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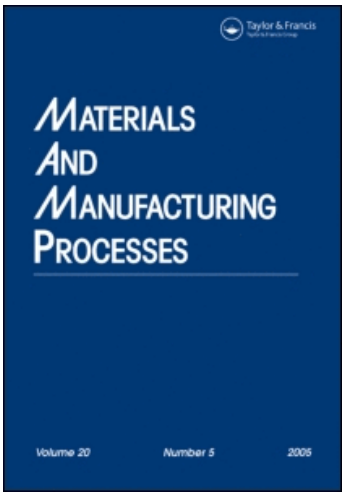

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Understanding the Role of Weight Percentage and Size of Silicon Carbide Particulate Reinforcement on Electro-Discharge Machining of Aluminium-Based Composites

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Understanding the Role of Weight Percentage and Size of Silicon Carbide Particulate Reinforcement on Electro-Discharge Machining of Aluminium-Based Composites

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This study investigates the feasibility of fabricating microholes in SiC_p-Al composites using micro-electro-discharge machining (micro-EDM) with a rotary tube electrode. Material removal rate (MRR), electrode wear rate (EWR), and hole taper were considered as responses for the study. Machining was performed on 5 and 10 wt% SiC_p-Al composites having particle size of 50 μm and 150 μm to evaluate machining characteristics. Pulse-on duration, pulse-off duration, sparking gap voltage, and servo-speed were used as input variables for EDM of SiC_p-Al composites by varying the weight percentage of SiC-reinforced particles and the size of reinforcement. The experimental results indicate the weight percentage and size of the SiC in SiC_p-Al metal matrix composites (MMCs) to be important parameters while machining using micro-EDM. The relative contributions of each process variable on MRR, EWR, and hole taper were found using the analysis of variance (ANOVA) technique. The experimental results reveal that servo-speed significantly affects the MRR and EWR, while pulse-on duration affected the taper.

Keywords Al metal matrix composites; Micro-EDM; Pulse-on duration; Pulse-off duration; Servo-speed; Sparking gap voltage.

Introduction

Metal-matrix composites (MMCs) are a unique class of material with the ability to blend the properties of ceramics with those of metals or alloys. The incorporation of a hard and brittle ceramic phase offers the potential for significant improvements in the mechanical performance of the composite over that of the monolithic metal or alloy. MMCs have received considerable attention in recent years because of their high strength and high stiffness. These properties, coupled with low density, and the ability to operate at elevated temperatures have made these materials suitable for use in the manufacture of a range of components in aerospace, defense to automobile industries [1–13]. However, the machining of MMCs using conventional methods or tool materials is very difficult due to the presence of the abrasive reinforcing phases, which can cause severe tool wear. Thus, nontraditional machining like electric discharge machining (EDM) can be used to perform precision machining of MMCs because the EDM process does not involve tool-workpiece contact, and the material removal rate is not affected by hardness, strength, or toughness of the workpiece material [3].

In order to produce a product having desired quality by micro-EDM, the process parameters should be selected properly. Pulse-on time, pulse-off time, servo-speed, and sparking gap voltage are the process parameters, which influence the machining process to a great extent. Apart from process parameters, material parameters have a significant effect on micro-EDM machining performance [2]. Among the various material parameters, weight percentage of SiC in SiC_p-Al metal matrix is an important material parameter, which determines the material removal rate (MRR), electrode wear rate (EWR), and hole taper. In addition to weight percentage of reinforcement, size of reinforcement has an important role in influencing response variables. Hence, in the present study an attempt has been made to assess the performance of micro-EDM of SiC_p-Al composites by using a rotary tube electrode including these two (weight percentage and size of reinforcement) aspects of composites.

Literature review

EDM and micro-EDM are widely used in a variety of industries such as automobiles, aerospace, textile, and others for different workpiece materials [1–6]. Hung et al. [4] investigated the feasibility of applying electrical discharge machining process for cast aluminum MMCs reinforced with silicon carbide particles (SiC_p). Statistical models were developed to predict the effect of process parameters on metal removal rate, recast layer, and surface finish. It was found that the SiC particles tend to shield and protect the aluminum matrix from being vaporized, thus reducing the metal removal rate. The input power controls the metal removal rate and the recast layer depth. However, the current alone dominates the finish of a surface processed by EDM.

Karthikeyan et al. [3] attempted to develop mathematical models for optimizing EDM characteristics such as the metal removal rate, tool wear rate, and surface roughness. The process parameters taken into consideration were the current, the pulse duration, and the percent volume fraction of SiC (25 μm size) present in the aluminium matrix. The MRR was found to be decreased with an increase in the volume

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percentage of SiC, whereas the TWR and surface roughness increased with an increase in volume percentage of SiC.

