Electro Discharge Machining Characteristics of Mg/SiC$_P$ Metal matrix composites by Powder Metallurgy (P/M) Techniques

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***Abstract*— The objective of this work is to investigate the effects of current, pulse on time and pulse off time in Electro Discharge Machining performance on material removal rate and tool wear rate of Mg/SiC$_p$ metal matrix composites. In this work the Mg/SiC$_p$ metal matrix composite specimens were prepared by powder metallurgy route. ELEKTRA PLUS spark erosion machine was used for the purpose. Brass tool of 10 mm diameter was chosen to drill the specimens. Experiments were conducted by varying the parameters of current (I), pulse on time (ton) and pulse off time (toff). A mathematical model is developed to correlate the influences of these variables with material removal rate of workpiece and tool wear rate. Design of experiments (DOE) method and response surface methodology (RSM) techniques are implemented. An L21 orthogonal array (OA), for the three machining parameters at three levels each, was opted to conduct the experiments. The experiments were performed in a random order with three successive trials. The validity test of the fit and adequacy of the proposed models has been carried out through analysis of variance (ANOVA).**

Keyword- EDM, Mg/SiC$_p$ composites, MRR, TWR

I. INTRODUCTION

Magnesium and its alloys are of interest because of their low density, 1.74 g/cm3, and high specific strength as compared to other structural metals. These properties are more important in automotive and aerospace applications in order to reduce fuel consumption and to reduce green house emission [1]. Magnesium and its alloys also possess several other benefits including high tensile strength, high damping capacity, machinability, a low production energy requirement in comparison with aluminum [2]. The main limitations of magnesium and its alloys are their low ductility and rapid loss of strength at high temperatures which limits their use in conventional and critical engineering applications as a structural material. Enhancement in mechanical properties of magnesium could be obtained by incorporation of temperature-stable reinforcements in the magnesium matrix. [3-5]. Silicon carbide (Sic) is particularly attractive as a reinforcing phase due to high hardness which improves the room and elevated temperature mechanical properties as well as wear and corrosion resistance [6]. There have been several methods to produce the metal matrix composites; powder metallurgy, stir casting, disintegrated metal deposition (DMD), melt infiltration, etc. Among the various metalworking technologies, powder metallurgy (P/M) is the most diverse manufacturing approach. One attraction of P/M is the ability to fabricate high quality, complex parts to close tolerances in an economical manner. In essence, P/M takes a metal powder with specific attributes of size, shape, and packing, and then converts it into a strong, precise, high performance shape and less prone to porosity and defects.

Accompanying the development of mechanical industry, the demands for Parts with extreme surface finish and tolerance requirements, Delicate components that cannot withstand large cutting forces , Parts without producing burrs or inducing residual stresses, Brittle materials or materials with very high hardness, toughness and impact resistance are increasing. Nevertheless, such materials are difficult to be machined by traditional machining methods. Hence, non-traditional machining methods including electrochemical machining (ECM), ultrasonic machining (UM), electrical discharging machine (EDM) etc, are applied to machine such difficult to machine materials. Since EDM was developed, much theoretical and experimental work has been done to identify optimum process parameters. Even though many research developments have been carried out in EDM process which is classified into four broad categories; work piece related, electrode performance related, EDM methods related and optimization of the EDM process based on performance parameters. A number of studies [7-10] have considered the machinability for different work piece materials. A few studies [11-13] have been devoted to the variation of the EDM process. The evaluation of the performance characteristics and optimization of machining parameters have received maximum research attention [14-16]. This is because proper selection of the machining parameters can yield the best performance with a particular machining setup. It is in general observed that out of the two main performance characteristics, MRR and TWR have traditionally received greater research attention in comparison to surface roughness even though EDM is largely used for its high precision quality. Statistical models have been developed using response surface methodology based on experimental results considering the machining parameters, viz., current (I, amp), pulse-on time (Ton, μs) and pulse-off time (Toff, μs) as independent variables. Finally, an attempt has been made to obtain optimum machining conditions with respect to each of the machining parameters considered in the present study with the help of response optimization technique.

II. EXPERIMENTAL PROCEDURE

2. 1 Material Preparation

Relatively coarse pure magnesium (Mg) powders were used as matrix materials. Average particle sizes of 180μm. Silicon carbide particle were used as reinforcement phase. Particles size ranging from 0.5 to 25μm. The addition of SiC particle improves the wear resistance and brittleness. The weight fraction of Sic particles was 12.0 Wt%. The composites were prepared using powder metallurgy route. The Mg powders and the SiC particulates were mixed by using a rotating ball milling machine under a rotating speed of 300 rpm for 3 hrs. Fabrications of the composites at appropriate sintering temperature of Mg were determined. Ball milled Mg/SiC_p powder was poured into a 30 mm diameter die and then pre-pressed with a pressure of 15MPa. After pressing, the die was put into the (furnace chamber) and then sintered at temperature of 550°C with pressure of 30MPa and holding time of 15 min.

