Investigation of recast layers generated by a powder-mixed dielectric micro electrical discharge machining process

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Abstract: The use of powder-mixed dielectrics in micro-electrical discharge machining (micro-EDM) is an important technological development with the potential to improve machined surface quality and impart functional properties to machined surfaces. These process capabilities are vital in the manufacture of microcomponents since enhancing machined surface characteristics can extend their service life and improve their functionality. While studies have been conducted on gap enlargement and surface roughness, there is limited work on sub-surface characteristics. The present study assessed the recast layer thickness, given the potential of applying powder-mixed dielectrics to recast layer reduction and surface modification. Moreover, its process characteristics under specific micro-EDM process parameters, such as low powder concentrations, nano-sized powder granularities, and sub-microsecond pulse-on time durations, which have received limited coverage, have been elucidated. The study has revealed evident changes in recast layer thickness under different machining conditions. The reductions in recast layer thickness at a powder concentration of 0.1 g/l were found to range between 15 per cent and 35 per cent for pulse-on time durations between 166 ns and 606 ns. Furthermore, flushing effects from tool electrode rotation have been shown to exert an influence on recast layer thickness as well as on the amount of powder particles within the discharge gap.

Keywords: micro-electrical discharge machining, powder-mixed dielectric, nano-sized powder, rotary electrode flushing, recast layer thickness, discharge gap enlargement

1 INTRODUCTION

Electrical discharge machining (EDM) is a material processing technique that is commonly applied to hard and electrically conductive materials, such as tool and mould steels. Besides being employed for material removal applications, Gangadhar *et al.* [1] highlighted that its most significant process characteristic is the surface modification during actual EDM operation, which endows the machined surface with functional properties. While Gangadhar *et al.* used a powder compact tool electrode in the surface modification process, Yan *et al.* [**2**] demonstrated the same process characteristic with a powder-mixed dielectric. In the same study, Yan *et al.* also reported that the introduction of metal powders enlarged the discharge gap distance, divided the discharge current, and reduced surface roughness. As well as reductions in surface roughness, Ming and He [**3**] showed that the presence of powder additives in the dielectric caused thinner recast layers and fewer microcracks to be generated. Not only can the machined surface quality of the EDM process be improved through the use of a powder-mixed dielectric, the machined surface can also be imparted with functional properties. Furutani and Shiraki [**4**] used a MoS_2 powder-mixed dielectric to generate a lubricant layer on steel for applications in ultrahigh vacuum environments, such as space. It was reported that the lubricant layer produced in the powder-mixed dielectric had a smaller friction coefficient than the machined surface produced in the powder-mixed dielectric. In a more recent study,

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Furutani *et al.* [**5**] employed a titanium powder-mixed dielectric to produce a TiC modified layer on carbon steel, which exhibited a maximum hardness of 2000 HV.

The improvement of machined surface quality becomes more vital when EDM is used to produce microfeatures since machining imperfections are amplified as feature size is reduced. The presence of thermally induced residual stresses and microcracks in the recast layer can degrade the cyclic-load-bearing strength of the material and shorten the service life of machined components. Sharing these concerns, Ekmekci *et al.* [**6**] pointed out that the recast layer thickness is an important consideration in predicting the service life of microcomponents produced by EDM. Micro-electrical discharge machining (micro-EDM) is typically carried out using discharge energies of microjoule magnitude, which are effected by reducing pulse-on time durations to the sub-microsecond range. The use of small discharge energies ensures a small unit removal which, according to Masuzawa and Toenshoff [**7**], is an important factor in precision machining. However, the utilization of small discharge energies will not guarantee the elimination of machined surface imperfections, such as recast layer and microcracks, since Ekmekci *et al.* [**6**] showed the existence of microcracks in the recast layer when machining was performed at 217 μJ discharge energy. Therefore, performing micro-EDM in a powder-mixed dielectric (PMD micro-EDM) has been proposed as an alternative method for improving the machined surface quality of microfeatures. Besides improving machined surface quality, the PMD micro-EDM technique also has the potential to be employed in surface modification applications.

A review of technology and research developments in powder-mixed electrical discharge machining by Kansal *et al.* [**8**] indicated that studies conducted on PMD micro-EDM are still limited. The relevance of conducting specific research on micro-EDM stems from the sensitivity of process characteristics to machining conditions, which is magnified by the minute feature sizes produced and small machining parameter magnitudes employed. Chow *et al.* [**9**] fabricated microslits using a rotating disc electrode, powder materials of Al and SiC, powder granularity of 1 μm, powder concentrations between 2.5 g/l and 75 g/l, and pulse-on time durations between 5 μs and 40 μs. Through the study, gap distance and slit expansion were shown to increase with pulse-on time and powder concentration, respectively, and display a smaller increment at larger pulse-on time and powder concentration. In addition, it was reported that Al powder material generated the largest inter-electrode gap and smallest surface roughness. Pecas and Henriques [**10**] used a powder-mixed dielectric, containing Si powder with 10 μm average powder granularity at a concentration of 2 g/l, during the last three regimes of the finishing phase in conventional EDM equipment where discharge energies were 20 μJ, 10 μJ, and 9 μJ. The study focused on improvements in surface roughness for electrode areas between 1 cm^2 and 64 cm^2. In a more recent study by Pecas and Henriques [**11**] using similar machining conditions, surface roughness was evaluated with respect to direct jet flushing flowrates between 0.25 l/min and 2.5 l/min and recast layer thickness was assessed for varying Si powder concentrations between 1 g/l and 20 g/l. The average recast layer thickness was shown to decrease from 3 μm to 2 μm for a powder concentration of 1 g/l and decreased to 1.8 μm for a concentration of 20 g/l, as indicated by an empirically plotted trend line. In a study to investigate the effects of powder-mixed dielectrics on the thermal influenced zone, Klocke *et al.* [**12**] employed discharge currents of 10 mA and 65 mA with pulse-on time of 10 μs. The powder materials were Al and Si, while the powder granularity distribution comprised about 50 per cent having granularities less than 10 μm, to ensure entry of powder particles into the discharge gap. The results showed contrasting recast layer characteristics, which were attributed to the energy storage ability of the powder material. These studies, however, did not cover an essential operating window of the micro-EDM process in which sub-millimetre sized rod electrodes and sub-microsecond pulse-on time durations are employed for machining. The use of sub-millimetre sized electrodes limits the use of jet flushing techniques so that debris flushing is accomplished by electrode rotation. The reduction of pulse-on time to the sub-microsecond range also casts uncertainty on the adequacy of time for powder particles to effectively absorb the discharge energy and bring about changes to process characteristics.

