Machinability Study on Al-SiC Metal Matrix Composite (MMC) using Electrical Discharge Machining (EDM)

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Abstract*: *In today's world of manufacturing, aluminum metal matrix composites are playing a vital role in enhancing the properties of different automobile and aircraft components. The post-production processing of the Al-SiC Metal Matrix Composites (MMC) is comparatively tricky because of dispersion of SiC particles in the aluminum matrix. One such processing method for machining the Al-SiC metal matrix composite to produce acceptable output properties is Electrical Discharge Machining (EDM). Generally, when abrasive particulates such as SiC are dispersed in the aluminum matrix, it is challenging to follow conventional machining operations due to high tool wear rate, frequent mechanical shocks on the tool and effects like delamination on the workpiece where the unconventional machining process like EDM is used since there is no direct contact between tool and the workpiece. In this paper, a unique powder metallurgy approach is attempted for fabricating four different compositions (2%, 4%, 6%, 8% of SiC) of Al-SiC composite and machinability study is carried out through EDM to reveal the effect of SiC particles on machinability of Al-SiC composite. The experimental investigation is made on EDM input parameters like a pulse on time, pulse off time and current, and their influence on machinability of Al-SiC composite is analyzed. The output results like Material Removal Rate (MRR) and Surface Roughness are obtained for different compositions of Al-SiC composite, and its influencing input parameters are observed.

***Index Terms*: EDM, MMC, MRR, Surface Roughness.**

I. INTRODUCTION

The manufacturing sector today is concentrating more on composites rather than conventional monolithic materials for high-end applications like defense, automotive and aircraft components. The main reason behind this is the strength to weight ratio of these composites which is high when compared with the usual alloys [1]. Moreover, the wear rate of these composites is also less because of the presence of abrasive particles in the matrix [2]. There are various techniques through which these composites are made like stir casting [3], powder metallurgy [4], etc. But the main problem comes in the machining of these composites because of the presence of abrasive particles which increases the tool wear rate in conventional machining. Non-traditional machining technique like Electrical Discharge Machining (EDM) [5] is developed since there would be no contact between the tool and the workpiece and thus reducing the tool wear rate and mechanical shocks. The current study deals with the fabrication of Al-SiC metal matrix composite through a unique approach of powder metallurgy. Four different compositions of Al-SiC is fabricated, and Chu two-step sintering method is followed for sintering purpose. After this, the samples are machined by EDM. Finally, the effect of SiC particles on the machinability of the composite is studied. Also, the impact of EDM input parameters like a pulse on time, pulse off time, and current on the machinability of the composite is analyzed and optimized.

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II. MATERIALS AND METHOD

A. Materials

In this paper, grade 1 aluminum powder with 74 microns in size and SiC powder with 63 microns in size is used for fabrication of Al-SiC composite using powder metallurgy route. Before processing, X-ray Diffraction (XRD) analysis is carried out on powder samples is shown in Figure 1 and 2. All the elements are taken in their weight percentage. Four different proportions, i.e., 98% Al-2%SiC, 96% Al-4%SiC, 94% Al-6%SiC, 92% Al-8%SiC by weight is used for fabrication of samples having the dimensions of 50 mm in diameter and 17 mm in height and those corresponding densities values are 2.487, 2.484, 2.512 and 2.494 respectively in gm/cc, measured using weighing balance based on Archimedes principle after sintering process.

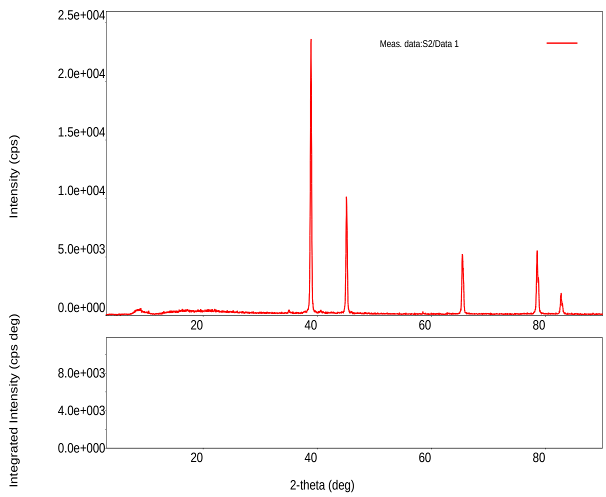

Fig. 1. XRD for Al Powder.

