where n is the number of experiments in the orthogonal array, n_i is the mean S/N ratio for the i^{th} experiment and n_m is the total mean S/N ratio of all experiments.

The percentage contribution P can be calculated as

$$P = \frac{SS_d}{SS_T} \tag{7}$$

where, SS_d is the sum of squared deviations. Further, the Fisher's *F*-ratio, the ratio between the regression mean square and the mean square error, is used to identify the most significant factor on the performance characteristic. The *P*-value reports the significance level (suitable and unsuitable). Percent (%) represents the significance rate of the machining parameters on the response.

4. Analysis of the experimental results and discussion

4.1. Regression analysis

The correlation between considered machining parameters and machining criteria for electrochemical machining of Al/B_4C composites are obtained by multiple linear regressions. The standard commercial statistical software package MINITAB14 is used to derive the models of the form:

MRR/SR/ROC=*f* (applied voltage, feed rate, electrolyte concentration and percentage of reinforcement). The models obtained are as follows:

$$MRR=-0.0373+0.1090A+0.1690B+0.0773C-0.0706D \tag{8}$$

$$SR=5.2900+0.0613A-0.2590B-0.2920C+0.1380D \tag{9}$$

$$ROC=0.8790+0.1060A-0.0994B+0.0694C-0.0833D \tag{10}$$

4.2. Analysis of signal-to-noise (S/N) ratio

The S/N ratio values for material removal rate are calculated by using equation (4) and S/N ratio values for surface roughness and radial over cut are calculated by using equation (5).

4.2.1. Material removal rate

The material removal rate response table for each level of machining parameters (applied voltage, feed rate, electrolyte concentration and percentage of reinforcement) is created in the integrated manner and the results are given in Table 3. Based on the analysis of the S/N ratio, the optimal machining performance for the material removal rate is obtained at 20 V applied voltage (level 3), 1.0 mm/min feed rate (level 3), 30 g/lit electrolyte concentration (level 3) and 2.5% of B_4C content (level 1). Figure 2 shows the effect of the electrochemical machining parameters on the material removal rate values.

Table 3. Average S/N ratio value by factor levels for MRR

Level	A	B	C	D
1	-7.660	-8.824	-7.340	-5.021[a]
2	-6.608	-6.512	-6.079	-5.763
3	-4.019[a]	-2.951[a]	-4.867[a]	-7.502
Delta	3.641	5.873	2.473	2.482

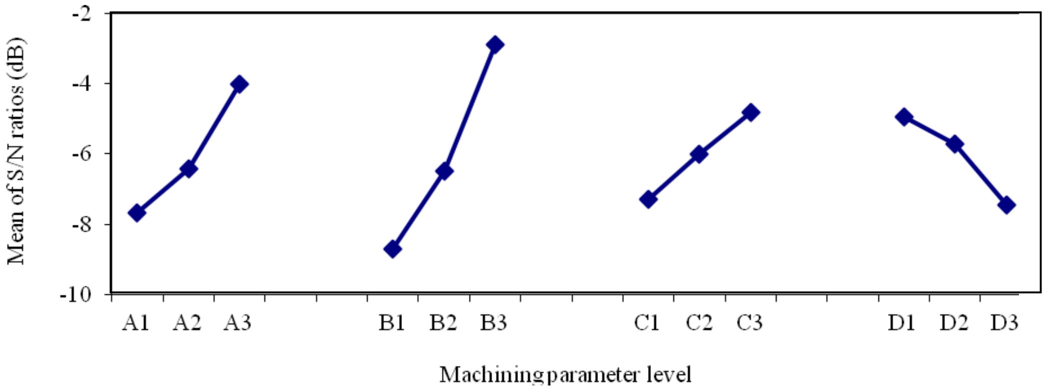

Figure 2. Effect of machining parameters on material removal rate

4.2.2. Surface roughness

The surface roughness response table for each level of the applied voltage, feed rate, electrolyte concentration and percentage of reinforcement is created in the integrated manner and the results are given in Table 4. Effect of the electrochemical machining parameters on the surface roughness values is shown in Figure 3. Based on the analysis of the S/N ratio, the optimal machining performance for the surface roughness is obtained with 16 V applied voltage (level 2), 1.0 mm/min feed rate (level 3), 30 g/lit electrolyte concentration (level 3), and 2.5% of B_4C content (level 1).

