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Experimental Investigation on Aluminium Composite Surface Machined by Electrical Discharge Machining Process Using Response Surface Methodology

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ABSTRACT

Aluminum based composite materials have many potential engineering applications for manufacturing industry. Nowadays there is a critical need for cost-effective machining processes for this material. Not much work has been reported for machining of Aluminum based composite with Electrical Discharge Machining (EDM) process. In this work, an attempt has been made to model the machinability evaluation through the Response Surface Methodology (RSM) while machining of Al-10% SiC_p Metal Matrix Composite (MMC) was manufactured through stir casting method. The experimental results obtained aims at the selection of optimal machining conditions for EDM of Aluminum based MMC. The work piece material has been cleverly considered as control factor along with the combined effect of six controllable input variables and its effect on the surface roughness has been investigated with the minimum number of experiments. Analysis of variance is performed to get contribution of each parameter on the performance characteristics and it was observed that the discharge current is the significant process parameter that affects the EDM robustness. The contour plots were generated to study the effect of process parameters as well as their interactions. The experimental analysis for the optimal setting shows that there is considerable improvement in the process. The application of this technique converts the response variable to a single response process parameters which are optimized using Box Behnken based approach RSM and thus simplifies the optimization procedure. Result of confirmation experiments shows that the established mathematical models can predict the output response which satisfy the real requirement in practice.

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Keywords: *Metal Matrix Composites (MMC), Optimization, Response Surface Methodology (RSM), Surface Roughness (SR) Electrical Discharge Machining (EDM)*

Introduction

EDM is a known electrical type unconventional machining process predominantly used in precise machining for complex shaped work pieces Ho and Newman [1]. It is a thermal erosion process where an electrically generated spark vaporizes electrically conductive material Lotfi [2]. The electrode (tool) and work piece must be electrically conductive John [3]. The spark occurs in a gap filled with dielectric solution between the tool and work piece. The process removes metal via electrical and thermal energy, that has no mechanical contact with the work piece Margaret [4]. Its unique feature of using thermal energy is to electrically machine the conductive parts regardless of their hardness; its distinctive advantage is in the manufacture of above said modern industry. EDM does not make direct contact between the electrode and the work piece, eliminating mechanical stresses, chatter and vibration problems during machining. Today, an electrode as small as 0.1mm can be used to make hole into curved surfaces at steep angles without drill. The spark is generated due to a gap between the work piece and a tool. Better SR can be achieved using smaller gaps.

Composites are materials consisting of at least or more than two constituents bonded jointly along the interface in the composite, where each originates from a separate ingredient material which pre-exists the composite. MMCs are materials in which one constituent is a metal or alloy forming at least one percolating network Hashim *et al.*, [5]. Typical MMCs combine a tough metallic matrix that is contiguous with a hard ceramic reinforcement. Most Common matrix materials are aluminum, magnesium and titanium while the most popular reinforcements are Silicon Carbide (SiC), Titanium Carbide (TiC), Titanium Boride (TiB_2), Boron Carbide (BiC) and Alumina (Al_2O_3). The density of a good number of the MMC's is approximately one third of steel, resulting in high-specific strength and stiffness. In machining of such materials, conventional manufacturing processes are being replaced by more advanced techniques that use different fashion of energy to eliminate the material because these advance materials are difficult to machine by the conventional machining processes and it is hard to attain good surface finish and close tolerance. With the progression of automation technology, manufacturers are more fascinated in the processing and miniaturization of components made by these costly and hard materials.

Possibility of determining a global optimum solution and its accuracy relies on the type of optimization modeling technique used to express the objective functions and constraints in terms of the decision variables Arunachalam *et al.,* [6]. Accurate and reliable models of the process can compensate for inability to completely understand and adequately describe the process mechanism.