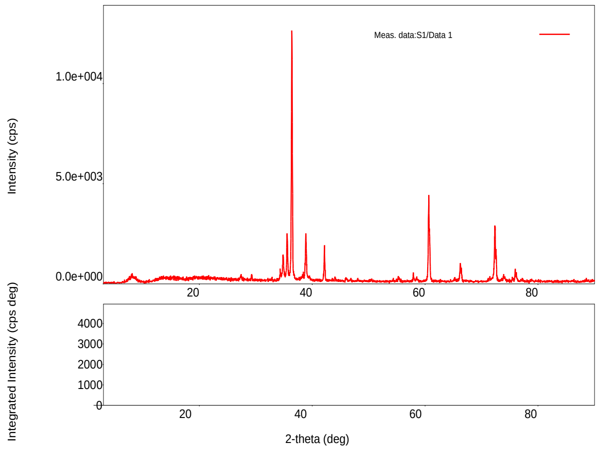

Fig. 2. XRD for SiC Powder.

B. Method of fabrication

Powder metallurgy approach is used for manufacturing of Al-SiC composite. Initially, the powders are taken in required proportion and ball milled to get a homogeneous mixture of Al and SiC powders. Samples of required dimensions are made through the compaction process followed Chu's two-step sintering in an electric furnace.

C. Machining through EDM

EDM works based on spark erosion of material. The spark generated in this process produces heat which removes the material by erosion and evaporation. Both workpiece and tool should be electrically conductive to carry out the machining operation. The machine used for machining is Precision Electric Spark Sinking Machine. The electrode used is a copper electrode of 10mm diameter. The parameters such as pulse on time, pulse on time and current were considered variables. Machining parameters like, electrode feed rate, dielectric fluid flush pressure and applied voltage are kept constant. The setup of the EDM is shown in Figure 3.

Fig. 3. EDM setup.

The samples made through powder metallurgy are fixed in the fixture for machining purpose. The electrode is attached in the tool holding fixture and tightened using the Allen key. Circular holes are machined on the surface of the sample till the depth of the hole is 2mm and time is recorded. The Material Removal Rate (MRR) is calculated.

$$MRR = \frac{\text{The volume of the machined hole}}{\text{Time take for machining}} \; \frac{mm^3}{min}$$

After machining, the white light interferometer is used for taking images of the machined hole, and Gwyddion software is used for finding the surface roughness values and analyzing the surface profile of the machined surface.

D. Experimental procedure

The Design of Experiment (DoE) values for four different compositions is shown in Table I, II, III and IV. The values are given for three factors using the L_9 orthogonal array. Experiments are carried out for all these compositions using their design of experiment values, and final values of material removal rate and surface roughness values are calculated and noted in the tables.

$$E_m = T_{on} \times V_g \times I_d \quad (1)$$

where T_{on} is a pulse on time, V_g is gap voltage, and I_d is discharged current.

Equation 1 reveals that the pulse on time, gap voltage and discharge current are directly proportional to spark energy [4].

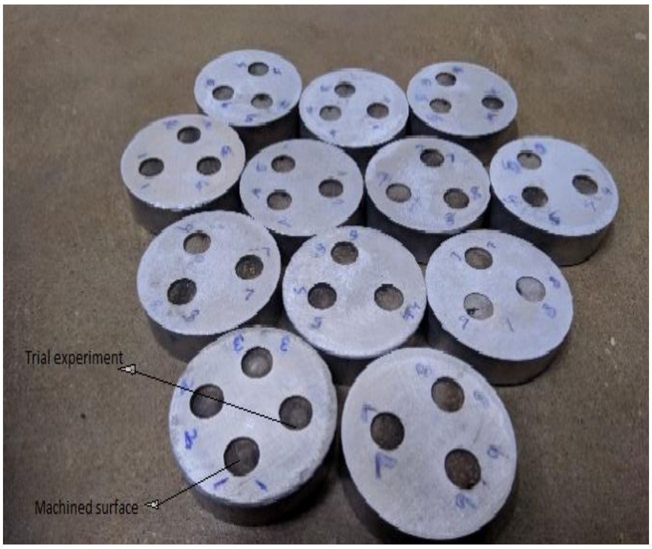

Fig. 4. EDM Machined Powder Metallurgy (P/M) samples.