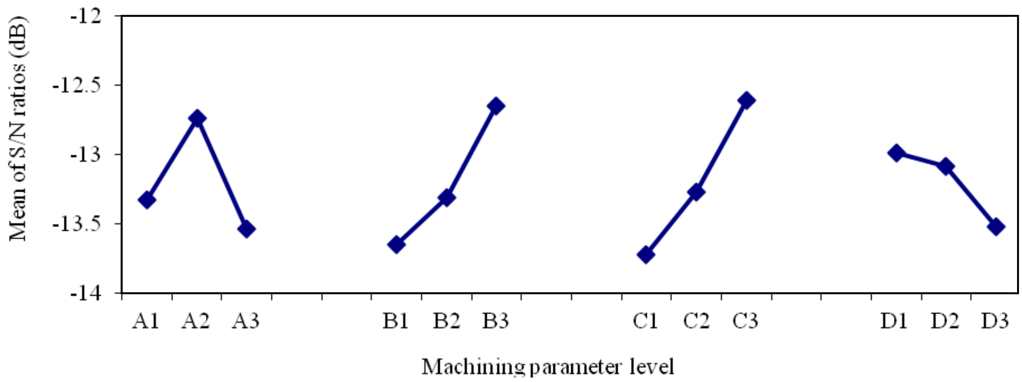

Figure 3. Effect of machining parameters on surface roughness

Table 4. Average S/N ratio value by factor levels for SR

Level	A	B	C	D
1	-13.33	-13.65	-13.72	-12.99 a
2	-12.74 a	-13.31	-13.27	-13.09
3	-13.54	-12.65 a	-12.61 a	-13.52
Delta	0.80	1.00	1.12	0.53

4.2.3. Radial over cut

The radial over cut response table for each level of machining parameters (applied voltage, feed rate, electrolyte concentration and percentage of reinforcement) is created in the integrated manner and the results are given in Table 5. Based on the analysis of the S/N ratio, the optimal machining performance for the radial over cut is obtained at 12 V applied voltage (level 1), 1.0 mm/min feed rate (level 3), 10 g/lit electrolyte concentration (level 1), and 7.5% of B_4C content (level 3). Figure 4 shows the effect of the electrochemical machining parameters on the radial over cut values.

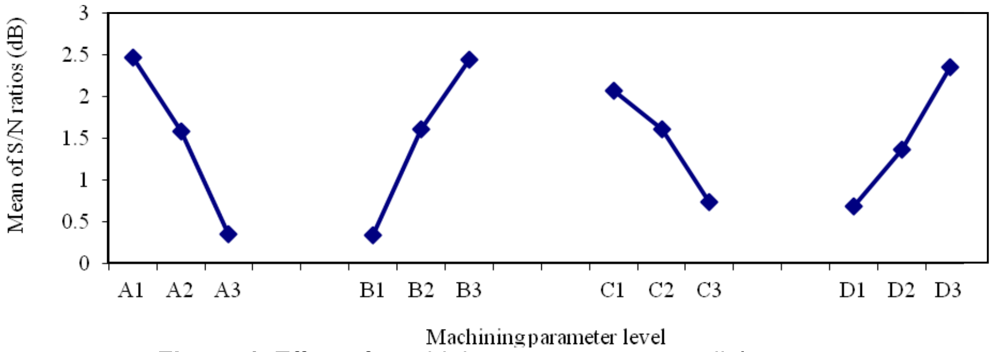

Figure 4. Effect of machining parameters on radial over cut

Table 5. Average S/N ratio value by factor levels for ROC

Level	A	B	C	D
1	2.4683 [a]	0.3468	2.0632 [a]	0.6846
2	1.5837	1.6152	1.6062	1.3697
3	0.3503	2.4403 [a]	0.7330	2.3480 [a]
Delta	2.1181	2.0935	1.3302	1.6633

4.3. Analysis of variance

4.3.1. Material removal rate

Table 6 shows the ANOVA results for material removal rate values. All the selected factors have statistical and physical significance on the material removal rate during the machining of the composites at 95% confidence level. From Table 6 it can be observed that the applied voltage (A), feed rate (B), electrolyte concentration (C) and percentage of reinforcement (D) affect the material removal rate by 22.84%, 52.67%, 10.54%, and 9.03%, respectively.

