Machining characteristics and optimisation of process parameters in micro-EDM of SiC_p–Al composites

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Abstract: The effects of machining parameters in micro Electrical Discharge Machining (micro-EDM) with a rotary tubular electrode on the SiC_p-Al composites were investigated. In this work, experiments were planned by using Taguchi's L_9 orthogonal array. Pulse-on duration, pulse-off duration, sparking gap voltage and servo speed were considered as typical process parameters. The capabilities of micro hole EDM process were measured by considering Material Removal Rate (MRR) and Electrode Wear Rate (EWR) as responses. Hole quality was assessed by considering taper angle as response. Effect of weight % and size of SiC particles was also investigated.

[Received 2 October 2008; Revised 24 May 2009; Accepted 5 June 2009]

Keywords: micro-EDM; Al metal matrix composites; pulse-on duration; pulse-off duration; sparking gap voltage; servo speed.

Reference to this paper should be made as follows: Dev, A., Patel, K.M., Pandey, P.M. and Aravindan, S. (2009) 'Machining characteristics and optimisation of process parameters in micro-EDM of SiC_p–Al composites', *Int. J. Manufacturing Research*, Vol. 4, No. 4, pp.458–480.

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1 Introduction

The search for new, lightweight materials with greater strength and toughness has led to the development of a new generation of composite materials namely Metal Matrix Composites (MMCs). The MMCs are gaining increasing attention for applications within the aerospace, defence and automobile industries. These applications require good performance under high cycle fatigue loading conditions. The system of short silicon carbide fibre reinforced aluminium composites is popular among the MMCs systems available currently. Intensive studies on the machining of MMCs have been conducted using a variety of cutting tool materials by traditional methods (Ramulu et al., 2001). Machining of MMCs using conventional methods or tool materials is very difficult owing to the presence of the abrasive reinforcing phases, which may cause severe tool wear. In addition, conventional material removal often introduces surface flaws and residual stresses in MMCs (Ramulu et al., 2001). Thus, non-traditional machining process like EDM can be used to perform the precision machining of MMCs because the EDM process does not involve tool–work contact and the removal rate is not affected by either hardness, strength, or toughness of the workpiece material (Karthikeyan et al., 1999). Therefore, EDM has been attempted successfully for processing of MMCs.

Hung et al. (1994) investigated the feasibility of applying electrical discharge machining process for cast aluminium MMCs reinforced with silicon carbide particles (SiC_p). Statistical models were developed to predict the effect of process parameters on MRR, re-cast layer and surface finish. Karthikeyan et al. (1999) attempted to develop mathematical models for optimising EDM characteristics such as the MRR, Tool Wear Rate (TWR) and surface roughness by considering process parameters like current, pulse duration and percent volume fraction of SiC (25 μm size) present in LM25 aluminium matrix. MRR was found to decrease with an increase in the percent volume of SiC, whereas the TWR and the surface roughness increase with an increase in the volume of SiC. Yan and Wang (1999) used rotary EDM with a tubular electrode to machine Al_2O_3/6061Al composite. In another attempt, Wang and Yan (2000) optimised the blind-hole drilling of Al_2O_3/6061Al composite by rotary EDM using Taguchi technique. The analysis of the Taguchi method revealed that the electrical parameters (polarity, peak current, pulse duration and powder supply voltage) had a more significant effect than the non-electrical parameters (rotational speed of the electrode, injection flushing pressure of the dielectric fluid) on the different machining characteristics like MRR, EWR and surface roughness. They also derived semi-empirical equations to simplify the evaluation of various machining characteristics under consideration. Yan et al. (2000) optimised the cutting of Al_2O_3/6061Al composite using rotary EDM with a disk-like electrode by using Taguchi technique. Rotary EDM with a disk-like electrode resulted in higher MRR although the EWR was also found to be higher. They concluded based on their findings that overall advantage made this revised technology an acceptable tool.

Mohan et al. (2002, 2004) used 20 and 25 vol% SiC_p–Al MMCs under various EDM conditions. They used copper and brass electrodes, rotation of tube electrodes, different types of flushing and polarity change to assess the optimal conditions. Ramulu and Taya (1989) used 15 and 25 vol% whisker-SiC_w/2124 aluminium matrix composite and 15 vol% SiC_p/A356 aluminium MMC to investigate EDM machinability and surface effect on the fatigue strength. Fatigue strength was found to be notably reduced by EDM processing owing to greater degradation resulting from higher MRRs. Seo et al. (2006) investigated EDM machinability of Al matrix composites with 15–35 vol% SiC_p reinforcement to find out the optimum EDM conditions and product quality. Singh et al. (2004a) investigated the effect of current, pulse-on time and flushing pressure on MRR, TWR, hole taper, radial overcut and surface roughness whereas EDM of cast Al-MMC with 10% SiC_p reinforcement. In their work, MRR was found to be higher for larger currents and pulse-on time at the expense of dimensional accuracy and surface finish of hole. Singh et al. (2004b) employed Grey Relational Analysis to optimise the multiresponse characteristics of EDM of 10% SiC_p composites. They observed that the process improved considerably at optimal setting. The application of this technique converts the multiresponse variable to a single response Grey Relational Grade and, therefore, simplifies the optimisation procedure. Singh et al. (2007) optimised multiperformance characteristics for EDM of alumina matrix composites using Taguchi methodology. Recently, Kansal et al. (2007) carried out experimental study of Powder Mixed Electric Discharge Machining (PMEDM) of Al–10% SiC_p MMCs and found significant improvement in the surface finish. Dvivedi et al. (2008) optimised process parameters in EDM of Al 6063 SiC_p MMC.

Lim et al. (2003) gave the idea of on-machine fabrication of the microelectrodes with high-aspect ratio, and studied the EDM of the workpiece in micrometre range. Kaminski and Capuano (2003) checked the possibility of micro-hole machining by conventional penetration electrical discharge machine and found that method was technically viable. The feasibility of applying the micro-EDM process on difficult-to machine materials has been studied by number of authors (Muttamara et al., 2003; Liu and Huang, 2000; Yan et al., 1999; Nakaoku et al., 2007). Muttamara et al. (2003) and Liu and Huang (2000) investigated the use of micro-EDM in machining of ceramics. Yan et al. (1999) investigated feasibility of use of micro-EDM process to machine cemented carbides. Liu et al. (2008) developed micro-fuel-based power unit for micro-EDM of Si_3N_4–TiN ceramic composites. Recently, Nakaoku et al. (2007) performed micro-EDM of sintered diamond by machining through-holes and trenches in sintered diamond plates. Experiments were carried out with four types of sintered diamond, composed of 1, 3, 10 and 20 μm diameter diamond particles. It was found that sintered diamond had machining characteristics similar to those of tungsten carbide alloys.

