Electric Discharge Machining of AA6061/Sicp Surface Metal Matrix Composite Fabricated Through Friction Stir Processing

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Abstract— Surface Metal Matrix Composites (SMMCs) are successfully being fabricated through Friction Stir Processing (FSP). In the present work, defect free SMMC of AA-6061 reinforced with Silicon Carbide (SiC) particles is fabricated through FSP. Subsequently Electric Discharge Machining (EDM) is carried out on the SMMC samples to evaluate the machinability characteristics. Taguchi technique with standard L9 Orthogonal Array is adopted for the design of experiments. ANOVA has been employed to identify the influence of a particular input parameter during EDM. Optimization of Electric Discharge Machining was achieved for the best values of Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness (SR).

Key words: FSP, SMMC, EDM, ANOVA, MRR, TWR

I. INTRODUCTION

Aluminium alloy 6061-T6 has been widely used in aerospace, automobile electronics and medical industries because of its strength to weight ratio, excellent machinability, low temperature performance and corrosion resistance properties. [1]. The Particulate Metal Matrix Composites (PMMCs) are light in weight and possess excellent stiffness, strength, superior thermal stability and wear resistance. These properties are acquired to them by the hard ceramic particles embedded as reinforcements.

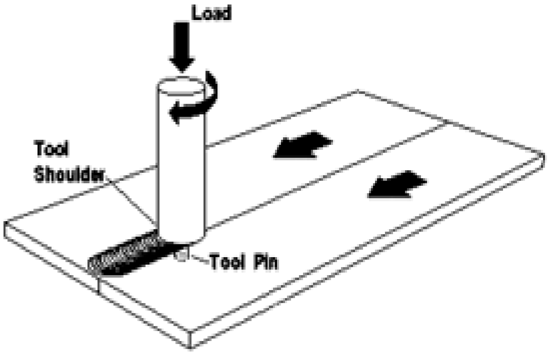

Fig. 1: Schematic of Friction Stir Processing

The MMCs with AA6061 as the matrix and SiC as the reinforcement is the interest of research because of its versatility in the mechanical and technological properties. Several processing methods such as stir casting, liquid infiltration, powder metallurgy, diffusion bonding etc are being employed to produce MMCs. However, the performance of so produced MMCs is constrained by many metallurgical defects such as dendritic porosity, particulate oxide inclusions, Secondary Dendritic Arm Spacing (SDAS), Iron phase intermetallics and agglomeration of particles in the matrix etc. The inhomogeneous and improper wetting of the particles is resulting into coarse grain structure and poor mechanical and technological properties in MMCs. Hence, an alternate generic process, Friction Stir Processing (FSP) has been adapted as the strategy to overcome these problems. During FSP the reinforcements are added in the surface layers in solid state, which in fact controls many of the defects that formed in the MMCs during the classical production processes.

A. Friction Stir Processing (FSP)

Friction Stir Processing (FSP) is a solid state material processing technique which is a clone of Friction Stir Welding (FSW), invented by The Welding Institute in 1991[2]. FSP has become a novel technique to produce Surface MMCs [3]. Although, stir casting method is widely used for producing MMCs, because of its ability to produce complex shaped components at relatively lower costs. However, its performance is limited by many metallurgical defects that creep up during fabrication. FSP provides unique opportunity to embed 'wrought' micro-structure in 'cast' components by a localized modification [4]. FSP locally refines microstructure and also eliminates inherent defects in the starting material, thus improving its ductility, corrosion resistance, fatigue resistance, formability and a host of other properties to a great extent. A fine grain size even in the range of 30-180 nm has also been demonstrated by the researchers [5].

FSP is also used to produce Surface Metal Matrix composites (SMMCs) by mixing the reinforcement particles in the stir zone during the process [6]. To Friction stir process a location within a plate or sheet, a specially designed cylindrical tool is rotated and plunged into the selected area. The tool has a small diameter pin with a concentric larger diameter shoulder. The rotating pin contacts the surface and as it descends to the part, friction heats the surface. When the shoulder contacts the surface, it causes additional frictional heat and plasticize a larger cylindrical column of metal around the inserted pin. The area to be processed and the tool are moved relative to each other such that the tool traverses, with overlapping passes, until the entire selected area is processed and a fine grain size and the material is transported from the leading to the trailing face of the pin. As the processed zone cools without solidification due to absence of any liquid, it forms a defects constrained recrystallized surface composite with fine grained microstructure [7].

