Fabrication of Surface MMC through Friction Stir Processing and Assessment of Machinability by EDM

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Abstract - *Friction Stir Processing (FSP) is being successfully employed in the fabrication of Surface Metal Matrix Composites (SMMCs). Defect free SMMC of Al-7075 alloy reinforced with Aluminium Oxide (Al_2O_3) particles was fabricated through FSP. Subsequently Electric Discharge Machining (EDM) is carried out on the SMMC samples to evaluate the machinability characteristics. Taguchi optimization technique followed by ANOVA had been employed to achieve the optimal values for the input process parameters during EDM so as to optimize Material Removal Rate (MRR), the Tool Wear Rate(TWR) and Surface Roughness (SR).*

Keywords — *FSP, SMMC, EDM, ANOVA, MRR, TWR*

1. INTRODUCTION

Particulate Metal Matrix Composites (PMMCs) offer various advantages in the applications where high specific strength and stiffness and wear resistance are required [1]. They are widely used in the field of automotive, aerospace, electronics and medical industries [2]. The 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. However, the same non-deformable ceramic particles diminish the ductility and toughness of the MMCs which in fact constraining the applications of MMCs.

1.1 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[3]. FSP has become a novel technique to produce Surface MMCs[4]. 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 features such as dendritic porosity, particulate oxide inclusions, Secondary Dendritic Arm Spacing, Iron phase inter-metallics, etc. FSP provides unique opportunity to embed 'wroght' 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 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 ductility, wear resistance, fatigue and creep resistance etc.

The advantages of FSP include: Simple equipment with easy process parameters such as tool rotation, traversing, tool geometry and downward load etc. These process parameters are easily controlled to tailor the mechanical and technological properties of the substrate material. The problems such as wettability, unrestrained chemical reactions, sintering temperatures and the cooling rates during the classical production methods of MMCs are easily overcome in FSP.

Zones in Friction Stir Processing:

The different zones of Friction Stir processing are listed below:

a. Stir Zone (SZ) or Nugget Zone
b. Thermomechanically affected Zone (TMAZ)

c. Heat Affected Zone (HAZ)
d. Unaffected or Parental Material

Advancing and retreating sides:
The side of the processing tool where surface motion (attained due to spinning) is in the same direction as the travel direction is referred to as the advancing side. The opposite side, where surface motion opposes the travel direction, is referred to as the retreating side.

Parameters of the Friction Stir Processing:
The microstructure and mechanical properties of surface MMCs are evaluated based on the controllable process parameters, such as, i) Downward axial force, ii) Rotational speed and iii) traversing speed, iv) Substrate thickness, and v) tool geometry

Downward axial force:
It imparts the severe plastic deformation and improves the microstructure of the alloy. However, excessive loads result in non-uniform deposition with a depression at the middle of the pass due to material expelling from the region beyond tool shoulder diameter. Insufficient forces results in poor consolidated surfaces.

Rotational speed:
Influences the quality of the surface. In fact, lower to intermediate rotational speeds enhance surface quality, higher rotation speeds produce a more flat and regular deposits.

Traverse speed:
Strongly influences surface composite thickness and width, since it determines the rate at which material is deposited. As such, higher travel speeds result in thinner deposits. Faster travel speeds lead to shorter heat exposure periods, resulting in less grain growth and finer microstructures. Thinner deposits also cool more rapidly. The substrate heat affected zone decreases for higher travel speeds. Bonding at coating edges deteriorates for faster travel speeds.

Tilt angle:
A small tilting of the tool, in less than 3° has proven to reduce the extension of the deposit, by enabling a gradual increase downward axial force applied by the tool on the substrate, from the tip to the tail zone being thermomechanically processed, at each instant.

Tool geometry:
The common FSP tool is a stepped cylindrical bar type. However, as per the requirement for the research interest, the geometry of the shoulder and pin profiles are altered.

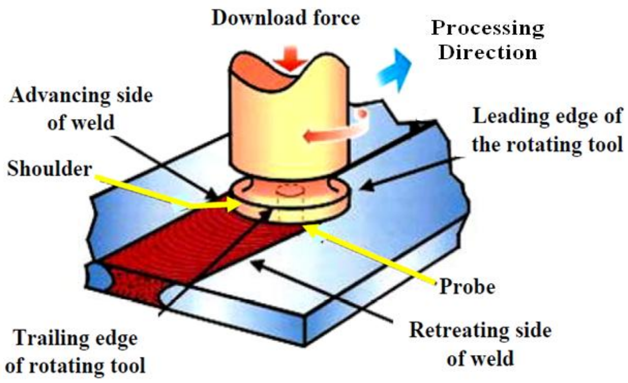

Fig. 1 Schematic of Friction Stir Processing [8]

1.2 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.

