Studies on the Material Removal Rate of Al-SiC Composites Machined by Powder-Mixed EDM Technique

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Abstract— **The metal-matrix composites are preferred due to their high hardness, light weight, flexibility, high strength, simplicity and ease of applicability which make them potentially valuable in every industrious area like motor vehicles industries, mechanical tools manufacturing industries, structural applications and aerospace industries. Electro-discharge machining is a non-conventional machining process which uses short electrical discharges to machine any material of any hardness and strength levels provided that they are electrically conductive.**

In this paper, an attempt was made to find the machinability of aluminium metal matrix composite using powder mixed electric discharge machining (PMEDM). The aluminium matrix was reinforced with different percentages of silicon carbide (3%, 9% & 15%) to form the composites using stir casting process. The Characteristic Material removal rate (MRR) was studied while varying the process parameters of discharge time (T_{ON}), peak current (I) and concentration of SiC in work material (C) according to the face cantered central composite design for a constant voltage of 40 volts. The Electric Discharge Machining of the composites was carried out using a copper electrode of Ø6mm and kerosene mixed with aluminium powder was used as dielectric fluid.

Keyword- Powder mixed EDM; Material removal rate; Al powder; Al-6061/SiC composite.

I. Introduction

The metal-matrix composites (MMCs) are preferred due to their high hardness, light weight, flexibility, high strength, simplicity and ease of applicability which make them potentially valuable in every industrious area like motor vehicles industries, mechanical tools manufacturing industries, structural applications and aerospace industries [1]. MMCs are fabricated by reinforcement of a metal with a high strength material like aluminium oxide, zirconium oxide, silicon carbide, etc.

The high strength properties of these composites which make them desirable for several applications also make them difficult to be machined by the conventional machining processes. These high strength composites can be machined by using higher strength tools such as carbide tools and poly crystalline diamond (PCD) cutting tools. In view of high tooling costs and high tool wear rates, machining of the MMCs by conventional means becomes uneconomical. Hence, non-conventional machining processes have to be adopted to economically machine these materials. Among the many non-conventional techniques available, Powder mixed Electric Discharge machining (PMEDM) has been found to be effective for processing of metal matrix composites [2,3].

Zhao et al. studied the machining efficiency and the surface roughness characteristics during rough machining of EDM & PMEDM and compared the results. The PMEDM experiments were carried out using red copper electrode and aluminium powder mixed in EDM special working fluid from Mobil while machining steel workpiece. The results show that at reduced pulse width and high peak currents, the machining efficiency is observed to increase from 2.06 mm3/min to 3.40 mm3/min (70% increase) in PMEDM in comparison to conventional EDM machining. The surface finish was also observed to be improved in PMEDM machining [4].

Kansal et al. studied the effect of suspending silicon powder in kerosene dielectric fluid on the machining rate of AISI D2 die steel. The process parameters of peak current, nozzle flushing, pulse-on time, pulse-off time, gain (advancing rate of tool towards work specimen) and concentration of Si powder in kerosene were varied to study their effects on the machining rate. The optimization was carried out to maximize machining rate using Taguchi method. The ANOVA analysis shows that the Si powder concentration in kerosene and peak current are the most significant parameters in maximizing machining rate [5].

Han Ming Chow et al. studied the effects of using SiC powder in pure water as dielectric fluid on the micro slit EDM machining of Ti–6A1–4V alloy plate. It was observed that with increasing concentration of SiC powder in water dielectric fluid increased the electrical conductivity of the fluid while simultaneously increasing the material removal rate of titanium alloy work piece and decreasing the tool wear rate of Cu electrode [6].

Kuldeep ojha et al. used the surface response methodology to study the performance of PMEDM in terms of material removal rate (MRR) and tool wear rate (TWR). The process parameters chosen were duty cycle, average current, angle of electrode and chromium powder concentration in kerosene dielectric fluid. The work piece material was EN-8 steel while Cu electrode was used as a tool. He concluded from the ANOVA results that with the increasing concentration of Cr powder in kerosene dielectric fluid from 2g/l to 6g/l , MRR increased [7].