Yan and Wang [5] investigated the machining characteristics of Al_2O_3/6061Al composite using rotary EDM with a tubular electrode. They confirmed that the peak currents of EDM drilling and volume fraction of Al_2O_3 significantly affected the MRR, EWR, and surface roughness. In comparison, the flushing pressure and electrode rotation speed had minor affects on the MRR, EWR, and surface roughness. In another attempt, Wang and Yan [6] optimized the blind-hole drilling of Al_2O_3/6061Al composite using rotary electro-discharging machining and the Taguchi technique. An analysis of the Taguchi method revealed that the electrical parameters had a more significant effect than the nonelectrical parameters on the machining characteristics like (a) MRR, (b) EWR, and (c) surface roughness. They also derived semi-empirical equations to simplify the evaluation of various machining characteristics under consideration. Yan et al. [7] optimized the cutting of Al_2O_3/6061Al composite using rotary EDM with a disklike electrode and by using Taguchi technique. Rotary EDM with a disklike electrode resulted in higher MRR although the EWR was also found to be higher. They concluded based on their findings that the overall advantage made this revised technology an acceptable tool.

Mohan et al. [2, 8] used 20 and 25 vol% SiC_p-Al MMCs for 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. They observed that irrespective of electrode material, polarity of the electrode or volume percentage of SiC, the MRR increased with an increase in discharge current. For a specific current the MRR decreased with an increase in pulse duration. An increase in volume percentage of SiC had an adverse effect on MRR and a positive effect on TWR and surface finish.

Ramulu et al. [9, 10] 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 fatigue strength. They observed that EDM sparking dramatically increased surface roughness and caused slight subsurface softening in the microstructure below the outer recast layer. The fatigue strength was found to be notably reduced by EDM processing due to a greater degradation resulting from higher MRRs.

Seo et al. [11] investigated EDM machinabilty of Al matrix composite with 15 to 35 vol% SiC_p reinforcement in order to find out the optimum EDM conditions and product quality. It was observed that the MRR increased with increasing peak current and pulse-on time up to an optimal value and thereafter decreases drastically. Higher peak current and pulse-on-time resulted in greater tool wear and a larger error in average diameter. As the percentage of SiC particles increased, MRR was found to increase, and electrode wear was found to decrease.

Singh et al. [12] investigated the effect of current, pulse-on time and flushing pressure on MRR, TWR, hole taper, radial over cut, and surface roughness, while 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 the hole. Singh et al. [13] used Grey Relational Analysis to optimize the multiresponse characteristics of EDM of 10% SiC_p composites. They observed the process to improve considerably at optimal setting.

Lim et al. [14] gave the idea of on-machine fabrication of microelectrodes having high aspect ratio, and studied the EDM of the workpiece in micrometer range. Kaminski and Capuano [15] checked possibility of micro-hole machining by conventional penetration EDM and found the method was technically viable. The feasibility of applying the micro-EDM process on materials difficult to machine has been studied by a number of authors [16–19]. Muttamara et al. [16] and Liu and Huang [17] investigated the use of micro-EDM in the machining of ceramics. Yan et al. [18] investigated feasibility of using micro-EDM process to machine-cemented carbide. Recently, Nakaoku [19] performed machining of sintered diamond using micro-EDM. Experiments were carried out using four types of sintered diamond, composed of 1, 3, 10, and 20 μm diameter diamond particles. It was found that the sintered diamond had machining characteristics similar to those of the tungsten carbide alloys.

It is evident from review of the literature presented that most of the research attempts in the area of EDM of MMCs have concentrated on aluminium matrix composites having discontinuous reinforcements particles [2, 4, 8, 10–13], whiskers of SiC [9], and aluminium oxide [5–7]. A few researchers have investigated the machining characteristics of aluminium metal matrix using rotary EDM having a tube electrode and found the rotary EDM process to improve the process performance [2, 3, 5–8]. No attempt has been made on micro-EDM of SiC_p-Al MMC using the rotary electrode. Debris disposal, which is of prime concern in microdrilling, is critical for the machining of MMCs because an insulation of the reinforcement that may incur an abnormal arcing. Micro-EDM of SiC_p-Al composite using a rotary tube electrode may be helpful in overcoming this problem. Most of the attempts [2, 8, 11] in the area of EDM of MMCs have concentrated on varying percentage of reinforcement. However, the effect of change in reinforcement size has not been studied so far. Therefore, in the present study, an attempt is made to study micro-EDM machinabilty as a function of process parameters, weight percentage and size of SiC particles by analyzing MRR, EWR, and hole taper on the SiC_p-Al composites.

Experimental work

Preparation of Al Metal Matrix

SiC_p-Al MMC can be produced via solid state (powder metallurgy), liquid metallurgy (casting techniques), or metal spray methods [20, 21]. In the present study, casting method was chosen for the preparation of MMCs. MMCs made by the casting technique are most common because of their low cost and ease of fabrication. Al-SiC_p was successfully fabricated in foundry with SiC particle size of 50 μm and 150 μm containing 5% SiC and 10% SiC powder by weight. Stir casting process was used to accomplish this task and an induction-type furnace was used to melt the aluminium.