2.2 Tool Selection

Copper tool having 99.9% copper in composition was used as tool electrode since it worked better in combination with the work piece materials considered in the present study. The tool electrode was in the form of cylinder of diameter 10 mm and mounted axially in line with work piece. The tool electrode was given negative polarity. Kerosene was used as dielectric fluid because of its high flash point, good dielectric strength, transparent characteristics and low viscosity and specific gravity.

2.3 Equipment Used

The machine used for machining is an ‘Electra plus’ EDM machine having the stepped drive servo system and filtration flushing capability. It is capable of generating maximum pulse current of 25 ampere, pulse on time of 2000 μs and pulse off time of 2000 μs.

Metal removal rate (MRR) is expressed as the ratio of the difference of weight of the work piece before and after machining to the machining time,

$$MRR = \left[\frac{\text{Wwb}-\text{Wwa}}{\text{t}}\right] \quad \text{(g/min)} \quad (1)$$

Where Wwb and Wwa are the weights of the work piece before and after machining, and t is the machining time. Tool wear rate is expressed as the ratio of the difference of weight of the tool before and after machining to the machining time,

$$TWR = \left[\frac{\text{Wtb}-\text{Wta}}{\text{t}}\right] \quad \text{(g/min)} \quad (2)$$

Where Wtb and Wta are the weights of the tool before and after machining and t is the machining time. MRR and TWR are directly calculated from the experimental data. The weight of the specimen is taken before and after the machining process using a digital weighing machine with an accuracy of 0.0001g. Before weighing, the specimen is cleaned and dried to relieve it from debris and dirt. The difference of weight before and after machining gives the weight loss of the work piece during machining process. This weight is divided with machining time to get the metal removal rate and tool wear rate in g/min.

2.4 Design of Experiment (DOE)

The design of experiments technique is a very powerful tool, which permits us to carry out the modeling and analysis of the influence of process variables on the response variables. The response variable is an unknown function of the process variables, which are known as design factors. There are a large number of factors that can be considered for machining of a particular material in EDM. However, the review of literature shows that the following three machining parameters are the most widespread among the researchers and machinists to control the EDM process: pulse current (I, amp), pulse-on time (ton, μs) and pulse-off time (toff, μs). In the present study these are selected as design factors while other parameters have been assumed to be constant over the experimental domain. The upper and lower limits of a factor are coded as +1 and -1 respectively, the coded value being calculated from the following relationships:

$$xi = \frac{[2x-(xmax+xmin)]}{(xmax-xmin)} \quad (3)$$

Where xi is the required coded value of a variable x. The process variables / design factors with their values on different levels are listed in Table 1. The selection of the values of the variables is limited by the capacity of the machine used in the experimentation as well as the recommended specifications for different workpiece tool material combinations. Table 2 shows the experimental matrix composite design employed in the present study.

***2.5 Machining Parameters and their Corresponding Variation Levels*:**

Three controllable machining parameters were identified namely, current, pulse on time, pulse off time. On the basis of preliminary experiments conducted using one variable at a time approach, the range of the current, pulse on time, pulse off time were selected as 5 to 10A, 200 to 1000 µs, 50 to 200 µs respectively. At current values less than 5 A, it was observed that metal removal rate (MRR) was not significant and for current values more than 10A, the tool wear rate was high less than 5A and more than 10A. The range selected for the pulse on time was commonly used for the EDM of metal matrix composites. The response variables selected for this work are metal removal rate (MRR) and tool wear rate (TWR). Machining time for each experiment was taken as 10 minutes.

