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A Modelling Approach for Prediction of Electric Discharge Machining of Al6061-SIC MMC Composite

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***Abstract* -** The machining of composites using non-conventional machining methods had been an area of intense research for more than thirty years. The optimisation of machining input parameters was identified to be the major concern among the researchers. This work aims at developing a mathematical model to identify the optimum and the most contributing parameters on the Electric Discharge Machining (EDM) of Al6061-SiC composites with varying percentages of SiC. The result indicate that the current has major contribution in both the output parameters. The optimum current was observed to reduce as the percentage of reinforcement increases. The optimum value observed for composites with 3%SiC were current (6A), pulse on time (38 µs) and pulse off time (8 µs). For composite with 5% SiC the optimum values identified were current (6A), pulse on time (56 µs) and pulse off time (8 µs) and for composite with 9% SiC optimum input values were current (12A), pulse on time (56 µs) and pulse off time (7 µs)

INTRODUCTION

The development of composite materials has revolutionized the manufacturing sector due to the capability to develop tailor-made materials that meet the requirement of a specific application. The machining of the developed material using conventional methods require skilled work-force. This have led to the machining of these materials using non-conventional machining methods. Electric Discharge Machining (EDM) was identified to be one of the most sought manufacturing processes for the composite components developed for these applications. Al6061 based composites finds its application in the area of automobile and aerospace due to its inherent properties and low thermal expansion coefficient and better wear resistance. Improved strength to weight ratio, higher hardness and the tailor-made proportions for specific applications were identified to be the major reasons for the increased interest in the application of composite materials [1]. Ajithkumar et al [2] worked on the grey relation analysis for optimisation of the machining parameters of Al7075 based composites. The major challenge in the non-conventional machining process was the control of the tool and the work piece, which was answered by the introduction of CNC based control systems [3]. Electric Discharge Machining (EDM) have been identified to be capable of solving this challenge of machining of composites. The major difficulty faced for machining using EDM has been the identification and optimisation of the critical factors for economic machining of the component[4]. The researches of the past decade were oriented towards optimising the process parameters for the identification of the best inputs leading to the desired output. A lot of works were observed in the area of Electric Discharge Machining of Metal Matrix composites in the recent past [5]. The models developed by Kalajahi[6] and Sahu[7] have developed models in ANSYS for identifying the relationship of the flushing efficiency with the pulse current and pulse on time. Nandakumar and Kanakaraj [8] carried out experimental study on the mechanical properties of two different aluminium-based composites. The study concluded that the addition of reinforcements had enhanced the mechanical properties of the composite. Arunkumar and Swamy [9] carried out the study on the mechanical properties of the Al6061 –fly ash- E-glass fibre composites. The work identified improvement in hardness and tensile strength with the addition of fly ash whereas no variation in properties were observed due to the addition of E-glass fibre. Prasanth et al. [10] worked on comparing the mechanical properties of Al6061 mixed with SiC and graphite as the reinforcements. It was identified in the work that the addition of SiC increased hardness as well as tensile strength whereas addition of graphite reduced the hardness and increased the tensile strength. Nagendran et al. [11] studied the mechanical properties of Al6061 reinforced with SiC and titanium dioxide. The work identified that there was an increase in tensile strength till 4% of the reinforcement addition after which, there is a drop in tensile strength. But hardness kept on increasing with increased reinforcement percentage. Nagendra Maurya et al. [12] researched on the different mechanical properties of the Al6061 composite with varying percentages of SiC. The work observed that addition of SiC had increased both hardness and tensile strength of the composite. Uthayakumar et al. [13] carried out research on aluminium matrix composites which were functionally graded, for different major machining parameters like surface roughness, overcut, electrode wear rate etc. in EDM. The work targeted for the usage of the material in disc brake rotor. The analysis recognized that the main influencing factor for the considered parameters was pulse current. Marafona and Araujo [14] conducted investigations on the effect of the workpiece hardness for the EDM process for various alloys. It was identified in the work that the workpiece properties have substantial contribution in the output parameters of the EDM process. The work had successfully developed a model for the prediction of the output parameters based on the input data for steel. Raza et al. [15] conducted experimental investigation on Al6061-SiC composite using different electrodes and the effect on its performance variation for MRR and surface roughness was studied. The work concluded that brass electrode provided a better MRR when compared to the other electrodes. S Singh [16] conducted experiments on Al6061 reinforced with Al_2O_3 by employing grey relational analysis. The pulse current was the most contributing factor for MRR and surface roughness of Al6061-Al_2O_3 composite. Kashif Ishfaq et al. [17] carried out experimental studies for the wire EDM machining of Al6061-7.5%SiC composite. The work provided the in-sight on the problems faced for the machining of Al6061 based composites. The work assessed the level of errors due to the wire vibrations and lag viz. corner variations and errors in cutting orientations. These variations were identified to be due to the presence of SiC in the composite. The work concluded that the low current, pulse on time and a high gap voltage provide lesser variations in the evaluated parameters. Doresamy et al. [18] worked on the modelling and optimization of wire EDM of Al6061- SiC composite. The work evaluated the optimum values of current, pulse on time, pulse off time, voltage and wire speed for the MRR of the specimens. It was concluded that current is the major contributing factor for the considered parameter. The work also developed a regression model for predicting the MRR for different compositions. H. Singh et al. [19] worked on the MRR and tool wear rate of Al6061 workpiece using copper and brass electrodes. The work identified that the peak current of 15A produced maximum MRR for both the electrodes. The tool wear was identified to be lower for copper electrode. Mythili and Thanigaivelan [20] had carried out study of wire EDM in Al6061- 6%Al_2O_3 and Al6061- 8%Al_2O_3 composite. The input parameters of current, gap voltage, wire tension and dielectric pressure were considered for this work. The work identified current as the major contributor for the variation in MRR and surface roughness. TOPSIS analysis was employed for obtaining the optimum values.