Hence it comes in picture that the formulation of optimization model is the most important task in optimization. It involves expressing optimization problem as a mathematical model in a standard format which could be directly solved by RSM. Optimization of EDM, type of objective function and constraints, number of objectives and extend of the importance or priority to be given to objective depends on the output parameter SR and input parameters such as Peak Current (I_p), Pulse On Time (T_{on}), Pulse Off Time (T_{off}), Discharge Voltage, Gap Width and Oil Pressure, machining of Al/10% SiC_p was performed and influential performances are compared.

RSM have been used to analyze the effect of the six input parameters and output parameter of SR in EDM process. The main objective for the EDM processes is to minimize SR.

Different researchers have carried out process parameter optimization of different types of EDM from time to time using different optimization models and solution techniques as shown in Figure 1. The summary of such past studies highlights the decision variables, objective functions, constraints, variable bounds, remarks and their limitation Dev and Rajesh [7].

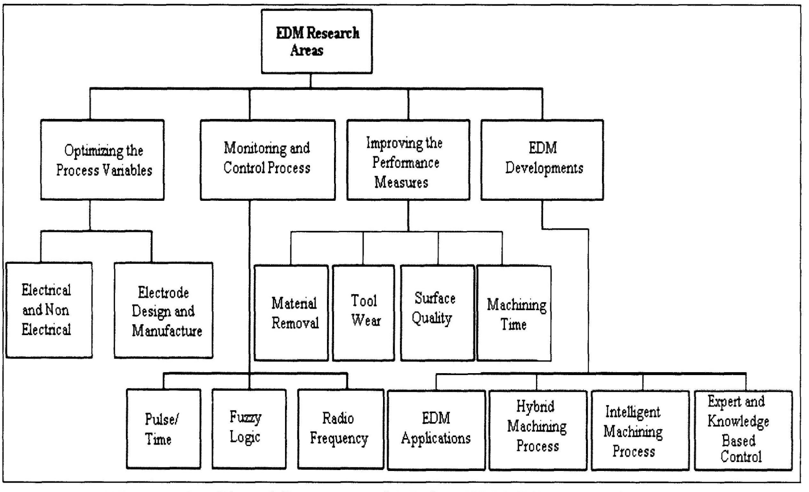

Figure 1: Classification of Major EDM Research Areas

The retro analysis of literature revealed and brought out into sight that there was no work carried out in EDM of Al/10% SiC and with more than three parameters.

Experimental Details

A number of experiments were conducted inorder to investigate the performance and study the effects of various machining parameters of EDM process on MMC in the form of rectanguar block of test pieces. These studies have been undertaken to investigate the effects of Peak Current (I_p), Discharge Voltage (V), Spark Gap, Pulse On Time (T_{on}), Pulse Off Time (T_{off}) and Oil Pressure (P_{oil}) on SR and in this optimization process these parameters are considered as design variables.

The formulation of an optimization problem begins with identifying the underlying design variables, which are primarily varied during the optimization process. The constraints represent some functional relationship among the design variables and other design satisfying certain physical phenomenon and certain resource are greater than or equal to, a resource value. In this paper, oversize and the EDM hole are considered as constraints.

Work material

The work material Al-10% SiC_p (MMC) was manufactured through stir casting method, properly evaluated and selected for the study was of rectangular piece (120mm x 120mm x 8mm dimensions). The material is selected due to its growing range of applications in the field of manufacturing tools in mould industries and also used highly in aeronautical and automobile industries because of their high strength to weight ratio, mechanical and physical properties compared to monolithic material. Table-1 shows the physical and mechanical properties of Al-10% SiC_p MMC material. Table–2 shows the chemical composition of Al-10% SiC_p MMC material.