In an attempt to address the knowledge gap in PMD micro-EDM, Yeo *et al.* [**13**] performed single discharge experiments using discharge energies less than 25 μJ, pulse-on time durations less than 400 ns, and a powder-mixed dielectric comprising SiC nanopowder at a concentration of 0.02 g/l, with granularities between 45 nm and 55 nm. The use of nano-sized powder granularities facilitated the entry of powder particles into the discharge gap while the low powder concentration minimized the occurrence of short-circuiting caused by bridging of powder particles between the tool electrode and workpiece. The results showed the presence of significant resolidified material build-up within the craters produced in a powder-mixed dielectric, which were absent in craters produced in a powder-free dielectric. Moreover, the craters produced in a powder-mixed dielectric were smaller and more regular in shape than those produced in a powder-free dielectric. These contrasting differences in crater morphology and geometry suggested the possibility of PMD micro-EDM at these conditions. The single discharge experiment results were extended to actual machining conditions by Tan *et al.* [**14**], whereby the effects of a powder-mixed dielectric on surface roughness were evaluated. Al_2O_3 and SiC powder materials with powder granularities in the range of 40–47 nm and 45–55 nm, respectively, were mixed into the dielectric in concentrations ranging between 0.02 g/l and 0.16 g/l. The arithmetic mean surface roughness of 150 μm deep microholes machined with input energies of 1.1 μJ and 16.5 μJ were compared with respect to powder material and concentration. The results showed that reductions in surface roughness of 14–24 per cent could be achieved. While these studies have revealed some characteristics of the PMD micro-EDM technique, there are other effects on process performance that need to be clarified. To further elucidate the process characteristics of PMD micro-EDM, investigations into the effects of electrode rotation speed, pulse-on time duration, and powder concentration on recast layer thickness were conducted in the present study. Recast layer thickness was chosen as the machining performance measure for evaluation as it not only serves as a gauge of the depth of subsurface machining defects, it also represents the thickness of functional layers in surface modification applications. The investigation also assessed the enlargement of gap distance due to increasing powder concentration and considered the effects of gap distance enlargement on recast layer thickness.

2 EXPERIMENTAL METHODS

A test rig was developed for the experiments on PMD micro-EDM to study the effects of tool electrode rotation, pulse-on time duration, and powder concentration on recast layer thickness. The test rig includes a resistance–inductance–capacitance (RLC) type pulse generator with capability for independent control of peak discharge current and pulse-on time duration. In addition, a motor possessing variable speed control is used to rotate the tool electrode during machining. The following sections give a detailed description of the experimental method.

2.1 Experimental set-up

Figure 1 gives a schematic representation of the experimental set-up. The pulse generator design is based on a resistance–capacitance generator circuit, which is commonly used in micro-EDM machines. However, a limitation of the resistor–capacitor circuit is a lack of independent control over peak discharge current and pulse-on time. Thus, the implemented pulse generator circuit includes a variable capacitor and inductor. On their own, the capacitor determines the input energy for electrical discharge, while the inductor prolongs the pulse-on duration with a reduction in peak current. Used concurrently, the capacitor and inductor allow pulse-on time to be varied with minimal changes to peak current.

The pulse generator circuit is connected to the tool electrode and workpiece such that the tool electrode is set as the cathode and the workpiece the anode, which is the conventional polarity arrangement in micro-EDM. The tool electrode is housed in a mandrel that is connected to the negative terminal of the pulse generator via a metal ball bearing so as to facilitate electrode rotation. The mandrel is rotated by a variable-speed motor through a belt connection. The mandrel and motor are mounted on a stage adapter, which is attached to a linear stage having a vertical displacement step size of 0.2 μm. The workpiece is directly connected to the positive terminal of the pulse generator and is secured in a dielectric tank.

2.2 Workpiece and tool electrode

The workpiece material used in the experiments is stainless mould steel (AISI 420-MOD). In order to aid the inspection of recast layers, blind microholes are machined at predefined locations along the mating line of a workpiece formed by wringing two workpieces together in a way similar to the wringing of

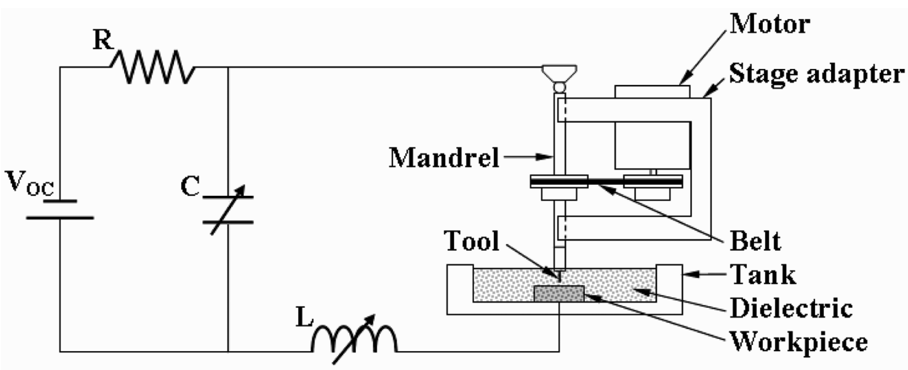


Fig. 1 Schematic diagram of the experimental set-up

gauge blocks. Then by exposing the mating faces, the cross-sections of the microholes are revealed for inspection. After being wrung together, the top surfaces of both workpieces are also lapped to ensure that the surface to be machined is levelled and to remove crevices caused by rounded workpiece edges along the mating line.