It is evident from the literature review presented earlier that most of the research attempts in the area of EDM of MMCs have been concentrated to aluminium matrix composites with discontinuous reinforcements-particles (Ramulu et al., 2001; Hung et al., 1994; Mohan et al., 2002, 2004; Seo et al., 2006; Singh et al., 2004a, 2004b), whiskers of SiC (Ramulu and Taya, 1989) and aluminium oxide (Yan and Wang, 1999; Wang and Yan, 2000; Yan et al., 2000). Many researchers have investigated the machining characteristics of aluminium metal matrix using rotary EDM with a tube electrode and they found that the rotary EDM process improved the process performance (Karthikeyan et al., 1999; Yan and Wang, 1999; Wang and Yan, 2000; Yan et al., 2000; Mohan et al., 2002, 2004). No attempt appears to be made in the knowledge of authors on micro-EDM of SiC_p–Al MMC using a rotary electrode. Debris disposal, which is of prime concern in micro-drilling, is critical for the machining of

MMC owing to its insulation of the reinforcement that may incur an abnormal arcing. Micro-EDM of SiC_p–Al composites using a rotary tube electrode may be helpful in overcoming this problem. Moreover, most of the attempts (Mohan et al., 2002, 2004; Seo et al., 2006) in the area of EDM of MMCs have been concentrated on varying percentage of reinforcement however effect of change in reinforcement size is not studied so far. This work involved a series of experiments using Electronica small hole drilling EDM super drill ED-32U with a 0.3 mm diameter brass electrode on SiC_p–Al composites. MRR, EWR and hole taper were measured during micro-EDM of 5 and 10 weight % SiC_p–Al composites using a rotary electrode. In both the MMCs, particles of the reinforcement have two different sizes, i.e., 50 μm and 150 μm. In this investigation, the experiments were conducted using Taguchi technique to determine micro-EDM systematically and economically. Therefore, the four essential machining parameters of micro-EDM process namely pulse-on duration, pulse-off duration, sparking gap voltage and servo speed (sensitivity) were chosen to explore their impact on experimentally observed responses using the Taguchi technique. The experimental data were statistically analysed by the ANOVA and *F*-test was carried out to determine the significant parameters associated with each machining characteristics namely MRR, EWR and hole taper. Moreover, the optimal combinations of levels of machining parameters that optimised each machining characteristic were determined.

2 Planning of experiments

Experiments were planned by using Taguchi method as it is considered to be a powerful tool when a process is governed by number of parameters. In classical methods of experimental planning (like factorial designs, fraction factorial designs, etc.), a large number of experiments have to be carried out as number of process parameters increases, which is difficult and time-consuming and also results in higher cost typically in the case of micro-EDM. To handle such problems, Taguchi proposed an experimental plan in terms of orthogonal array that gives different combinations of parameters and their levels for each experiment (Raghunath and Pandey, 2007; Bagchi, 1993). According to this technique, entire parameter space is studied with minimum number of experiments. A brief description of Taguchi method is presented here.

2.1 Details of experiments

The experiments were conducted using Electronica small hole drilling, EDM super drill ED-32U equipped with a transistor switched power supply. The electrode is fed downward into the workpiece under servo control in this machine. A hollow rotary tubular electrode of brass having diameter 0.3 mm was used to drill the workpiece. Through-holes were machined in the workpiece to determine the machining characteristics. Deionised water was circulated as the dielectric fluid. The dielectric fluid was maintained at a pressure of 5.6 kg/cm^2 and injected through the tube electrode.

The MRR was calculated based on the machined workpiece volume and the total cutting time. The EWR was also calculated based on the electrode wear volume and the total cutting time. A precision electronic balance was used to measure the electrode weight before and after the machining. The hole taper (θ) was calculated by

$$\theta = \tan^{-1}\left(\frac{d_{jt} - d_{jb}}{2H}\right) \tag{1}$$

where d_{jt} and d_{jb} are the diameters of the machined hole at the top and the bottom of the workpiece, respectively, and H is the height of the workpiece. The top and bottom diameters of the holes were measured with help of profile projector.

Various levels of different parameters used in this work are given in Table 1. In this study, L_9 orthogonal array with four columns and nine rows is used. To select an appropriate orthogonal array, total degrees of freedom need to be computed. The degrees of freedom are the number of comparisons to be made between design parameters. For example, a three-level design parameter counts for two degrees of freedom. Therefore, in this work, total degrees of freedom are 9, 8 owing to 4 parameters with three levels and one for overall mean. Basically, degrees of freedom for an orthogonal array should be greater than or at least equal to number of design parameters. Each parameter was assigned to each column of the orthogonal array. Therefore, only nine experiments were required to study the entire parameter space using L_9 orthogonal array.

Table 1 Levels of each of the parameters

S. No.	*Parameter*	*Unit*	*Levels of each parameter*		
			Level 1	*Level 2*	*Level 3*
1	Pulse-on duration (T_{on})	μs	2.0	3.0	4.0
2	Pulse-off duration (T_{off})	μs	3.5	4.5	5.0
3	Sparking gap voltage (S_{v}) on the scale of 10, OCV 94 Volt	V	2	3	4
4	Servo speed (SEN) in no load condition	mm/min	24	50	82

3 Analysis of experimental data

Experimental data is analysed by using S/N ratio and ANOVA. On the basis of the results of the S/N ratio and ANOVA, optimal parameter settings for maximum MRR, minimum EWR and minimum taper are obtained.

3.1 Analysis using S/N ratio

In Taguchi method, S/N ratio is a measure of quality characteristics and deviation from the desired value. The term signal represents the desirable value (mean) and the noise represents the undesirable value (standard deviation from mean) for the output characteristic (Raghunath and Pandey, 2007). The S/N ratio (η) is defined as

$$\eta = -10 \log(\text{M.S.D.}) \tag{2}$$

where M.S.D. is the mean square deviation for the output characteristic. MRR is the dominant phenomenon in micro-EDM, which decides the machinability of the material under consideration. To obtain optimal cutting performance, the-higher-the-better quality characteristic for MRR must be used. For the-higher-the-better case, the S/N ratio is obtained by Yang and Tarng (1998)

$$\text{M.S.D.} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{M_i^2} \tag{3}$$

where n is the total number of the experiments in the orthogonal array and M_i is the mean MRR for the ith experiment. S/N ratio for each of the experiment was calculated and is presented in Table 2.

Table 2 S/N ratio and average MRR for each trial

	5%/50 μm SiC$_p$–Al		*10%/50 μm SiC$_p$–Al*		*5%/150 μm SiC$_p$–Al*		*10%/150 μm SiC$_p$–Al*	
Exp. No.	*S/N ratio*	*Average MRR* (mm^3/min)	*S/N ratio*	*Average MRR* (mm^3/min)	*S/N ratio*	*Average MRR* (mm^3/min)	*S/N ratio*	*Average MRR* (mm^3/min)
1	3.7644	1.5424	3.3649	1.4731	3.8796	1.5630	4.2242	1.6263
2	10.6441	3.4056	11.8163	3.8977	9.4412	2.9652	9.1413	2.8646
3	15.6287	6.0455	15.0052	5.6267	10.2888	3.2691	10.4580	3.3334
4	18.2025	8.1306	15.8571	6.2066	17.1125	7.1717	17.2143	7.2563
5	6.5774	2.1324	–1.7271	0.8197	3.9064	1.5679	3.0301	1.4174
6	10.8713	3.4959	11.9682	3.9665	14.8336	5.5167	11.4626	3.7422
7	12.8028	4.3665	13.6586	4.8187	11.0525	3.5696	11.4695	3.7451
8	16.3940	6.60236	18.4354	8.3515	19.5323	9.4758	18.2087	8.1364
9	7.4116	2.3473	4.4353	1.6664	–1.3286	0.8581	0.6924	1.0829

The effect of a factor level is defined as the deviation it causes from the overall mean. The overall mean S/N ratio (m) of the experiments is calculated by Raghunath and Pandey (2007)

$$m = \frac{1}{n}\sum_{i=1}^{n}\eta_i \tag{4}$$

where η_i is the mean S/N ratio of the ith experiment. All three levels of every factor are equally represented in nine experiments. Thus, m is a balanced overall mean for the entire experiment. Since the experimental design is orthogonal, it is possible to separate out the effect of each factor at each level (Bagchi, 1993). Mean response is the average of quality characteristic for each parameter at different levels. S/N ratio and average MRR for each parameter at each level can be calculated from mean S/N ratio and MRR value of each of the experiment. MRR for each of the parameter at each level has been calculated. These are also called as main effects. Figures 1–3 show main effects plots of the MRR for various input parameters. The ideal product or process will only respond to the operator's signals and will be unaffected by random noise factors. Therefore, S/N ratio is to be maximised. On the basis of the S/N analysis, the optimal parameters for maximum MRR are given in Table 3.