The mechanical properties of so fabricated Surface MMCs are better in-terms of micro hardness, ductility, wear resistance, fatigue and creep resistance.

II. MACHINING OF SMMCS

Technologically advanced fields like aeronautics, nuclear reactors, war gadgets industries etc., demand advanced materials such as Surface Metal Matrix Composites. These materials obviously require advanced metal cutting tools and techniques. Non-conventional machining processes are appropriate to machine such intricate, complex profiles of jobs on such advanced and hard materials.

Electric Discharge Machining (EDM) is one of such machining processes that is widely used. EDM proved to be the best for machining MMCs safely and accurately for a sustained productivity. EDM is thermo-electric process in which there is no physical contact between the tool electrode and work piece. The gap between tool and work is flooded with a dielectric fluid while a power supply system supplies the appropriate electric pulses. The controlled electric sparks erode the work material by the shaped electrode tool. The dielectric fluid plays a vital role in spark generation and flushing of the debris. Servo system advances the tool accordingly. In EDM the thermal energy is utilized to machine electrically conductive materials despite of their hardness.

III. MATERIALS AND METHODS

A brief description of various materials used in this work is furnished below.

A. Substrate Material for SMMC

For the fabrication of Surface MMC, AA-6061-T6 was considered as the substrate material.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
0.66	0.25	0.31	0.08	0.99	0.16	0.01	balance

Table 1. The chemical composition of AA6061 by Wt%

Density	2.7 gm/cm^3
Elastic Modulus	68.9 GPa
Tensile Strength	310 Mpa
Poisson's ratio	0.33
Yield Strength	276 Mpa
Percentage Elongation	17
Hardness HB 500	60

Table 2. The vital properties of Al-6061

B. Typical Applications for Aluminium Alloy 6061

Aircraft and aerospace components, Marine Fittings, Trnasport, Bicycle frames, Camera lenses, Drive shafts, Electrical Fittings and connectors, Brake components, Valves, Couplings etc.

C. Reinforcement Particles

Silicon Carbide (SiC) 50 microns size was used as the reinforcement particles. Silicon carbide is an excellent abrasive and has been produced and made into grinding wheels and other abrasive.

SiC is used in abrasive particles, refractories, ceramics and numerous high-performance applications. The material can also be made an electrical conductor and has applications in resistance heating, flame igniters and electronic components. Structural and wear applications are constantly developing.

D. Friction Stir Processing Machine

The fabrication process of Surface MMCs was carried out on Vertical Milling Machine, HMT make FN-2, 10HP, 3000 rpm. The FSP tool was made of H13 tool steel with shoulder diameter of 24 mm, pin dimensions of 2 mm length and 5 mm diameter.

E. Electric Discharge Machine

Complete machining was carried out on Electronica Electraplus 500 x 300/ZNC series Sinker Electric Discharge Machine with 500 x 300 mm table dimension and the electrode made of copper with 24 mm diameter.

IV. EXPERIMENTAL

A. Fabrication of SMMC

In this study Aluminium alloy, AA-6061-T6 plate of 150 x 100 x 6 mm size is used as substrate material to fabricate surface composite. The plate is fixed on the machine table along with dynamometer to read the axial load using suitable fixtures. A rectangular groove of 1mm width and 2 mm depth is cut on the surface of the plate so as to accommodate the SiC reinforcement powder in the required quantity. Initially, the capping pass is applied by the pinless FSP Tool so that the reinforcement power may be retained within the groove for subsequent passes of the tool[8]. In the later stage the FSP tool with pin is plunged into the metal to initiate the stirring of base metal along with the powder. The optimum rotational speed and traversing speed of 900 rpm with 40 mm/min respectively and axial load of 5 kN were considered to fabricate single pass Surface Metal Matrix Composite with optimum mechanical properties.

