International Journal of Advance Research and Innovation
Vol. 4(1), Jan-Mar 2016, pp. 294-300
Doi: 10.51976/ijari.411643

Article Info
Received: 20 Jan 2016 | Revised Submission: 10 Feb 2016 | Accepted: 28 Feb 2016 | Available Online: 15 Mar 2016

An Experimental Study on Electro-Discharge Machining of Al2014/Al_2O_3 Composite

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ABSTRACT

Aluminium metal matrix composites are possessing the properties such as light weight, good wear resistance, high stiffness etc. Due to unique combination of properties, these composites are replacing conventional materials in industries such as transport, civil aviation, recreation etc. However, wider applications are still marred by poor machinability by conventional machining processes, due to presence of hard reinforcements such Al2O3, SiC, B4C etc in the composite. Electro-discharge machining (EDM) is a potential advanced process for the machining for aluminium metal matrix composites (AlMMC). The present work encompasses an experimental investigation on electro-discharge machining of aluminium alloy 2014 reinforced with 10wt% Al2O3 particles (Al2014/Al2O3). The central composite rotatable design using response surface methodology (RSM) is used to formulate the design of experiment (DOE) to analyse the effects of EDM process parameters on the machining characteristics viz. material removal rate (MRR) and surface roughness(SR). The four process parameters namely current, pulse on time, pulse off timeand gap voltage are considered for the experimental study. Regression analysis is performed and the significance of the model developed is checked by analysis of variance (ANOVA). Results obtained are further optimized using desirability functions to maximize MRR and minimize SR. The recommended optimal conditions have been validated by performing the confirmatory experiment.

Keywords: *EDM; MRR; SR; Aluminum Metal Matrix Composite (MMC); ANOVA.*

1.0 Introduction

Aluminium matrix composites (AMCs) refer to the category of light weight matrix composites which are potential materials for various applicationsdue to their good physical and mechanical properties. The reinforcement in AMCs could be inthe form of continuous/discontinuous fibres, whisker or particulates (1). Theexisting properties of matrix composites can be altered according to the growing needs of different industrial applications by proper combination of matrix, reinforcement and different processing routes. Due to abrasive and brittle nature of reinforcing ceramics like SiC or Al2O3, high tool wear, poor surface finishing are common challenges in traditional machining of hard composites (2). EDM process is widely used for conductive materials irrespective of their hardness (3) Electrical discharge machining process becomes viable method for metal matrix composites.Hocheng*et al*. (4) analysed the material removal rate (MRR) of SiC/Al composite on the basis of single and continuous spark in electrical discharge machining (EDM) process. High current and long pulse on time reported optimum setting to achieve highest MRR of composite materials.Seo*et al*. (5)analysed the machining characteristics of functionally graded Al359/15-35% volSiC composite using EDM process. MRR reported improvement with increase in peak current, pulse on time, and SiC percentage in Al alloy. Singh *et al*. (6) analysed the machining characteristics of 6061 aluminium alloy reinforced with 10%SiC particles with EDM process. The enhancement in current and pulse on time observed to be significant factors for higher crater size and subsequently higher surface roughness. Habib (7) investigated the machinability of aluminium reinforced with varying volume fraction from 5% to 25% of SiC in

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metal matrix composite. MRR showed increment with increase in peak current and pulse on time. When SiC particles increase in aluminium matrix phase, MRR depicted decreasing trend up to 15% and thereafter reverse trend with increase in percentage of reinforcement.

As observed from past research, there is little research work on Al2014 reinforced with Al2O3.The objective of this experimental work is to establish the correlation between EDM machining parameters (such as current, pulse on time, pulse off time and gap voltage) and response parameters MRR and SR in electro-discharge machining of Al2014/10wt%Al2O3compositeusing response surface methodology.

2. 0 Materials and Methods

Al alloy of 2014/10% wt.Al2O3 is fabricated by mechanical stir casting process. The chemical composition of aluminium alloy 2014 is shown in Table 1. To examine the effect of process parameterson MRR and SR experiments in EDM of Al2014/10wt% Al2O3 composite, experimental investigation was undertaken using Sparkonix ZNC EDM as shown in Fig.1 (b). Electrolytic copper electrodes as shown in Fig.1 (a) were used for machining the aluminium matrix composite. The variables of ZNC EDM are presented in Table 2. The process parameters and their levels are shown in Table 3. In the present paper, four process parameters namely peak current, pulse on time, pulse off time and gap voltage are considered for study of MRR and SR under different experimental conditions.