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Experimental Setup and Procedure

This work involved a series of experiments using Electronica small hole super drill machine equipped with a transistor switched power supply. A hollow tubular electrode of brass having diameter 0.3 mm was used to drill 5 and 10 wt% SiC_p-Al composites. In both MMCs, particles of the reinforcement have two different sizes, i.e., 50 μm and 150 μm. The electrode is fed downward into the workpiece under servo control in this micro-EDM machine. Figure 1 depicts the experimental setup of a Electronica small hole drilling EDM super drill ED-32U. Through holes were machined in the workpiece in order to determine the machining characteristics. Deionized 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 effects of micro-EDM machining parameters like pulse-on duration, pulse-off duration, sparking gap voltage, and servo-speed (sensitivity) were considered in this work. The various experimental conditions are given in Table 1. The machinability was evaluated in terms of MRR and EWR. The EDMed hole quality was evaluated in terms of hole taper. The MRR was calculated based on machined workpiece volume and total cutting time. The EWR was also calculated based on electrode wear volume and the total cutting time. A precision electronic balance was used to measure the electrode weight both before and after machining. The hole taper (θ) was calculated using the expression

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

FIGURE 1.—Electronica small hole drilling EDM super drill ED-32U.

TABLE 1.—Experimental conditions.

Machine tool	Small hole super drill EDM machine
Workpiece materials (anode)	Al-5% SiC_p, SiC particle size 50 μm Al-10% SiC_p, SiC particle size 50 μm Al-5% SiC_p, SiC particle size 150 μm Al-10% SiC_p, SiC particle size 150 μm
Workpiece size	25 × 25 × 10 mm^3
Electrode (cathode)	ø 300 μm (0.3 mm) Brass wire with density as 8.6 gm/cm^3
Pulse-on duration (T_{on})	2.0, 3.0, and 4.0 μs
Pulse-off duration (T_{off})	3.5–5.0 μs
Open Circuit Voltage (OCV)	94 Volt
Sparking gap voltage setting (S_v)	2 and 3 on the scale of 1 to 10
Servo-speed (SEN) in no load condition	24, 50, and 82 mm/min
Flushing pressure of die-electric fluid	5.6 kg/cm^2
Dielectric used	Deionized water

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 as shown in Fig. 2. The top and bottom diameters of the holes were measured with the help of profile projector.

Some of the pictures of micro-holes after machining under different micro-EDM conditions are shown in Fig. 2. All the pictures were taken by optical microscope at 100 X magnification. Despite the difference in machining conditions, all of the hole shapes obtained are similar and appear to be more or less circular. The circularity would be affected by erosion of the workpiece material due to flow of the debris, particularly the refractory grains of SiC.

RESULTS AND DISCUSSION

MRR

Despite the low electrical conductivity and high thermal resistance of the SiC 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 using rotary micro-EDM. The variation of MRR with pulse-on duration and servo-speed at different levels of pulse-off duration and sparking gap voltage for 5% SiC_p-Al and 10% SiC_p-Al having SiC particles size 50 μm and 150 μm is shown in Fig. 3. Results show that MRR increases with pulse-on duration in rotary micro-EDM of SiC_p-Al composites. This is due to an increase in the discharge energy conducted into the machining gap within a single discharge as the period increased with an increase in pulse-on duration. This could possibly be due to a superior debris removal effect of the rotating electrode. The dielectric forced through the small hole of the tubular electrode enhances better debris removal, which might have resulted in an improvement in MRR. The maximum pulse-on duration used in this study is 4 μs, which is considered as comparatively small duration. However, a further increase in pulse-on duration can result in reduction in MRR because of an increase in the diameter of the discharge column reducing the energy density at the electrical discharge spot [2, 22]. It is observed from Fig. 3 that as the pulse-off duration increases, the

