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Parametric Investigation of Powder Mixed Electrical Discharge Machining of Al-Sic Metal Matrix Composites

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Abstract – **In recent few years composite materials have gained pace in engineering application. But they have poor machinability by using conventional machining methods. So it is required to study about these materials for better use in engineering application. To fulfillment of this aim, a study is done by conduct experiments (i.e. Machining) on Al/SiC metal matrix composite (MMC). From the non-conventional machining process, Powder Mixed Electrical discharge machining (PMEDM) is used to machining of Al/SiC MMC. PMEDM is a technological improvement in conventional EDM, which was previously studied by many researchers to better MRR with good surface roughness (SR). In this study, the controllable machining process parameters (i.e. Peak Current (I_p), Duty Cycle, Powder Concentration (PC), Gap Control and Sensitivity) of PMEDM was selected to experimental investigation. The process performance is measured in terms of material removal rate (MRR) and surface finish (SR). The research outcome will identify the important parameters and their effect on MRR of Al/SiC MMC in the presence of suspended graphite (Gr) powder in a kerosene dielectric of EDM. Response surface methodology (RSM) has been used to plan and analyze the experimental results. The experimental results emerged that only sensitivity has non-significant effect on MMR and SR from the selected process parameters, but it gives significant effects with other factors in interaction. Further it found that, the MRR is directly proportional to I_p and inversely proportional to the PC and duty cycle, and the SR improves at lower I_p and optimum range of PC, gap control and duty cycle.**

Keywords – **PMEDM, MMC, ANOVA, RSM.**

I. INTRODUCTION

Metal matrix composites (MMCs) are such materials, which are manufactured by suspending the reinforcing agents (in the form of fibers, particulates, whiskers, etc.) into the matrix of the base material [1]. While many engineering components, made from PMMC, are produced by the near net shape forming and casting processes, they frequently require machining to achieve the desired dimensions and surface finish. The machining of PMMCs presents a significant challenge, since a number of reinforcement materials are significantly harder than the commonly used high-speed steel (HSS) and carbide tools [2]. The reinforcement phase causes rapid abrasive tool wear and therefore the widespread usage of PMMCs is significantly impeded by their poor machinability and high machining costs. The hard, brittle phase in this composite can cause problems when machining such materials. The most commonly encountered problems are involved in producing an acceptable surface finish, avoiding very rapid tool wear and achieving acceptable machining costs, through the use of higher machining speeds. Machining MMC's using conventional machining processes such as turning, drilling etc. generally results in excessive tool wear due to the presence of the hard particles which results in a very abrasive nature of this material. Consequently non-conventional machining processes such as EDM, laser cutting and Abrasive Water Jet (AWJ) techniques are increasingly being used [3].

EDM technique has been widely used in the modern metal working industry for producing complex cavities in dies and moulds, which are otherwise difficult to create by conventional machining [4]. The process also has the advantage of being able to machine hardened tool steels. However, its low machining efficiency and poor surface finish restricted its further applications [5]. To address these problems, one relatively new technique used to improve the efficiency and surface finish is EDM in the presence of powder suspended in the dielectric fluid [6–14]. This new hybrid material removal process is called powder mixed electrical discharge machining (PMEDM). In this technique, abrasive/metal powders are mixed into the dielectric fluid of EDM. The added powder significantly affects the performance of EDM process. The electrically conductive powder reduces the insulating strength of the dielectric fluid and increases the spark gap between the tool and workpiece [5, 7, 10-19]. As a result, the process becomes more stable thereby improving the MRR and surface finish.

From the available literature, it can be concluded that, a few researchers investigated the effect of different input process parameters on the response characteristics of PMEDM for MMC. Fuqiang Hu *et al.* [20] present an article on PMEDM of silicon carbide particle reinforced aluminium matrix composites (SiC_p/Al).

After processing the observation was found that, the surface roughness value of the former is R_a 1.386μm while the latter is R_a0.406μm which is only 29.3% of the former. The surface hardness was 1.3 times of the former. Singh *et al.* [21] applied a new approach of performance evaluation, gray relational analysis, to evaluate the effectiveness of optimizing multiple performance characteristics of abrasive powder mixed EDM of

$Al6061/Al_2O_3$MMC and concluded that the T_{on} time has the strongest effect among the other process parameters used to study the multiple performance characteristics. The order of importance of the process parameters of the multiple performance characteristics is T_{on} time, aspect ratio, tool electrode lift time, duty cycle, abrasive particle size, abrasive powder concentration, gap voltage, and pulse current. Kumar *et al.* [22] conducted an experimental study with the objective to understand the mechanism of material removal in PMEDM, while machining the Al-SiC metal matrix composites and found that the appropriate addition of silicon powder into the dielectric fluid of EDM increases the machining rate and decreases the surface roughness (SR). It was also found that the powder concentration, peak current, and pulse duration are the significant variables, while the supply voltage is an insignificant variable.