Figure 1 Effect of process parameters on MRR for 5%/50 µm SiC_p–Al (see online version for colours)

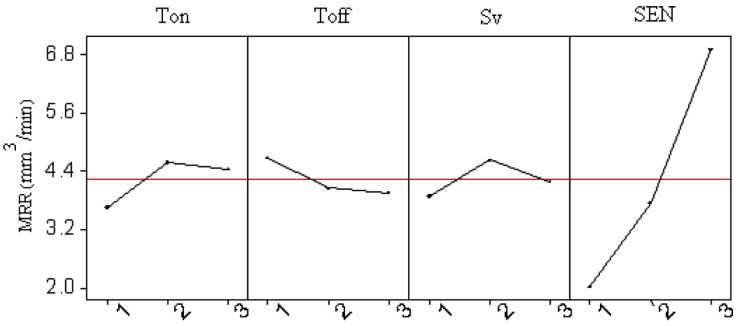


Figure 2 Effect of process parameters on MRR for 10%/50 µm SiC_p–Al (see online version for colours)

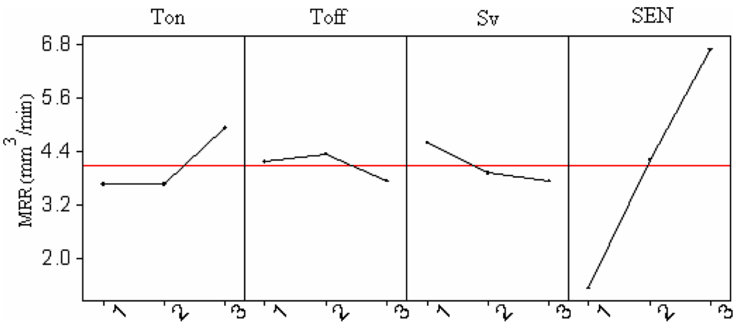


Figure 3 Effect of process parameters on MRR for 5%/150 µm SiC_p–Al (see online version for colours)

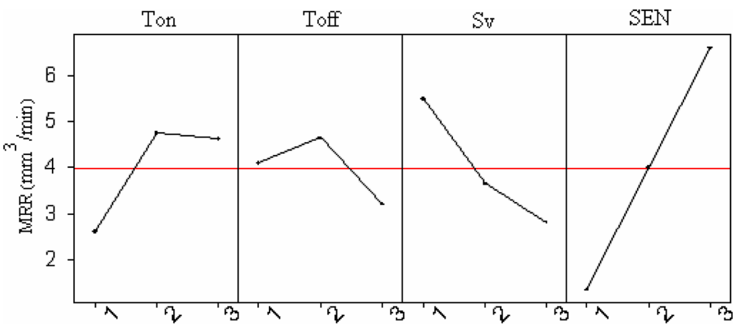


Table 3 Optimum process parameter values for maximum MRR obtained from S/N ratio

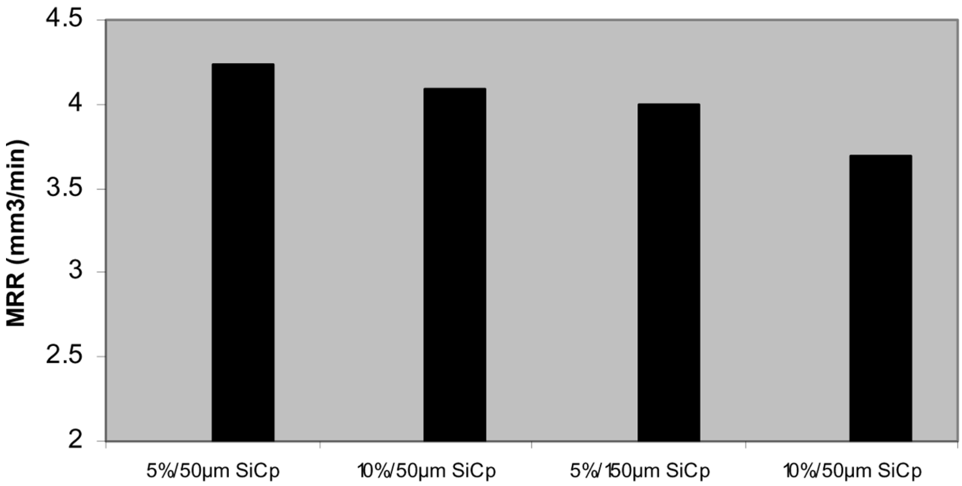
			Value			
S. No.	*Parameter*	*Unit*	*5%/50 µm SiC_p–Al*	*10%/50 µm SiC_p–Al*	*5%/150 µm SiC_p–Al*	*10%/150 µm SiC_p–Al*
1	Pulse-on duration (T_{on})	µs	4.0	4.0	3.0	3.0
2	Pulse-off duration (T_{off})	µs	3.5	3.5	4.5	3.5

Table 3 Optimum process parameter values for maximum MRR obtained from S/N ratio (continued)

S. No.	*Parameter*	*Unit*	*Value* 5%/50 μm SiC_p–Al	10%/50 μm SiC_p–Al	5%/150 μm SiC_p–Al	10%/150 μm SiC_p–Al
3	Sparking gap voltage (S_v) on the scale of 10	V	3	2	2	2
4	Servo speed (SEN) in no load condition	mm/min	82	82	82	82

From main effects plots for MRR (Figures 1–3), it is observed that MRR increases with pulse-on duration could be possibly due to increase in the discharge energy, superior debris removal effect and forced injection of dielectric to machining gap through the small hole of the tubular electrode. It has been observed that as the pulse-off duration increases, the MRR decreases slightly. It can also be observed that as the servo speed (sensitivity) increases, MRR increases. As servo speed increases, discharge frequency of the pulse generator increases with the shorter pulse duration, which causes higher MRR. It is evident that as sparking gap voltage decreases the MRR increases. As the value of gap voltage increases, it widens the gap width between the electrode and the workpiece. However, a wide gap implies a lower discharge current, which affects the MRR (Liu et al., 2006). Figure 4 shows the effect of weight % and size of SiC on MRR. The results clearly show that weight % and size of SiC particles are the important parameters in micro-EDM of SiC_p–Al metal matrix.