Response surface methodology approach was used to formulate the design of experiment (DOE). As per the design of experiments, 30 trials were performed in random order as shown in Table 4. The conducted experiments were repeated twice to reduce the possibility of error in the system. For statistical analysis average of the two reading was used for computation of MRR and SR. SRT-6210 surface roughness tester was used for checking the surface roughness. The machined workpiece is shown in Fig.1(c) MRR is measured on a weighing scale by weighing the workpiece pre and post machining using (DENVER SI-234) with readability of 0.1 milligrams

Fig 1 (a) : Copper Electrodes, (b) EDM Setup and (c) Machined Work Piece

Table 1: Chemical Composition of AA2014 Alloy

Alloy	Cu	Si	Mg	Fe	Zn	Ti	Mn	Cr	Al
AA2014	3.9-5.0	0.5-0.7	0.3-0.8	0.7	0.25	0.15	0.4-0.12	0.1	90.4-95.0

Table 2: Experimental Conditions of EDM

Machine	Electrode	Electrode Polarity	Workpiece	Dielectric	Pressure
Sparkonix EDM	Copper	Positive	AA2014/10%wt Al_2O_3	Kerosene	1.0 kgf/cm^2

MRR selected as investigated characteristics is calculated by expression as shown by equation [1].

$$MRR\ (g/min) = \frac{Wi - Wf}{t} \quad [1]$$

Where, W_i = Initial weight of work piece material (g),

W_f = Final weight of workpiece material after machining (g), t = Machining time in minutes. Surface roughness was measured directly as Ra value, taking average of three readings taken at different points. RSM technique is used for modeling and analysis of problems. This approach is used to correlate the relation between the responses and the input parameters. This approach is also utilized in optimizing the process parameters for two conflicting responses (MRR & SR).

Table 3: Machining Process Parameters and their Levels

Factors/Levels	-2	-1	0	1	2
A:Current(A)	3	6	9	12	15
B:Pulse on time(µs)	30	60	90	120	150
C:Pulse on time(µs)	8	56	104	152	200
D:Gap voltage (V)	30	40	50	60	70

Table 4: Design Layout with Actual Parameters and Experimental Results for MRR and SR

Std Order	Random Order	Current (A)	Pulse On Time(μs)	Pulse Off Time(μs)	Gap Voltage(V)	MRR (g/min)	SR (μm)
7	1	6	120	152	40	0.0502	4.723
3	2	6	120	56	40	0.0834	8.478
29	3	9	90	104	50	0.0857	4.272
1	4	6	60	56	40	0.0383	4.0005
27	5	9	90	104	50	0.0816	6.949
6	6	12	60	152	40	0.0578	9.544
2	7	12	60	56	40	0.14	8.3905
9	8	6	60	56	60	0.0324	6.1985
8	9	12	120	152	40	0.1267	8.4785
23	10	9	90	104	30	0.1218	7.3447
12	11	12	120	56	60	0.4376	8.3145
13	12	6	60	152	60	0.0389	5.9035
5	13	6	60	152	40	0.0989	4.362
17	14	3	90	104	50	0.0086	4.5955
19	15	9	30	104	50	0.0173	5.6737
21	16	9	90	8	50	0.4046	8.6902
20	17	9	150	104	50	0.116	5.9365
18	18	15	90	104	50	0.1986	8.386
15	19	6	120	152	60	0.0336	6.2699
30	20	9	90	104	50	0.0667	3.5305
28	21	9	90	104	50	0.2041	4.592
25	22	9	90	104	50	0.1798	5.674
4	23	12	120	56	40	0.3922	12.37
26	24	9	90	104	50	0.0906	6.166
14	25	12	60	152	60	0.0367	5.77
10	26	12	60	56	60	0.0974	5.4065
16	27	12	120	152	60	0.1116	4.608
11	28	6	120	56	60	0.0693	7.675
24	29	9	90	104	70	0.0685	6.7315
22	30	9	90	200	50	0.0542	6.5595

3.0 Results and Discussion

The worth of the model are gauged by using analysis of variance (ANOVA) approach. The results of the second order response surface model fitting in the form of ANOVA, after neglecting the insignificant parameters are mentioned in Table 5 and Table 6 respectively.

As per ANOVA techniques, if the values of the "Prob>F" less than 0.05, then the model terms are statistically significant.