In available literatures it was observed that there has been no work reported on the influence of addition of graphite powder in dielectric fluid during PMEDM of Al-SiC MMC. Graphite has high thermal/electrical conductivity and excellent lubricity, which helps to improve surface finish as well as MRR [23]. In the present study, it was decided to investigate the influence process parameters of PMEDM on output characteristics by suspending fine graphite powder in dielectric fluid at different concentration.

II. EXPERIMENTAL SETUP

An additional powder mixing unit was fabricated on electronica (EMS 5030) die sinking EDM machine. In this setup a machining tank used to separate the dielectric fluid from the main dielectric tank of EDM. A proper circulation and mixing of powder mixed dielectric fluid was maintained to get efficient machining condition. Fig.1 shows the schematic of PMEDM setup. In this setup the powder mixed dielectric was stored and flushed through a separate unit other than the main dielectric tank.

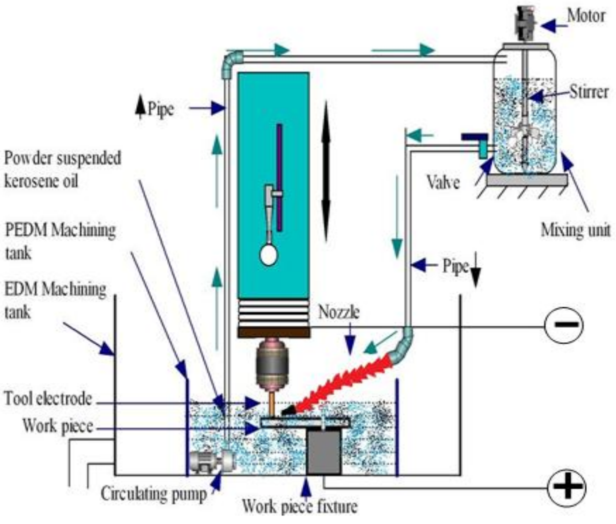

Fig.1. Schematic of PMEDM setup

The tool of pure copper (99%) was used, with the diameter of 6 mm in order to provide a realistic energy density. Copper has received much attention as a tool material as it has the qualities for high stock removal, and is stable under sparking conditions along with some work-piece materials. Copper electrodes yields to a finer surface finish and low wear ratio while machining Al-SiC MMC [23].

The Al-SiC MMC was used as a workpiece, prepared by using SiC as reinforcement with mean particle size of 30µm by melt-stir–squeeze –quench casting sequence [23]. Samples for microstructure analysis were taken from the central vortex region of the cast composite. The field emission scanning electron microscope (FESEM) of stir cast Al-SiC composite is shown in Fig. 2.

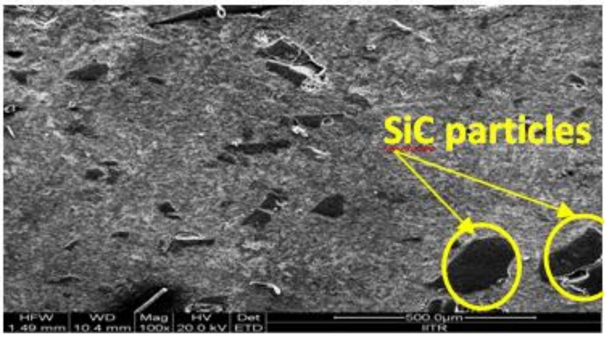

Fig.2. FESEM of Al-SiC MMC at 100X

Table 1: Machining conditions for PMEDM

Machining condition	Description
Powder type	Graphite
Powder size	25 µm
Flushing	Nozzle
Workpiece	Al/10% Sic MMC
Tool	99% pure Copper
Depth of cut	3mm
Dielectric fluid	Kerosene + Gr powder
Polarity	Positive

Design of experiments and the selection of process parameter and their range have been done by pilot experimentation. Pilot experiments were conducted with one-factor-at-time (OFAT) approach. By this approach evolution of factors carried out to observe the influence on quality characteristics of PMEDM. Following five controllable process parameters and their range was selected after conducting OFAT experiments.