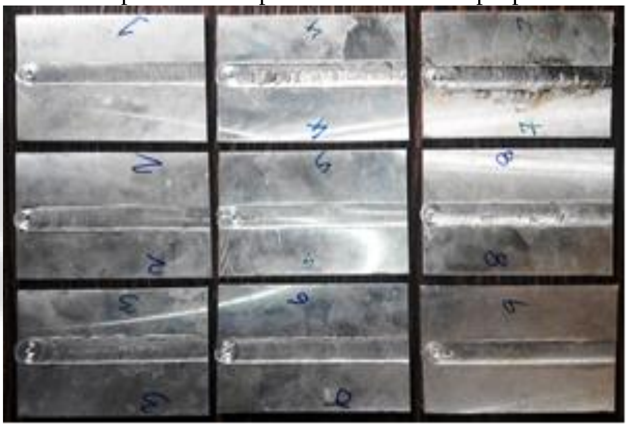

Fig. 2: SMMC billets fabricated by FSP

B. Electric Discharge Machining

The machinability of the SMMC samples was tested by the Electric Discharge Machining. The depth of cut has been fixed as 2 mm. The process parameters at three different levels and three different response parameters considered. To determine the optimal set of process parameters such as Discharge current, Pulse on time, and Pulse off time that results into maximum Metal Removal Rate (MRR) and minimum Tool Wear Rate (TWR) and Surface Roughness (Ra); following levels are considered during machining of SMM

Response Variables		Material Removal Rate(mm^3/min) Tool Wear Rate(mm^3/min) Surface Roughness (µm)		
Process Parameters		Levels		
		1	2	3
Discharge Current(A)	A	10	20	30
Pulse ON time (µs)	B	50	150	250
Pulse OFF time (µs)	C	6	8	10

Supply Voltage : 420 V, 3 Phase, 50Hz Open Gap Voltage : 140± 5% tolerance Electrode : Electrolytic Copper (20 mm diameter) Dielectric : Spark fusion oil Rated 450 Dielectric Pressure : 250 N/mm^2 Depth of Cut : 2 mm Gap Width : 0.05mm

Table 3. Experimental Parameters and their levels

Design of experiment is an effective tool to design and conduct the experiments with minimum resources. In this study the experiments were planned and conducted as per Taguchi's standard Orthogonal Array (OA) L-9. Table 4 shows the OA design matrix used to set process parameters to evaluate the response variables.

Exp. No.	Process parameters		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 4. Design Matrix of L-9 Orthogonal Array

A hole of 20 mm diameter and 2 mm depth was produced by EDM process with the copper electrode for each combination of parameters as per the orthogonal array. The SMMC billets and tool electrode were weighed before and after the machining operation with the help of electronic weighing machine so as to calculate MRR, TWR. The surface roughness (Ra) was evaluated by the Surface Roughness tester Mitutoyo SJ 301.

1) Material Removal Rate (Mrr)

The material removal rate of the samples is the volume of the material removed per minute which can be calculated from the relation.

MRR = (Wi – Wf) x 1000 / (Dw x t)

Where, MRR = Material Removal Rate (mm3/min)
Wi = Initial weight of the SMMC sample (gm)
Wf = Final weight of the SMMC Sample (gm)
Dw = Density of the SMMC sample (gm/cm3)
t = Trial period (min)

ii. Tool Wear Rate (TWR):

The Tool wear rate of the electrode is the amount of the tool wear per minute which can be calculated from the relation [9]

TWR = (Ti – Tf) x 1000 / (Dw x t)

Where, TWR = Tool Wear Rate (mm3/min)
Ti = Initial weight of the tool (gm)
Tf = Final weight of the Tool (gm)
Dw = Density of the Tool Material (gm/cm3)
t = Trial period (min)

C. Surface Roughness (Ra)

The average Surface Roughness (Ra) is the predictor for the performance of SMMC components since irregularities in the surface may form nucleation sites for cracks. The surface Roughness of the SMMC samples was tested on Mitutoyo Surface roughness tester SJ-301 and the corresponding graphs were obtained.

V. Results and Discussion

The experimental results obtained by machining the SMMCs were tabulated as followed

Exp No.	Current (A)	Pulse ON (ηs)	Pulse OFF (ηs)	MRR (mm^3/min)	TWR (mm^3/min)	Ra (ηm)
1	10	50	6	0.834	0.113	3.917
2	10	150	8	2.317	0.163	11.271
3	10	250	10	3.402	0.206	5.602
4	20	50	8	4.496	0.107	3.762
5	20	150	10	6.672	0.213	10.816
6	20	250	6	8.049	0.290	8.946
7	30	50	10	5.391	0.211	4.267
8	30	150	6	8.463	0.306	12.611
9	30	250	8	9.003	0.407	9.657

Table 5. Experimental Results of ED Machining of SMMCs

A. Analysis of MRR, TWR And Ra

ANOVA had been carried out for the effect of process parameters on MRR, TWR and Ra. MINITAB-17 Software was used to carry out the analysis.