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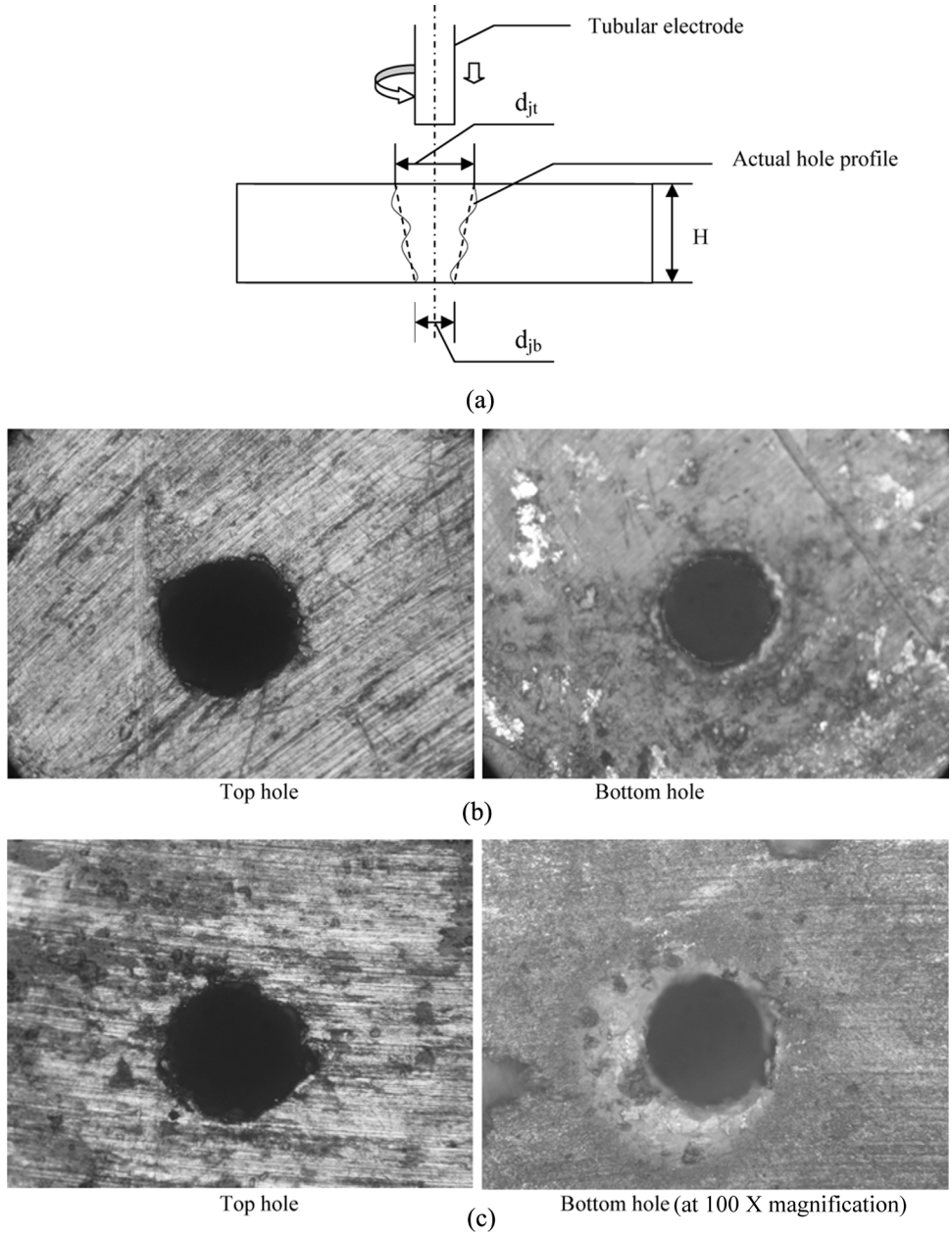

FIGURE 2.—Geometry of machined holes at top and bottom surfaces. (a) Proportionate sketch of micro-EDM using a rotary electrode; (b) Al-SiC (5%/50 μm SiC) at machining condition: $T_{on} = 3.0\,\mu s$, $T_{off} = 5.0\,\mu s$, $S_v = 2$ on the scale of 1 to 10, OCV = 94 V and SEN = 50 mm/min (in no-load condition); (c) Al-SiC (5%/150 μm SiC) at machining condition: $T_{on} = 2.0\,\mu s$, $T_{off} = 3.5\,\mu s$, $S_v = 2$ on the scale of 1 to 10, OCV = 94 V and SEN = 24 mm/min (in no-load condition).

MRR decreases slightly. This trend is expected because a long pulse-off duration causes less energy density on the SiC_p-Al metal composite workpiece coupled with less vaporization of the workpiece material while at the same time it improves the removal of entrapped SiC particles from the spark gap. It is also observed that as the servo-speed (sensitivity) increases, the MRR increases. As servo-speed increases, discharge frequency of the pulse generator increases with a shorter pulse duration causing higher MRR. From Fig. 3, it is evident that as the sparking gap voltage decreases the MRR increases. As value of gap voltage increases, it widens the gap width between the electrode and the workpiece. However, a wide gap shows a lower discharge current, which affects the MRR with an appreciable amount of electrode material depositing onto the workpiece surface [23]. The comparative performance analysis of the variation of MRR with respect to pulse-on duration for 5% SiC_p-Al and 10% SiC_p-Al has been carried out. It was found that MRR increased with an increase in content of SiC from 5% to 10 % for particles having a size of 50 μm. Similar results have been recently reported for SiC_p-Al composite [11]. The variation of MRR with respect to pulse-on duration for 5% SiC_p-Al and 10% SiC_p-Al for SiC particles having a size of 150 μm is shown in Fig. 3.