MATERIALS AND METHODOLOGY

The work was conducted on Al6061-SiC composite which has a wide range of applications in automobile and aerospace industry. Three different composites were developed with 3,5 and 9% SiC added to the Al6061 matrix. The composite was developed using stir casting method. The methodology adopted for the fabrication were as explained below:

- Preheating of the casting die. The temperature of preheating was set to 400°C.
- Addition of Al6061 pieces of size Φ25 × 95mm length into the crucible
- Kept the crucible in the furnace
- Heated Al6061 to 850°C and taken it to liquid state.
- Stir the molten Al6061 at 700rpm and permitting it for slow cooling.
- Addition of the reinforcement (SiC) powder to the molten metal during the stirring process
- Added the molten composite into the die to obtain the final composite.
- The composite was allowed to cool at room temperature obtaining the final composite.

The specimen was carried out with Scanning Electron Microscope (SEM) analysis to identify the even distribution of the reinforcement in the base matrix. The SEM and optical microscope images are provided in fig 1.

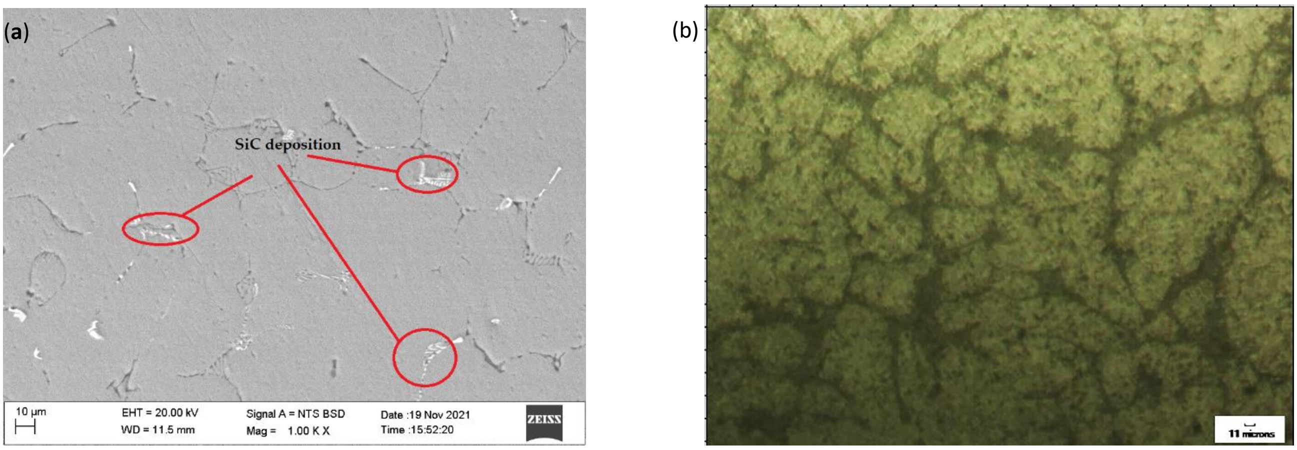

Fig 1: (a) SEM image of the sample **(b)** Optical microscope image of the sample.