The tool electrode is a solid tungsten wire of 300 μm diameter. The tool electrode is rotated to aid flushing of debris from the discharge gap, which is typical in micro-EDM. Two electrode rotation speeds of 1000 r/min and 3000 r/min are used to assess the contrasting effects of electrode rotation speed on recast layer thickness. The electrode rotation speed of 1000 r/min was chosen as it corresponds to the maximum electrode rotation speed employed by Soni and Chakraverti [**15**] for studies on recast layer thickness in EDM, while 3000 r/min is a representative speed used in micro-EDM for flushing.

2.3 Dielectric and powder additive

The dielectric used is synthetic electric spark oil from Idemitsu named Daphne™Cut HL-25. The powder material is SiC and the powder particles are spherical in shape with granularities ranging between 45 nm and 55 nm. SiC was chosen as the powder material for PMD micro-EDM owing to its semi-conductive nature which, according to Chow *et al.* [**9**], produces a smaller enlargement of discharge gap distance compared with conductive powder materials and is thus better suited at minimizing machining over-cut. The SiC powder material has also been reported to generate thicker recast layer thickness by Tzeng and Chen [**16**] and would therefore facilitate the measurement of recast layer thickness. The powder concentration used has to ensure machining process stability while satisfying the objectives of the experiment. A powder concentration of 0.5 g/l is used in the initial experiment to study the influence of powder additives on recast layer thickness. This powder concentration has been selected to allow the effects of SiC powder on recast layer thickness to be evidently displayed under both electrode rotation speeds while providing a suitable degree of process stability. In the subsequent experiment, the powder concentration is increased gradually from 0 to 0.2 g/l for improved process stability through minimizing the flocculation of nanopowder particles. The reduced occurrence of flocculation also provides a sufficiently long powder settling time and maintains a relatively uniform powder suspension during the duration of machining. In the preparation of the powder-mixed dielectric, the required amounts of powder additive and dielectric are measured separately before being mixed together and homogenized in an ultrasonic bath.

Table 1 Experimental parameters for PMD micro-EDM investigation

Experimental parameter	Setting(s)
Open circuit voltage, V_{OC} (V)	100
Peak discharge current, I_{pk} (A)	1.45
Pulse-on time, t_{on} (ns)	166, 362, 606
Discharge energy, E (μJ)	5.0, 11.7, 21.0
Workpiece material	Stainless mould steel (AISI 420MOD)
Tool electrode material/size (μm)	Tungsten/Ø300
Powder material/granularity (nm)	Silicon carbide/45–55
Dielectric	Idemitsu Daphne™ Cut HL-25
Powder concentration (g/l)	0, 0.02, 0.05, 0.1, 0.2, 0.5
Electrode rotation speed (r/min)	1000, 3000
Hole depth (μm)	150

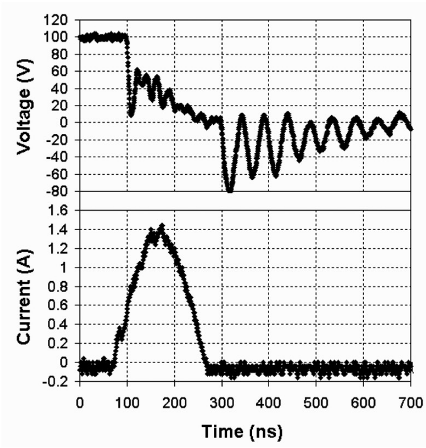
2.4 Machining parameters

Table 1 lists the entire range of parameters used during the investigation. Generally, a peak current of 1.45 A is used in combination with pulse-on time durations of 166 ns, 362 ns, and 606 ns to generate discharge energies of 5 μJ, 11.7 μJ, and 21 μJ, respectively. Only the pulse-on time duration is varied as Lee and Tai [**17**] noted that it affected recast layer thickness more significantly than changes in peak discharge current.

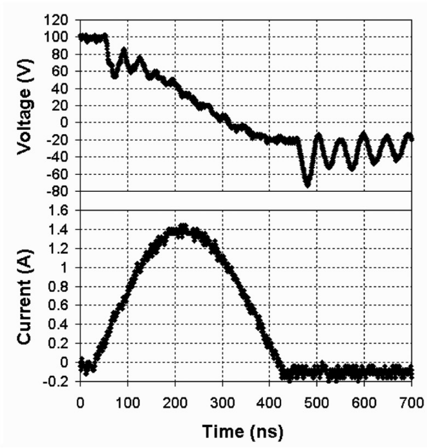
Figure 2 shows the discharge voltage and current waveforms for the three pulse-on time durations, which is measured from the occurrence of voltage breakdown to the cessation of current flow. All three pulse-on time durations are tested for each tool electrode rotation speed and/or powder concentration setting employed. For each combination of experimental parameters, five holes of 150 μm depth are machined.