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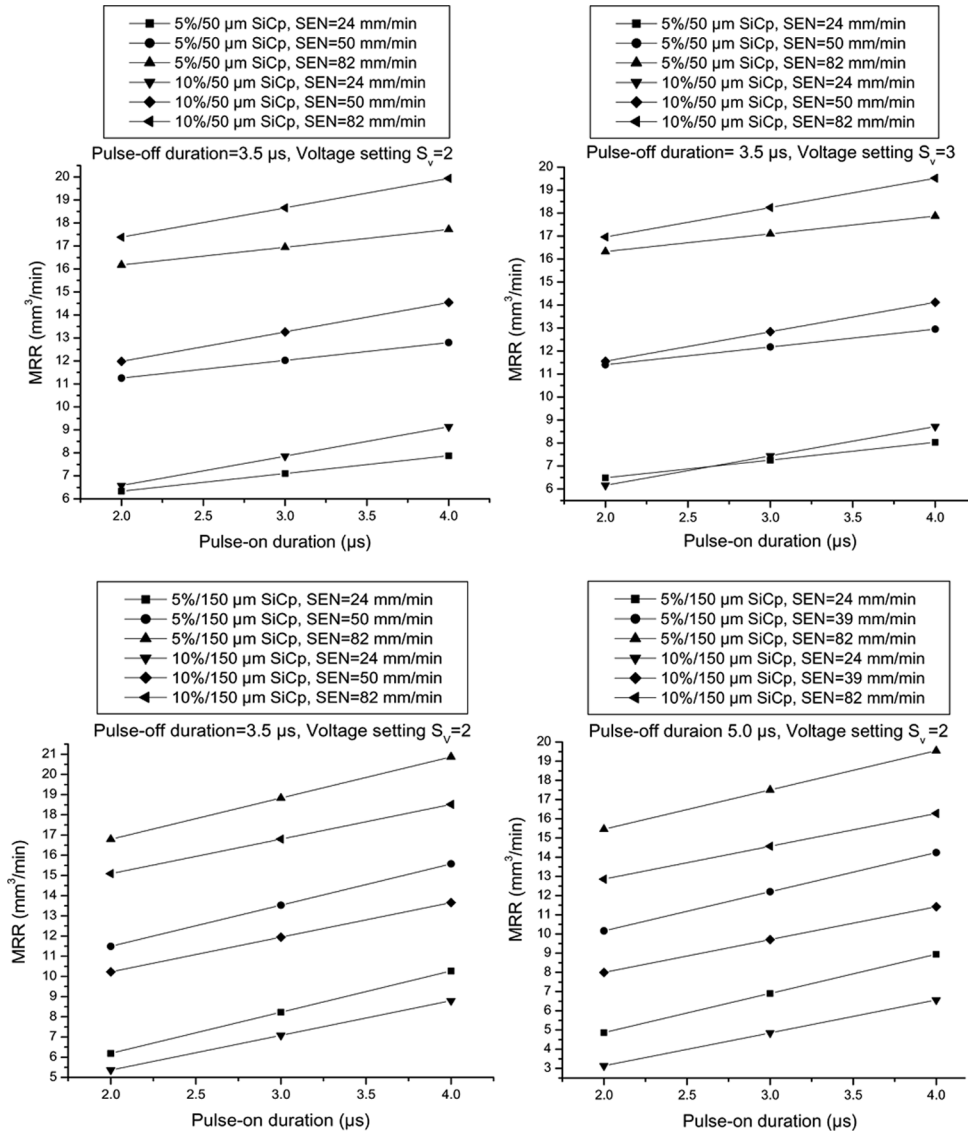

FIGURE 3.—Variation of MRR with pulse-on duration at various levels of pulse-off duration, sparking gap voltage and servo-speed.

The MRR of 5% SiC_p-Al was more than 10% SiC_p-Al for a particular sparking gap voltage, pulse-on duration and pulse-off duration. This could be due to a decrease in flow ability, and hence, an abrasive action of SiC as reinforcement when the 10% SiC_p-Al composite used having SiC_p particles size 150 μm. Similar results have been recently reported SiC_p-Al composite [2]. These results show that the particles size of SiC is one of the important parameter in EDM of SiC_p-Al metal matrix.

EWR

In Fig. 4, the relationship of EWR with pulse-on duration and servo-speed at different levels of pulse-off duration and sparking gap voltage for 5% SiC_p-Al and 10% SiC_p-Al having SiC particles size 50 μm and 150 μm is shown. The experimental results reveal the EWR to increase 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 wears out the rotary tube electrode. It is evident from Fig. 4 that EWR is minutely affected by the pulse-off duration. It has been observed that the EWR for 10% SiC_p-Al was more than 5% SiC_p-Al for 50 μm size SiC. This is due to an increase abrasive action of the SiC particles. It has also been observed that EWR was more in the case of 5% SiC_p-Al than 10% SiC_p-Al when the SiC particles size was 150 μm. It is evident that this result matches with the trend observed for MRR while micro-EDM of the same composite. The EWR deceases with increasing sparking gap voltage. High electrode gap voltage widens the gap between the electrode and the work piece. However, a wider gap implies a lower discharge current, which affects the MRR with an appreciable amount of electrode material depositing onto the workpiece surface. A lower MRR results in unwanted materials piling on the surface, thus undermining the quality of machining. Nevertheless, poor