The developed composites were machined in the EDM machine available at A1 Cosmic Tools Pvt. Ltd, located at Coimbatore, India. The major input parameters were identified to be current, pulse-on-time and pulse-off-time for three different percentages of SiC. The output parameters considered were material removal rate (MRR)and the surface roughness (R_a). Taguchi L9 array was used for the analysis. The details of the values considered for the analysis is provided in Table 1. These values were identified based on the previous studies conducted by the researchers for similar materials in EDM.

Table 1. Process parameters

Parameters	Level 1	Level 2	Level 3
Current (A)	6	9	12
Pulse on time (μs)	36	48	56
Pulse off time (μs)	7	8	9

Analysis of Variance (ANOVA) was carried out to identify the most contributing parameters. Grey Relation Analysis was carried out for optimisation of the input parameters for the different compositions of SiC. For the output value of MRR, larger the better condition was considered whereas for the R_a, smaller the better condition was desired.

RESULTS AND DISCUSSION

Nine experiments for the various combination of SiC were conducted. Table 2 provide the details of the experiments carried out.

Table 2: Experimental results of the EDM machining

Exp. No	CURRENT (A)	PULSE ON TIME (μs)	PULSE OFF TIME (μs)	% of SiC	MRR (g/min)	R_a (μm)
1	6	36	7	3	0.070	4.200
2	6	48	8	3	0.130	5.800
3	6	56	9	3	0.120	8.320
4	9	36	8	3	0.140	6.250
5	9	48	9	3	0.1500	7.420
6	9	56	7	3	0.1800	9.240
7	12	36	9	3	0.1300	8.330
8	12	48	7	3	0.1700	9.540
9	12	56	8	3	0.2020	9.340
10	6	36	7	5	0.1420	6.200
11	6	48	8	5	0.1800	7.100
12	6	56	9	5	0.1750	8.300
13	9	36	8	5	0.1810	7.500
14	9	48	9	5	0.2120	8.600
15	9	56	7	5	0.2180	8.900
16	12	36	9	5	0.1850	10.620
17	12	48	7	5	0.2000	9.609
18	12	56	8	5	0.2640	10.050
19	6	36	7	9	0.252	9.805
20	6	48	8	9	0.286	10.351
21	6	56	9	9	0.292	9.412
22	9	36	8	9	0.294	10.852
23	9	48	9	9	0.351	10.720
24	9	56	7	9	0.319	9.820
25	12	36	9	9	0.353	12.330
26	12	48	7	9	0.372	11.850
27	12	56	8	9	0.374	11.950

The experimental data was analysed by considering nine experiments for the different percentages of SiC added to the mixture considering L9 (3^3)matrix in Taguchi method. The details of the Analysis of Variance (ANOVA) is provided from Table 2 to 7.

Table 2: ANOVA- MRR – Al6061-3%SiC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Regression	8	0.011830	100.00%	0.011830	0.001479
CURRENT	1	0.005521	46.67%	0.000461	0.000461
PULSE ON TIME	1	0.004525	38.25%	0.000134	0.000134
PULSE OFF TIME	1	0.000067	0.56%	0.000855	0.000855
CURRENT^2	1	0.000774	6.54%	0.000774	0.000774
PULSE ON TIME^2	1	0.000036	0.30%	0.000047	0.000047
PULSE OFF TIME^2	1	0.000854	7.22%	0.000885	0.000885
CURRENT × PULSE ON TIME	1	0.000043	0.36%	0.000054	0.000054
CURRENT × PULSE OFF TIME	1	0.000011	0.10%	0.000011	0.000011
Error	0	0.000000	0.00%	0.000000	*
Total	8	0.011830	100.00%		