2.5 Experimental procedure

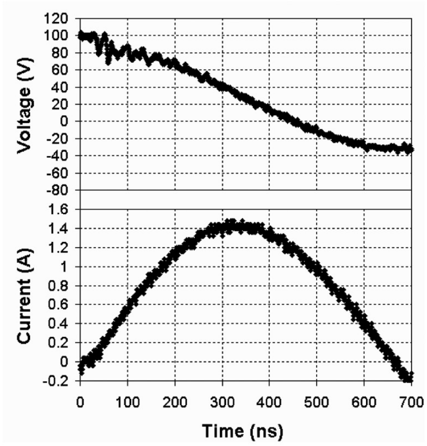
The present study involves the conduct of three experiments. The first experiment investigates the effects of tool electrode rotation speed on recast layer thickness. The rotation of the tool electrode causes the continuous flow of dielectric fluid through the discharge gap, thereby subjecting the machined surface to flushing effects. In a study on recast layer thickness generated at various pulse-on time durations under a constant direct flushing pressure of 0.5 kg/cm^2, Bhattacharyya *et al.* [**18**] attributed the effect of increasing recast layer thickness with increasing pulse-on time to the constant amount of molten material flushed away by the dielectric. An increased tool electrode rotation speed may impart a faster dielectric flow and stronger flushing effects than a slower rotation speed. Thus, comparing the recast layer thickness generated under electrode rotation speeds of 1000 r/min and 3000 r/min may show the contrasting effects of electrode rotation speed on flushing strength and



(a) $t_{on} = 166$ ns



(b) $t_{on} = 362$ ns



(c) $t_{on} = 606$ ns

Fig. 2 Discharge voltage and current waveforms at various pulse-on times

its consequence on recast layer thickness. Flushing effects from tool electrode rotation may also cause removal of powder particles from the discharge gap since distinction between the powder and debris particles is not made. With the decrease in amount of powder particles in the discharge gap, the effectiveness of PMD micro-EDM may fall. Thus, the second experiment investigates the influence of tool electrode rotation on the effectiveness of PMD micro-EDM. The powder concentration of 0.5 g/l is used to ensure that the effects from powder additives may be evident under all machining conditions while tool electrode rotation speeds of 1000 r/min and 3000 r/min are retained. Besides the influence of electrode rotation speed on flushing effects, Wong *et al.* [**19**] have also proposed that the presence of powder particles in the discharge gap causes discharge gap enlargement and a reduction in back pressure, which facilitates dielectric flow into the discharge gap and more effective flushing. The presence of powder particles in the enlarged discharge gap, as suggested by Zhao *et al.* [**20**], also prevents intensive discharge. In addition, it has been suggested that the enlarged discharge gap eases plasma channel expansion which increases the discharge heat-influenced area and reduces the discharge density. The effects of discharge gap enlargement, brought about by powder additives, on flushing and discharge intensity may be reflected in the resulting recast layer thickness and are studied in the third experiment. In this experiment, powder concentrations between 0.02 g/l and 0.2 g/l are used while the electrode rotation speed is maintained at 1000 r/min to promote the accumulation of powder particles within the discharge gap. To determine the gap distance, a reference height corresponding to the vertical location at which the tool electrode comes into contact with the workpiece is defined. Next the tool electrode is retracted by a distance of 50 μm from the reference height and the required dielectric is poured into the tank before the electrode is advanced towards the workpiece until electrical discharges occur. Then the vertical location of the tool electrode measured from the reference height is recorded as the gap distance.

2.6 Recast layer thickness measurements

Through the machining of blind microholes, recast layers are generated at the wall and floor of each microhole. The recast layer thickness at the floor of the blind microhole is measured since it is the surface subjected to continuous machining throughout the microhole drilling process and possibly the surface where the effects of flushing and powder additives are most predominant. The mating surfaces of the workpiece pieces that had been wrung together are polished and etched to reveal the recast layer which is visible as a white layer under an optical microscope with a 50× magnification lens. Figure 3 shows an image of the recast layer captured using optical microscopy, as well as a scanning electron microscopy (SEM) micrograph of an extracted region from the image.

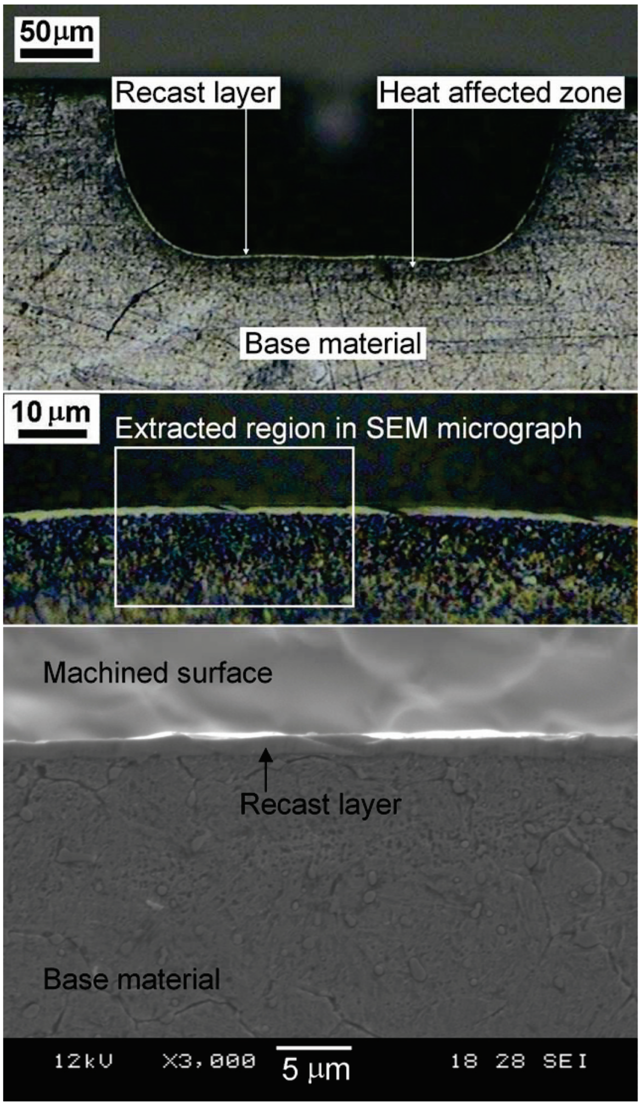


Fig. 3 Optical microscopy and SEM images of recast layer

To ensure that the recast layer thickness measured is representative of the entire recast layer, a 100 μm sample length of recast layer thickness is extracted for measurement. Furthermore, as recast layer thickness is not uniform throughout the sample length, a representative average recast layer thickness is determined. While Ekmekci *et al.* [**6**] took measurements of recast layer thicknesses from ten different locations in a sample section to study the deviations of thickness within a recast layer, the average recast layer thickness in the present study is estimated based on the area of the extracted recast layer. To estimate the area, the extracted recast layer is first discretized into unit areas with unit area magnitude of 0.02 μm^2/unit. Then the number of units required to fill the recast layer is summed and multiplied with the unit area magnitude to determine the measured area of recast layer. Next, the average recast layer thickness is estimated by discretizing the extracted recast layer into vertical elemental strips and applying the equation