Muniu et al. studied the effects of suspending diatomite powder in distilled water dielectric fluid. He studied the performance of PMEDM in terms of TWR and MRR while the process parameters were peak current and pulse on time. It was concluded from the results that with the addition of diatomite powder in distilled water dielectric fluid increased the MRR of mild steel workpiece while decreasing the TWR of graphite electrode [8].

Xue Bai et al., studied the differences in the machining efficiency of powder mixed near dry electric discharge machining (PMND-EDM) process for the various combinations of work piece and tool electrodes. Single factor experiments were performed to get the effects of peak current, pulse off time, pulse on time, air pressure, tool rotation and powder concentration on the MRR for the various combinations of work piece and tool electrodes. It was concluded that the workpiece and tool combinations of W18Cr4V and brass tool gave highest MRR in most discharge conditions, while the superiority of 45 carbon steel workpiece and copper tool in MRR aroused when there was improper heat dissipation [9].

Nimo Singh Khundrakpam et al., studied the effect of mixing Zinc Powder in kerosene dielectric fluid in EDM machining of EN-8 steel. The effects of process parameters such as peak current, pulse off time, powder concentration, flushing pressure and tool electrode diameter on MRR had been investigated based on Taguchi's L-27 orthogonal array designs. It was concluded that the peak current and the powder concentration were significant parameters for maximizing MRR [10].

Satpal Singh and Kalra studied the effects of mixing tungsten powder in the dielectric fluid during the EDM machining of EN 24 steel alloy. The effects of process parameters such as peak current, duty cycle, pulse on time and tungsten powder concentration on MRR and TWR were investigated based on Taguchi's L-9 orthogonal array design for the maximum machining efficiency. It was concluded that the increasing concentration of Cr powder in dielectric fluid from 0 g/l to 4 g/l increased the mean of means of MRR 90.78% [11].

Mahammadumar and Kavade studied the effects of mixing Aluminium powder in dielectric fluid (IPOL oil) during EDM machining of AISI D3 die steel. The influence of the process parameters such as pulse on time, peak current and aluminium powder concentrations on the machining characteristics of AISI D3 die steel while using copper tool. The machining characteristics were evaluated in terms of TWR, MRR and surface roughness (SR). It was observed from the experiments that the maximum MRR and the least TWR & SR were observed at highest concentration of Al powder concentration in dielectric fluid (6 g/l) [12].

Khalid et. al., studied the effect aluminium powder concentration in kerosene dielectric fluid has on the surface roughness of the Al-SiC metal matrix composite. Peak current and the concentration of aluminium powder in the dielectric fluid were considered as the process parameters and copper tool was used for machining. It was observed from the experimental results that the increasing concentration of Al powder improved the surface roughness and the least surface roughness values were obtained at lowest peak current value of 2A [13].

Literature survey reveals that several researches carried out pertaining to the PMEDM field has concentrated on the effects of changing concentration of the suspended particles in the dielectric fluid during EDM machining. But, not much work pertaining to the process optimization for a fixed quantity of suspended particles in PMEDM process has been carried out which is very much essential to make the process commercially useful.

II. INVESTIGATION OF POWDER MIXED DI-ELECTRIC FLUID EDM (PMEDM)

PMEDM is one of the recent experimentation for improvement of capabilities of EDM process. Powder mixed EDM is also called as "additive EDM". In PMEDM the electrically conducting powders such Al ,Cu, and chromiums are added to dielectric fluid to increase the conductive strength and enhancing the spark gap between the tool and work piece [14]. In our present work we added Al powder (mesh size – 27 microns) to the kerosene for the experimentation resulting in good surface finish and improved machinability.

In PMEDM the direct involvement of thermal interaction takes place for the MRR, while mechanical interaction only assists in improving the mechanical capabilities [16].The PMEDM greatly reduces thermal stress and tendency for the crack formation .Examining the work piece surface of PMEDM consists more surface finish with less cracks which can be used directly without requirement of polishing and grinding[15,18].