TABLE: 1 Control Parameters and their Levels

Machining Parameters	Symbols	Units	Levels		
			-1	0	1
Current	I	A	5	7.5	10
Pulse On Time	t_{on}	µs	200	600	1000
Pulse Off Time	t_{off}	µs	50	125	200

TABLE: 2 Composite Design Matrixes

Std Order	Run order	I	$-t_{on}$	t_{off}
1	15	-1	-1	-1
2	7	1	-1	-1
3	6	-1	1	-1
4	19	1	1	-1
5	8	-1	-1	1
6	11	1	-1	1
7	12	-1	1	1
8	5	1	1	1
9	13	-1	0	0
10	20	1	0	0
11	4	0	-1	0
12	14	0	1	0
13	16	0	0	-1
14	18	0	0	1
15	10	0	0	0
16	9	0	0	0
17	2	0	0	0
18	17	0	0	0
19	1	0	0	0
20	3	0	0	0

III. RESULT AND DISCUSSION

3.1 Effect of Process Parameters in MRR & TWR

TABLE: 3 Observed MRR and TWR

Std Order	Run Order	MRR(g/min)	TWR(g/min)
1	15	0.1112	0.0008
2	7	0.0852	0.0008
3	6	0.1302	0.0012
4	19	0.1112	0.0008
5	8	0.1516	0.0013
6	11	0.1001	0.0012
7	12	0.1238	0.001
8	5	0.0643	0.0008
9	13	0.111	0.001
10	20	0.1112	0.0008
11	4	0.1432	0.0012
12	14	0.1179	0.0009
13	16	0.1112	0.0008
14	18	0.1112	0.0008
15	10	0.1368	0.0011
16	9	0.0683	0.0006
17	2	0.1267	0.0014
18	17	0.1112	0.0008
19	1	0.0609	0.001
20	3	0.0808	0.0007

The influence of current, pulse on time and pulse off time on the material removal rate were investigated. The material removal rate reaches its maximum of 0.1504 g/min at the highest current level of 10 Amps with pulse on time and pulse off time of 1000 µs & 200 µs respectively. Similarly the minimum MRR of 0.05631 g/min attained at 5 Amps with pulse on time and pulse off time of 200 µs and 50 µs respectively.

Significance changes in the tool wear rate is noted at the highest current rate of 10A with pulse on time and pulse off time of 200 µs and 50 µs is 0.001489g/min is the maximum and the minimum is 0.000569g/min at the current rate of 5A with pulse on time 600 µs and pulse off time 125 µs respectively.

The influences of the electrical discharge machining parameters (current, pulse on- time and pulse off time) on the response variables selected have been assessed for silicon carbide. The second order model was postulated in obtaining the relationship between the metal removal rate, tool wear rate parameters and the machining variables. The analysis of variance (ANOVA) was used to check the adequacy of the second order model. The second order response surface equations have been fitted using the equations can be given in terms of the coded values of the independent variables as the following:

$$MRR=0.11+0.033I+0.010ton+0.0026toff-0.00036I.ton+0.00051I.toff+0.00074ton.toff+0.0091I^2+0.00032\,ton^2+0.0028toff^2$$

$$TWR=0.00084+0.00023I-0.00006ton-0.00003toff+0.000025I.ton+0.00001I.toff+.000075ton.toff-0.00004I^2+0.00021ton^2+0.000059toff^2$$

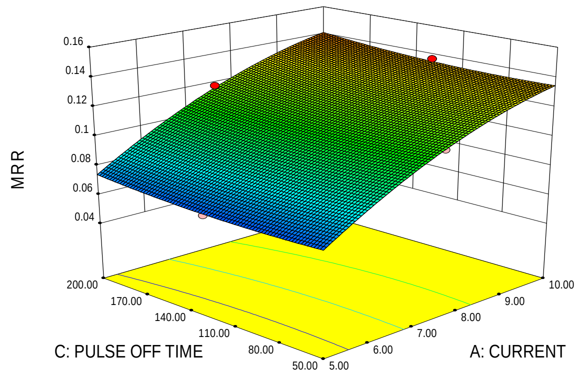

Fig 1(a)

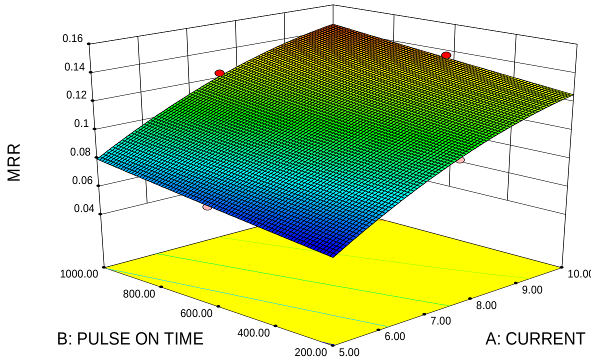

Fig 1(b)