The 12 samples of four different compositions of SiC and 36 machined surfaces based on a different design of experiment values along with one trail experiment is shown in Figure 4.

TABLE I

DESIGN OF EXPERIMENTS (DOE) FOR AL-2%SIC

S.No	T_{on} (µs)	T_{off} (µs)	Current (A)	Machining Time (minutes)	MRR (mm^3/min)	Ra (µm)
1	80	40	4	16.76	9.36	9.53
2	80	50	5	10.25	13.32	8.93
3	80	60	6	7.433	21.13	10.51
4	90	40	4	28.75	5.46	10.83
5	90	50	5	10.03	15.66	9.15
6	90	60	6	7.56	20.75	10.16
7	100	40	4	24.83	6.32	9.91
8	100	50	5	83.50	0.98	11.13
9	100	60	6	46.00	1.73	13.24

TABLE II

DESIGN OF EXPERIMENTS (DOE) FOR AL-4%SIC

S.No	Ton (µs)	Toff (µs)	Current (A)	Machining Time (minutes)	MRR (mm3/min)	Ra (µm)
1	80	40	4	15.7	10.00	8.79
2	80	50	5	9.83	15.96	11.92
3	80	60	6	17.00	9.239	9.24
4	90	40	4	15.66	10.03	8.49
5	90	50	5	9.34	16.82	9.54
6	90	60	6	16.63	9.44	13.29
7	100	40	4	16.42	9.57	8.70
8	100	50	5	10	15.71	9.43
9	100	60	6	19.75	7.95	9.76

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TABLE III

DESIGN OF EXPERIMENTS (DOE) FOR AL-6%SIC

S.No	T_{on} (µs)	T_{off} (µs)	Current (A)	Machining Time (minutes)	MRR (mm^3/min)	Ra (µm)
1	80	40	4	16.00	9.82	12.24
2	80	50	5	40.45	3.88	9.13
3	80	60	6	22.13	7.09	9.68
4	90	40	4	24.33	6.46	12.45
5	90	50	5	58.67	1.91	10.23
6	90	60	6	29.67	5.29	13.53
7	100	40	4	16.72	9.39	9.57
8	100	50	5	49.33	3.18	12.11
9	100	60	6	11.17	14.06	9.73

TABLE IV

DESIGN OF EXPERIMENTS (DOE) FOR AL-8%SIC

S.No	T_{on} (µs)	T_{off} (µs)	Current (A)	Machining Time (minutes)	MRR (mm^3/min)	Ra (µm)
1	80	40	4	18.73	8.385	9.03
2	80	50	5	32.25	3.879	11.24
3	80	60	6	24.5	6.4114	10.68
4	90	40	4	16.833	9.332	8.088
5	90	50	5	29.06	5.404	11.38
6	90	60	6	18.50	8.4608	9.233
7	100	40	4	15.33	10.245	12.88
8	100	50	5	11.25	13.955	8.089
9	100	60	6	23.5	6.681	9.137

III. RESULTS AND DISCUSSIONS

Considering the manufacturing point in view, better machining parameters are those which give maximum material removal rate and minimum surface roughness because maximum MRR gives you less time of manufacturing and hence reduces overall production time whereas minimum surface roughness gives you good aesthetics, less stress concentration on the surface and also reduces the use of any further finishing operations.