The model F value of 20.07 and 12.01 indicate that both the models are statistically significant. Lack of fit is not significant relative to the pure error which is the desired condition for the model to compute and interpretation of the results. It means that polynomial model is fitting all of design points well. The R^2 is the ratio of variability explained by the model to the total variability in the actual data. This is used to measure goodness of fit [9]. If the value of R^2 is unity, then it shows best result in terms of model. The calculated value of 0.8646 and 0.8206 in Tables 5 and 6, respectively indicates that model explain 86.47% and 82.06% variability of MRR and SR. The value of predicted R^2 0.7134 and 0.6638) are in agreement with that of adjusted R^2 (0.8215 and 0.7523) in case of MRR and SR respectively. Adequate precision checks the S/N ratio. Ratio greater than 4 indicates adequate model discrimination.

The ratios of 17.431 and 14.118 in Table 5 and Table 6 respectively indicate an adequate signal in the machining process. At the same condition, a relatively lower value of coefficient of variation (39.76 and 14.98) indicates better precision and reliability of the conducted experiments.

Table 5: ANOVA Analysis for MRR

Source	Sum of square	Degree of freedom	Mean square	F value	p-value Prob>F	
Model	0.31	7	0.044	20.07	< 0.0001	significant
A-Current	0.074	1	0.074	33.66	< 0.0001	
B-Pulse On Time	0.039	1	0.039	17.47	0.0004	
C-Pulse Off Time	0.086	1	0.086	39.01	< 0.0001	
AB	0.031	1	0.031	14.21	0.0011	
AC	0.034	1	0.034	15.21	0.0008	
BC	0.021	1	0.021	9.68	0.0051	
C^2	0.025	1	0.025	11.27	0.0029	
Residual	0.049	22	2.206E-003			
Lack of fit	0.032	17	1.856E-003	0.55	0.8393	not significant
Pure error	0.017	5	3.396E-003			
Cor. total	0.36	29				
Standard deviation	0.047		R-squared		0.8646	
Mean	0.12		Adjusted R-squared		0.8215	
Coefficient of variation	39.76		Predicted R-squared		0.7134	
PRESS	0.10		Adequate Precision		17.431	

Table 6: ANOVA Analysis for SR

Source	Sum of Square	Degree of freedom	Mean Square	F value	p-value Prob>F	
Model	91.70	8	11.46	12.01	< 0.0001	significant
A-Current	21.76	1	21.76	22.80	0.0001	
B-Pulse On Time	5.87	1	5.87	6.15	0.0217	
C-Pulse Off Time	9.93	1	9.93	10.40	0.0041	
D-Gap Voltage	5.44	1	5.44	5.70	0.0264	
AD	22.96	1	22.96	24.06	< 0.0001	
BC	12.86	1	12.86	13.47	0.0014	
C^2	9.18	1	9.18	9.62	0.0054	
D^2	5.05	1	5.05	5.30	0.0317	
Residual	20.04	21	0.95			
Lack of Fit	11.81	16	0.74	0.45	0.8986	not significant
Pure Error	8.23	5	1.65			
Cor Total	111.74	29				
Standard deviation		0.98	R-squared		0.8206	
Mean		6.52	Adjusted R squared		0.7523	
Coefficent of variation		14.98	Predicted R-squared		0.6638	
PRESS		37.57	Adequate Precision		14.118	

Table 7: Experimental Values At Optimized Setting and Confirmatory Result

Process	Current (A)	Pulse on Time (μs)	Pulse off Time (μs)	Gap Voltage (V)	Optimized MRR Predicted (g/min)	Optimized SR Predicted (μm)	MRR from confirmatory Experiment (g/min)	SR from confirmatory Experiment (μm)
EDM	15	150	110	70	0.438	4.290	0.374	5.110

After deleting the insignificant terms by backward elimination method, the model representing relation between response parameters MRR and SR respectively and the input process parameters in coded form for both responses are given in Eqs.(2) and (3).

The input parameters and their interactions have been found to be statistically significant for their effects on MRR and SR at 95% confidence level, as observed from Table 5 and Table 6. The normal probability plots of residuals for MRR and SR are shown in Figs. 2 and 3.

These figures show that the residuals are lying on the straight line. This means thaterrors are uniformly distributed.