Table 3: ANOVA- R_a – Al6061-3%SiC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Regression	8	41.7382	100.00%	41.7382	5.21727
CURRENT	1	21.7741	52.17%	0.0379	0.03786
PULSE ON TIME	1	18.0642	43.28%	0.7368	0.73683
PULSE OFF TIME	1	0.1980	0.47%	0.0550	0.05496
CURRENT^2	1	0.2812	0.67%	0.2813	0.28125
PULSE ON TIME^2	1	1.2801	3.07%	1.3518	1.35175
PULSE OFF TIME^2	1	0.0365	0.09%	0.0238	0.02375
CURRENT × PULSE ON TIME	1	0.0060	0.01%	0.0028	0.00282
CURRENT × PULSE OFF TIME	1	0.0980	0.23%	0.0980	0.09802
Error	0	0.0000	0.00%	0.0000	*
Total	8	41.7382	100.00%		

Table 4: ANOVA- MRR – Al6061-5%SiC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Regression	8	0.009334	100.00%	0.009334	0.001167
CURRENT	1	0.003851	41.26%	0.000022	0.000022
PULSE ON TIME	1	0.003714	39.79%	0.000006	0.000006
PULSE OFF TIME	1	0.000024	0.26%	0.000336	0.000336
CURRENT^2	1	0.000321	3.44%	0.000321	0.000321
PULSE ON TIME^2	1	0.000006	0.07%	0.000009	0.000009
PULSE OFF TIME^2	1	0.000774	8.29%	0.000394	0.000394
CURRENT × PULSE ON TIME	1	0.000460	4.93%	0.000204	0.000204
CURRENT × PULSE OFF TIME	1	0.000184	1.97%	0.000184	0.000184
Error	0	0.000000	0.00%	0.000000	*
Total	8	0.009334	100.00%		

Table 5: ANOVA- R_a – Al6061-5%SiC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Regression	8	12.6340	100.00%	12.6340	1.57925
CURRENT	1	9.0258	71.44%	0.0605	0.06054
PULSE ON TIME	1	3.0052	23.79%	0.0002	0.00022
PULSE OFF TIME	1	0.3705	2.93%	0.0640	0.06405
$CURRENT^2$	1	0.0174	0.14%	0.0174	0.01736
PULSE ON $TIME^2$	1	0.0127	0.10%	0.0174	0.01742
PULSE OFF $TIME^2$	1	0.1438	1.14%	0.0756	0.07564
CURRENT × PULSE ON TIME	1	0.0534	0.42%	0.0337	0.03375
CURRENT × PULSE OFF TIME	1	0.0051	0.04%	0.0051	0.00511
Error	0	0.0000	0.00%	0.0000	
Total	8	12.6340	100.00%		

Table 6: ANOVA- MRR – Al6061-9%SiC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Regression	8	0.014892	100.00%	0.014892	0.001862
CURRENT	1	0.012060	80.98%	0.000002	0.000002
PULSE ON TIME	1	0.001482	9.95%	0.000507	0.000507
PULSE OFF TIME	1	0.000468	3.14%	0.000085	0.000085
$CURRENT^2$	1	0.000000	0.00%	0.000000	0.000000
PULSE ON $TIME^2$	1	0.000748	5.02%	0.000650	0.000650
PULSE OFF $TIME^2$	1	0.000053	0.36%	0.000096	0.000096
CURRENT × PULSE ON TIME	1	0.000079	0.53%	0.000060	0.000060
CURRENT × PULSE OFF TIME	1	0.000001	0.01%	0.000001	0.000001
Error	0	0.000000	0.00%	0.000000	*
Total	8	0.014892	100.00%		

Table 7: ANOVA- R_a– Al6061-9%SiC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Regression	8	8.85223	100.00%	8.85223	1.10653
CURRENT	1	7.17664	81.07%	0.15308	0.15308
PULSE ON TIME	1	0.47168	5.33%	0.18136	0.18136
PULSE OFF TIME	1	0.16236	1.83%	0.25972	0.25972
$CURRENT^2$	1	0.47174	5.33%	0.47174	0.47174
PULSE ON $TIME^2$	1	0.22682	2.56%	0.25301	0.25301
PULSE OFF $TIME^2$	1	0.31179	3.52%	0.26690	0.26690
CURRENT × PULSE ON TIME	1	0.00364	0.04%	0.00011	0.00011
CURRENT × PULSE OFF TIME	1	0.02756	0.31%	0.02756	0.02756
Error	0	0.00000	0.00%	0.00000	*
Total	8	8.85223	100.00%		