Table 2 : Input process parameters and their levels

Factor	Process Parameter	Level		
		1	2	3
A	Peak current (A)	8	10	12
B	Powder concentration (g/l)	2	4	6
C	Gap control	6	7	8
D	Duty cycle	0.7	0.75	0.8
E	Sensitivity	3	4	5

A vertical depth of cut 3 mm was maintained for the electrode to penetrate down after its first electrical contact with the work-piece. The total machining time was determined using a stopwatch.

A precision weight loss was measured by using an AUX220 electronic balance by SHIMADZU with least count of 0.1mg.

The MRR signifies the amount of material that has been removed from a workpiece observed machining time.

$$\boldsymbol{MRR}\left(\frac{\mathrm{mm}^3}{\mathrm{min}}\right) = \frac{(\text{Initial weight (g)} - \text{Final weight (g)})\ \mathrm{X}10^6}{\text{density}\ (\mathrm{g/mm}^3) \times \text{machining time (min)}}$$

The Surface Roughness (SR) is measured in arithmetic mean (R_a) by using a digital surface tester of 'Mitutoyo SJ 400'.

Experimental design can be used at the point of greatest leverage to reduce design costs by speeding up the design process, reducing late engineering design changes, and reducing product material and labor complexity. Experiments can be designed in many different ways to collect this information. Design of Experiments (DOE) is a powerful tool to get maximum information about experiments by taking minimum trail (experiments) [27]. In DOE, Response surface methodology (RSM) is the most useful tool to investigate the localized effect of input parameters on output parameters of the process.

RSM is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [28, 29].

III. RESULTS AND DISCUSSION

The experiments were conducted according to RSM design and the average values of MRR and SR along with design matrix are tabulated in Table 3. For analysis the data, the checking of goodness of fit of the model is very much required. The model adequacy checking includes tests for the significance of the regression model, test for significance on model coefficients and test for lack of fit [30]. For this purpose, analysis of variance (ANOVA) is performed.

To decide about the adequacy of the model, three different tests viz. sequential model sum of squares, lack of fit tests and model summary statistics were performed for MRR and WR characteristics of PMEDM process. The "sequential model sum of squares" test in each table shows, how the terms of increasing complexity contribute to the model. It can be observed that for all the responses, the quadratic model is appropriate. The "lack of fit" test compares the residual error to the pure error from the replicated design points. The results indicate that the quadratic model with all the characteristics does not show a significant lack of fit; hence the adequacy of quadratic model is confirmed. Another test "model summary statistics" given in the following sections further confirms that the quadratic model is the best to fit as it exhibits low standard deviation, high "R-Squared" values, and a low "PRESS" (Adequate Precision).

Table 1: Design of PMEDM experiment and their results

S.N.	**Factors**					**Responses**	
	A	**B**	**C**	**D**	**E**	**Avg. MRR (mm^3/min)**	**Avg.SR (µm)**
1	8	2	6	0.7	3	**45.60**	**1.85**
2	12	2	6	0.7	3	**58.80**	**2.06**
3	8	6	6	0.7	3	**57.69**	**2.30**
4	12	6	6	0.7	3	**65.90**	**2.41**
5	8	2	8	0.7	3	**22.40**	**1.50**
6	12	2	8	0.7	3	**30.46**	**1.79**
7	8	6	8	0.7	3	**23.75**	**1.72**
8	12	6	8	0.7	3	**38.57**	**1.79**
9	8	2	6	0.8	3	**50.50**	**1.90**
10	12	2	6	0.8	3	**66.92**	**2.12**
11	8	6	6	0.8	3	**43.80**	**1.75**
12	8	2	8	0.8	3	**39.80**	**1.81**
13	12	6	6	0.8	3	**43.74**	**1.69**
14	12	2	8	0.8	3	**40.28**	**2.01**
15	8	6	8	0.8	3	**24.12**	**1.45**
16	12	6	8	0.8	3	**19.37**	**1.51**
17	8	2	6	0.7	5	**52.18**	**2.08**
18	12	2	6	0.7	5	**75.74**	**2.50**
19	8	6	6	0.7	5	**61.25**	**2.13**
20	12	6	6	0.7	5	**67.43**	**2.35**
21	8	2	8	0.7	5	**31.75**	**1.75**
22	12	2	8	0.7	5	**50.54**	**1.98**
23	8	6	8	0.7	5	**30.81**	**1.54**
24	12	6	8	0.7	5	**42.98**	**1.95**
25	8	2	6	0.8	5	**46.10**	**1.98**
26	12	2	6	0.8	5	**63.77**	**2.49**
27	8	6	6	0.8	5	**26.66**	**1.49**
28	12	6	6	0.8	5	**46.17**	**1.88**
29	8	2	8	0.8	5	**23.40**	**1.93**
30	12	2	8	0.8	5	**38.81**	**2.20**
31	8	6	8	0.8	5	**20.79**	**1.31**
32	12	6	8	0.8	5	**21.19**	**1.51**
33	8	4	7	0.75	4	**51.41**	**1.85**
34	12	4	7	0.75	4	**62.14**	**1.95**
35	10	2	7	0.75	4	**57.22**	**1.98**
36	10	6	7	0.75	4	**49.35**	**1.78**
37	10	4	6	0.75	4	**39.11**	**2.15**
38	10	4	8	0.75	4	**21.14**	**1.80**
39	10	4	7	0.7	4	**55.82**	**2.07**
40	10	4	7	0.8	4	**53.19**	**1.85**
41	10	4	7	0.75	3	**50.49**	**1.87**
42	10	4	7	0.75	5	**47.66**	**1.81**
43	10	4	7	0.75	4	**60.20**	**1.95**
44	10	4	7	0.75	4	**50.13**	**1.84**
45	10	4	7	0.75	4	**57.35**	**2.05**
46	10	4	7	0.75	4	**52.03**	**1.85**
47	10	4	7	0.75	4	**49.89**	**2.04**
48	10	4	7	0.75	4	**55.05**	**1.94**
49	10	4	7	0.75	4	**45.26**	**1.81**
50	10	4	7	0.75	4	**47.19**	**1.84**