$$h_{\text{ave}} = \frac{A_{\text{recast}}}{\Delta x \cdot i} \tag{1}$$

where h_{ave} represents the average height of the recast layer, A_{recast} the measured area of the recast layer, Δx the width of a vertical elemental strip measuring 125 nm, and i the total number of elemental strips spanning the recast layer. The average recast layer thickness as determined gives a closer estimate of recast layer thickness for each hole. In this way, the average recast layer thickness can be used to study the variations in recast layer thickness across different microholes so that a more representative comparison of the effects of machining conditions on recast layer thickness can be done. The minimum, maximum, and average values of h_{ave} for each machining condition are plotted (as shown in Figs 4 and 6 in sections 3.1 and 3.2).

3 RESULTS AND DISCUSSION

In this section, the effects of tool electrode rotation coupled with process conditions in micro-EDM on average recast layer thickness are compared. Following this, the effects of tool electrode rotation and process conditions in PMD micro-EDM on average recast layer thickness are covered. Finally, observations on discharge gap enlargement and recast layer thickness due to varying powder concentrations are discussed.

3.1 Tool electrode rotation without powder additive

Figure 4 illustrates the effects of tool electrode rotation speed and pulse-on time duration on recast layer thickness. The rotation speed of 3000 r/min generated a thinner recast layer thickness than the rotation speed of 1000 r/min. Thus the stronger flushing effect caused by a faster electrode rotation speed in micro-EDM not only promotes debris flushing, it also reduces the amount of molten material retained within the crater and subsequently resolidified on the machined surface. The reduction in recast layer thickness at 166 ns, 362 ns, and 606 ns is 47 per cent, 48 per cent, and 49 per cent, respectively.

Figure 4 also shows that when pulse-on time duration is increased, recast layer thickness also increases regardless of electrode rotation speed. However, at 1000 r/min, the variation in recast layer thickness is larger than that at 3000 r/min. Furthermore, as pulse-on time duration is increased the deviation in recast layer thickness also increases for 1000 r/min, but remains relatively constant for 3000 r/min. The increase in recast layer thickness as a result of increasing pulse-on time duration is mainly attributed to the production of more molten material by the greater discharge energy magnitudes at longer pulse-on time durations. Although more molten material is produced, the amount of molten material removed by flushing remains relatively constant and results in a net increase in recast layer thickness. The weaker flushing effect at 1000 r/min is also not as effective in flushing compared with 3000 r/min and is thus unable to provide adequate flushing to maintain process stability. The inconsistency in debris flushing and discharge gap condition leads to the larger deviation in recast layer thickness at 1000 r/min compared with that at 3000 r/min.

3.2 Tool electrode rotation with powder additive

The effects of powder additive on recast layer thickness are observable under electrode rotation speeds of 1000 r/min and 3000 r/min. Despite the higher rotation speed of 3000 r/min, thinner recast layers generated in the powder-mixed dielectric compared with the powder-free dielectric are still evident, as shown in Fig. 5. Also obvious is the increase in recast layer thickness with increasing pulse-on time duration, which occurs for both dielectric conditions.

The reductions in recast layer thickness caused by increasing the electrode rotation speed from 1000 r/min to 3000 r/min in the powder-free dielectric have been estimated to be 47 per cent, 48 per cent, and 49 per cent for 166 ns, 362 ns, and 606 ns, respectively. Figure 6 shows that the reductions in recast layer thickness due to higher rotation speed in the powder-mixed dielectric are 60 per cent, 37 per cent, and 41 per cent at 166 ns, 362 ns, and 606 ns, respectively. Thus a greater reduction in recast layer thickness occurs at 166 ns in the powder-mixed dielectric