Figure 4 Effect of weight % and SiC particles size on MRR



EWR is the most important measure of micro-EDM performance. Process parameters for micro-EDM are still at the development stage and their effects on EWR have yet to be clarified. To obtain optimal cutting performance, the-smaller-the-better quality characteristic must be used for minimising EWR. For the-smaller-the better case, the S/N ratio is obtained by (Raghunath and Pandey, 2007)

$$\text{M.S.D.} = \frac{1}{n}\sum_{i}^{n} E_i^2 \tag{5}$$

where n is the total number of the experiments in the orthogonal array and E_i is the mean EWR for the ith experiment.

S/N ratio of EWR for each of the experiment was calculated and is presented in Table 4. The overall mean S/N ratio (m) of the experiments is calculated by equation (4). On the basis of the S/N analysis, the optimal parameters for minimum EWR are given in Table 5. Figures 5–7 show main effects plots of the EWR for various input parameters. The experimental results (Figures 5–7) reveal that the EWR increases with servo speed and pulse-on duration. The electrical discharge column formed in the machining gap not only removes the unwanted workpiece material but also induces wear on the rotary tube electrode. It could be observed from Figures 5–7 that the servo speed is the most significant factor among all the considered factors in micro-EDM of all types of SiC_p–Al used. This is due to the reason that increases in servo speed cause increase in discharge energy to be conducted into the machining gap, improve MRR and increase the EWR. It is evident that EWR is less affected by the pulse-off duration. The EWR deceases with increasing sparking gap voltage. High electrode gap voltage widens the gap between the electrode and the workpiece. However, a wider gap implies a lower discharge current, which would affect the MRR with an appreciable amount of electrode material depositing on the workpiece surface. A lower MRR results in unwanted materials piling on the surface and affects the quality of machining. Nevertheless, poor material removal efficiency reduces tool wear; hence, the EWR decreases. This is in agreement with findings of Liu et al. (2006) involving micro EDM of high-nickel alloy. Figure 8 shows that there is a little increase in the EWR with increase in weight % and size of SiC particles in the composites. This is due to low conductivity, high thermal resistance and abrasive nature of SiC particles.

Table 4 S/N ratio and average EWR for each trial

	5%/50 μm SiC_p–Al		*10%/50 μm SiC_p–Al*		*5%/150 μm SiC_p–Al*		*10%/150 μm SiC_p–Al*	
Exp. No.	*S/N ratio*	*Average EWR* (mm^3/min)	*S/N ratio*	*Average EWR* (mm^3/min)	*S/N ratio*	*Average EWR* (mm^3/min)	*S/N ratio*	*Average EWR* (mm^3/min)
1	9.2221	0.3458	10.0116	0.3158	10.2579	0.3069	10.2251	0.3081
2	4.1682	0.6188	4.0547	0.6270	2.1039	0.7848	1.9421	0.7996
3	–1.7084	1.2173	–0.5338	1.0633	–1.7888	1.2286	3.0651	0.7026
4	–1.6148	1.2043	–1.0475	1.1281	–3.8683	1.5610	–1.9785	1.2558
5	12.8741	0.2271	13.4914	0.2115	14.5790	0.1866	14.3264	0.1921
6	2.0409	0.7905	1.6143	0.8304	4.2868	0.6104	–2.5324	1.3385
7	4.3194	0.6081	2.5782	0.7431	2.3925	0.7592	1.0885	0.8822
8	–5.8001	1.9498	–6.2625	2.0564	–3.9958	1.5841	–4.2517	1.6314
9	10.4488	0.3003	8.5513	0.3736	7.0033	0.4465	8.5468	0.3738

Table 5 Optimum process parameter values for minimum EWR obtained from S/N ratio

			Value			
S. No.	*Parameter*	*Unit*	*5%/50 µm SiCp–Al*	*10%/50 µm SiCp–Al*	*5%/150 µm SiCp–Al*	*10%/150 µm SiCp–Al*
1	Pulse-on duration (T_{on})	µs	3.0	3.0	3.0	2.0
2	Pulse-off duration (T_{off})	µs	3.50	3.50	4.50	4.50
3	Sparking gap voltage (S_v) on the scale of 10	V	4	4	4	4
4	Servo speed (SEN) in no load condition	mm/min	24	24	24	24

Figure 5 Effect of process parameters on EWR for 5%/50 µm SiC_p–Al (see online version for colours)

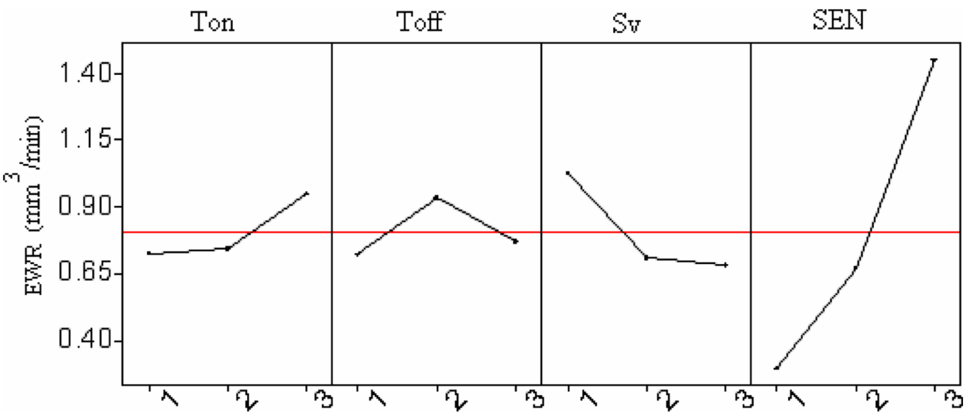


Figure 6 Effect of process parameters on EWR for 10%/50 µm SiC_p–Al (see online version for colours)

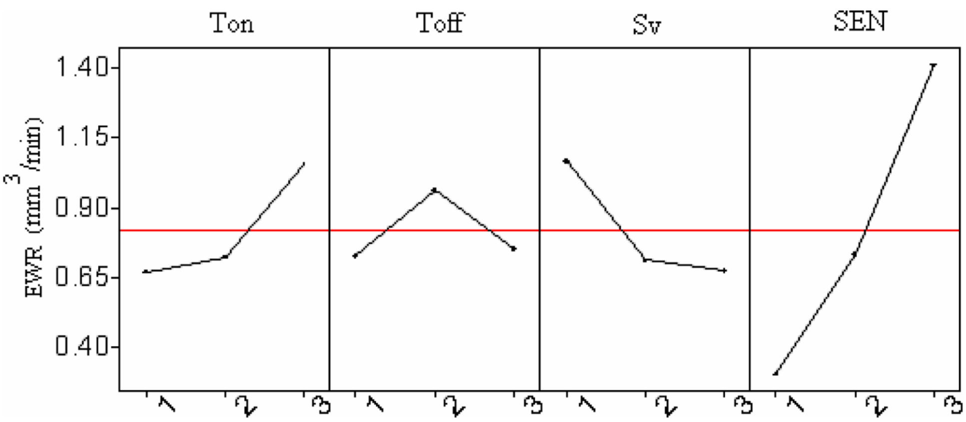


Figure 7 Effect of process parameters on EWR for 5%/ 150 µm SiC_p–Al (see online version for colours)