2. Materials and Methods

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

2.1 Substrate Material for SMMC:

For the fabrication of Surface MMC, AA-7075-T6 was considered as the substrate material.

Table1: The chemical composition of AA7075-T6 by Wt%

Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
0.4	0.5	1.2 to 2	0.3	2.1 to 2.9	0.18 to 0.28	5.1 to 6.1	87.1 to 91.4

Table 2: The vital properties of Al-7075:

Density	0.28 gm/cm^3
Elastic Modulus	70-80 GPa
Tensile Strength	220 Mpa
Poisson's ratio	0.3
Yield Strength	95 Mpa
Percentage Elongation	17
Hardness HB 500	60

Typical applications of AA7075 are into Aircraft fittings, gears and shafts, fuse parts, meter shafts and gears, missile parts, regulating valve parts, worm gears, keys, aircraft, aerospace and defense applications; bike frames, All Terrain Vehicle (ATV) sprockets, etc.[9]

2.2 Reinforcement Particles:

Aluminium Oxide (Al_2O_3) of 50 microns size was used as the reinforcement particles. The typical properties of Al_2O_3 powder include Hard, wear-resistant, resistance to acid and alkali attack, High strength and stiffness, Good thermal conductivity, Excellent size and shape capability, etc.

2.3 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 6 mm length and 4 mm diameter.

2.4 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.

3. Experimental

3.1 Friction Stir Processing:

In this study Aluminium alloy, AA-7075-T6 plate of 100 x 100 x6 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 Al_2O_3 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. 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 FSP set up for fabrication of SMMC

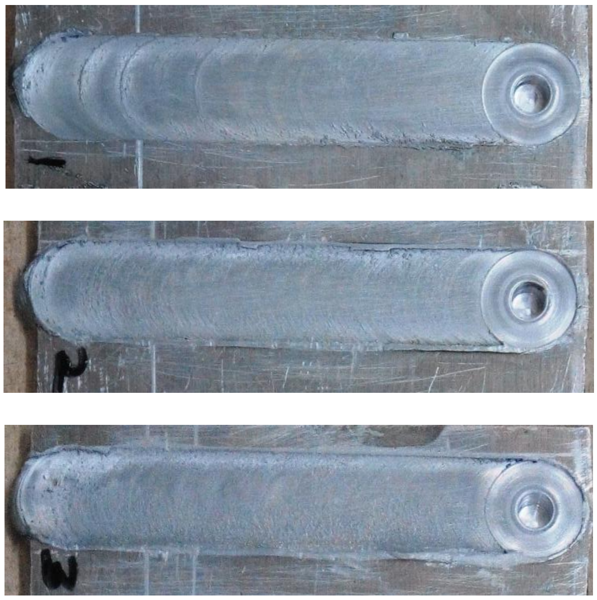

Fig. 3. SMMC billets fabricated by FSP

3.2 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.

Table 3: Experimental Parameters and their levels

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	15	25
Pulse ON time (µs)	B	50	100	150
Pulse OFF time (µs)	C	5	7	9
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				

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.

Table 4: Design Matrix of L-9 Orthogonal Array

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

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.

3.2.1 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[11]

$$MRR = (W_i - W_f) \times 1000 / (D_w \times t)$$

Where, MRR = Material Removal Rate (mm^3/min)
W_i = Initial weight of the SMMC sample (gm)
W_f = Final weight of the SMMC Sample (gm)
D_w = Density of the SMMC sample (gm/cm^3)
t = Trial period (min)

3.2.2 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[11]

$$TWR = (T_i - T_f) \times 1000 / (D_w \times t)$$

Where, TWR = Tool Wear Rate (mm^3/min)
T_i = Initial weight of the tool (gm)
T_f = Final weight of the Tool (gm)
D_w = Density of the Tool Material (gm/cm^3)
t = Trial period (min)

3.3 Surface Roughness (R_a):

The average Surface Roughness (R_a) 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.