3.1 ANOVA for MRR

The fit summary recommended that the quadratic model is statistically significant for analysis of MRR. From the ANOVA result the associated p-value for the model is lower than 0.05 indicates that the model is considered to be statistically significant [30]. The peak current (I_p), powder concentration (PC), gap and duty cycle are significant parameters for MRR. Additionally, the model contains some significant two-way interaction of (I_p× PC), (I_p× sensitivity), (PC × duty cycle), (gap × duty cycle), (duty cycle × sensitivity) and second order terms of factor peak current and gap. The "Lack of Fit F-value" of 0.88 implies that the Lack of Fit is not significant relative to the pure error. There is a 63.07% chance that a "Lack of Fit F-value" this large could occur due to noise. The "Predicted R^2" of 0.8337 is in reasonable agreement with the "Adjusted R^2" of 0.8860."Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable; here the ratio of 23.942 indicates an adequate signal.

The sensitivity and interaction of peak current with duty cycle does not have a significant effect. To fit the quadratic model for MRR appropriate, the non-significant terms are eliminated from backward elimination process.

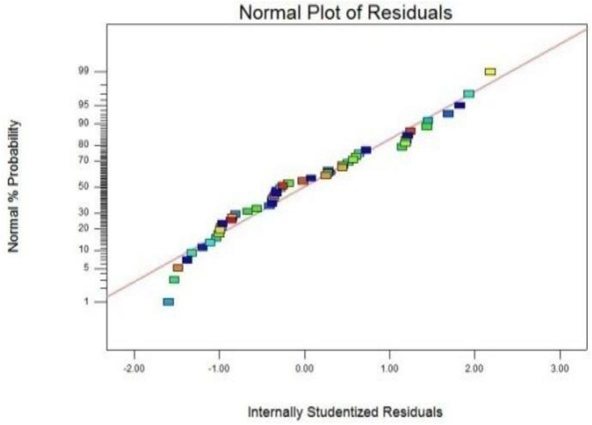

Fig.3. Normal probability plot of residuals for MRR

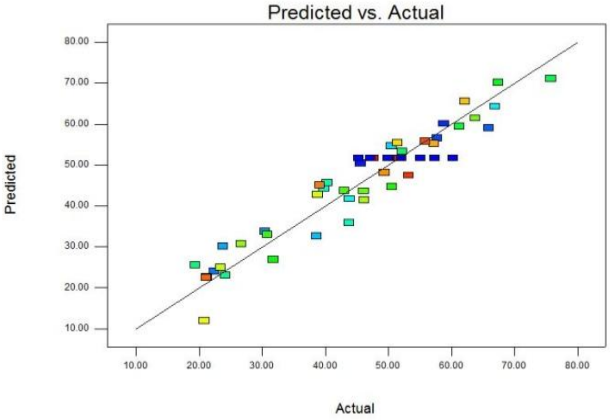

Fig.4. Plot of predicted value to actual MRR

The reduced model results indicate that the model is significant (R^2 and adjusted R^2 are 91.21% and 88.67%, respectively), lack of fit is non-significant (p-value is less than 0.05). Fig. 4 displays the normal probability plot of the residuals for MRR. Notice that the residuals are falling in a straight line, which means that the errors are normally distributed. Further, each observed value is compared with the predicted value calculated from the model in Fig. 5. It can be seen that the regression model fairly well fits with the observed values.