Table 1: Physical and mechanical properties of Al-10% SiC_p MMC

Material	Density (gms/cm^3)	Tensile Strength (N/mm^2)	Hardness (BHN)	Modulus of Elasticity (x10^{3}N/mm^2)	% Elongation
Al-SiC10_p	2.68	275	110	90	1.2 – 1.8

Table 2: Chemical composition of Al-10% SiC_p MMC

Work Material	LM 25 Al-SiC10_p
Mg (%)	0.45
Si(%)	7.5
Cu(%)	0.2
Mn (%)	0.1
Fe (%)	0.2
Zn (%)	0.1
Ti (%)	0.2
SiC (%)	10
Reinforcement	10% SiC Particles (by Volume)
Particle Size (μm)	20

Tool material

A cylindrical pure copper (Graphite Grade EDM) with a diameter of 10mm was used as a tool electrode (of positive polarity) and it is used to drill the work piece to 1mm depth as per ISO specification cutting tool was supplied by Sandvick and tool holder M16 type were used for the machining trials under various setting condition.

EDM machine

Experiments are conducted on Electronica 5030 Die Sinking EDM machine as show in Figure 2. The dielectric fluid used was (DEF-92) and the electrode suction flushing method was used. The scheme of experimental conditions for EDM machining is given in Table 3.

Table 3:EDM machining conditions

Conditions	Descriptions
Machine	Electronica 5030 die sinking EDM machine
Test Specimen	Composite material (Mg .45%,Si 7.5%, Cu -.2,Mn.1, Fe .2, Zn .1, Ti .2,SiC 10%)
Tool	Copper Electrode of Diameter 10mm
Tool Polarity	Positive
Dielectric Fluid	EDM Oil (DEF-92)
Flushing Type	External
Depth of Cut (mm)	1
Electrode Polarity	Positive
Dielectric Flushing	Injection Flushing
Weight Measuring Instrument	Digital Balance (FX-3000)
SR Measuring Instrument	Portable SR Tester SJ201
Technical Data	**Co-Ordinate Table**

Supply Voltage : 415V, 3Ph.,50Hz	Mounting Surface (l*b) : 500*300mm
Taps : 380V, 415V, 440V	Maximum Workpiece Height : 175mm
Power Factor : 0.8 Approx	Maximum Workpiece Weight : 175kg
Height : 2075mm	Longitudinal Travel (X-axis) : 280mm
Width : 1230mm Depth : 1035mm	Transverse Travel (Y-axis) : 200mm
Net Weight : 800Kg (Approx.)	L.C of Hand Wheel Graduations with Vernier Scale : 0.005mm
	Width of Work Tank – Internal : 725mm
	Depth of Work Tank – Internal : 415mm
	Height of Work Tank : 315mm
Working Parameters	
Machining Current Max.: 35 Amps	Pulse Current : 2Amps
Open Gap O/V : 140 ± 5%	Current Range Selection : 10 Selection
	1 = 1Amp 2 = 2Amps 3-10 = 4Amps
Pulse Current : 2 Selection	Pulse On Duration : 2 to 1000□s
1 = 1Amp 1 = 1 Amp	
Weight : 250 Kg. (Approx.)	

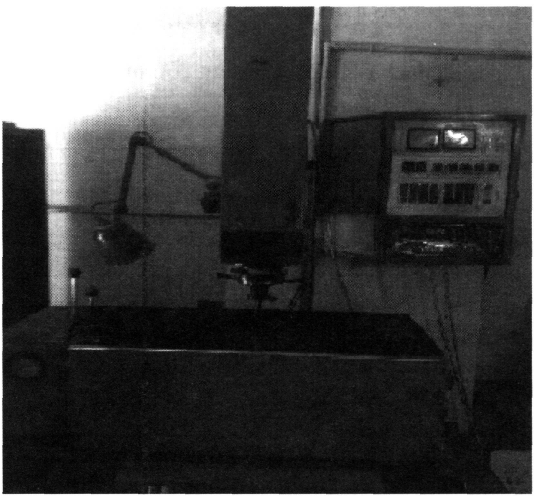

Figure 2: Electronica 5030 die sinking EDM machine

Experimental procedure

The machining process is carried out in ELECTRONICA EMS5030 as shown in Figure 3; the work piece is mounted on the V- block which is placed on the magnetic table of the machine. The tool is placed on the tool holder and its alignment is checked with the help of dial gauge. The number of runs was decided to be 54 with different parameter combinations based on Analysis of Variance.