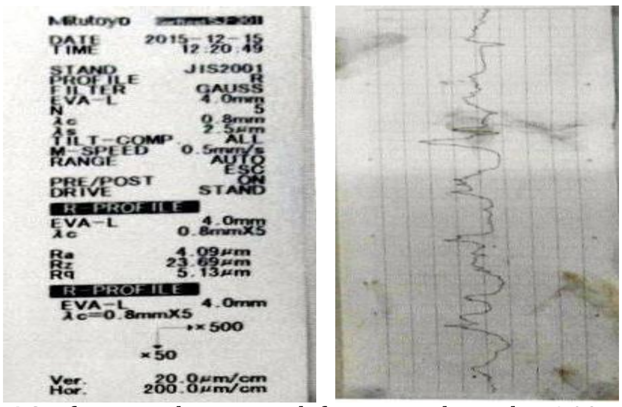

Fig.4 Surface Roughness graph for a typical R_a value 4.09 ηm

4. Experimental Results and Discussion:

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

Table 5: Experimental Results of ED Machining of SMMCs

Exp No.	Current (A)	Pulse ON (ηs)	Pulse OFF (ηs)	MRR (mm^3/ min)	TWR (mm^3/ min)	Ra (ηm)
1	10	50	5	0.612	0.129	4.127
2	10	100	7	2.091	0.182	11.451
3	10	150	9	3.126	0.237	5.978
4	15	50	7	4.262	0.138	4.090
5	15	100	9	6.467	0.269	11.021
6	15	150	5	7.863	0.318	9.114
7	25	50	9	5.012	0.237	4.567
8	25	100	5	8.178	0.367	12.993
9	25	150	7	8.879	0.439	9.967

4.1 Analysis of MRR, TWR and R_a

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.

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

Exp No.	Response Values			S/N Ratios		
	MRR (mm^3 /min)	TWR (mm^3/ min)	Ra (ηm)	MRR (dB)	TWR (dB)	Ra (dB)
1	0.612	0.129	4.127	-4.264	17.788	-12.312
2	2.091	0.182	11.451	6.407	14.799	-21.177
3	3.126	0.237	5.978	9.899	12.505	-15.531
4	4.262	0.138	4.090	12.592	17.202	-12.048
5	6.467	0.269	11.021	16.214	11.405	-20.844
6	7.863	0.318	9.114	17.912	9.952	-19.194
7	5.012	0.237	4.567	14.002	12.505	-13.193
8	8.178	0.367	12.993	18.253	8.707	-22.274
9	8.879	0.439	9.967	18.967	7.151	-19.971

4.1.1 Taguchi analysis of MRR Vs Current, Pulse-on and Pulse-off.

Table 7: Response table for Signal to Noise Ratio

(Larger is the better)

Level	Current	Pulse On	Pulse Off
1	4.014	7.443	10.633
2	15.573	13.625	12.656
3	17.073	15.593	13.371
Delta	13.060	8.150	2.738
Rank	1	2	3

Table 8: ANOVA MRR Vs Pulse ON

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pulse On	2	17.37	8.687	1.05	0.406
Error	6	49.65	8.275		
Total	8	67.02	67.02		

The effect of current on MRR is shown in Table5. The initial trend shows the MRR marginally increases with gap current. The current exceeds 15 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 (17.07%). Pule ON time and Pulse OFF time contribute 15.59% and 13.37% respectively on the MRR as shown in Table 7.

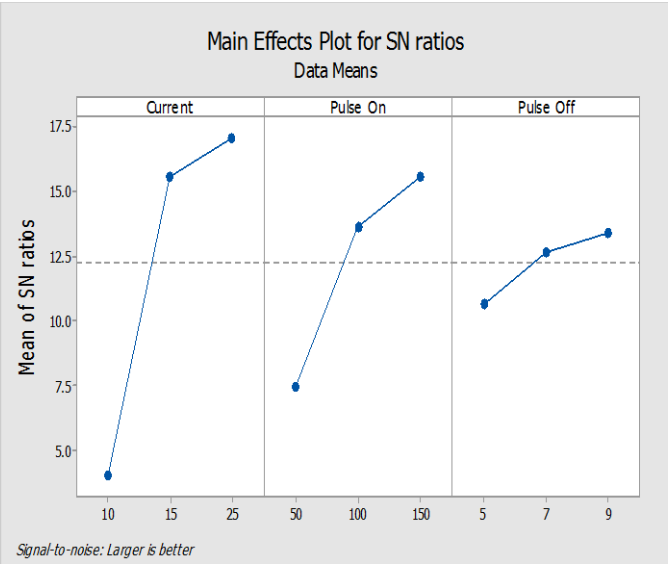

Fig. 5 Main effect plot for S.N ratios

4.1.2 Taguchi analysis of TWR Vs Current, Pulse-on and Pulse-off

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

Level	Current	Pulse On	Pulse Off
1	15.031	15.832	12.149
2	12.853	11.637	13.051
3	9.454	9.869	12.138
Delta	5.576	5.963	0.912
Rank	2	1	3

Table 10: ANOVA Vs Pulse ON

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pulse On	2	0.041	0.0205	2.74	0.143
Error	6	0.045	0.0075		
Total	8	0.086			