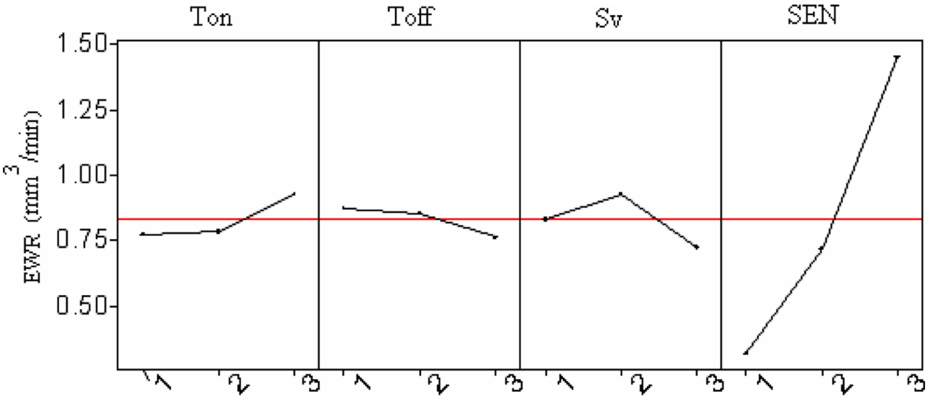
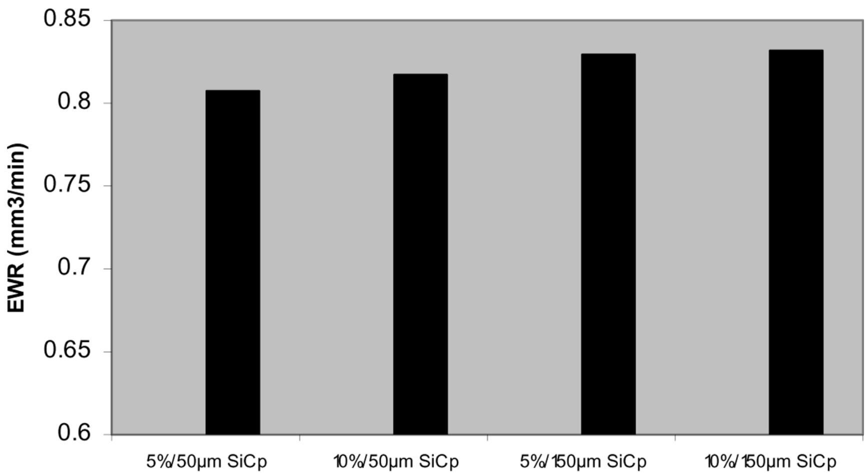


Figure 8 Effect of weight % and SiC particles size on EWR



On the other hand, the-smaller-the-better quality characteristics for hole taper should be considered for obtaining optimal cutting performance. In micro-EDM process, the micro-hole is drilled using a micro-tool. Therefore, to machine accurate micro-holes dimensionally with form, diameter variation between the entrance and exit or the taper is a very important response (Liu et al., 2005). For the-smaller-the-better case, the S/N ratio has been obtained by (Raghunath and Pandey, 2007)

$$\text{M.S.D.} = \frac{1}{n}\sum_{i}^{n} T_i^2 \tag{6}$$

where n is the total number of the experiments in the orthogonal array and T_i is the mean taper for the ith experiment.

S/N ratio of taper for each of the experiment was calculated and is presented in Table 6. The overall mean S/N ratio (m) of the experiments is calculated by equation (4). On the basis of the S/N analysis, the optimal parameters for minimum taper are given in Table 7.

Table 6 S/N ratio and average taper for each trial

Exp. No.	*5%/50 μm SiCp–Al*		*10%/50 μm SiCp–Al*		*5%/150 μm SiCp–Al*		*10%/150 μm SiCp–Al*	
	S/N ratio	*Average taper (Degree)*	*S/N ratio*	*Average taper (Degree)*	*S/N ratio*	*Average taper (Degree)*	*S/N ratio*	*Average taper (Degree)*
1	25.3437	0.0541	23.2590	0.0687	27.8966	0.0402	25.0632	0.0558
2	35.7437	0.0160	26.9546	0.0449	17.2293	0.1375	35.3471	0.0170
3	29.7568	0.0325	28.8473	0.0361	28.2176	0.0388	20.2459	0.0972
4	18.1691	0.1234	14.7753	0.1824	11.6025	0.2629	16.4332	0.1507
5	32.0576	0.0249	20.2085	0.0976	28.9533	0.0356	17.5967	0.1318
6	26.5706	0.0469	20.2501	0.0971	34.2885	0.0193	15.8444	0.1613
7	17.8625	0.1279	15.5050	0.1677	13.2463	0.2176	13.3743	0.2144
8	13.6921	0.2067	12.6436	0.2332	12.2080	0.2452	11.3804	0.2797
9	16.2283	0.1543	15.0614	0.1765	18.6949	0.1162	19.9333	0.1007

Table 7 Optimum process parameter values for minimum taper obtained from S/N ratio

S. No.	*Parameter*	*Unit*	*Value*			
			5%/50 μm SiC_p–Al	*10%/50 μm SiC_p–Al*	*5%/150 μm SiC_p–Al*	*10%/150 μm SiC_p–Al*
1	Pulse-on duration (T_{on})	μs	2.0	2.0	3.0	2.0
2	Pulse-off duration (T_{off})	μs	4.5	5.0	5.0	5.0
3	Sparking gap voltage (S_v) on the scale of 10	V	4	4	2	2
4	Servo speed (SEN) in no load condition	mm/min	82	82	24	82

Figures 9–11 show main effect plots of the taper for various input parameters. The pulse-on duration is found to be the most significant factor influencing the taper in all varieties of SiC_p–Al MMCs. It can be seen from Figures 9–11 that the micro-hole depicts a minimum taper at lower pulse-on duration. This is due to less discharge energy density and smooth machining process. At higher value of pulse-on time, the discharge energy density is too large, which results in more amount of work material removal from entrance diameter. In addition, the debris can pile up easily and unusual second sparking can be induced. This phenomenon causes the entrance of micro-hole to be larger, so the taper becomes more. The increase in pulse-off duration decreases the values of taper. Longer pulse-off duration gives more time for generation of recast layer at entrance diameter, which causes the lower taper in the material. It was inferred from Figures 9–11 that the increase in servo speed resulted in an increase in the taper. High servo speed causes more wear of electrode during the machining and thus reduces the exit hole diameter. Sparking gap voltage decreases the taper as its value increases. An increase in percentage and size of SiC particles (Figure 12) causes the increase in taper. The low electrical conductivity and the high thermal resistance of the SiC particles decrease the conductivity of workpiece material. When these particles are eroded, they make erosion on the wall of the workpiece and erode the electrode owing to their abrasive nature.

These occurrences may preferentially result in more erosion of the workpiece at entrance diameter owing to exit of debris mixed with eroded reinforcement, subsequently causing a large diameter variation between the entrance and exit.