Model for MRR in coded form

$$MRR = 0.095 + 0.056 * A + 0.040 * B – 0.060 * C + 0.040 * AB – 0.046 * AC – 0.037 * BC + 0.29 * C^2 \quad (2)$$

Model for SR in coded form

$$SR = + 5.73 + 0.95 * A + 0.49 * B – 0.64 * C – 0.48 * D – 1.20 * AD – 0.90 * BC + 0.57 * C^2 + 0.42 * D^2 \quad (3)$$

Fig 2: Normal GRAPh of REsiduals (MRR)

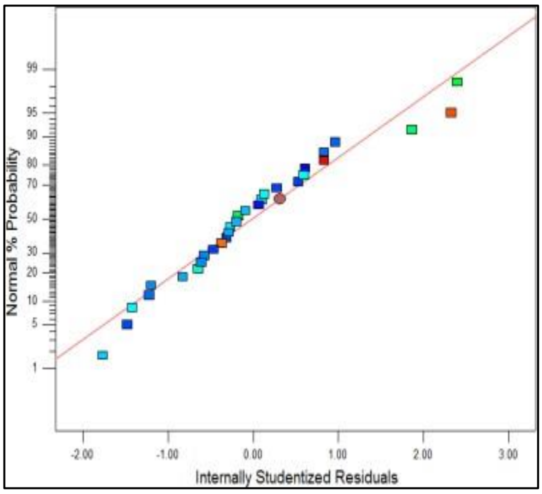
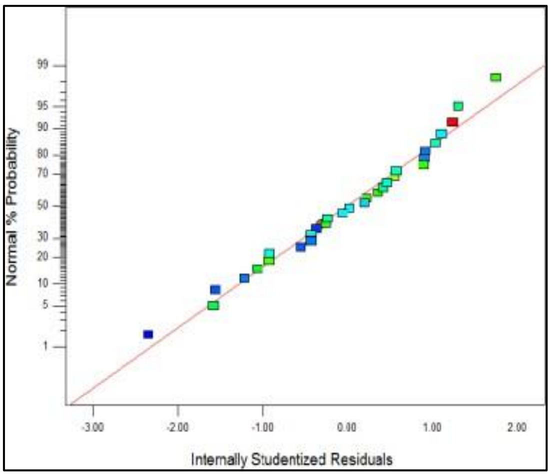


Fig 3: Normal GRAph of Residuals (SR)



Actual value are analyzed with respect to predicted values for MRR and SR as shown in Figs. 4 and Figs. 5. Asdepicted from the figure that the regression model is quite well suited to actual settings. It also confirms that the obtained model for MRR can be considered significant for fitting and estimating the experiments finding.

Fig 4: Actual Vspredicted (MRR)

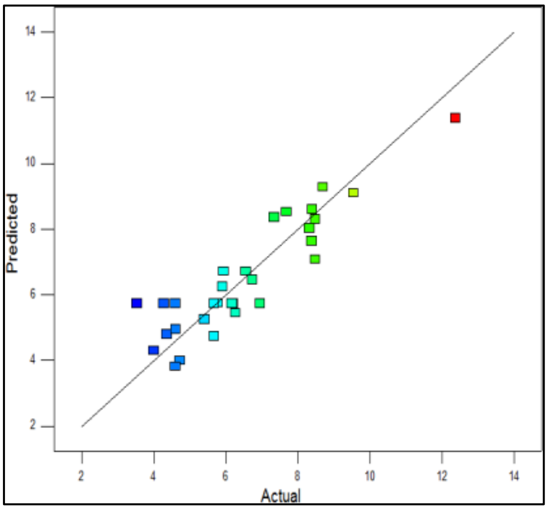
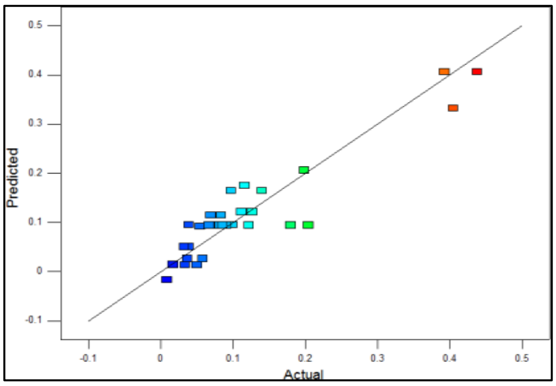


Fig 5: Actual vs Predicted (SR)