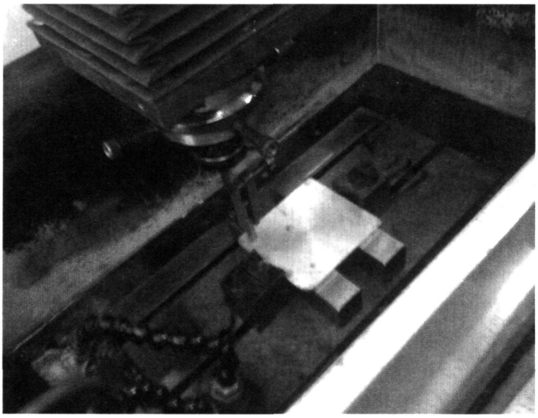

Figure 3: Electronica 5030 Die Sinking EDM machining process underway

Measurement procedure

Roughness measurement has been done using a portable roughness tester SJ201 shown in Figure 4. This instrument (Surtronic 3^+) is a portable, self-contained instrument for the measurement of surface texture. The parameter evaluations are microprocessor based. The measurement results are displayed on an LCD screen and can be output to an optional printer or another computer for further evaluation. The instrument is powered by non-rechargeable alkaline battery (9V). It is equipped with a diamond stylus having a tip radius 5μm. The measuring stroke always starts from the extreme outward position. At the end of the measurement the pickup returns to the position ready for the next measurement. The selection of cut-off length determines the traverse length. Usually as a default, the traverse length is five times the cut-off length though the magnification factor can be changed. The profilometer has been set to a cut-off length of 0.8mm, filter 2CR, and traverse speed 1mm/sec and 4mm traverse length. Roughness measurements, in the transverse direction, on the work pieces have been repeated four times and average of four measurements of SR parameter values has been recorded.

Figure 4: Experimental set up for measuring roughness

Experimental set-up

The tests were conducted under different machining conditions using Electronica 5030 Die Sinking EDM machine, which is 3HP/2.2kW power. The input parameter was derived from the setting machining and the shape of the surface of the work piece. The tests were carried out with normal above mentioned procedure. The levels were specified for each process parameter as given in the Table 4. The parameter levels were chosen within the intervals recommended by the machining tool manufacturer and investigation of the present study. Six process parameters at two and three levels led to a total of 54 tests for machining operation. After each test, the work piece is measured with the SR tester SJ201 to determine the SR. The observations are presented in the Table v for further analysis and studies. The machining operations were carried out as per the conditions given by the design matrix at random to avoid systematic errors.

Table 4: Different variables used in the experiment and their levels

Variable	**Coding**	**Level**		
		1	**2**	**3**
Discharge Voltage (V) in V	A	60	65	70
Discharge Current in A	B	5	10	15
Pulse on Time (T_{on}) in s	C	15	30	45
Pulse Off Time (T_{off}) in s	D	5	7	9
Spark Gap (G) in mm	E	0.1	0.2	0.3
Oil Pressure in kg/cm^2	F	1	1.5	3

In the next step, the planning to accomplish the experiments by means of RSM using a Box Behnken approach with six variables. Total numbers of experiments conducted with the combination of machining parameter and the corresponding recorderd SR are presented in Table 5.