After eliminating the non-significant terms, the final regression coefficients of the second order equation for MRR are given as: (In coded terms)

$$\mathbf{MRR\ (mm^3/min)} = 51.67 + (5.09*A) - (3.49*B) - (11.27*C) - (4.21*D) - (1.78*A*B) + (2.04*A*E) - (4.77*B*D) + (1.92*C*D) - (3.47*D*E) + (8.80*(A^2) - (17.85*C^2) \pm \varepsilon$$

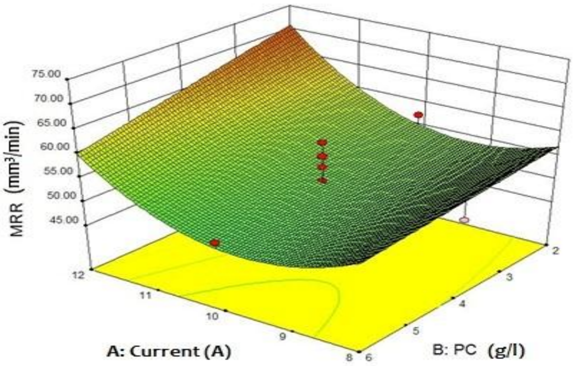

Fig.6. Contour plot of MRR with effect of current and powder concentration

Fig. 6 shows the estimated response surface for MRR in relation to the design parameters of peak current and PC. The powder added into the dielectric fluid enhances the MRR at minimum concentration with peak current (12 A).This is because the added additive causes bridging effect between both the electrodes, facilitates the dispersion of discharge into several increments and hence increases the MRR [24]. Further increase in concentration of the powder, the MRR tends to decrease. Because higher PC in the dielectric fluid results in inter-electrode gap contamination due to the debris and disturbs the discharging between the tool electrode and the work material, eventually leading to abnormal discharges and frequent sorting of the two electrodes, and subsequently low MRR [21].

Fig. 7 shows the effect of sensitivity and peak current on MRR. As can see from Fig. 4 at higher current MRR is an increase with maximum level of sensitivity. This is due to dominant control over the input energy. If the current is increased, more powerful spark with higher energy is produced. Due to this a lot of heat is generated and a substantial amount of heat is used to melt and vaporize the work material. This leads to increase in MRR [33].Sensitivity leads to the feed rate of tool toward the workpiece. The higher feed rate provides better MRR at dominated control of dielectric flushing.