Generally, an increase in the pulse on time, the energy at the tool and workpiece interface increases and this increase the material removal rate. The same effect as for gap voltage and discharge current. But the above parameters inversely affect the surface roughness. So, we have to optimize those machining parameters and so that we get maximum material removal rate and minimum surface roughness

A. Analysis of Material Removal Rate (MRR)

An increase in the pulse on time, the material removal rate decreases. From 80 to 90 microseconds, the reduction in MRR is comparatively less. But, from 90 to 100 microseconds significant reduction in MRR is shown in Figure 5 and Figure 6. Due to the increase in the pulse on time that increases the number of vaporized particles which obstructs further machining to take place. To minimize this effect higher flush rates should be used. An increase in pulse off time, there is an increase in material removal rate because the longer the pulse off time longer the pulse takes to be turned off and more is the time for machining. The effect is not significantly high, but it affects MRR at a moderate level. From the Spark energy equation, the current plays a significant role in MRR. From 4 to 5 amperes, there is a decrease in MRR, and then it increases until 6 amperes because of the improper blending of powders which might have left lumps of SiC particles which makes it difficult to machine.

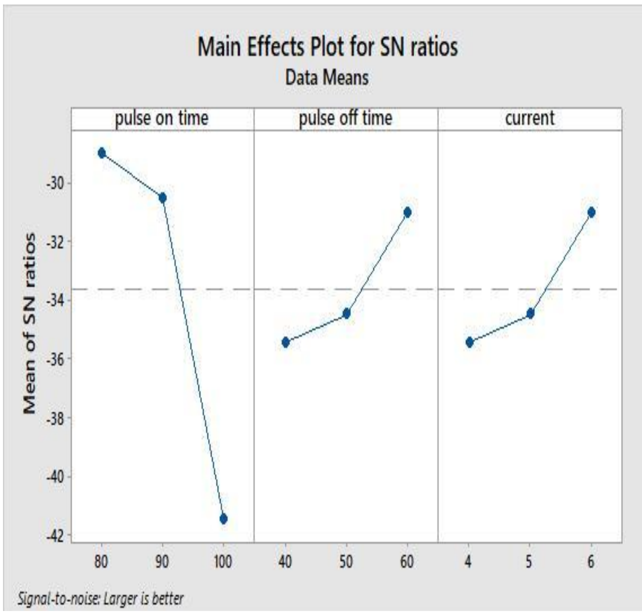

Fig. 5. Signal to Noise (S/N) ratio of Al-2%SiC for MRR.

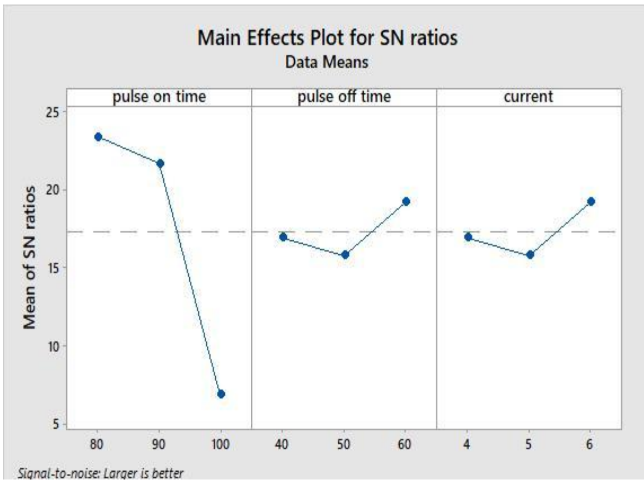

Fig. 6. Signal to Noise (S/N) ratio of Al-4%SiC for MRR.

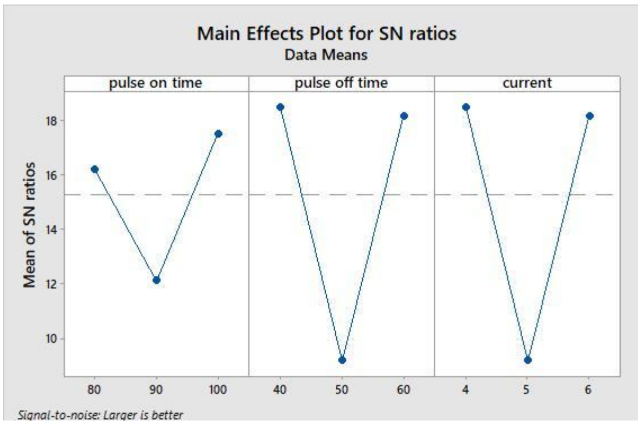

Fig. 7. Signal to Noise (S/N) ratio of Al-6%SiC for MRR.