Figure 9 Effect of process parameters on taper for 5%/50 µm SiC_p–Al (see online version for colours)

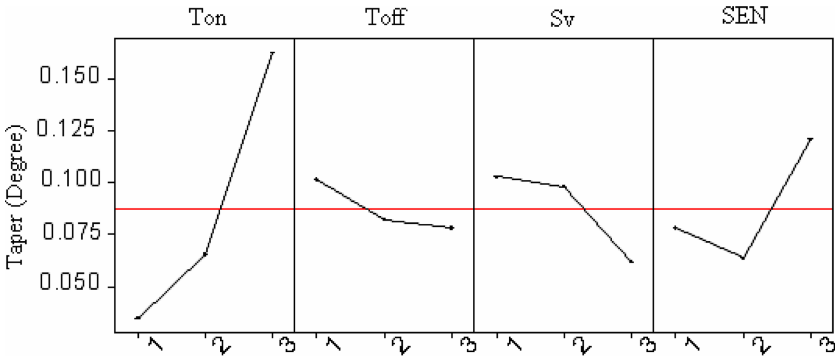


Figure 10 Effect of process parameters on taper for 10%/50 µm SiC_p–Al (see online version for colours)

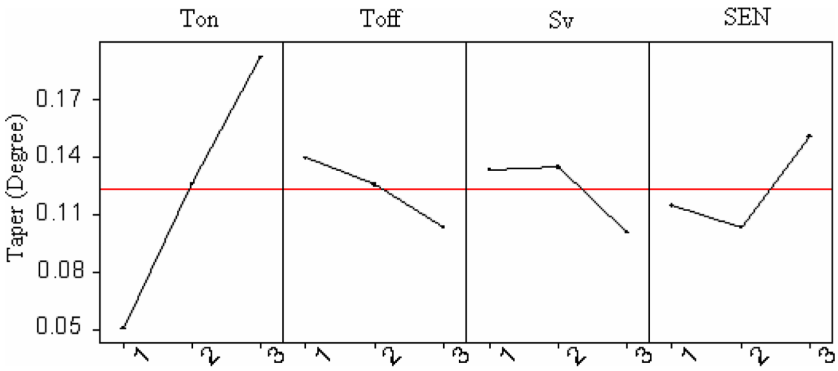


Figure 11 Effect of process parameters on taper for 5%/150 µm SiC_p–Al (see online version for colours)

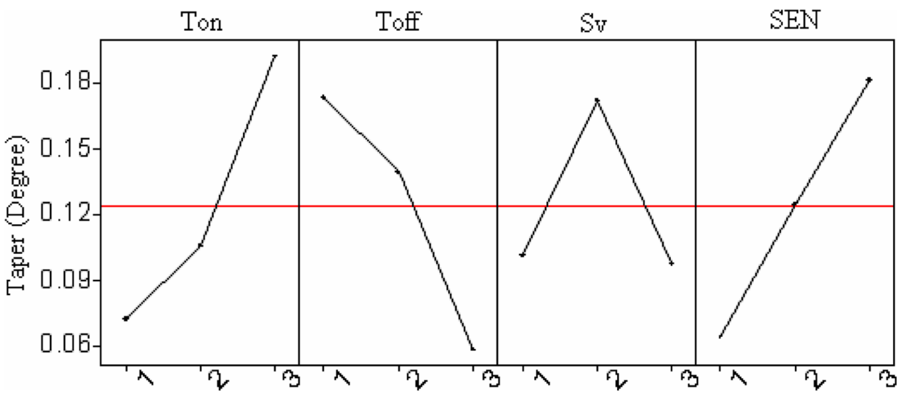
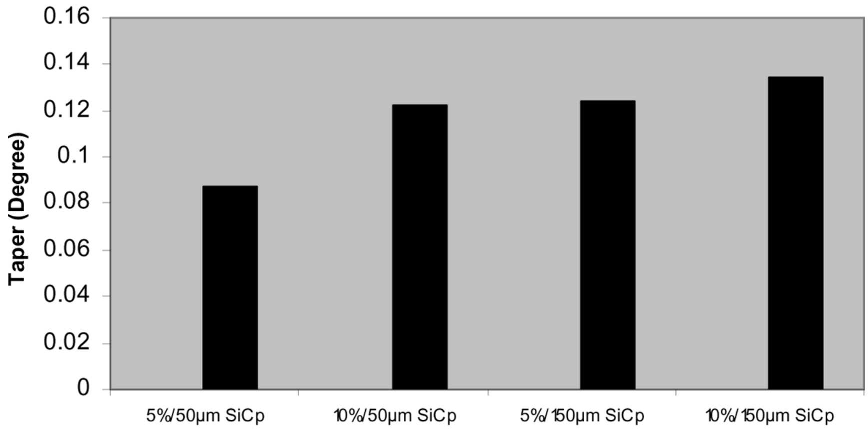


Figure 12 Effect of weight % and SiC particles size on taper



3.2 Analysis of Variance

ANOVA is a standard statistical technique to interpret the experimental results. It is extensively used to identify the performance of group of parameters under investigation. Purpose of ANOVA is to investigate the parameters, whose combination to total variation is significant (Raghunath and Pandey, 2007). In ANOVA, total sum of squares deviations (SS_T) is calculated by

$$SS_T = \sum_{i=1}^{n} (\eta_i - m)^2 \tag{7}$$

where m is the overall mean S/N ratio.

Total sum of squared deviations SS_T is divided into two sources

$$SS_T = \sum_{j=1}^{n_p} SS_j + SS_e \tag{8}$$

where SS_j is the sum of squared deviations for each design parameter and is given by

$$SS_j = \sum_{i=1}^{l} (\eta_{ji} - m)^2 \tag{9}$$

here, n_p is the number of significant parameters and l is the number of levels of each parameter. SS_e is the sum of squared error without or with pooled factor, which is sum of squares corresponding to the insignificant factors. Mean square of a factor (MS_j) or error (MS_e) is found by dividing its sum of squares with its degrees of freedom. Percentage contribution (ρ) and F-value of each of the design parameters is given by

$$\rho_j = \frac{SS_j}{SS_T} \tag{10}$$

$$F_j = \frac{MS_j}{MS_e}. \tag{11}$$

If the factor is highly influencing the process response, then the *F*-value is large and is used to rank the factors (Raghunath and Pandey, 2007). The obtained *F*-values for MRR owing to pulse-on time, pulse-off time, spark gap voltage and servo speed in this work is given in Tables 8 and 9. It can be seen from Tables 8 and 9 that servo speed is the most significant parameter for MRR in micro-EDM of SiC_p–Al composites with SiC particle size 50 μm and 150 μm containing 5% SiC and 10% SiC powder by weight. Pulse-on duration significantly affects MRR in case of SiC_p–Al with SiC particle size 50 μm containing 10% SiC powder by weight.

Table 8 ANOVA table for MRR in micro-EDM of 5 and 10 wt. % SiC_p–Al composites, SiC_p 50 μm

			Sum of square		*Mean square*		*F*		*Contribution* (%)	
S. No.	*Factor*	*DOF*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*
1	Pulse-on duration	2	1.4707	3.2792	0.7354	1.6396	1.73	5.75	3.63	6.69
2	Pulse-off duration	2	0.9218	0.5705*	0.4609	0.2852	1.09		2.27	
3	Sparking gap voltage	2	0.8490*	1.1910	0.4245	0.5955		2.09		2.43
4	Servo speed	2	37.3017	43.962	18.6508	21.9813	43.94	77.07	92.00	89.16
5	ERROR	2	0.8490	0.5705	0.4245	0.2852				
6	Total	8	40.5432	49.0032						

*Indicates the minimum mean square values of pooled parameters as their % contribution is low.