Table 5: Planning matrix of the experiments with the optimal model data

Sl. No	**A (V) Voltage**	**B (A) Current**	**C (s) Pulse ON Time**	**D (s) Pulse OFF Time**	**E (mm) Gap**	**F Oil Pressure (Kg/cm$^{2)}$**	**G SR (µm)**
1.	65	5	15	7	0.3	1.5	3.01
2.	75	10	45	7	0.2	2.0	6.09
3.	75	10	30	9	0.1	1.5	5.82
4.	65	15	45	7	0.3	1.5	6.86
5.	75	15	30	5	0.2	1.5	5.88
6.	75	5	30	5	0.2	1.5	4.43
7.	65	10	15	9	0.2	1.0	4.32
8.	75	15	30	9	0.2	1.5	5.22
9.	75	10	45	7	0.2	1.0	6.27
10.	65	5	45	7	0.3	1.5	6.16
11.	60	10	30	9	0.1	1.5	6.20
12.	60	5	30	5	0.2	1.5	4.41
13.	60	10	30	5	0.3	1.5	5.77
14.	60	10	30	9	0.3	1.5	6.41
15.	65	5	30	7	0.1	1.0	5.69
16.	65	10	30	7	0.2	1.5	5.39
17.	60	10	45	7	0.2	2.0	6.36
18.	65	5	30	7	0.3	2.0	4.35
19.	65	10	15	5	0.2	2.0	4.86
20.	60	5	30	9	0.2	1.5	4.91
21.	75	10	30	5	0.1	1.5	5.79
22.	65	15	15	7	0.1	1.5	4.12
23.	75	5	30	9	0.2	1.5	4.87
24.	75	10	30	5	0.3	1.5	6.17
25.	75	10	15	7	0.2	2.0	5.18
26.	65	10	15	9	0.2	2.0	5.14
27.	65	5	30	7	0.1	2.0	5.09
28.	65	10	45	5	0.2	2.0	7.44
29.	65	5	30	7	0.3	1.0	4.30
30.	65	15	30	7	0.1	1.0	6.39
31.	65	15	30	7	0.3	2.0	6.33
32.	65	10	30	7	0.2	1.5	5.10

33.	65	10	45	9	0.2	1.0	5.60
34.	60	10	15	7	0.2	1.0	3.74
35.	65	10	45	9	0.2	2.0	5.60
36.	65	10	45	5	0.2	1.0	8.19
37.	65	5	15	7	0.1	1.5	4.20
38.	75	10	15	7	0.2	1.0	5.31
39.	65	15	30	7	0.1	2.0	8.12
40.	65	15	15	7	0.3	1.5	4.01
41.	65	10	30	7	0.2	1.5	6.82
42.	75	10	30	9	0.3	1.5	7.08
43.	65	10	30	7	0.2	1.5	6.49
44.	65	10	30	7	0.2	1.5	6.51
45.	65	15	45	7	0.1	1.5	7.77
46.	60	15	30	5	0.2	1.5	7.70
47.	60	10	45	7	0.2	1.0	7.98
48.	65	15	30	7	0.3	1.0	8.02
49.	60	15	30	9	0.2	1.5	7.31
50.	65	10	30	7	0.2	1.5	5.01
51.	65	10	15	5	0.2	1.0	4.91
52.	60	10	15	7	0.2	2.0	4.97
53.	65	5	45	7	0.1	1.5	5.28
54.	60	10	30	5	0.1	1.5	6.54

Mathematical Modeling

Models for Al SiC_p EDM machining

Table 6 shows the ANOVA table for SR Estimated Regression Coefficients and Table 7 shows the ANOVA table Analysis of Variance for SR when EDM machining of MMC with copper tool. The regression model fitted for SR was obtained and is represented by Equation 1.

Surface Roughness = $4.4805-0.1893A+1.2479B+0.6101C-0.4769D-41.5598E-3.2685F+0.0021A^2-0.0163B^2-0.0023C^2+0.0165D^2+22.4167E^2+1.3300F^2-0.0116AB-0.0043AC+0.0060AD+0.4410AE-0.0007AF+0.0038BC-0.0249BD+0.1575BE+0.0295BF-0.0172CD+0.1058CE-0.0368CF+1.1625DE+0.2025DF-6.9250EF\ 0.0249BD+0.1575BE+0.0295BF-0.0172CD+0.1058CE-0.0368CF+1.1625DE+0.2025DF-6.9250EF$ **(1)**