Table 6. Results of analysis of variance for MRR

Source	DF	Seq SS	Adj MS	F	P	Percent(%)
A	2	0.2337	0.1168	41.80	0.00	22.84
B	2	0.5388	0.2694	96.38	0.00	52.67
C	2	0.1078	0.0539	19.28	0.00	10.54
D	2	0.0924	0.0462	16.53	0.00	9.03
Error	18	0.0503	0.0028			4.92
Total	26	1.0231				100

4.3.2 Surface roughness

The ANOVA results for surface roughness values are shown in Table 7. The percent numbers depict that all the considered machining parameters have significant effect on the surface roughness. It can be observed from Table 7 the applied voltage (A), feed rate (B), electrolyte concentration (C) and percentage of reinforcement (D) affect the surface roughness by 19.70%, 29.13%, 36.04%, and 9.35% in the electrochemical machining of Al/B_4C composites, respectively.

Table 7. Results of analysis of variance for SR

Source	DF	Seq SS	Adj MS	F	P	Percent (%)
A	2	0.8419	0.4209	30.66	0.00	19.70
B	2	1.2447	0.6223	45.32	0.00	29.13
C	2	1.5400	0.7700	56.08	0.00	36.04
D	2	0.3995	0.1997	14.55	0.00	9.35
Error	18	0.2471	0.0137			5.78
Total	26	4.2734				100

4.3.3. Radial over cut

Table 8 shows the ANOVA results for radial over cut values. From Table 8 it can be observed that the applied voltage (A), feed rate (B), electrolyte concentration (C) and percentage of reinforcement (D) affect the radial over cut by 30.55%, 27.55%, 13.29% and 19.12%, respectively. At 95% confidence level, all the considered machining parameters have significant effect on radial over cut since their P-values are lower than 0.05.

Table 8. Results of analysis of variance for ROC

Source	DF	Seq SS	Adj MS	F	P	Percent(%)
A	2	0.2032	0.1016	28.97	0.00	30.55
B	2	0.1832	0.0916	26.12	0.00	27.55
C	2	0.0883	0.0441	12.60	0.00	13.29
D	2	0.1271	0.0635	18.12	0.00	19.12
Error	18	0.0631	0.0035			9.49
Total	26	0.6650				100

5. Confirmation experiments

The experimental confirmation test is the final step in verifying the results drawn based on Taguchi's design approach. In this study, confirmation experiments are conducted by utilizing the optimum levels of machining parameters (A3 B3 C3 D1) for material removal rate, (A2 B3 C3 D1) for surface roughness and (A1 B3 C1 D3) for the radial over cut value in the electrochemical machining of Al/B_4C composites. Predicted optimum value ($\hat{\alpha}$) of the responses is calculated from the following equation [11, 12]:

$$\hat{\alpha} = \alpha_m + \sum_{i=1}^{q} \left(\overline{\alpha} - \alpha_m\right) \tag{11}$$

where α_m is total mean response, $\overline{\alpha}$ is the mean of the response at the optimal level and q is the number of parameters that significantly effects the performance.

Predicted values determined by using Equation (11) and confirmation experimental results for all the responses are given in Table 9. From Table 9 it is observed that the difference in predicted and the experimental value is small for all the responses. Therefore, the optimum responses can be obtained under the above mentioned machining conditions.