ANOVA for the different composites developed was carried out to identify the most dominating parameter for the MRR as well as R_a. The ANOVA clearly indicate current as the most dominating factor for both the output parameters. The influence percentage of current increases with the increase in percentage of SiC from 46% for 3% SiC to 81% for 9% SiC, whereas the influence of pulse-on-time diminishes with the increase in percentage of SiC. Pulse off time is least contributing factor with the percentage varying from 0.26% to 3.24%. The increased influence of current for both MRR and Ra can be attributed to the fact that the change in properties due to the increase in the percentage of reinforcement require more energy for the removal of material from the composite. The Grey Relational Analysis (GRA) was carried out to identify the optimum parameters for the machining of the composite.

Fig 1(a): Factorial plot for MRR - Al6061- 3% SiC

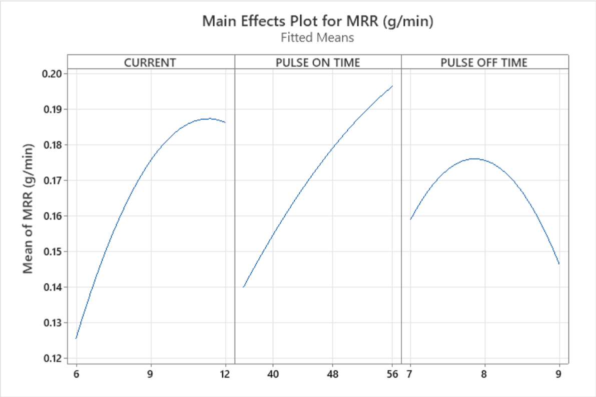

Fig 1(b): Factorial plot for Ra- Al6061- 3% SiC

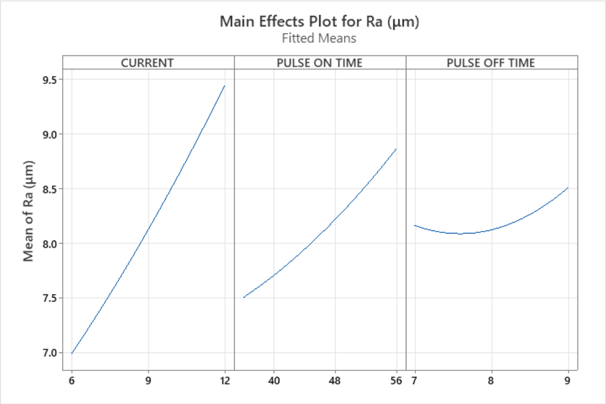

Fig 2(a): Factorial plot for MRR - Al6061- 5% SiC

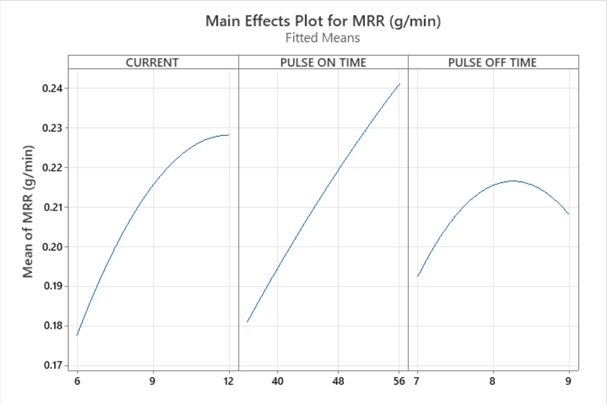

Fig 2(b): Factorial plot for Ra- Al6061- 5% SiC

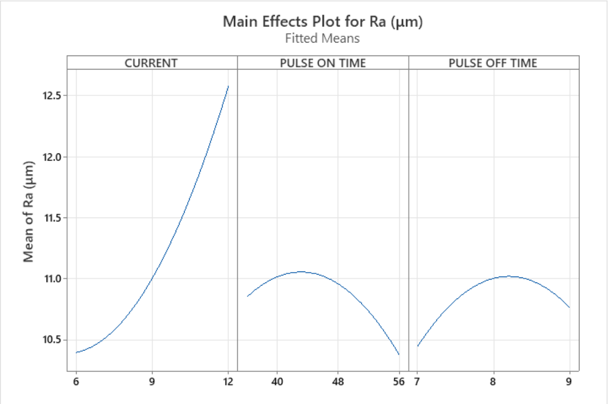

Fig 3(a): Factorial plot for MRR - Al6061- 9% SiC

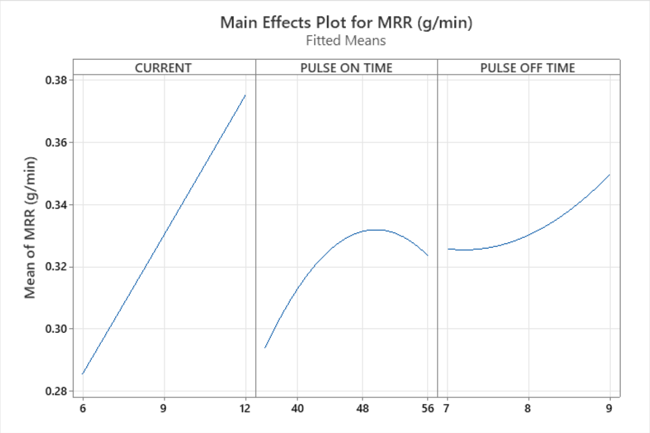

Fig 3(b): Factorial plot for Ra- Al6061- 9% SiC

The factorial plot shows that the MRR variation is lower at larger current for lower percentages of reinforcements, whereas the increase of MRR is noticeable in the higher percentage of reinforcements. The pulse on time shows a positive slope for the lower percentage of reinforcements whereas at 9% SiC composite, it shows a drop at increased value. The pulse off time shows a lower slope and trend is similar for composite added with 3% and 5% SiC, but shows the opposite trend for the 9% SiC added composite.