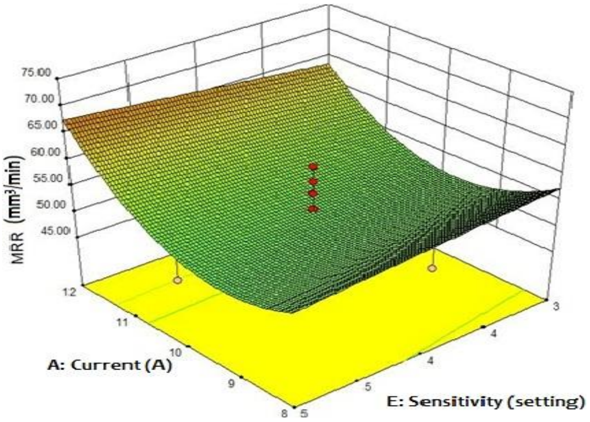

Fig.7. Contour plot of MRR with effect of current and sensitivity

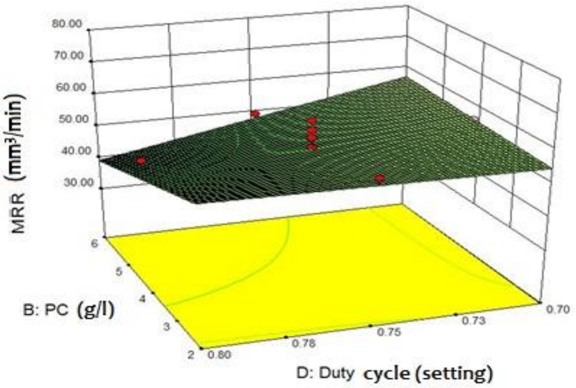

Fig.8 Contour plot of MRR with effect of duty and powder concentration

The effect of powder in EDM fluid can be seen in Fig. 8. Usually increment in duty cycle increases MRR, but in case of PMEDM it reverses. This is because, at higher duty cycle there is a possibility of accumulation of more debris within sparking area leading to unfavorable flushing conditions, thereby reducing MRR [32]. Another observation of Fig.8 is the higher concentration of powder is feasible at lower setting of duty cycle to increase MRR. This observation suggests that the addition of an appropriate amount of additives into the dielectric fluid of EDM causes greater erosion of the material with proper flushing condition [32].

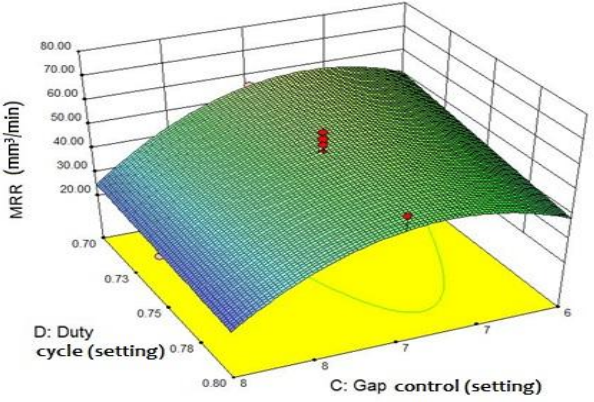

Fig.9. Contour plot of MRR with effect of gap and duty

Fig. 9 shows the contour plot to estimate the effect of duty cycle with the interaction of gap control. It can be seen in Fig. 9, mid-level of gap control with minimum setting of duty cycle provides optimum MRR [33]. The reason behind that, increase in gap voltage increases the energy per spark and higher retract distance leads to better flushing conditions [32]. This results in increase in MRR. But at higher values of gap voltage, inadequate cooling of work material is due to unfavorable concentrated discharging. It results in lowering of MRR [33].Minimum setting of duty cycle is feasible. The reason is same as stated earlier [32].

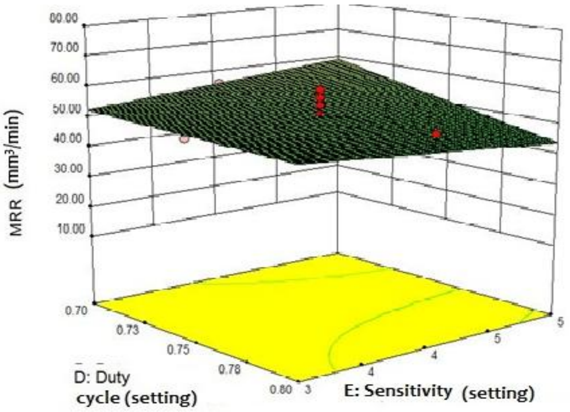

Fig.10. Contour plot of MRR with effect of duty cycle and sensitivity

The effect of duty cycle and sensitivity is shown in Fig. 10. It is evident from the Fig. 10 that the value of MRR increases with increase in sensitivity with the least level of duty cycle. In this way, in order to obtain a good MRR, low values of duty cycle and high level of sensitivity should be used. On the other side, the higher MRR can be also obtained at high values of duty cycle with low level of sensitivity. The lower value of sensitivity provides better removal of contamination at higher values of duty cycle.

3.2 ANOVA for SR

The SR fit summary recommended that the quadratic model is statistically significant for analysis of SR. The ANOVA result is shows that the I_p, PC, gap and duty cycle are significant parameters affecting SR. The interaction effect between Ip with gap, PC with duty cycle, PC with sensitivity and second order terms of factor PC, gap and duty cycle has a significant effect on SR.

The "Lack of Fit F-value" of 0.85implies the Lack of Fit is not significant relative to the pure error. There is a 65.77% chance that a "Lack of Fit F-value" this large could occur due to noise. The “Predicted R^2” of 0.8806 is in reasonable agreement with the "Adjusted R^2" of 0.9115."Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable; here ratio of 26.388 indicates an adequate signal. The associated p-value for the model is lower than 0.05 indicates that the model is considered to be statistically significant [30].

The sensitivity comes out to be insignificant factor. To fit the quadratic model for SR appropriate, the non-significant terms are eliminated by a backward elimination process.