Table 9. Results of confirmation experiment

Response	Optimal machining parameters			
	Parameter level	Prediction	Experiment	Error
MRR	A3 B3 C3 D1	0.994	0.979	1.53%
SR	A2 B3 C3 D1	3.656	3.598	1.61%
ROC	A1 B3 C1 D3	0.532	0.570	7.14%

6. Conclusions

This study has discussed an application of the Taguchi method for investigating the effects of machining parameters on the material removal rate, surface roughness and radial over cut values in the electrochemical machining of Al/B_4C composites. From the analysis of the results in the electrochemical machining process using the regression analysis, S/N ratio approach, analysis of variance (ANOVA) and Taguchi's optimization method, the following can be concluded:

a) The applied voltage (A), feed rate (B), electrolyte concentration (C) and percentage of reinforcement (D) affect the material removal rate by 22.84%, 52.67%, 10.54%, and 9.03% in the electrochemical machining of Al/B_4C composites, respectively.
b) Statistical results (at a 95% confidence level) show that the applied voltage (A), feed rate (B), electrolyte concentration (C) and percentage of reinforcement (D) affect the surface roughness by 19.70%, 29.13%, 36.04%, and 9.35% in the electrochemical machining of Al/B_4C composites, respectively.
c) Statistical results (at a 95% confidence level) show that the applied voltage (A), feed rate (B), electrolyte concentration (C) and percentage of reinforcement (D) affect the radial over cut by 30.55%, 27.55%, 13.29%, and 19.12% in the electrochemical machining of Al/B_4C composites, respectively.
d) Parametric combination for maximum MRR is A3 B3 C3 D1, for minimum SR is A2 B3 C3 D1 and for minimum ROC is A1 B3 C1 D3.

References

[1] Fortana, M. G. 1986. "*Corrosion Engineering*". McGraw-Hill, New York.

[2] Senthilkumar, C., Ganesan, G., and Karthikeyan R. 2009. Study of electrochemical machining characteristics of Al/SiCp composites. *International Journal of Advanced Manufacturing Technology*, 43: 256-263.

[3] Kao, P. S. and Hocheng, H. 2003. Optimization of electrochemical polishing of stainless steel by grey relational analysis. *Journal of Materials Processing Technology*, 140: 255-259.

[4] Jagannath, M. and Bhattacharya, B. 2008. Investigation in to electrochemical micromachining (EMM) through response surface methodology based approach. *International Journal of Advanced Manufacturing Technology*, 35, 7: 821-832.

[5] Asoken, P., Ravi Kumar, R., Jeypaul, R., and Santhi, M. 2008. Development of

multi-objective optimization models for electrochemical machining process. *International Journal of Advanced Manufacturing Technology*, 39: 55-63.

[6] Rama Rao, S., Sravan, C. R. M., Padmanabhan, G., and Pandu R. V. 2009. Fuzzy logic based forward modeling of electrochemical machining process. *IEEE Proceedings of the World Congress on Nature and Biologically Inspired Computing*, Chennai, India, pp.1431-1435.

[7] Rama Rao, S., Padmanabhan, G., Sureka, B., and Pandu R. V. 2009. Optimization of electrochemical machining process using evolutionary algorithms. *Journal of machining and forming technology*, 1(3/4): 265-278.

[8] Chakradhar, D. and Venu Gopal, A. 2011. Multi-objective optimization of electrochemical machining of EN31 steels by grey relational analysis. *International Journal of Modeling and Optimization*, 1, 2: 113-117.

[9] Sorkhel, S. K. and Bhattacharya, B. 1992. Parametric combinations for controlled machined rate and surface quality in electrochemical machining. *In proceedings of the 15th All India machine tool design and research conference*, 421-426.

[10] Yang, W. H. and Tarng, Y. S. 1998. Design optimization of cutting parameters for turning operations based on the Taguchi method. *Journal of Materials Processing Technology*, 84: 122-129.

[11] Palanikumar, K. 2008. Application of Taguchi and response surface methodologies for surface roughness in machining glass fiber reinforced plastics by PCD tooling. *International Journal of Advanced Manufacturing Technology*, 36: 19-27.

[12] Davidson, M. J., Balasubramanian, K., and Tagore, G. R. N. 2008. Surface roughness prediction of flow-formed AA6061 alloy by design of experiments. *Journal of Materials Processing Technology*, 202: 41-46.