The grey relation analysis for the MRR was calculated based on 'larger the better' condition and surface roughness on 'smaller the better condition'.

The equations employed for the identification of the normalising coefficient are as follows:

For MRR, where 'larger the better' condition is desired, the equation is

$$NC = \frac{y_i - y_{min}}{y_{max} - y_{min}}$$

Where NC- Normalised values, y_i is the value of MRR in the i'th experiment, y_{min} and y_{max} are the minimum and maximum values of MRR in the considered set of experiments

Similarly for R_a, where 'smaller the better' condition is desired, the equation is

$$NC = \frac{y_{max} - y_i}{y_{max} - y_{min}}$$

Where NC- Normalised values, y_i is the value of R_a in the i'th experiment, y_{min} and y_{max} are the minimum and maximum values of R_a in the considered set of experiments.

The GRA tables for the composites are calculated and tabulated in Table 8, 10 and 12.

Table 8: Grey Relation Analysis chart of Al6061-3% SiC

Exp. No	Normalised values		Deviation		Grey relation co-efficient		Grey Relation Grade	Order
	MRR	R_a	MRR	R_a	MRR	R_a		
1	0.000	1.000	1.000	0.000	0.333	1.000	0.667	2
2	0.455	0.700	0.545	0.300	0.478	0.625	0.552	3
3	0.379	0.228	0.621	0.772	0.446	0.393	0.420	9
4	0.530	0.616	0.470	0.384	0.516	0.566	0.541	5
5	0.606	0.397	0.394	0.603	0.559	0.453	0.506	6
6	0.833	0.056	0.167	0.944	0.750	0.346	0.548	4
7	0.455	0.227	0.545	0.773	0.478	0.393	0.435	8
8	0.758	0.000	0.242	1.000	0.673	0.333	0.503	7
9	1.000	0.037	0.000	0.963	1.000	0.342	0.671	1

Table 9: Response Table for GRG- Al6061- 3%SiC

Parameter	Level 1	Level 2	Level 3	Max- Min
Current	**0.546**	0.532	0.537	0.014
Pulse on time	**0.548**	0.520	0.546	0.027
Pulse off time	0.573	**0.588**	0.454	0.134