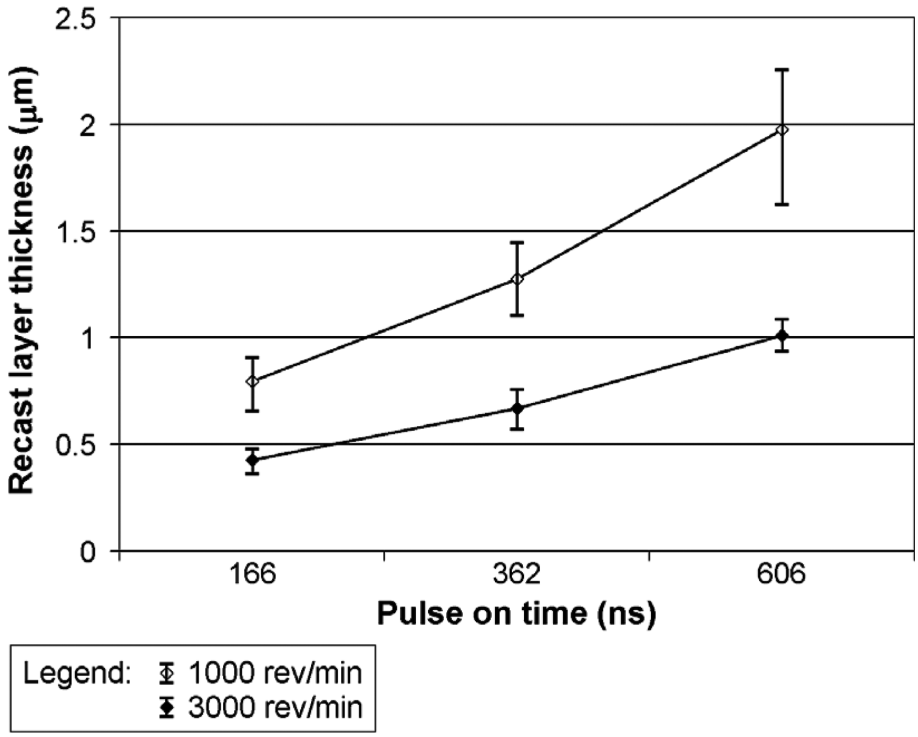
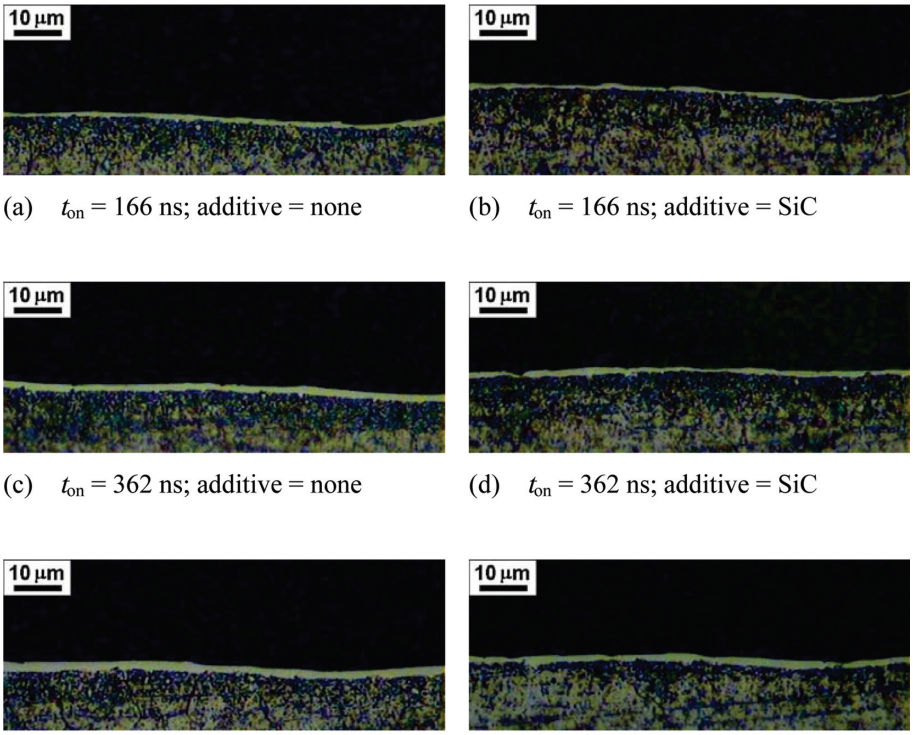


Fig. 4 Recast thickness at various pulse-on time and rotation speed values



(a) t_{on} = 166 ns; additive = none (b) t_{on} = 166 ns; additive = SiC

(c) t_{on} = 362 ns; additive = none (d) t_{on} = 362 ns; additive = SiC

(e) t_{on} = 606 ns; additive = none (f) t_{on} = 606 ns; additive = SiC

Fig. 5 Recast layers generated using electrode rotation speed of 3000 r/min

compared with the powder-free dielectric. On the other hand, a smaller reduction in recast layer thickness occurs at 362 ns and 606 ns in the powder-mixed dielectric compared with the powder-free dielectric. This suggests that recast layer thickness is affected not only by changes in flushing conditions, but also by a time-dependent interaction between the plasma channel and powder-mixed dielectric.

With the same powder concentration, discharge gap enlargement is similar for all pulse-on time durations. Thus, the flushing condition due to improved dielectric flow is similar for all pulse-on time durations. On the other hand, a longer pulse-on time results in a wider plasma channel and as the plasma channel grows the overpressure within the plasma channel decreases. The decrease in overpressure reduces the amount of superheated molten material that is boiled away at the end of discharge, as highlighted by Pandey and Jilani [**21**]. In addition to the larger amount of retained material, some molten material is also displaced by the plasma overpressure and flows into neighbouring craters where it resolidifies to produce overlapping recast layers as observed by Ekmekci [**22**]. Therefore the retained molten material and overlapping in recast layers cause the smaller reduction in overall recast layer thickness. At 166 ns, the time for plasma channel expansion is shorter and the plasma channel expansion facilitated by the presence of powder particles does not reduce the plasma overpressure significantly. Thus, similar amounts of molten material are expelled due to collapse of the plasma channel in both dielectric conditions. However, improved flushing in the powder-mixed dielectric causes additional molten material removal and a greater reduction in recast layer thickness.

Considering 362 ns and 606 ns, where the interactions between the plasma channel and powder-mixed dielectric are more evident, Fig. 6 also shows that the reduction in recast layer thickness due to use of the powder-mixed dielectric is more considerable at 1000 r/min than 3000 r/min. The reductions for 1000 r/min are 23 per cent and 22 per cent at 362 ns and 606 ns, respectively, while the corresponding reductions for 3000 r/min are 8 per cent and 10 per cent. Thus, the weaker flushing effects at 1000 r/min aid the accumulation of powder particles within the discharge gap, which consequently cause a more significant reduction in recast layer thickness.