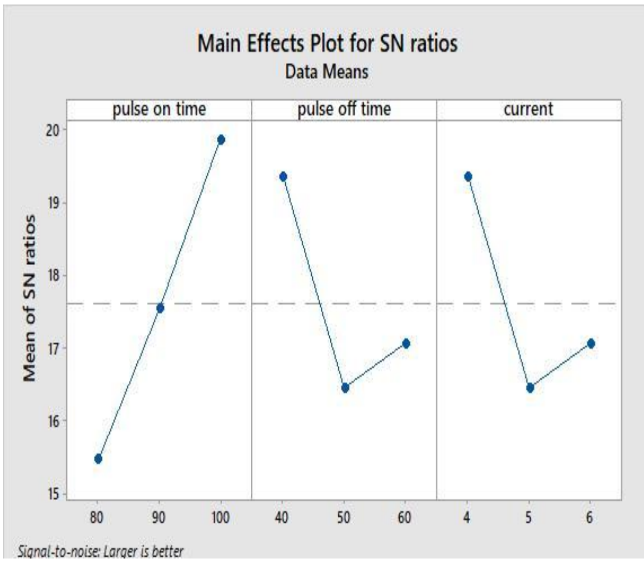

Fig. 8. Signal to Noise (S/N) ratio of Al-8%SiC for MRR.

For Al-6%SiC, Pulse off time and current have more impact compared with a pulse on time is shown in Figure 7. For Al-8%SiC, the Linear fashion of pulse on time is observed and Pulse off time as well as the current had similar fashion effect on the sample as shown in Figure 8.

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TABLE V
VARIANCE ANALYSIS OF AL-2%SIC ON MRR

Factor	Degree of freedom	Adj Sum of squares	Adj Mean of squares	F-value
Pulse on time	2	0.001416	0.000708	3.49
Pulse off time	2	0.000589	0.000294	0.86
Current	2	0.000589	0.000294	0.86

TABLE VI
VARIANCE ANALYSIS OF AL-4%SIC ON MRR

Factor	Degree of freedom	Adj Sum of squares	Adj Mean of squares	F-value
Pulse on time	2	277.9	138.96	4.17
Pulse off time	2	79.55	39.77	0.60
Current	2	79.55	39.77	0.60

TABLE VII
VARIANCE ANALYSIS OF AL-6%SIC ON MRR

Factor	Degree of freedom	Adj Sum of squares	Adj Mean of squares	F-value
Pulse on time	2	28.17	14.08	0.96
Pulse off time	2	64.96	32.497	3.78
Current	2	64.96	32.497	3.78

TABLE VIII
VARIANCE ANALYSIS OF AL-8%SIC ON MRR

Factor	Degree of freedom	Adj Sum of squares	Adj Mean of squares	F-value
Pulse on time	2	25.39	12.693	1.69
Pulse off time	2	7.359	3.679	0.35
Current	2	7.359	3.679	0.35

From the analysis of variance table, V, VI, VII and VIII shows that the factor which has higher F-value has more influence on Material Removal Rate (MRR).

It is evident that the pulse on time has more impact on the material removal rate. Generally current should play a significant role in material removal rate, but we have selected low current values since these are the top specifications of the machine.

So, these low current values don't contribute much to the MRR. Mainly, Pulse on time influenced the MRR followed by current and pulse off time.

B. Analysis of Surface Roughness (R_a)

Generally, as the current increases, there would be more heat generation at the tool and the workpiece interface and thus causing more surface irregularities.