The "Lack of Fit F-value" of 0.82 implies the Lack of Fit is not significant relative to the pure error. There is a 67.53% chance that a "Lack of Fit F-value" this large could occur due to noise. The "Predicted R^2" of 0.8872 is in reasonable agreement with the "Adjutant R^2" of 0.9134. "Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. This ratio of 28.10 indicates an adequate signal.

Fig. 11 displays the normal probability plot of the residuals for SR. Notice that the residuals are falling in a straight line, which means that the errors are normally distributed. Further, each observed value is compared with the predicted value calculated from the model in Fig.12. It can be seen that the regression model fairly well fits with the experimental observed values.

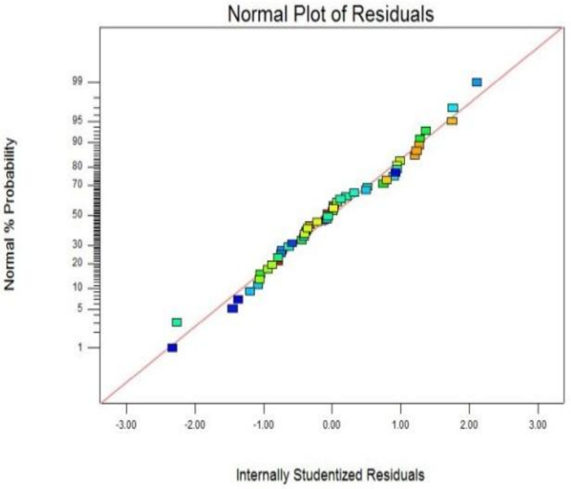

Fig.11. Normal probability plot of residuals for SR

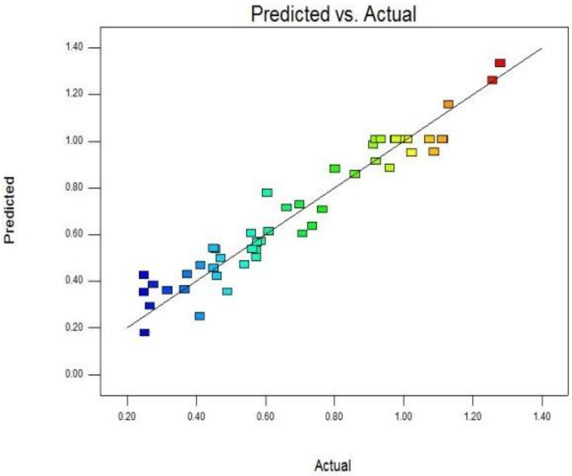

Fig.32. Plot of predicted value to actual SR

After eliminating the non-significant terms, the final regression coefficients of the second order equation for SR are given as: (In coded terms)

SR (μm) $=2.22 + (0.18*A) – (0.046*B) – (0.14*C) – (0.057*D)– (0.071*A*C) – (0.060*B*D) – (0.042*B*E) + (0.35*B^2) – (0.47*C^2) – (0.41*D^2)) \pm Ɛ$

The Fig.13 shows that the interaction effect of current and gap control on response SR. As it can be seen from Fig. 22, surface finish is improving at the higher gap with a minimum level of current. This is the effect low input energy [24] and proper removal of debris. Higher retract distance (inter electrode gap) leads to better flushing conditions [32].