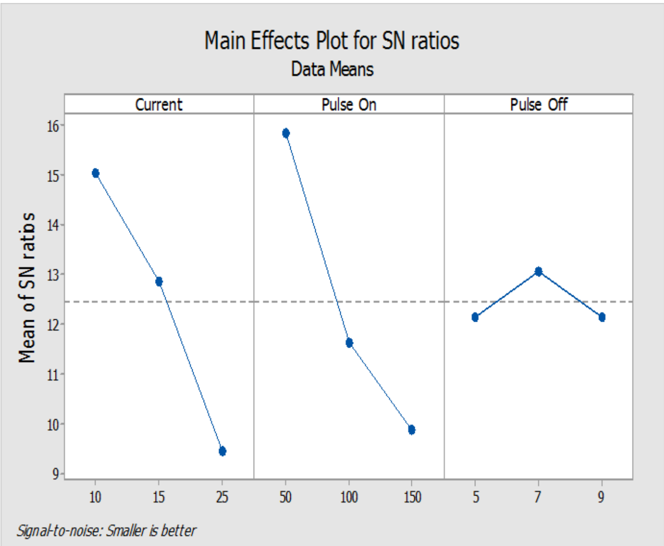

Fig. 6 Main effect plot for S.N ratios

The effect of current on TWR is shown in Table5. The initial trend shows the TWR decreases with gap current. The current exceeds 15 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 Pulse ON time has maximum effect (15.83%). Gap Current and Pulse OFF time contribute 15.83% and 13.05% respectively on the TWR as shown in Table 9.

4.1.3 Taguchi analysis of R_a Vs Current, Pulse-on and Pulse-off

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

Level	Current	Pulse On	Pulse Off
1	-16.34	-12.52	-17.93
2	-17.36	-21.43	-17.73
3	-18.48	-18.23	-16.52
Delta	2.14	8.91	1.40
Rank	2	1	3

Table 12: ANOVA Vs Pulse ON

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pulse On	2	86.61	43.31	23.30	0.001
Error	6	11.15	1.858		
Total	8	97.76			

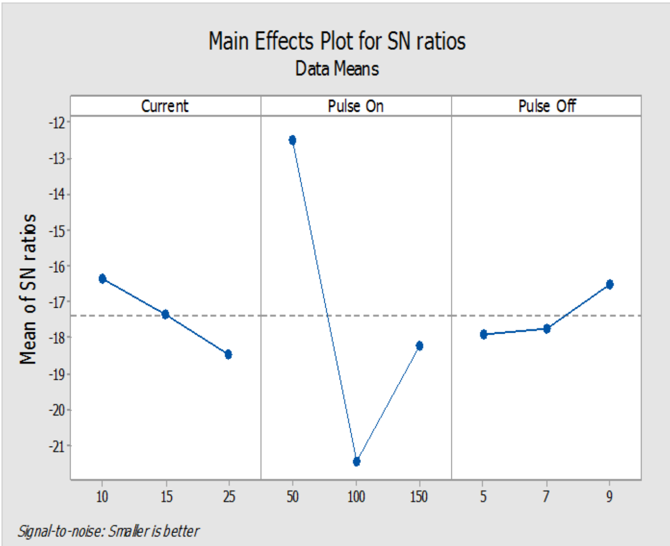

Fig. 7 Main effect plot for S.N ratios

The effect of current on R_a is shown in Table 5. The trend shows the R_a values are maximum with 100A gap current. The current exceeds 15 A the R_a sharply decreases due to high energy in the gap provides the variable conditions for R_a.

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

4.2 Confirmation Experiments:

Three confirmation experiments were conducted at the optimum levels of the process parameters. The mean value of MRR, TWR and R_a 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 R_a was tabulated in Table 13.

Table13. Optimum set of value for Process parameters for MRR, TWR and R_a.

Process Parameter	MRR	TWR	R_a
Current (A)	25	15	15
Pulse ON time (µs)	100	150	150
Pulse OFF time (µs)	5	5	5

5. Conclusions:

The Al7075-T6 Aluminium Alloy was taken as substrate material to fabricate Al/Al_2O_3 Surface Metal Matrix Composite through Friction Stir Processing. Electric Discharge Machining of SMMC billets was carried out on Electronica Electraplus 500 x 300/ZNC series Sinker Electric Discharge Machine so as to evaluate the machining characteristics. The Gap Current, Pulse ON time and Pulse OFF time were taken as input process parameters of the EDM. Design of Experiment were planned and conducted as per Taguchi's standard L-9 Orthogonal Array. Three levels with three factors of process parameters and response variables were considered to carryout experiments on EDM. The MRR and TWR values were calculated. The surface roughness, R_a 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 Optimum values of Current, Pulse ON time and Pulse Off time for the most optimum MRR are obtained as 25A, 100µs and 5 µs respectively. 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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