From Figure 9,10,11 and 12, it is evident that the effect of parameters like a pulse on time, pulse off time and currently affects the surface roughness unevenly. In Al-2%SiC the linear decrease of R_a with a pulse on time is observed and pulse off time, and current has a similar effect on R_a. In Al-4%SiC pulse off time and current had a significant impact on R_a compared with a pulse on time. In Al-6%SiC and Al-8% SiC pulse on time had substantial implications on R_a compared with pulse off time and current. One of the reasons behind the irregularity is the use of a white light spectrometer while capturing an image. This image is only a small spot in the entire machined surface. So, the average value of surface roughness cannot be estimated clearly.

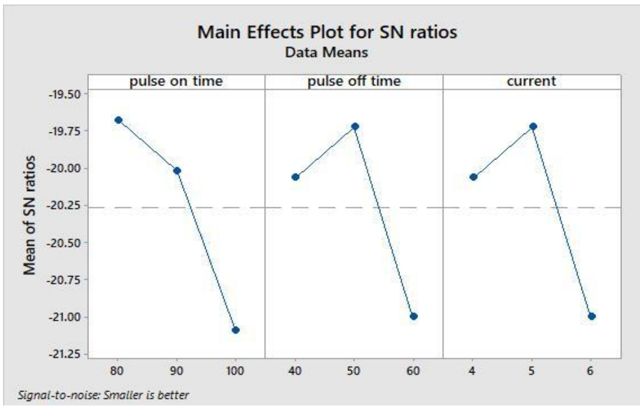

Fig. 9. Signal to Noise (S/N) ratio of Al-2%SiC for Ra.

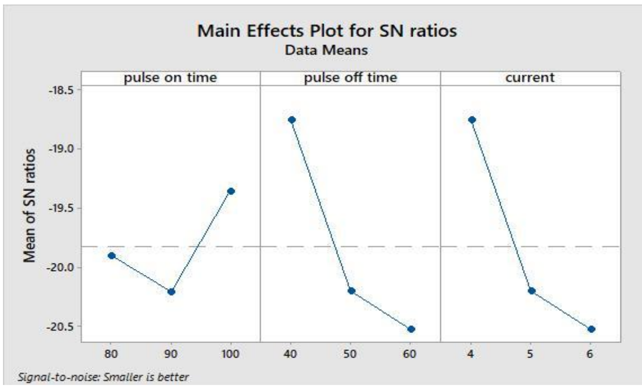

Fig. 10. Signal to Noise (S/N) ratio of Al-4%SiC for Ra.

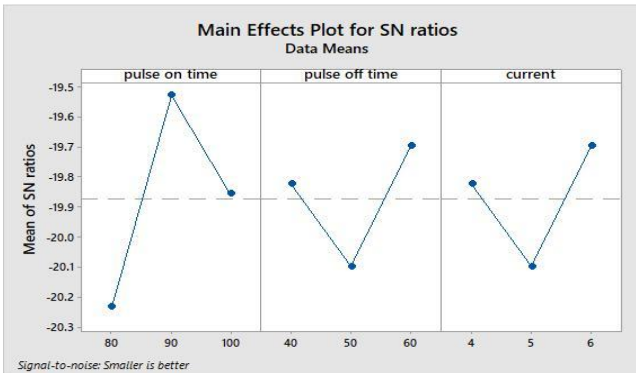

Fig. 11. Signal to Noise (S/N) ratio of Al-6%SiC for Ra.

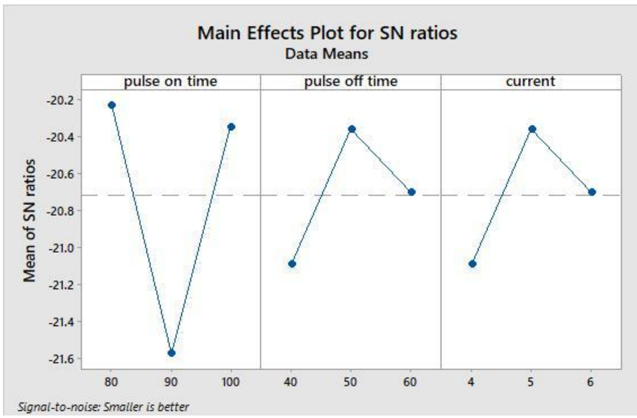

Fig. 12. Signal to Noise (S/N) ratio of Al-8%SiC for Ra.