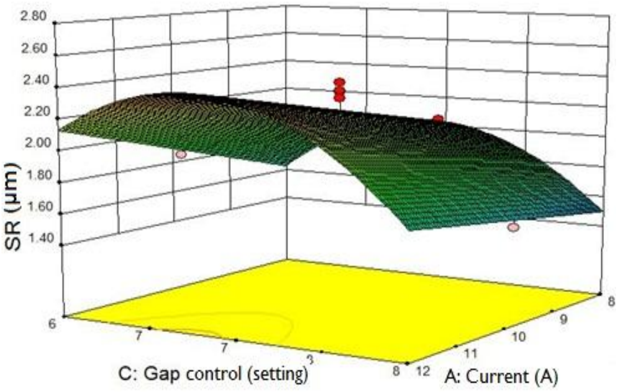

Fig.13. Contour plot of SR with effect of current and gap control

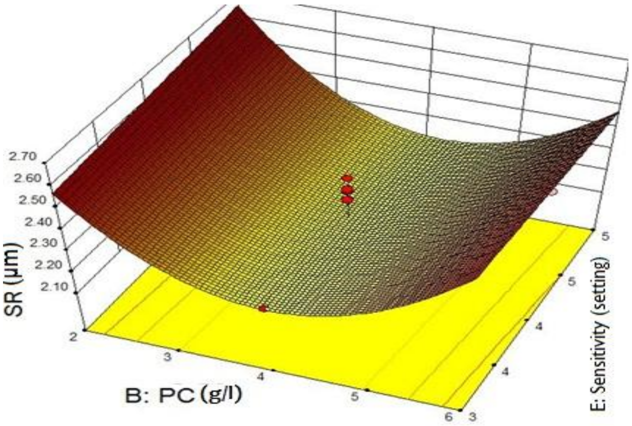

Fig.14. Contour plot of SR with effect of powder concentration and sensitivity

It is clear from Fig. 14 that the effect of PC is same with all sensitivity settings. The sensitivity provides a negligible effect on SR. It was also observed that the mid-level gives a better surface finish at a minimum level of sensitivity. This proves that the added additive plays a significant role to modify the plasma channel. The plasma channel becomes enlarged and widened [5]. The electric density decreases, hence sparking is uniformly distributed among the powder particles. As a result, even and uniform surfaces are produced. But further increment in PC results high contamination of powder and debris at inter-electrode gap due to the discharging disturbs between the tool electrode and the work material, eventually leading to abnormal discharges and frequent sorting of the two electrodes, and poor surface finish [21].

Fig. 15 shows the estimated response surface for SR in relation to the design parameters of duty cycle and PC. It is evident from Fig. 15 that the SR is low at PC of 4g/l with lower and higher setting of duty cycle. This effect of duty cycles comes because the powder in dielectric fluid of EDM plays an important role. In higher duty cycle there is a possibility of accumulation of more debris within sparking area leading to unfavorable flushing conditions, this cause insufficient discharging thereby the SR is reduced [32]. At the lowest level of duty cycle low input heat energy is available and results in lower SR. This is due to their dominant control over the input energy [24].

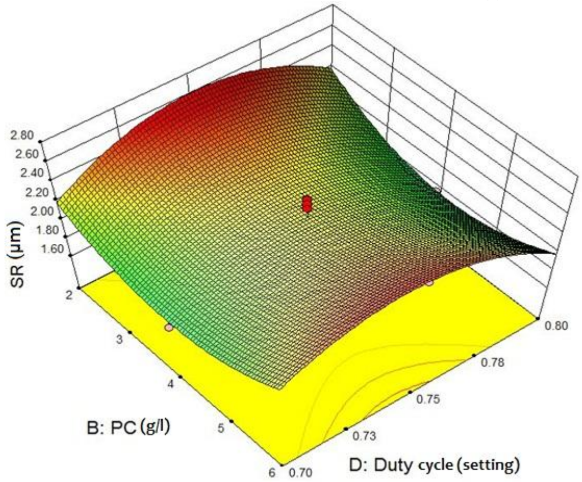

Fig.15. Contour plot of SR with effect of powder concentration and duty cycle

IV. CONCLUSION

This study presents an investigation of the process parameters in the PMEDM of Al/SiC. Graphite is used as a powder and mixed with dielectric fluid of EDM. Empirical modeling with the help of response surface methodology has led to the following conclusions about the variation of response parameters in terms of controllable parameters within the specified range. Finally high numbers of interaction effects of process parameters over response characteristics of PMEDM was obtained and the nature of PMEDM process has been revealed.

The graphite powder suspended in the dielectric fluid of EDM affects all the process responses of PMEDM. The slope of the curve indicates that the MRR decreases with the increase in the concentration. But SR are obtained good at concentration of graphite powder at 4g/l.

The PMEDM process provides better MRR at higher values of peak current, lower concentration of powder, mid value of gap control and lower value of duty cycle. Also in the interaction effect plot of factors the optimum MRR is obtained at higher values of peak current with a lower concentration of powder and higher setting of sensitivity. Duty cycle has a significant effect with PC, sensitivity and gap control. The lower value of duty cycle with a mid-level of gap setting, higher PC and higher sensitivity provides maximum MRR.

To achieve good surface finish on Al-SiC MMC by PMEDM, the results concluded the optimum setting of process parameters. Improvement in SR can be obtained at the lowest setting of peak current, mid-level of PC, higher level of gap control and higher setting of duty cycle. In interaction effects of process parameters the SR is optimum at minimum supply of peak current with the maximum gap setting. PC at suitable mid-level affects the TWR with lower setting of sensitivity and higher level of duty cycle.

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