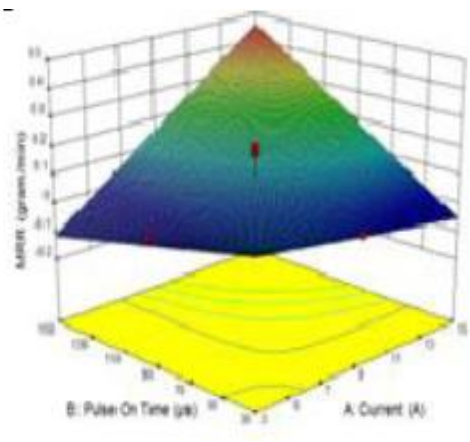


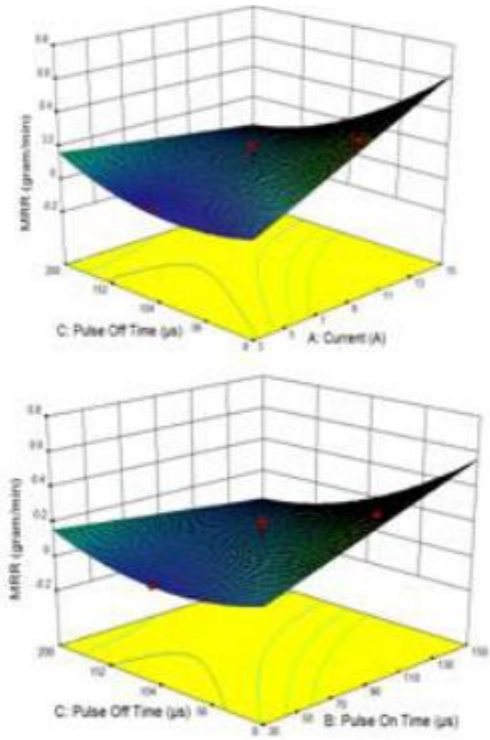
The combined effects of input process variables on MRR and SR are depicted by 3D surface graphs as shown in Figs. 6 and 7. Fig. 6 represents the two factor interaction effect when AA2014/10%wtAl2O3 composite is machined with ZNC EDM. Fig. 6(a) displays the interactive influence of current and pulse on time with respect to MRR. Higher MRR reported at higher setting of current and pulse on time.

Fig. 6(b) depicts the combined effect of current and pulseoff time on MRR. There is an increase in MRR with increase in current, however marginal increment in MRR is observed with increase in pulse off time from 104 to 200µs. Fig. 6(c) shows the interactive effect of pulse on and pulse off time on MRR.

It is revealed that there is increase in MRR with increase in pulse on time and marginal increase with pulse off time.

Fig 6: (a), (b) and (c) Combined Effects of Current, Pulse 0ffTime And Pulse on Time on Mrr

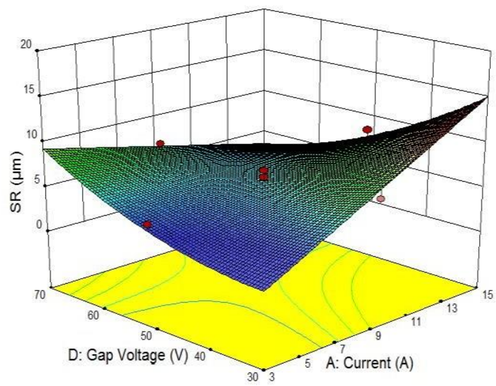


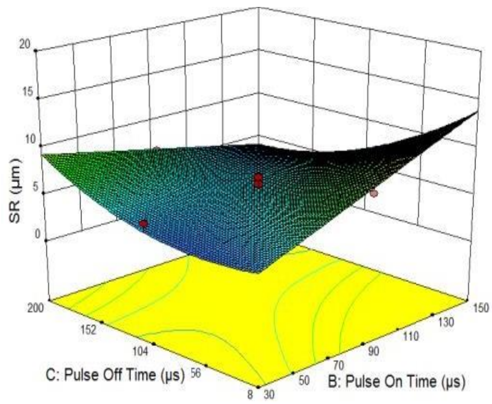


The three-dimensional surface plots for surface roughness are presented in the above figures. Fig.7 (a) depicts the combined interactive effect of current and gap voltage on surface roughness.

SR increases with increase in voltage however rate of increment in SR is obtained more with increase in current (8). Fig.7 (b) indicates the interactive effect of pulse on and pulse off time on SR. It was seen gradual increase in SR with increase in pulse off time however, SR is higher with increase in pulse on time due to more heat input.

Fig 7: (a) and (b) Combined Effects of Current, Voltage,Pulse on Time and Pulse off Time





4.0 Conclusions

1. The process has been successfully modeled using RSM approach. The second-order response models have been validated with analysis of variance. The relation between process parameters and MRR is obtained with regression modeling.
2. Higher MRR can be achieved at higher setting of current, pulse on time and optimum setting of pulse off time.
3. Current, pulses on time and gap voltage are significant factors affecting surface roughness.
4. Processes parameters are optimized to get best combination of MRR and SR. Optimization of the process enhanced the MRR and reduced SR as obtained from confirmatory experiment.
5. This study can help researchers and industries for developing reliable knowledge base and early prediction of MRR and SR with EDM process for Al 2014/Al2O3 composite.

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