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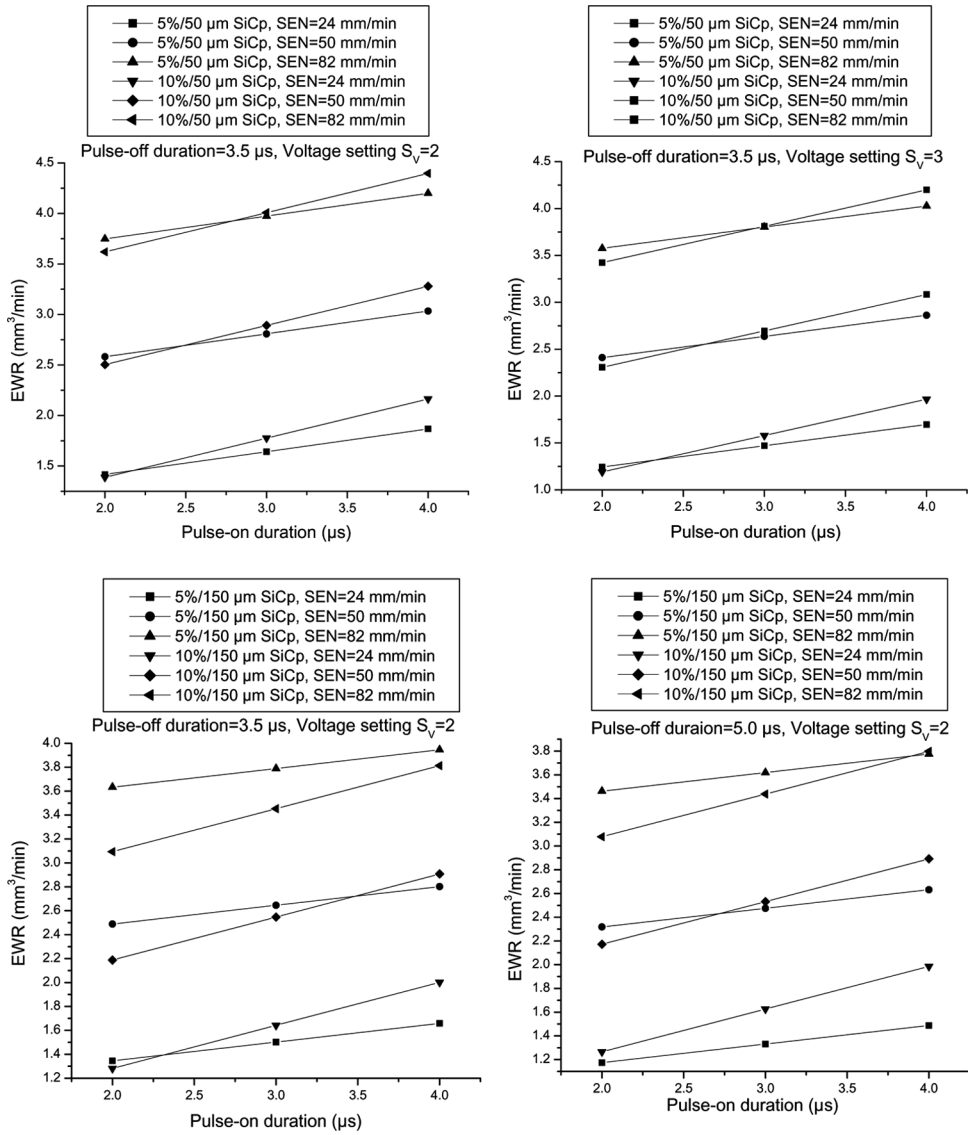

FIGURE 4.—Variation of EWR with pulse-on duration at various levels of pulse-off duration, sparking gap voltage and servo-speed.

material removal efficiency reduces tool wear and hence decreasing the EWR [23].

Taper

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 of the hole is a very important response [24]. It is observed from Fig. 5 that the micro-hole depicts a minimum taper at lower pulse-on duration. This is due to less discharge energy density and the 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. Results obtained in this study are in agreement with findings in literature [24] that taper of EDMed hole depended on pulse-on duration and pulse-peak current. It is observed from Fig. 5 that an increase in pulse-off duration decreases the values of taper. Increasing the pulse-off duration lowers heat flux due to shorter pulse-on duration at the discharge spot results in lower energy efficiency. Longer pulse-off duration gives more time for generation of recast layer at entrance (top) diameter, which causes the lowering of taper in the material. It is observed from Fig. 5 that an 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 (bottom) hole diameter. An increase in percentage of SiC particles causes an increase in taper. The low electrical conductivity and the high thermal resistance of the SiC particles decreased the conductivity of workpiece material. When these particles are eroded, they make erosion on the wall of the workpiece and also erode the electrode due to their abrasive nature.