Exp. No.	Response Values			S/N Ratios		
	MRR (mm^3/min)	TWR (mm^3/min)	Ra (ηm)	MRR (dB)	TWR (dB)	Ra (dB)
1	0.834	0.113	3.917	-1.577	18.938	-11.86
2	2.317	0.163	11.271	7.299	15.756	-21.04
3	3.402	0.206	5.602	10.635	13.723	-14.97
4	4.496	0.107	3.762	13.056	19.412	-11.51
5	6.672	0.213	10.816	16.485	13.432	-20.68
6	8.049	0.290	8.946	18.115	10.752	-19.03
7	5.391	0.211	4.267	14.633	13.514	-12.60
8	8.463	0.306	12.611	18.551	10.286	-22.02
9	9.003	0.407	9.657	19.088	7.808	-19.71

Table 6. Response Values and their corresponding S/N ratios

B. Taguchi Analysis of MRR Vs Current, Pulse-On And Pulse-Off

Level	Current	Pulse On	Pulse Off
1	5.542	8.704	11.696
2	15.885	14.111	13.148
3	17.424	15.946	13.918
Delta	11.972	7.241	2.222
Rank	1	2	3

Table 7. Response table for Signal to Noise Ratio (Larger is the better)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Current	2	48.33	24.14	8.45	0.018
Error	6	17.33	2.889		
Total	8	66.16			

Table 8. ANOVA MRR Vs Current

The effect of current on MRR is shown in Table5. The initial trend shows the MRR marginally increases with gap current. The current exceeds 17 A the MRR slightly decreases due to high energy in the gap provides the stable condition for MRR.

On observing the ANOVA and S/N ratio on MRR, it is understood that Gap Current has the maximum effect (17.42%). Pule ON time and Pulse OFF time contribute 7.24% and 2.22% respectively on the MRR as shown in Table 7.

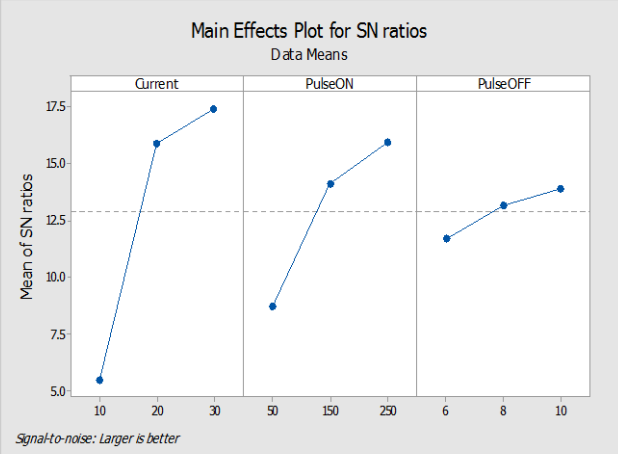

Fig. 3: Main effect plot for S.N ratios2

C. Taguchi Analysis Of TWR Vs Current, Pulse-On And Pulse-Off

Level	Current	Pulse On	Pulse Off
1	16.14	17.29	13.33
2	14.53	13.16	14.33
3	10.54	10.76	13.56
Delta	5.60	6.53	1.00
Rank	2	1	3

Table 9. Response table for Signal to Noise Ratio (Smaller is better)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Current	2	0.034	0.017	2.56	0.157
Error	6	0.041	0.007		
Total	8	0.0749			

Table 10. ANOVA Vs TWR

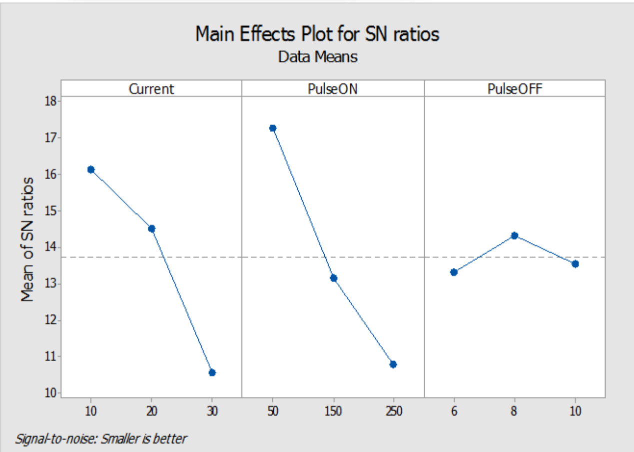

Fig. 4: Main effect plot for S.N ratios

The effect of current on TWR is shown in Table5. The initial trend shows the TWR decreases with gap current. The current exceeds 21 A the TWR values fluctuate due to high energy in the gap provides the variable conditions for TWR.