Table 10: Grey Relation Analysis chart of Al6061-5% SiC

Exp. No	Normalised values		Deviation		Grey relation co-efficient		Grey Relation Grade	Order
	MRR	R_a	MRR	R_a	MRR	R_a		
10	0.000	1.000	1.000	0.000	0.333	1.000	0.667	2
11	0.311	0.796	0.689	0.204	0.421	0.711	0.566	3
12	0.270	0.525	0.730	0.475	0.407	0.513	0.460	7
13	0.320	0.706	0.680	0.294	0.424	0.630	0.527	4
14	0.574	0.457	0.426	0.543	0.540	0.479	0.510	6
15	0.623	0.389	0.377	0.611	0.570	0.450	0.510	5
16	0.352	0.000	0.648	1.000	0.436	0.333	0.385	9
17	0.475	0.229	0.525	0.771	0.488	0.393	0.441	8
18	1.000	0.129	0.000	0.871	1.000	0.365	0.682	1

Table 11: Response Table for GRG- Al6061- 5%SiC

Parameter	Level 1	Level 2	Level 3	Max.Min
Current	**0.564**	0.516	0.503	0.062
Pulse on time	0.526	0.506	**0.551**	0.045
Pulse off time	0.539	**0.592**	0.452	0.140

Table 12: Grey Relation Analysis chart of Al6061-9% SiC

Exp. No	Normalised values		Deviation		Grey relation co-efficient		Grey Relation Grade (GRG)	Order
	MRR	R_a	MRR	R_a	MRR	R_a		
19	0.000	0.865	1.000	0.135	0.333	0.788	0.561	6
20	0.279	0.678	0.721	0.322	0.409	0.608	0.509	8
21	0.328	1.000	0.672	0.000	0.427	1.000	0.713	1
22	0.344	0.507	0.656	0.493	0.433	0.503	0.468	9
23	0.811	0.552	0.189	0.448	0.726	0.527	0.627	5
24	0.549	0.860	0.451	0.140	0.526	0.781	0.654	4
25	0.828	0.000	0.172	1.000	0.744	0.333	0.539	7
26	0.984	0.164	0.016	0.836	0.968	0.374	0.671	3
27	1.000	0.130	0.000	0.870	1.000	0.365	0.683	2

Table 13: Response Table for GRG- Al6061- 9%SiC

Parameter	Level 1	Level 2	Level 3	Max- Min
Current	0.594	0.583	**0.631**	0.048
Pulse on time	0.523	0.602	**0.683**	0.161
Pulse off time	**0.629**	0.553	0.626	0.075

From the Grey Relation Analysis, we can observe that for Al6061 composite with 3% SiC, the optimum value was Current-6A, Pulse on time- 38μs and Pulse off time -8μs provided the optimum condition. For the Al6061-5% SiC composite, the optimum condition was observed at Current-6A, Pulse on time- 56μs and Pulse off time -8μs. For the Al6061-9% SiC composite, the optimum condition was observed at Current-12A, Pulse on time- 56μs and Pulse off time -7μs The lower current for the optimum value can be attributed to the fact that the current.

CONCLUSION

The experimental study carried out for the different combination of SiC percentage in the Al6061 composite indicate that the current is the major contributing factor for both surface roughness as well as MRR of the composite. The contribution level was observed to be increasing with increased percentage of reinforcements which shows that the current will be the major contributor as the percentage of reinforcements increase. The optimum condition for satisfactory MRR and R_a was found to be

- 6A current, 38μs pulse on time and 9μs pulse off time for composite with 3%SiC.
- The optimum level of current and pulse off time was identified to be the same for the composite with 5% SiC, but the optimum pulse on time changed to 56μs and lowest pulse off time of 7μs.
- For the composite with 9% SiC, the optimum current was changed to 12A, pulse on time as 56μs and lowest pulse off time of 7μs.

It was clearly identified that the increased current provides the optimum condition for higher percentages of reinforcement when the conflicting parameters of MRR and R_a were considered. The increased current requirement can be identified to be due to the improved material properties which require more energy for the material removal. The increased pulse on time for 5% and 9% SiC reinforced composites can be identified to be due to the fact that increased energy supply time is required for the proper material removal. The reduction in optimum pulse off time for 9% SiC can be attributed to the fact that the deposition of the molten material can reduce both MRR and R_a due to the formation of white layer on the machined surface.

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