TABLE IX
VARIANCE ANALYSIS OF AL-2%SIC ON R_a

Factor	Degree of freedom	Adj Sum of squares	Adj Mean of squares	F-value
Pulse on time	2	5.194	2.597	1.86
Pulse off time	2	4.062	2.031	1.28
Current	2	4.062	2.031	1.28

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TABLE X
VARIANCE ANALYSIS OF AL-4%SIC ON R_a

Factor	Degree of freedom	Adj Sum of squares	Adj Mean of squares	F-value
Pulse on time	2	1.969	0.9847	0.31
Pulse off time	2	7.301	3.651	1.60
Current	2	7.301	3.651	1.60

TABLE XI
VARIANCE ANALYSIS OF AL-6%SIC ON R_a

Factor	Degree of freedom	Adj Sum of squares	Adj Mean of squares	F-value
Pulse on time	2	5.545	2.772	1.09
Pulse off time	2	1.297	0.6483	0.20
Current	2	1.297	0.6483	0.20

TABLE XII
VARIANCE ANALYSIS OF AL-8%SIC ON R_a

Factor	Degree of freedom	Adj Sum of squares	Adj Mean of squares	F-value
Pulse on time	2	0.8625	0.4313	0.12
Pulse off time	2	0.4620	0.2310	0.07
Current	2	0.4620	0.2310	0.07

TABLE XIII
OPTIMIZED INPUT PARAMETERS FOR MACHINING DIFFERENT SIC COMPOSITIONS

Sample Composition	T_{on} (μs)	T_{off} (μs)	Current (A)	Machining Time (Minutes)	MRR (mm^3/min)	R_a (μm)
Al-2%SiC	80	55.96	6	7.4	21.1	9.64
Al-4%SiC	80	42.97	6	10.8	16.4	8.84
Al-6%SiC	100	60	6	22.1	7.91	9.47
Al-8%SiC	100	40	4	24.5	6.42	8.67

TABLE XIV
REGRESSION EQUATION OF MRR AND RA FOR FOUR DIFFERENT COMPOSITIONS

	Regression equation	
Samples	MRR	R_a
Al-2%SiC	37.2 - 0.613X + 0.374 Y + 2.00 Y	0.42 + 0.0885 X + 0.0607 Y - 0.209 Z
Al-4%SiC	39.3 - 0.624X + 0.364Y + 1.90Z	11.08-0.0341X + 0.1050Y - 0.671Z
Al-6%SiC	18.53 + 0.0059X - 0.0220Y- 1.401Z	-2.7 + 0.098 X + 0.013 Y+ 0.02 Z
Al-8%SiC	4.88 - 0.0141X - 0.0158Y + 1.431 Z	2.4 + 0.2034 X - 0.1068 Y - 1.457 Z

From the analysis of variance table IX, X, XI and XII, the source factor which has higher F-value has more influence on surface roughness. Almost all the variance tables above are showing that pulse on time, and current have a significant impact on surface roughness. Optimized input parameters for different SiC composition on Al Matrix has been attained is shown in table XIII. For validation purpose, the regression analysis is carried out, and the equation is generated as shown in table XIV (Where X is a pulse on time, Y is pulse off time, Z is current).

IV. CONCLUSIONS

From the experimental investigations, the below facts are observed;

- Initially, the Chu's two-step sintering method is preferred for fabricating the Al-SiC composite for proper densification and grain growth of the green compact of all samples.
- Generally, the pulse on time has more influence on the material removal rate as well as surface roughness.
- In Al-4SiC sample, surface roughness was more influenced by Pulse off time and current than pulse on time.
- In Al-6SiC sample, the material removal rate was more influenced by Pulse off time and current than pulse on time.
- The current parameter in EDM did not have a significant effect on material removal rate because of its minimal value.
- An increase in the proportion of SiC leads to an increase in machining time and MRR.
- The effect of pulse on time on the surface roughness of Al-6SiC is found high when compared to Al-8SiC.

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