Table 9 ANOVA table for MRR in micro-EDM of 5 and 10 wt. % SiC_p–Al composites, SiC_p 150 μm

			Sum of square		*Mean square*		*F*		*Contribution* (%)	
S. No.	*Factor*	*DOF*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*
1	Pulse-on duration	2	8.7918	5.3116	4.3959	2.6558	2.73	1.27	13.35	10.73
2	Pulse-off duration	2	3.2261*	4.2403	1.6131	2.1201		1.01		8.56
3	Sparking gap voltage	2	11.5581	4.1907*	5.7790	2.0954	3.58		17.55	
4	Servo speed	2	42.2835	35.7807	21.1417	17.8903	13.11	8.54	64.20	72.25
5	ERROR	2	3.2261	4.1907	1.6131	2.0954				
6	Total	8	65.860	49.5233						

*Indicates the minimum mean square values of pooled parameters as their % contribution is low.

The obtained *F*-values for EWR in this work are given in Tables 10 and 11. Servo speed is the most significant parameter affecting the EWR in all varieties of SiC_p–Al MMC. Spark gap voltage significantly affects EWR in addition to servo speed in case of SiC_p–Al with SiC particle size 150 μm containing 10% SiC powder by weight.

Table 10 ANOVA table for EWR in micro-EDM of 5 and 10 wt. % SiC_p–Al composites, SiC_p 50 μm

S. No.	*Factor*	*DOF*	*Sum of square*		*Mean square*		*F*		*Contribution* (%)	
			5%/50 μm	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*
1	Pulse-on duration	2	0.09598	0.26614	0.04799	0.13307	1.3	2.66	3.82	10.44
2	Pulse-off duration	2	0.07407*	0.10016*	0.03704	0.05008				
3	Sparking gap voltage	2	0.22227	0.28541	0.11114	0.14270	3.00	2.85	4.42	11.19
4	Servo speed	2	2.12089	1.89818	1.06045	0.94909	28.63	18.95	84.39	74.44
5	ERROR	2	0.07407	0.10016	0.03704	0.05008				
6	Total	8	2.51322	2.54990						

*Indicates the minimum mean square values of pooled parameters as their % contribution is low.

Table 11 ANOVA table for EWR in micro-EDM of 5 and 10 wt. % SiC_p–Al composites, SiC_p 150 μm

S. No.	*Factor*	*DOF*	*Sum of square*		*Mean square*		*F*		*Contribution* (%)	
			5%/50 μm	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*
1	Pulse-on duration	2	0.04534	0.23589	0.02267	0.11794	2.10	28.03	2.11	11.86
2	Pulse-off duration	2	0.02164*	0.00842*	0.01082	0.00421				
3	Sparking gap voltage	2	0.06370	0.37769	0.03185	0.18884	2.94	44.88	2.96	19.00
4	Servo speed	2	2.0211	1.36739	1.01058	0.68370	93.42	162.48	93.93	68.73
5	ERROR	2	0.02164	0.00842	0.01082	0.00421				
6	Total	8	2.15183	1.98938						

*Indicates the minimum mean square values of pooled parameters as their % contribution is low.

The obtained *F*-values for hole taper generated while micro-drilling of Al–SiC composites using EDM are given in Tables 12 and 13. It can be seen from Tables 12 and 13 that pulse-on duration significantly affects taper generated for all kinds of Al–SiC composites considered in this work.

Table 12 ANOVA table for taper in micro-EDM of 5 and 10 wt. % SiC_p–Al composites, SiC_p 50 μm

			Sum of square		*Mean square*		*F*		*Contribution* (%)	
S. No.	*Factor*	*DOF*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*
1	Pulse-on duration	2	0.02708	0.03055	0.01354	0.0152	28.28	15.17	74.48	79.41
2	Pulse-off duration	2	0.000958*	0.00201*	0.00047	0.00100				
3	Sparking gap voltage	2	0.002998	0.002227	0.00149	0.00111	3.13	1.11	8.24	5.79
4	Servo speed	2	0.00532	0.00368	0.00266	0.00184	5.56	1.83	14.64	9.57
5	ERROR	2	0.000958	0.002013	0.00047	0.00100				
6	Total	8	0.036378	0.038476						

*Indicates the minimum mean square values of pooled parameters as their % contribution is low.

Table 13 ANOVA table for taper in micro-EDM of 5 and 10 wt. % SiC_p–Al composites, SiC_p 150 μm

			Sum of square		*Mean square*		*F*		*Contribution* (%)	
S. No.	*Factor*	*DOF*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*	*5%/50 μm*	*10%/50 μm*
1	Pulse-on duration	2	0.02528	0.02966	0.01264	0.01483	25.36	36.37	61.11	61.59
2	Pulse-off duration	2	0.013749	0.0008155*	0.00687	0.00040	13.79		33.24	
3	Sparking gap voltage	2	0.0013391	0.008902	0.00066	0.00445	1.34	10.92	3.24	18.48
4	Servo speed	2	0.0009969*	0.0087845	0.00049	0.00439		10.77		18.24
5	ERROR	2	0.0009969	0.0008155	0.00049	0.00040				
6	Total	8	0.0413670	0.0481668						

*Indicates the minimum mean square values of pooled parameters as their % contribution is low.

3.3 Empirical models derivation

For each combination of parameter settings in L_9 matrix, MRR, EWR and taper values for different varieties of SiC_p–Al MMCs are already tabulated (Tables 2, 4 and 6). Empirical models are derived by linear regression using standard statistical software. Insignificant (pooled) parameters are neglected while deriving these models. The developed models predict the MRR, EWR and taper for any set of parameters to understand the EDM of SiC_p–Al MMCs. In this study, the following models are formulated for SiC_p–Al composites with SiC particle size of 50 μm and 150 μm containing 5% SiC and 10% SiC powder by weight.

For 5 wt. % SiC_p–Al composite having SiC particle size of 50 μm:

$$MRR = –0.75 + 0.387\ T_{on} – 0.358\ T_{off} + 2.46\ SEN \tag{12}$$

$$EWR = –0.240 + 0.113\ T_{on} – 0.172\ S_v + 0.583\ SEN \tag{13}$$

$$Taper = –0.0437 + 0.0644 – 0.0204\ S_v + 0.0215\ SEN. \tag{14}$$

For 10 wt. % SiC_p–Al composite having SiC particle size of 50 μm:

$$MRR = –1.75 + 0.640\ T_{on} – 0.421\ S_v + 2.70\ SEN \tag{15}$$

$$EWR = –0.293 + 0.194\ T_{on} – 0.197\ S_v + 0.558\ SEN \tag{16}$$

$$Taper = –0.0236 + 0.0713\ T_{on} – 0.0163\ S_v + 0.0182\ SEN. \tag{17}$$

For 5 wt. % SiC_p–Al composite having SiC particle size of 150 μm:

$$MRR = –0.63 + 1.02\ T_{on} – 1.36\ S_v + 2.65\ SEN \tag{18}$$

$$EWR = –0.362 + 0.0783\ T_{on} – 0.0545\ S_v + 0.572\ SEN \tag{19}$$

$$Taper = 0.123 + 0.0604\ T_{on} – 0.0577\ T_{off} – 0.0021\ S_v. \tag{20}$$

For 10 wt. % SiC_p–Al composite having SiC particle size of 150 μm:

$$MRR = –1.40 + 0.857\ T_{on} –0.745\ T_{off} + 2.43\ SEN \tag{21}$$

$$EWR = 0.068 + 0.180\ T_{on} – 0.250\ S_v + 0.453\ SEN \tag{22}$$

$$Taper = –0.0693 + 0.0708\ T_{on} –0.0089\ S_v + 0.0399\ SEN \tag{23}$$

where T_{on} is the pulse-on duration in μs, T_{off} is the pulse-off duration in μs, S_v Sparking gap voltage setting position, *SEN* is servo speed in mm/min.