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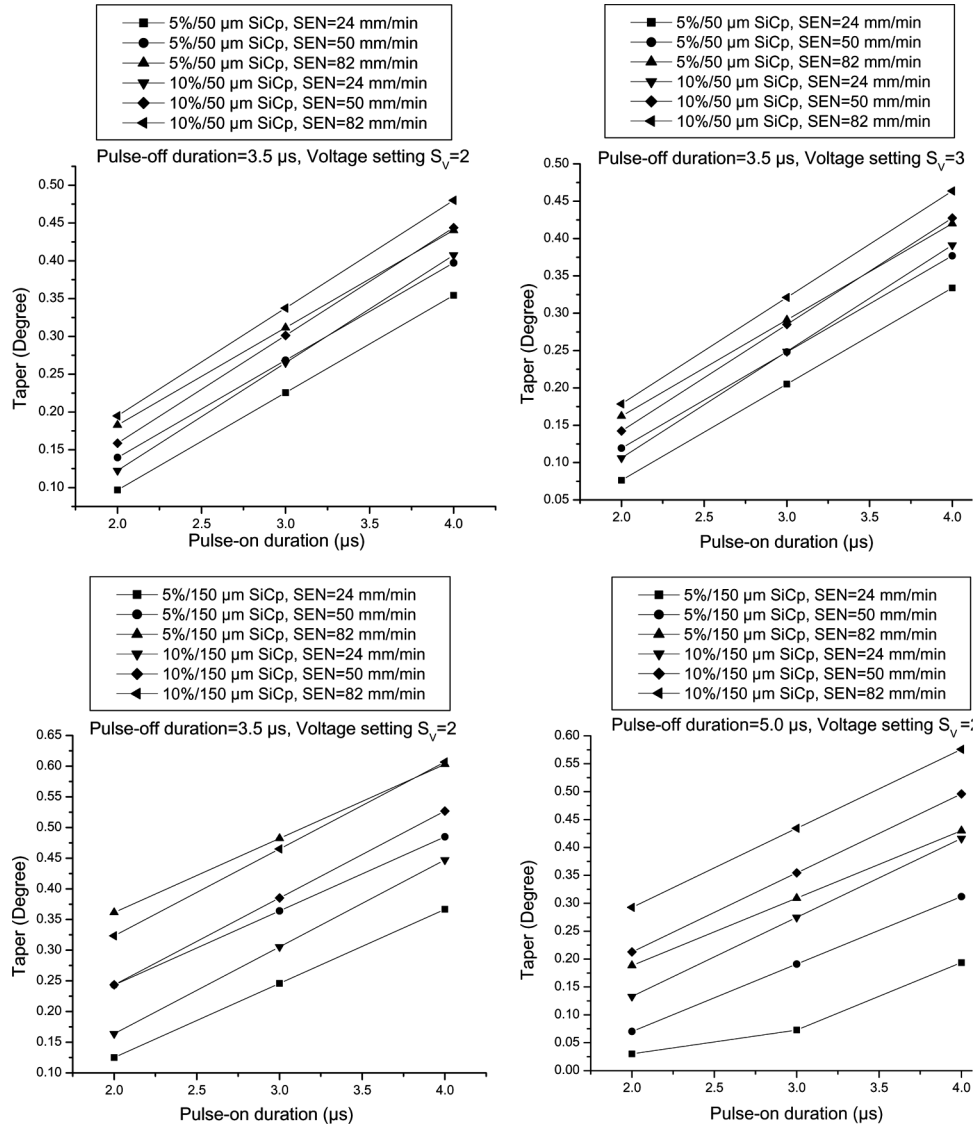

FIGURE 5.—Variation of taper with pulse-on duration at various levels of pulse-off duration, sparking gap voltage and servo-speed.

It was also observed that increase in size of reinforcement resulted in an increase in the taper. These occurrences may preferentially result in more erosion of the workpiece at entrance diameter due to exit of debris mixed with eroded reinforcement and thinning of electrode at end subsequently causing a large diameter variation between the entrances and exits. Sparking gap voltage decreased the taper as its value increases.

The relative contribution of each process variable on MRR was obtained in micro-EDM of different types of SiC_p-Al MMCs using analysis of variance (ANOVA) [25, 26] and shown in Fig. 6. The relative contributions of various factors on MRR in all variants of MMCs are more or less the same. The servo-speed is found to be the most significant factor influencing the MRR in all variety of SiC_p-Al MMCs. As the servo-speed increases, discharge frequency of the pulse generator increases with a

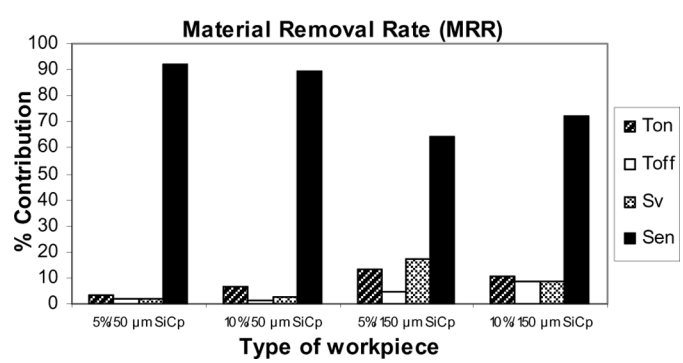

FIGURE 6.—Relative contribution of each factor (pulse-on duration 'T_{on},' pulse-off duration 'T_{off},' sparking gap voltage 'S_v,' and servo-speed 'SEN') on MRR.