MECHANISM OF PMEDM:

In PMEDM the aberration of electric field takes place in spark gap due to the powder mixed dielectric fluid, resulting the increase in spark gap. According to "W.S Zhao" [16] due to applied gap voltage the formation of + ve and – ve charges respectively at the top and bottom of the abrasive powders causes the Bridging effect bellow the spark area creating a multiple discharging effects within a single input pulse. This can be explained by Figure 1 [16, 18].

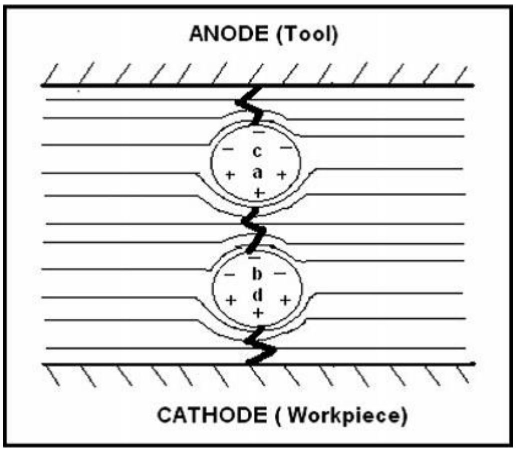

Fig.1. Schematic representation of series of discharge in PMEDM [16,18].

Between the points a and b two adjacent powder particles, where the electrical density is higher , break down occurs the field density goes beyond than dielectric break down resistance. The electric discharge causes the short circuit between the two powder particles and redistribution of electric charges. The redistribution of electric charges than increases at points c and d creates a discharge between these two powder particles and consequently leading to series of discharge.[16,17].

Because of bridging effect the powder particles cause inter locking between the different powder particles and formation of powder particles chain occurs under the sparking area [18]. This phenomenon enhances the sparking intensity within a discharge, leading to faster erosion from the surface of work metal and consequently metal removal increases. Thus the electric discharge can be easily occurred in PMEDM with larger spark gap than the conventional EDM.

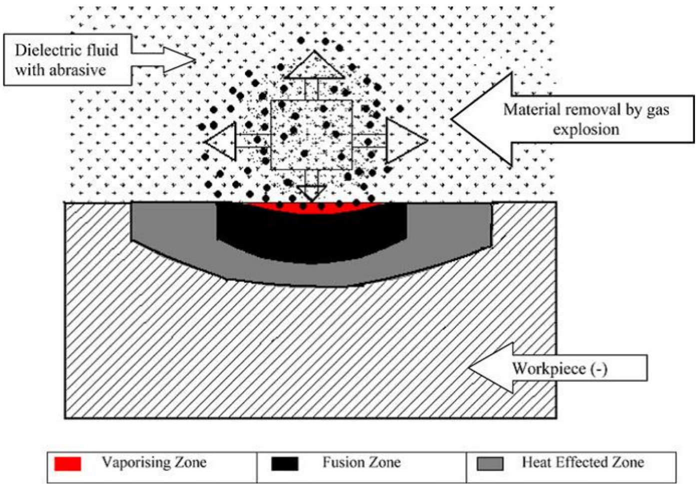

Fig. 2. Material removal by gas explosion during PMEDM [16, 17]

From the Figure 2, the powder suspended dielectric fluid removes the metal due to combined effect of mechanical thrust driven by the gas explosion caused mainly from the working fluid evaporation and striking impact of suspended particles [19]. This makes easier to the removal of debris and other semi conductive grains from the spark gap while machining composites, thus increase in speed of discharge process.