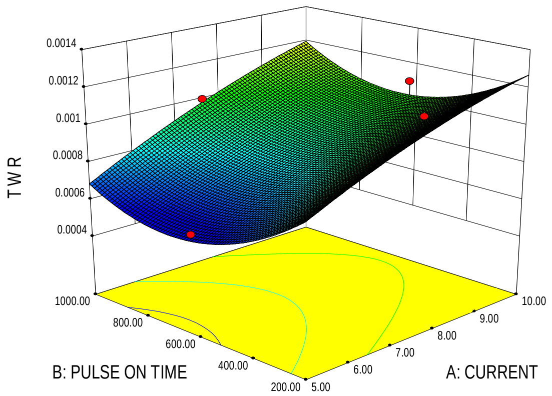

Fig 2(a)

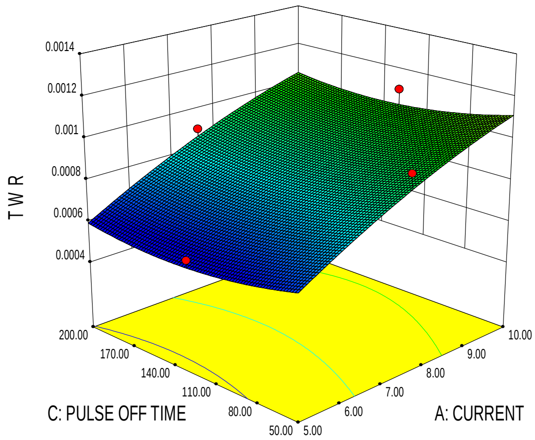

Fig 2(b)

Fig 1(a) and Fig 1(b) are presented the influence of current and pulse on time on material removal rate. The experimental results evidence that increasing ampere increase the material removal rate for pulse on time. In EDM process, the material removal rate is a function of electrical discharge energy. The increase of current generates high energy intensity and due to this energy melts more material from the workpiece. Thus material removal rate increases with increases of current. The effect of pulse on time on MRR is appeared as, the MRR increases with increase of pulse on time at all amperes. In general, the power of the spark and frequency defined by the number of pulse per second determine the process performance [20]. The low frequency and high power combination results in high metal removal. As pulse on time increases the frequency reduces and consequently the long pulse duration increases material removal. It is revealed from the results that the combination of high pulse on time and high power conceive more MRR. The same results are achieved by the researches of [21] and [22]. Fig 1(a) shows the effect of current and pulse on time against material removal rate. The impact of current and pulse off time on MRR are illustrated in the Fig 2(b)**.** The 3-D surface plot shows that increasing current increases the MRR on the other hand the pulse off time exhibits similar effect on MRR. The MRR initially increases with increasing pulse off time.

Fig 2(a) & 2(b) illustrates the impact of current, pulse on time and pulse off time on the tool wear rate. With the increase of these parameters, the energy of each pulse increases, and since one end of the pulse is on the tool and the other end is on the workpiece, this increases the amount of wear in the tool. Tool wear depends to a large extent on tool material and pulse energy; and for a specific tool, the amount of tool wear increases with the increase of pulse energy. The analysis of Fig 2(a) indicates that increasing pulse on time the tool wear start to decreases and then increases. These changes occur due to the fact that at the onset of electro discharge, the diameter of plasma channel is small, and lightweight electrons move towards the anode (positive pole) under the influence of electric field and cause the melting and evaporation of the tool. As time passes, the plasma channel diameter increases and more positive ions move towards the cathode (negative pole) and thus, more material is removed from the workpiece. The increase of current and pulse off time during the machining of Mg/Sic with brass tools and de-ionized water dielectric leads to the reduction of tool wear, and the increase of voltage results in the increase of tool wear (Fig 2(b)).

3.2 Effect of Pulse on Time and Current on MRR

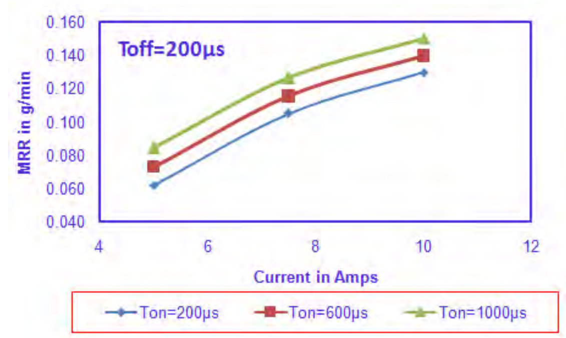

Fig 3(a)