Table 6: ANOVA Table for SR estimated regression coefficients

Term	Co_{eff}	SE Co_{eff}	T	P
Constant	5.81547	0.3257	17.857	0.000
A	-0.17458	0.1533	-1.138	0.265
B	0.77978	0.1636	4.767	0.000
C	0.96944	0.1636	5.926	0.000
D	-0.14045	0.1547	-0.908	0.372
E	-0.03233	0.1636	-0.198	0.845
F	-0.05013	0.1636	-0.306	0.762
A*A	0.11703	0.2697	0.434	0.668
B*B	-0.40708	0.2342	-1.738	0.094
C* C	-0.52750	0.2342	-2.252	0.033
D*D	0.06583	0.2342	0.281	0.781
E*E	0.22417	0.2342	0.957	0.347
F*F	0.33250	0.2342	1.419	0.168
A*B	-0.43409	0.2563	-1.694	0.102
A*C	-0.48065	0.2563	-1.875	0.072
A*D	0.08973	0.1844	0.487	0.631
A*E	0.33078	0.2563	1.291	0.208
A*F	-0.00246	0.2563	-0.010	0.992
B*C	0.28375	0.2656	1.068	0.295
B*D	-0.24875	0.2656	-0.937	0.358
B*E	0.07875	0.1878	0.419	0.678
B*F	0.07375	0.2656	0.278	0.783
C*D	-0.51500	0.2656	-1.939	0.063
C*E	0.15875	0.2656	0.598	0.555
C*F	-0.27625	0.1878	-1.471	0.153
D*E	0.23250	0.2656	0.875	0.389
D*F	0.20250	0.2656	0.762	0.453
E*F	-0.34625	0.2656	-1.304	0.204
	S = 0.7512	**R-Sq = 81.4%**	**R-Sq(adj) = 62.2%**	

Table 7: Analysis of Variance for SR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	27	64.426	64.426	2.3861	4.23	0.000
Linear	6	47.588	33.918	5.6530	10.02	0.000
Square	6	5.614	5.614	0.9356	1.66	0.171
Interaction	15	11.224	11.224	0.7483	1.33	0.256
Residual Error	26	14.673	14.673	0.5644		
Lack-of-Fit	21	11.416	11.416	0.5436	0.83	0.656
Pure Error	5	3.258	3.258	0.6515		
Total	53	79.099				

From the Table 6 – 8 the value of "P" in Table vii for model is less than 0.05 which indicates that the model is adequately significant at 95% confidence level, which is desirable as it indicates that the terms in the model have a significant effect on the response. The discharge current has the most dominant effect on SR, followed by the discharge voltage and the spark gap. This is expected because, it is well known that increase in current will increase SR; the classical energy is primarily a function of the discharge current. The predicted results were discussed through the Table viii with experimental validation. The error range obtained during that analysis was 7% and it was considered as acceptable model.

Table 8: Predicted result with experimental validation of MMCs for SR

Optimization for SR	Machining Parameters						SR		
							Predictod Ra	Actual Ra	Error %
	A	B	C	D	E	F	G		
	65	5	15	7	0.3	1.5	3.087113	3.01	0.077113