III. EXPERIMENTAL SETUP

A Die sinking EDM machine is used to perform the experiments. This machine has tank dimensions 800mm X 500mm X 350mm. So, it needs large amount of aluminium powder, for mixing with dielectric fluid to get desired concentration in powdered dielectric fluid. Besides, filter of machine may get an impediment due to presence of aluminium powder in dielectric fluid and debris particles, due to machining, when using existing circulation system of machine. A new tank having capacity of 6.5 litres has been used for experiment and also a separate work holding device (as shown in Figure 3(a)) is used to hold the work piece in proper position, to overcome the difficulties occurring with the original machine. For proper circulation and mixing, of dielectric (kerosene) and powder (aluminium) into the discharge gap between the tool electrode and work piece material, a small pump is installed in the machine tank. The experiment setup is shown in the Figure 3(b).

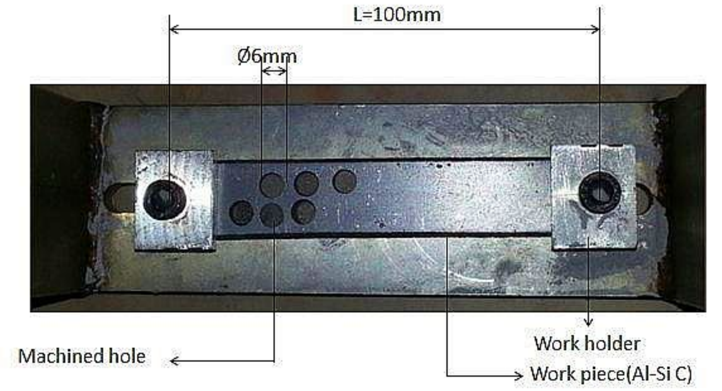

Fig. 3(a). Clamped work piece showing dimensions

Aluminium reinforced with three different percentages of silicon–carbide (3%, 9% and 15%) is used as work piece material, and these work pieces are prepared by using stir casting method. Copper electrode of 6mm diameter is used as tool electrode. Aluminium powder with mesh size of 27 microns mixed (2 grams per litre) with kerosene is used as dielectric fluid for flushing. A random experiment is carried to fix the values and to find out the range of process parameters used to conducting the main experiments. The process parameters used in EDM machining are shown in table 1.

After fixing the process parameters, experiments are designated on the basis of “Face centered central composite design”. This FCCCD comprises three level factorial points and the star points are at the center of each face.

Fig. 3(b). Photograph of experimental setup

TABLE I. EDM process parameters

Work piece	Al-SiC
Electrode	Cu
Polarity	Negative
Machining time(min)	10
Dielectric fluid	Kerosene+ aluminium powder
Powder particle size	27 microns
Concentration of SiC	3%, 9% and 15%
Pulse on time T_{ON}(μs)	120, 220 and 320
Duty cycle	75%

IV. REGRESSION ANALYSIS

Regression model for MRR is developed in this section. The results for REGRESSION analysis and ANOVA are given in the table 3. In these tables I ,T_{ON} and C are indicates variables, I×I , $T_{ON} \times T_{ON}$, C×C are the higher order terms and I×T_{ON}, T_{ON}×C, C×I represents the interaction terms.

TABLE 2. Experimental plan and output responses

S.No	I(A)	T_{ON}(μs)	%C(wt)	MRR(mg/min)
1	2	220	9	3.82
2	4	220	9	23.51
3	4	220	9	23.51
4	6	320	3	66.89
5	2	320	3	2.51
6	4	320	9	17.19
7	4	220	9	23.51
8	6	120	15	93.34
9	6	320	15	67.05
10	4	220	9	23.51
11	4	120	9	30.95
12	6	120	3	73.22
13	4	220	3	21.61
14	4	220	9	23.51
15	6	220	9	77.99
16	2	120	15	3.96
17	4	220	15	20.67
18	2	120	3	4.27
19	2	320	15	1.42
20	4	220	9	23.51

MATERIAL REMOVAL RATE:

The value for the MRR in uncoded units can be obtained by the following equation considering all the parameters.

MRR (mg/min) = $10.3747 - 14.7939\, I + 0.0346T_{ON} + 1.5335\, C + 43476\, I\times I+0.0001\, T_{ON}\times T_{ON}-0.0660\, C\times C - 0.0177\, I\times T_{ON} + 0.2258\, I\times C - 0.0043\, T_{ON}\times C$.