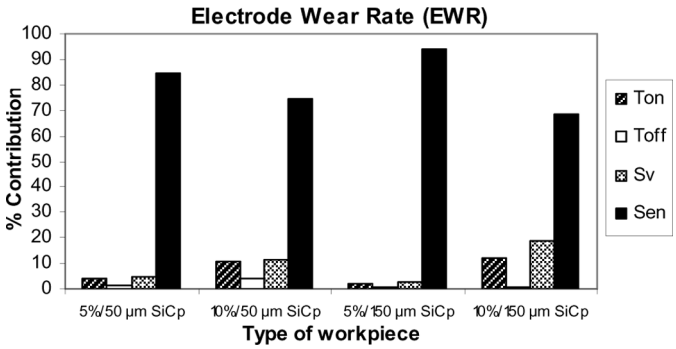

FIGURE 7.—Relative contribution of each factor (pulse-on duration 'T_{on},' pulse-off duration 'T_{off},' sparking gap voltage 'S_v,' and servo-speed 'SEN') on EWR.

shorter pulse duration, which causes higher MRR. Hence, the prominent influence of servo speed on MRR is justified.

ANOVA has been performed to find out the influence of different factors on EWR and is presented in Fig. 7. It has been found that the relative contributions of each factor on EWR in EDM of all types of SiC_p-Al used were close to each other. Figure 7 shows that the servo-speed is the most significant factor among all the considered factors. This is due to an increase in discharge energy conducted into the machining gap with an increase in servo-speed which improves MRR and increases the EWR. This signifies the need to include the servo-speed in empirical and analytical models of EWR.

The relative contribution of each process variable on hole taper were found in micro-EDM of different types of SiC_p-Al MMCs using ANOVA and shown in Fig. 8. It is observed from Fig. 8 that the relative contributions of various factors on taper in all variants of MMCs more or less the same. The pulse-on duration is found to be the most significant factor influencing the taper in all variety of SiC_p-Al metal matrix composites. As the hole taper in the micro-EDM directly depend upon the discharge energy density and unusual second discharge due to pile up debris, the prominent influence of pulse-on duration on hole taper is justified.

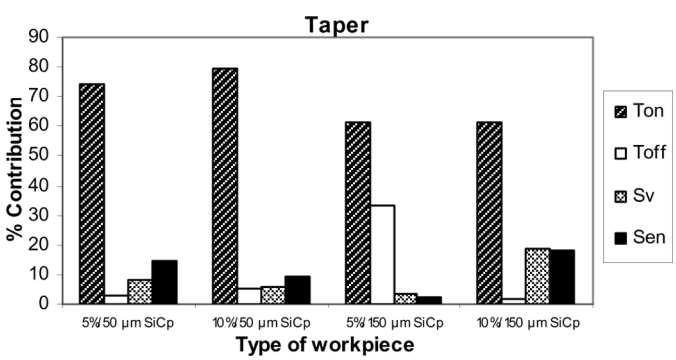

FIGURE 8.—Relative contribution of each factor (pulse-on duration 'T_{on},' pulse-off duration 'T_{off},' sparking gap voltage 'S_v,' and servo-speed 'SEN') on taper.

CONCLUSIONS

This study 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 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 by micro-EDM.

1. In present study, the relationship between the MRR, EWR, and taper with various process parameters, namely, pulse-on duration, pulse-off duration, servo-speed, and sparking gap voltage has been discussed. Results show that MRR increases with pulse-on duration and servo-speed, whereas it decreases with an increase in pulse-off duration and sparking gap voltage for all variety of SiC_p-Al composites used for the SiC_p-Al investigation.
2. The experimental data also reveals that the EWR increases with servo-speed and pulse-on duration. EWR has little variation with change in the pulse-off duration, deceases with increasing sparking gap voltage.
3. Hole taper increases with an increase in pulse-on time and servo-speed, whereas it decreases with an increase in pulse-off duration and sparking gap voltage. Experimental findings reveal that the weight percentage and size of the SiC particles in SiC_p-Al MMC are important parameters.
4. ANOVA of experimental data related to the cutting conditions and material properties of SiC_p-Al MMC using a rotary tube electrode reveals that servo-speed significantly affects the MRR, and EWR, while pulse-on duration affectes the taper.

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