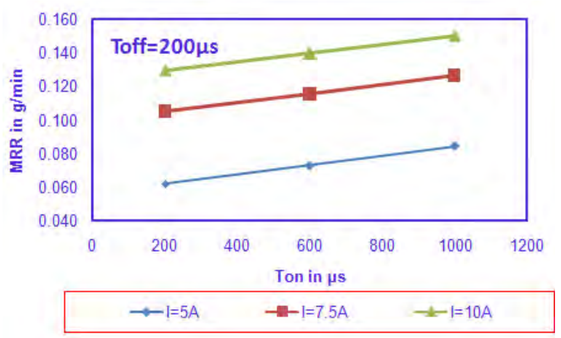

Fig 3(b)

The machinability of EDM depends on the electrical conductivity of the work material. Despite the low electrical conductivity and high thermal resistance of the SiCp reinforced particles, which ultimately reduces the electrical conductivity of the work material, the results obtained indicate that mg/SiCp can be machined effectively using EDM. MRR was found to increase with increase in current and pulse ON-time (Fig (3 a & b)). High current results in higher thermal loading on both electrodes (tool and workpiece) followed by higher amount of material being removed from both electrodes and hence lead to high MRR.

3.3 Effect of pulse on time and current on TWR

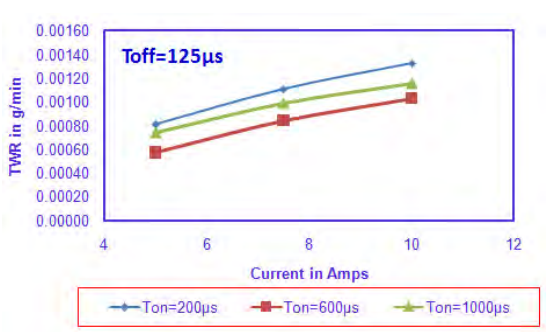

Fig 4(a)

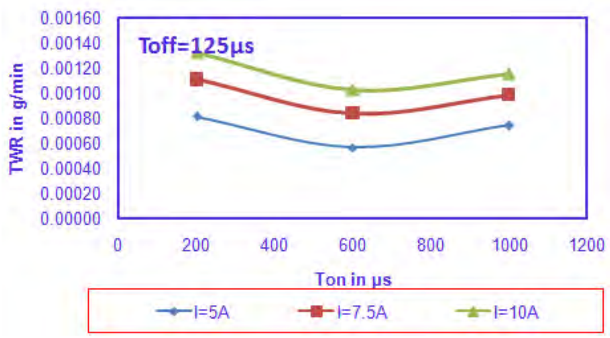

Fig 4(b)

TWR was also found to be increasing with increase in current (Fig. 4(a)). The high wear rate is attributed by the presence of low-melting alloy, zinc, in the brass tool However; the machining stability is achieved satisfactorily with brass tool since its high rate of erosion allows zinc vapours in the plasma channel, which might reduce arc resistance and helps quicker ionization. High current results in higher thermal loading on both electrodes (tool and workpiece) followed by higher amount of material being removed from both electrodes and hence lead to high TWR.

The TWR reduced upon increasing the pulse duration, even though the TWR became less at 600µs pulse duration with 5 to 10A currents (Fig 4(b)).In general, the effects of material removal mechanisms caused by melting, vaporization, as well as impulsive force of exploding dielectric fluid were decreased. Therefore, the TWR decreased at longer pulse duration. In addition, the TWR became high under 5-10 A peak currents with 200µs duration. This can be attributed to the fact that increased pulse duration at larger current would result in the generation of massive amount of pyrolytic carbon from kerosene dielectric. The pyrolytic carbon could deposit on the electrode surface to form a protective layer, resulting in a High TWR.

IV. Conclusion

This experiment was carried to investigate the influence of the current, pulse on time and pulse off time for the MRR and TWR characteristics. It was also attempted to formulate mathematical model for the responses such as MRR, and TWR and finally to derive the optimal settings of the parameters for the EDM process. The conclusions from the analysis of this experimental interpretation can be stipulated as follows.

The MRR is influenced considerably by peak current and pulse on time. A significant impact of pulse off time on the material removal rate is also investigated. The material removal rate increases with current and as well as pulse on time and pulse off time The material removal rate reaches its maximum at the highest current level of 10 Amps with pulse on time and pulse off time of 1000 µs & 20 µs respectively. Similarly the minimum attained at 5 Amps with pulse on time and pulse off time of 200 µs and 50 µs respectively.

The tool wear rate is noted at the highest current rate of 10A with pulse on time and pulse off time of 200 µs and 50 µs is the maximum and the minimum at the current rate of 5A with pulse on time 600 µs and pulse off time 125 µs respectively.

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