The ANOVA analysis indicates that I, I×T_{ON}, I×C, T_{ON}×C are most significant terms since their P values are less than 0.05.Neglecting the insignificant terms from the above equation ,the approximate values for the MRR can be calculated by using the following equation.

MRR (mg/min) = $10.3747 - 14.7939I – 0.0177I\times T_{ON} +0.2258I\times C - 0.0043T_{ON}\times C$.

TABLE 3. ANOVA FOR MRR

Source	DF	SEQ SS	ADJ SS	ADJ MS	F	P
Regression	9	14987.3	14987.31	1665.256	242.23	0.000
Residual Error	10	68.7	68.75	6.875		
Total	19	15056.1				

V. RESULTS AND DISCUSSION

Effects of Process Parameters on MRR:

The effects of the process parameters (i.e., peak current, pulse on time and concentration of SiC in Al matrix) on the characteristic material removal rate (MRR) have been elaborated in the following section. Graphs have been plotted showing the change in MRR for variations in any two process parameters while holding the third process parameter as constant at its central value.

A. Effects of Peak Current on MRR:

The plot for changes in MRR for variations in peak current for different pulse-on times at 9%wt. SiC concentration in Al matrix is shown in figure 4. It can be noted from the plot that for any given value of pulse on time, the material removal rate (MRR) increases with increase in peak current. Therefore, for any given pulse on time the maximum MRR was observed at high peak current value (6 A), which is due to the dominant control of peak current over the energy input. As the MRR directly depends on the energy per pulse, an increase in the energy per pulse resulting from the increase in peak current causes the MRR to increase. Similar trend was observed by Kathiresan et al., who had also concluded that with increase in peak current, the MRR increased [20].

In EDM primarily metal is removed in the form of liquid or vapour. From the graph it can also be noted that for the higher values of T_{ON}, the MRR is lower. This may be due to the fact that for the same amount of peak current an increase in the duration of the pulse-on time, causes the expansion of the plasma channel resulting in the distribution of the energy and therefore the energy density on the work piece reduces. This reduction in the energy density results in lower MRR at higher values of pulse-on time (T_{ON}). Therefore for the same peak current value, the highest MRR is observed at the lowest T_{ON} of 120µs and the lowest MRR is observed at the highest T_{ON} of 320µs.

B. Effects of Pulse-on time on MRR:

The plot for changes in MRR for variations in pulse-on time at different concentrations of SiC in Al matrix while, maintaining the peak current at a constant value of 4A is shown in figure 5. It can be observed from the plot that with an increase in T_{ON}, the MRR decreases. This is due to the fact that the increase in pulse on time causes an increase in the thickness of the plasma channel and this results in the reduction of intensity of spark and this causes the MRR to decrease. Hence, for any given percentage weight concentration of SiC in Al, the maximum material removal was observed for the minimum pulse on time (120µs). A similar trend was observed by Jilani et al. & Pandey et al., who also observed the higher material removal rates (MRR) for lower values of pulse-on time (T_{ON}) [21].

It can also be noted from the graph that the decrease in the MRR of 15%wt SiC concentration in Al is significantly higher in comparison to 3%wt & 9%wt concentration of SiC in Al. This may be due to the fact that the SiC is a hard to machine substance and at 15%wt SiC concentration in Al, the reduced intensity of spark due to the longer T_{ON} is not sufficient to machine the hard SiC particles. As a result, the rate of reduction of MRR for 15%wt SiC concentration in Al is higher than that of the 3%wt & 9%wt SiC concentration in Al.