Results and Discussion

Effect of machining parameters on SR

The effect of the machining parameters (V, I_p, T_{on}, T_{off}, Gap Width and P_{oil}) on the response variables SR have been evaluated by conducting experiments. The results are put into the Minitab software for further analysis. The second-order model was proposed in find the correlation between the SR and the process variables taken into account. The Analysis of Variance (ANOVA) was used to check the sufficiency of the second order model. Figure 5 show the estimated response surface for SR in relation to the process parameters of discharge current and discharge voltage while T_{off}, T_{on}, gap width and P_{oil} are remain constant at their lowest values. It can be seen from the figure, the SR tends to increase significantly with the increase in discharge current for any value of discharge voltage. Increase in discharge current produces stronger spark and higher temperatures. The effect of pulse on time and discharge current is on the estimated response surface of SR is depicted in Figure 6, pulse off, gap width, V and P_{oil} remains constant in its lower levels. It can be noted that the SR increases when the current increases and the pulse on time increases. This causes more melting of the material and eroding the work piece and consequent increase in SR. Figure 7 represent SR as a function of pulse off time and discharge voltage, whereas the I_p, current, gap width and P_{oil} remains constant at its lower levels. It is observed that the SR values are high when pulse off time and discharge voltage is low. This is expected because a decrease in pulse off time produces less intense spark and consequently lower temperatures, causing less material to melt and erode from the work piece. Figure 8 represent SR as a function of gap width and pulse on time, whereas the discharge voltage, discharge current, T_{off} and P_{oil} remains constant at its lower levels. It is observed that the SR values are high when gap width high and pulse on time low. Figure 9 represent SR as a function of p_{oil} and discharge voltage, whereas the gap width, discharge current, T_{off} and P_{oil} remains constant at its lower levels. It is observed that the SR values are higher when discharge current and oil pressure high. SR with flow rate has increased and decreased at the higher values of flow rate. This is because of the cooling effect of increasing dielectric flow rate on the work piece surface. The other possible reason could be that increased flow on the work piece may prevent debris adhering to the surface.

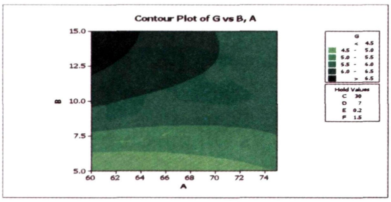

Figure 5: (Effect of SR Vs Discharge Current and Discharge Voltage)

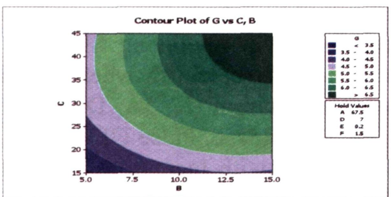

Figure 6: (Effect of SR Vs Pulse on Time and Discharge Current)

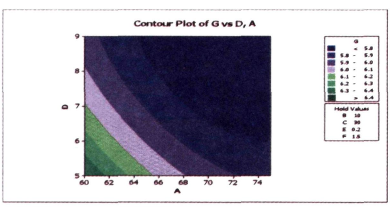

Figure 7: (Effect of SR Vs Pulse off Time and Discharge Voltage)

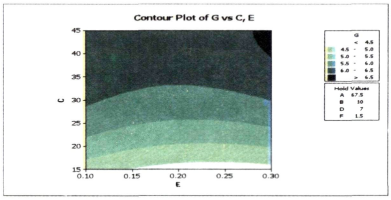

Figure8: (Effect of SR Vs Pulse on Time and Gap Width)

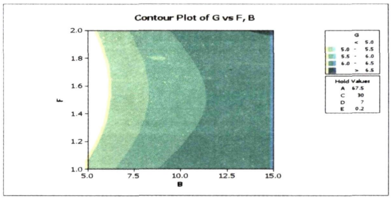

Figure 9: (Effect of SR Vs Oil pressure and Discharge Current)

Conclusion

The selection of machining parameters is one of the most important aspects to be considered in the majority of advanced manufacturing processes. RSM model have been developed for predicting SR. The optimized machining condition that gives better surface finish when machining Al SiC_p MMCs have been identified: Peak Current (I_p) 5A, Discharge Voltage 65V, Spark Gap 0.3mm, Pulse ON Time 15sec, Pulse OFF Time 7sec and Oil Pressure 1.5kg/cm^2. The SR improves with increase of the discharge current whilst increasing pulse off time adversely affects the SR. Among the machining parameters, discharge current has the most dominant effect on SR through ANOVA. The machining parameters for EDM process are optimized using RSM techniques for minimizing the SR. The developed model has been validated experimentally and exhibit low values of error.

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[1] M. K. Ghosh and A. Nagraj, "Turbulence flow in bearings," Proceedings of the Institution of Mechanical Engineers 218 (1), 61-4 (2004).
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