3.4 Expected range of performance at optimum condition

Levels of optimum process parameters for maximum MRR and minimum EWR and taper are given in Tables 3, 5 and 7. The estimated response using the optimal level of the design parameters is expected to fall in the range given here (Roy, 1990).

$$\text{Expected response} = S_m \pm \text{C.I.} \tag{24}$$

where

$$S_{\text{opt}} = S_m + \sum_{i=1}^{n_p} (S_i^* - S_m) \tag{25}$$

and confidence interval

$$\text{C.I.} = \left[\frac{F_{(1,\text{DOF}_e)} \times V_e}{N_e} \right]^{0.5}. \tag{26}$$

In the above-mentioned three equations (9)–(11), S_m and S_i^* are the overall mean and the mean at the optimum level for responses MRR, EWR and taper used in this study, respectively. n_p is the number of main design parameters that affect the quality characteristic, $F_{(1,\text{DOF}_e)}$ is Fisher value at DOF_e, which is degrees of freedom of error term, and V_e is the variance of the error term. Effective number of replications (N_e) is given by (Roy, 1990)

$$N_e = \frac{n}{\text{DOF}_m + \sum_{i=1}^{n_p} \text{DOF}_i} \tag{27}$$

where DOF_m is the degrees of freedom of mean, which is always 1 and DOF_i is the degrees of freedom of the significant parameters.

The expected values of MRR, EWR and taper at optimal set of parameters for different varieties of Al–SiC composites are calculated from equations (24)–(27). Tables 14–16 show the comparison of the expected MRR, EWR and taper predicted from equations (24)–(27) at 90% confidence level with the calculated values for different responses using empirical models. The range of the expected MRR of 10% SiC_p–Al composite having SiC particles size 150 μm and the ranges of the expected EWR and taper formed in 10% SiC_p–Al composite having SiC particles size 50 μm are more. This may be due to some other factor or interaction, which is not considered in this study, that influences MRR, EWR and taper while EDM of these composites. The analysis confirms the effectiveness of the prior design used for this study.

Table 14 Comparison of MRR predicted by ANOVA and calculated by empirical models

		MRR (mm^3/min)	
S. No.	*Type of composite*	*Expected range of values from ANOVA at confidence level of 90%*	*From empirical models*
1	5% SiC_p–Al composites, SiC_p 50 μm	6.309–8.859	7.433
2	10% SiC_p–Al composites, SiC_p 50 μm	6.73–9.445	7.849
3	5% SiC_p–Al composites, SiC_p 150 μm	1.69965–8.24365	8
4	10% SiC_p–Al composites, SiC_p 150 μm	3.481559–10.94	6.859

Table 15 Comparison of EWR predicted by ANOVA and calculated by empirical models

		EWR (mm^3/min)	
S. No.	*Type of composite*	*Expected range of Values from ANOVA at confidence level of 90%*	*From empirical models*
1	5% SiC_p–Al composites, SiC_p 50 μm	0–0.5970	0.053
2	10% SiC_p–Al composites, SiC_p 50 μm	0–0.6395	0.0604
3	5% SiC_p–Al composites, SiC_p 150 μm	0–0.4325	0.2031
4	10% SiC_p–Al composites, SiC_p 150 μm	0–0.458	0.2320

Table 16 Comparison of taper predicted by ANOVA and calculated by empirical models

		Hole taper (*Degree*)	
S. No.	*Type of composite*	*Expected range of Values from ANOVA at confidence level of 90%*	*From empirical models*
1	5% SiC_p–Al composites, SiC_p 50µm	0–0.113	0.0285
2	10% SiC_p–Al composites, SiC_p 50µm	0–0.0829	0.0352
3	5% SiC_p–Al composites, SiC_p 150µm	0–0.0752	0.0686
4	10% SiC_p–Al composites, SiC_p 150µm	0.03306–0.136067	0.0724

4 Conclusions

This work evaluates the feasibility of machining SiC_p–Al MMC by micro-EDM using a rotary tube electrode. Despite the low electrical conductivity and high thermal resistance of the SiC reinforced particles, the results obtained indicate that SiC_p (5% and 10%, 50 µm)-Al and SiC_p (5% and 10%, 150 µm)-Al can be machined effectively.

1 In this work, the relationship between the MRR, EWR and hole taper and various process parameters namely pulse-on duration, pulse-off duration, sparking gap voltage and servo speed is developed.

2 Taguchi method is adopted for the design of experiments and analysis of experimental data is done successfully by maximising S/N ratio and ANOVA. The analysis of experimental data based on Taguchi method indicated the optimised levels of machining parameters for maximum MRR, minimum EWR and taper for all four types of SiC_p–Al MMCs. ANOVA and *F*-test of experimental data related to the essential machining parameters of micro-EDM revealed that servo speed significantly affected the MRR and EWR and pulse-on duration significantly affected the taper.

3 Experimental findings reveal that the weight percentage and size of the SiC in SiC_p–Al MMCs are important parameters. Increase in weight percentage of SiC_p as well as particle size has resulted in decrease in MRR, increase in EWR and taper.

In this method, it is observed that if an SiC particle comes ahead in the direction of progression of hole, the rate of machining becomes very less and the aluminium around this particle melts and particle is dislodged from its location. There is a scope to investigate easy and fast removal of SiC particle for obtaining a constant machining rate.

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Nomenclature

C.I.	Confidence interval
d_{jb}	Diameter of the machined hole at the bottom of the workpiece (mm)
d_{jt}	Diameter of the machined hole at the top of the workpiece (mm)
DOF_e	Degrees of freedom of error term
DOF_m	Degrees of freedom of mean (always 1)
e	Mean EWR (mm^3/min)
f	Fisher value
H	Height of the workpiece (mm)
η	Signal to noise (S/N) ratio
l	Number of parameter levels
M	Mean MRR (mm^3/min)
m	Overall mean S/N ratio
M.S.D.	Mean square deviation
MS_e	Mean square of error term
MS_j	Mean square of factor
n	Total number of experiments
N_e	Effective number of replications
n_p	Number of significant parameters
ρ	Percentage contribution
θ	Hole taper
SEN	Servo speed in no load condition (mm/min)
S_j^*	Mean of *i*th parameter at the optimum level for responses

S_m	Overall mean for responses
SS_e	Sum of squared error
SS_j	Sum of squared deviations for each design parameter
SS_T	Total sum of squares
S_v	Sparking gap voltage (V)
T	Mean taper (Degree)
T_{off}	Pulse-off duration (μs)
T_{on}	Pulse-on duration (μs)
V_e	Variance of error term