C. Effects of percentage concentration of SiC in Al matrix on MRR:

The plot for changes in MRR for variations in pulse-on time at different concentrations of SiC in Al matrix while, maintaining the peak current at a constant value of 4A is shown in figure 6. It can be observed from the graph that with an increase in the percentage concentration of SiC in Al, the MRR initially increases (upto 9%) and then decreases (upto15%). This trend was observed for lower current values (upto 4A) but not in higher currents (6A). This is because, at lower concentrations of SiC (3%wt & 9%wt), the SiC particles present in the composites were not sufficient to cause any significant effect on MRR but, as the concentration of SiC particles increases beyond 9%wt, the concentration of the particles becomes high enough to affect the MRR. The intensity of spark also plays an significant role in MRR, at lower peak currents the intensity of spark produced was not sufficient to melt and vaporize the higher concentrations of SiC (15%) present in the work material. But, as the peak current was increased (6A) the intensity of the spark produced was sufficient to melt and vaporize the higher concentrations of SiC and as a result significant decrease in MRR was not observed.

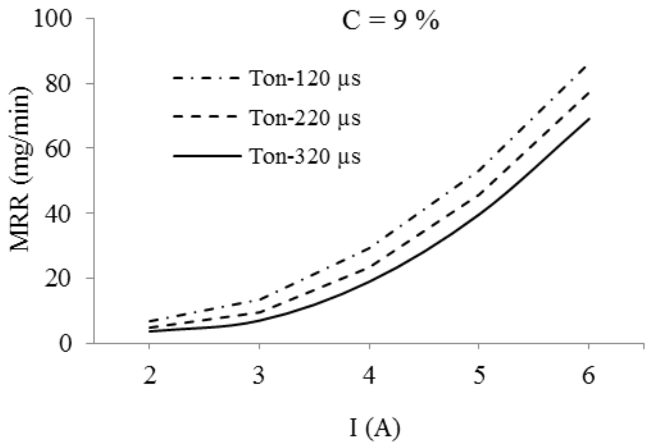

Fig. 4. I and T_{ON} vs. MRR

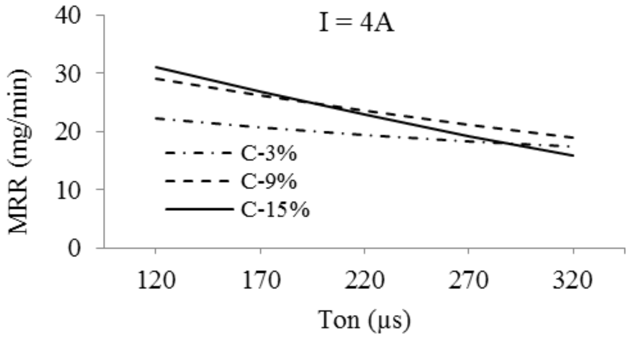

Fig. 5. T_{ON} and C vs. MRR

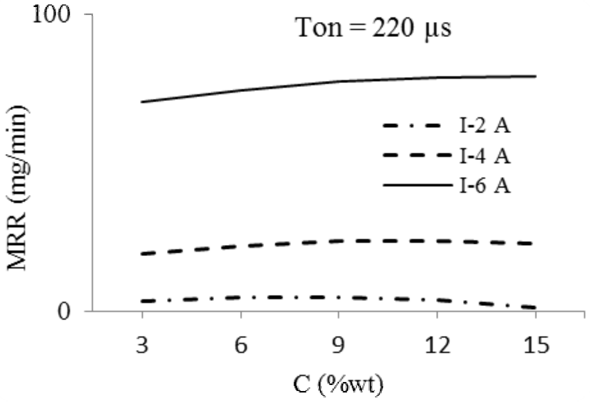

Fig. 6. C and I vs. MRR

VI. Conclusion

Considering the experimental results, following conclusions are obtained,

1. The increase in peak current causes an increase in the MRR irrespective of the choice of pulse-on time (T_{ON}).
2. For any fixed value of peak current, the MRR decreases with an increase in the pulse on time irrespective of the concentration of silicon carbide in aluminium.
3. For constant T_{ON} and peak current the MRR increases with increasing the composition of silicon carbide in aluminium.
4. For constant T_{ON} and peak current the MRR increases with increasing the composition of silicon carbide in aluminium.

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