Towards the end of the machining process, flocculation of powders particles is observed. This is due to the high powder concentration and an absence of external agitation forces to maintain the homogeneity of the suspension. At the same time the machining process stability is deteriorated, especially at the electrode rotation speed of 1000 r/min. Thus, to ensure homogeneity of the powder-mixed dielectric throughout the machining process, the range of powder

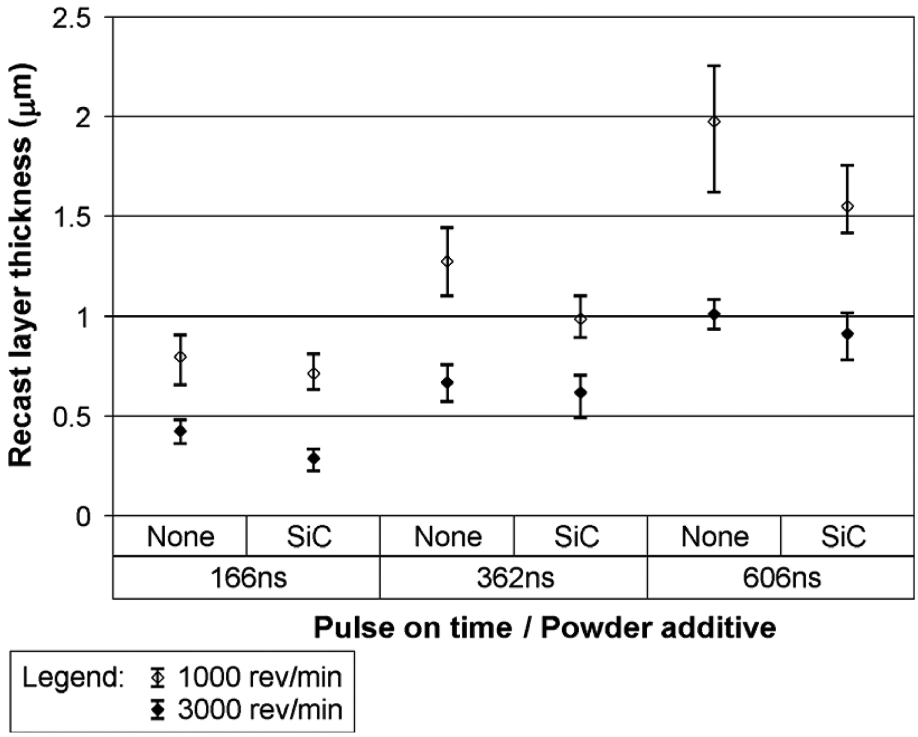


Fig. 6 Recast thickness due to machining in SiC powder-mixed dielectric

concentrations used is between 0.02 g/l and 0.2 g/l. The low powder concentration also facilitates the use of 1000 r/min electrode rotation speed so as to promote the accumulation of powder particles within the discharge gap.

3.3 Varying concentrations of powder additive

The measurements of discharge gap distance at different pulse-on time durations as shown in Fig. 7 indicate that discharge gap enlargement is similar for all pulse-on time durations. On the other hand, discharge gap distance is shown to vary with powder concentration. The rate of increase in gap distance with increasing powder concentration is higher for powder concentrations less than 0.05 g/l and significantly lower for powder concentrations between 0.05 g/l and 0.2 g/l. At 0.2 g/l the gap distance ranges between 35 μm and 38 μm, which represents a fivefold enlargement in the discharge gap.

The change in recast layer thickness with increasing powder concentration is also assessed and shown in Fig. 8. Reductions in recast layer thickness are present for all pulse-on time durations and display similarities to the increase in gap distance with increasing powder concentration. Generally, the rate of decrease in recast layer thickness with increasing powder concentration is higher for lower powder concentrations. The maximum reduction in recast layer thickness occurs at a powder concentration of 0.1 g/l, with reductions of 17 per cent, 15 per cent, and 35 per cent for 166 ns, 362 ns, and 606 ns, respectively. Since discharge gap enlargements at all pulse-on time durations are similar, the more significant reduction for 606 ns can be attributed to the longer time duration available for energy transfer interactions to occur at the plasma channel and powder-mixed dielectric interface. Eubank *et al.* [**23**] proposed that as the plasma channel expands during an electrical discharge, it vaporizes, disassociates, and ionizes the dielectric at the plasma channel and dielectric interface. Thus, powder particles at the interface will also absorb discharge energy, as observed by Klocke *et al.* [**12**]. As a result, a smaller fraction of discharge energy is available to melt the workpiece material and a shallower pool of molten material is formed. The shallower melt pool consequently limits the recast layer thickness. At low powder concentrations, an intermediate gap enlargement occurs which facilitates a similar degree of plasma channel expansion. In addition, the expansion of the plasma channel facilitated by the presence of powder particles is not as significant as that at higher powder concentrations. Therefore, with a greater plasma overpressure lesser molten material is retained and available to form overlapping recast layers, resulting in a reduction in recast layer thickness. With the increase in powder concentration and resulting gap enlargement, the ease of plasma expansion lowers plasma overpressure considerably and allows more molten material retention. However, more discharge energy is absorbed by the powder particles and a shallower melt pool is formed. Thus, the recast