On observing the ANOVA and S/N ratio on TWR, it is understood that the PulseON time has maximum effect (17.29%). Gap Current and Pulse OFF time contribute 16.14% and 13.33% respectively on the TWR as shown in Table 9.

D. Taguchi Analysis Of Ra Vs Current, Pulse-On And Pulse-Off

Level	Current	Pulse On	Pulse Off
1	-15.96	-11.99	-17.64
2	-17.07	-21.25	-17.41
3	-18.10	-17.90	-16.08
Delta	2.15	9.26	1.55
Rank	2	1	3

Table 11. Response table for Signal to Noise Ratio (Smaller is better)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Current	2	5.50	2.75	0.18	0.84
Error	6	92.19	15.37		
Total	8	97.70			

Table 12. ANOVA Vs Pulse ON

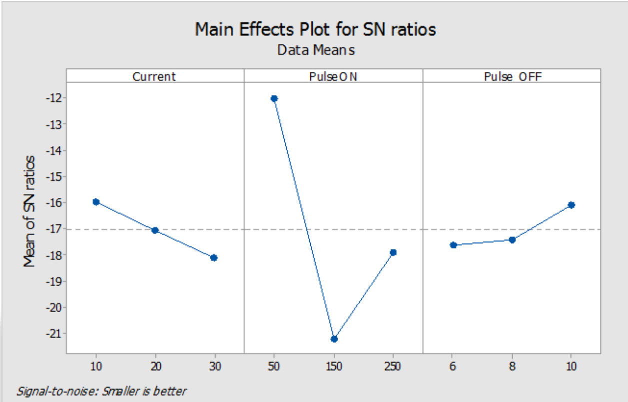

Fig. 5: Main effect plot for S.N ratios

The effect of current on Ra is shown in Table 5. The trend shows the Ra values are maximum with 100A gap current. The current exceeds 17A the Ra sharply decreases due to high energy in the gap provides the variable conditions for Ra.

On observing the ANOVA and S/N ratio on Ra, it is learnt that the PuleON time level 1 value has maximum effect on Ra. Gap Current and Pulse OFF time contribute next on the Ra as shown in Table 11.

E. Confirmation Experiments

Three confirmation experiments were conducted at the optimum levels of the process parameters. The mean value of MRR, TWR and Ra by the optimal setting of the process parameters was found within the confidence interval of the predicted optima of quality characteristics. Process parameters for MRR, TWR and Ra was tabulated in Table 13.

Process Parameter	MRR	TWR	R_a
Current (A)	30	20	20
Pulse ON time (μs)	150	250	250
Pulse OFF time (μs)	6	6	6

Table 13. Optimum set of value for Process parameters for MRR, TWR and Ra.

VI. CONCLUSIONS

The AA6061-T6 was taken as substrate material to fabricate Al/SiC Surface MMC through FSP. The SMMCs are fabricated at an rpm of 900 and 40 mm/min traverse and 5 kN downward load on FSP Machine. On EDM, the Gap Current, Pulse ON time and Pulse OFF time were taken as input process parameters. Design of Experiment were planned and conducted as per Taguchi's standard OA, L-9. Three levels for the three factors of process parameters were considered to carryout experiments on EDM. The MRR and TWR values were calculated and tabulated. The surface roughness Ra values were obtained by Mitutoyo surface roughness tester, SJ-301 and the relevant graphs were obtained.

ANOVA using MINITAB-17 software is carried out on the results to achieve the optimum values for the input process parameters with respect to the response variables.

The resulting analysis was tabulated and the graphs were obtained to reach the optimum values. The confirmation experiments were carried out on EDM with the set of optimum process parameters which was found within the confidence interval of the predicted optima of quality characteristics.

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