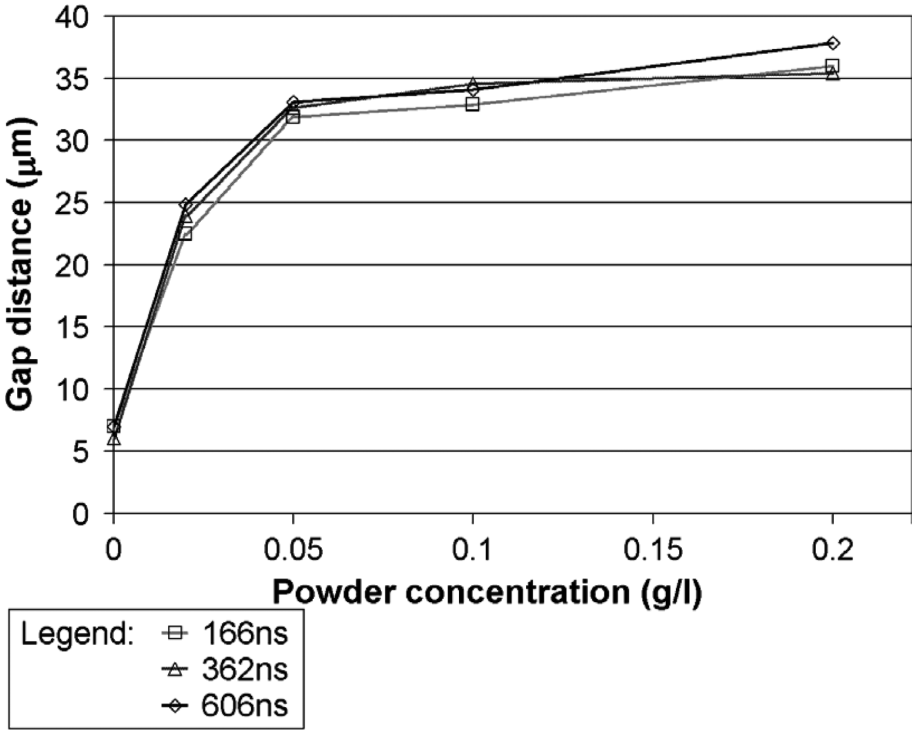


Fig. 7 Change in gap distance due to the presence of powder additive

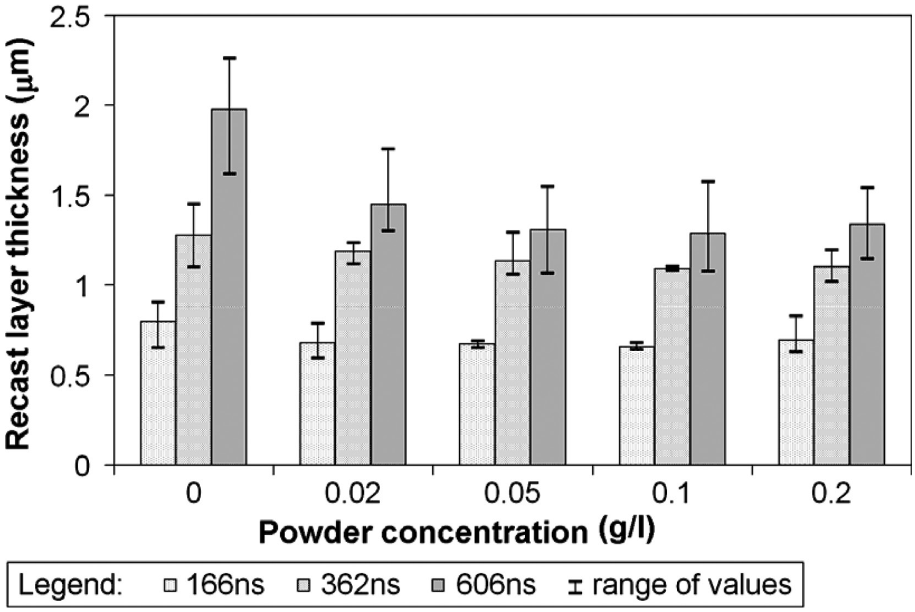


Fig. 8 Recast thickness due to different powder concentrations

layer thickness does not change considerably since the effect of a shallower melt pool is offset by the effects of more molten material retention and overlapping recast layer formation. At 166 ns and 362 ns, the shorter pulse-on time durations limit the interaction time between the plasma channel and powder-mixed dielectric. Thus, despite increases in powder concentration, the reductions in recast layer thickness are not as considerable compared with 606 ns.

4 CONCLUSIONS

The process characteristics of PMD micro-EDM in the generation of a recast layer have been revealed. In the investigation, machining conditions specific to PMD micro-EDM such as sub-millimetre size electrode, flushing with tool electrode rotation, discharge energies in the microjoule range, pulse-on time durations in the sub-microsecond range, powder granularities in the nanometer range, and powder concentrations less than 1 g/l have been employed. The process characteristics were studied through an assessment of changes in recast layer thickness, which can serve as a gauge for the depth of subsurface machining defects and as a measure of functional layer thickness in surface modification applications. The major findings of the investigation can be summarized as follows.

1. The use of SiC powder material, powder granularity in the nanometre range, and powder concentration of 0.5 g/l and below is conducive for PMD micro-EDM using discharge energies in the microjoule range and pulse-on time durations in the sub-microsecond range.
2. The pulse-on time duration of 606 ns provides a longer interaction time and allows a wider expansion of the plasma channel for energy transfers at the plasma channel and dielectric interface, compared with 166 ns and 362 ns.
3. Tool electrode rotation generates flushing effects which can affect recast layer thickness and the accumulation of powder particles within the discharge gap. The rotation speed of 1000 r/min promotes the accumulation of powder particles for PMD micro-EDM and generates thicker recast layers than 3000 r/min.
4. The presence of powder particles within the discharge gap creates two opposing effects that affect recast layer thickness. The absorption of discharge energy generates a shallower melt pool while the ease of plasma channel expansion reduces plasma overpressure and facilitates molten material retention and overlapping recast layer formation.

The findings of the present investigation should be considered in studies related to the use of PMD micro-EDM for surface quality improvement and surface modification. In relation to surface modification, an assessment of the effectiveness of PMD micro-EDM in alloying powder material onto the machined surface is recommended as future work.

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APPENDIX

Notation

A_{recast}	measured area of recast layer
E	discharge energy
h_{ave}	average height of recast layer
i	total number of elemental strips
I_{pk}	peak discharge current
t_{on}	pulse-on time
V_{OC}	open circuit voltage
Δx	width of a vertical elemental strip