Effects of Nanopowder Additives in Micro-electrical Discharge Machining

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The use of electrical discharge machining (EDM) for micro-machining applications requires particular attention to the machined surface roughness and discharge gap distance, as these factors affect the geometrical accuracy of micro-parts. Previous studies of conventional EDM have shown that selected types of semi-conductive and non-conductive powder suspended in the dielectric reduced the surface roughness while ensuring a limited increase in the gap distance. Based on this, an extension of the technique to micro-EDM was studied. Such work is necessary since the introduction of nanopowders suspended in the dielectric is not well understood. The experimental results showed that a statistically significant reduction in the surface roughness value was achieved at particular concentrations of the powder additives, depending on the powder material and the machining input energy setting. The average reduction in surface roughness using a powder suspended dielectric was between 14-24% of the average surface roughness generated using a pure dielectric. Furthermore, when these additive concentrations were used for machining, no adverse increase in the gap distance was observed.

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NOMENCLATURE

C = capacitance value of capacitor setting
d_{gap} = amount of over-cut
E = machining input energy setting
i = location of Ra measurement
j = micro-hole identification number
k = machining condition identification number
$L_{initial}$ = electrode length before machining
L_{final} = electrode length after machining
n = number of holes machined using the same machining conditions
Ra = arithmetic average surface roughness
Ra_{ave} = average surface roughness taken over all holes machined under the same machining conditions
V_{oc} = open-circuit voltage
Z_{set} = desired hole depth
Z_{hole} = measured hole depth

1. Introduction

Electrical discharge machining (EDM) is a fabrication technique that has been used both in conventional machining as well as micro-machining (micro-EDM). Micro-EDM shows promise due to the absence of physical contact between the tool electrode and the workpiece during machining. This results in negligible machining forces, making the process conducive to micro-machining applications. Micro-EDM covers a wide range of processes[1,2] that includes micro-hole boring, wire electro-discharge grinding, and three-dimensional machining. Since it is a micro-machining process, micro-EDM must satisfy the precision machining considerations highlighted by Masuzawa *et al.*,[3] specifically, the machined surface roughness must be reduced in proportion to the size of the micro-product, and the condition of the interface between the tool and workpiece will affect the accuracy of the shape reproduction. The surface roughness is significant because a machined surface produced by micro-EDM is characterized by overlapping craters that limit the achievable minimum surface roughness. The interface between the tool electrode and the workpiece is important in micro-EDM because machining occurs across a discharge gap, the distance of which has to be taken into account to ensure the geometrical accuracy of the machined workpiece.[4] The gap distance is affected by a number of factors, such as the presence of machined debris in the dielectric within the discharge gap[5] and the applied open-circuit voltage used during machining.[6]

In conventional EDM, a viable method of reducing the surface roughness of a machined workpiece involves the use of powder suspended dielectrics[7-9] (PSD-EDM). In the PSD-EDM technique, the dielectric is typically mixed with micro-sized powder particles that are made of a conductive material, such as silicon[10] or aluminum.[11] The use of PSD-EDM has been shown to generate small shallow uniformly sized craters through a mechanism in which the dielectric breakdown is achieved at a wider gap distance and the discharge current paths are broken up and distributed over the workpiece surface by the powder in the dielectric.[12] It has also been reported that as the concentration of powder additives mixed into the dielectric increases, the discharge gap also increases to a limit beyond which any further increase in additive concentration has no effect.[13] An excessive amount of powder additives in the dielectric is likely to cause similar machining process characteristics as an excessive accumulation of machined debris in the dielectric, which results in damage to the machined surface and degraded process stability due to the frequency of arc discharges and increased short-circuits. Thus, the choice of additive material, powder particle size, and additive concentration are some of the important considerations in PSD-EDM.

For micro-EDM, there has been little research into the use of powder suspended dielectrics for machining (PSD micro-EDM) However, based on studies conducted for PSD-EDM, findings that are potentially applicable to micro-EDM may be extracted and explored further for PSD micro-EDM. Chow *et al.*[14] investigated variations in the material removal depth and width expansion of micro-slits machined on a titanium alloy workpiece using a disc-shaped electrode in a powder suspended dielectric. The experiment was conducted using conventional EDM machining parameters with either semi-conductive silicon carbide (SiC) powder or conductive aluminum (Al) powder suspended in the kerosene dielectric. The results of the study showed that compared to machining in kerosene without any additives, the maximum material removal depth increased about 1.6 times and the maximum width expansion increased about 3 times as the concentration of additives was changed. In another PSD-EDM study by Yan *et al.*,[15] non-conductive alumina (Al_2O_3) powder suspended in a dielectric was used in the fabrication of holes in an SKD11 workpiece with a rotating tool electrode. The experimental results indicated that the alumina powder had no effect on the gap distance but improved the workpiece surface finish. Although these studies were conducted under machining conditions using conventional EDM, the findings related to the effects of powder additives on the surface finish and gap distance may be potentially useful for PSD micro-EDM since the possibility of reducing surface roughness while maintaining a small discharge gap is attractive for micro-EDM.

Given this possibility of reducing surface roughness while maintaining a limited increase in the gap distance by using powder suspended in dielectrics, a study into the use of semi-conductive and non-conductive powder materials for PSD micro-EDM is proposed. In this study, the effects of the powder material and concentration on the surface roughness and discharge gap distance using micro-EDM machining conditions are examined.

2. Experimental Details

2.1 Equipment Setup

The experiment was performed using a commercially available micro-EDM system (Panasonic MG-E72W) fitted with a closed-circuit TV (CCTV) camera with a 5× magnification lens as shown in Fig. 1. The machining process was monitored through the discharge voltage and current waveforms captured using a Tektronix P5205 voltage probe and a Tektronix TCP312 active current probe, and displayed on an HP54616 oscilloscope.

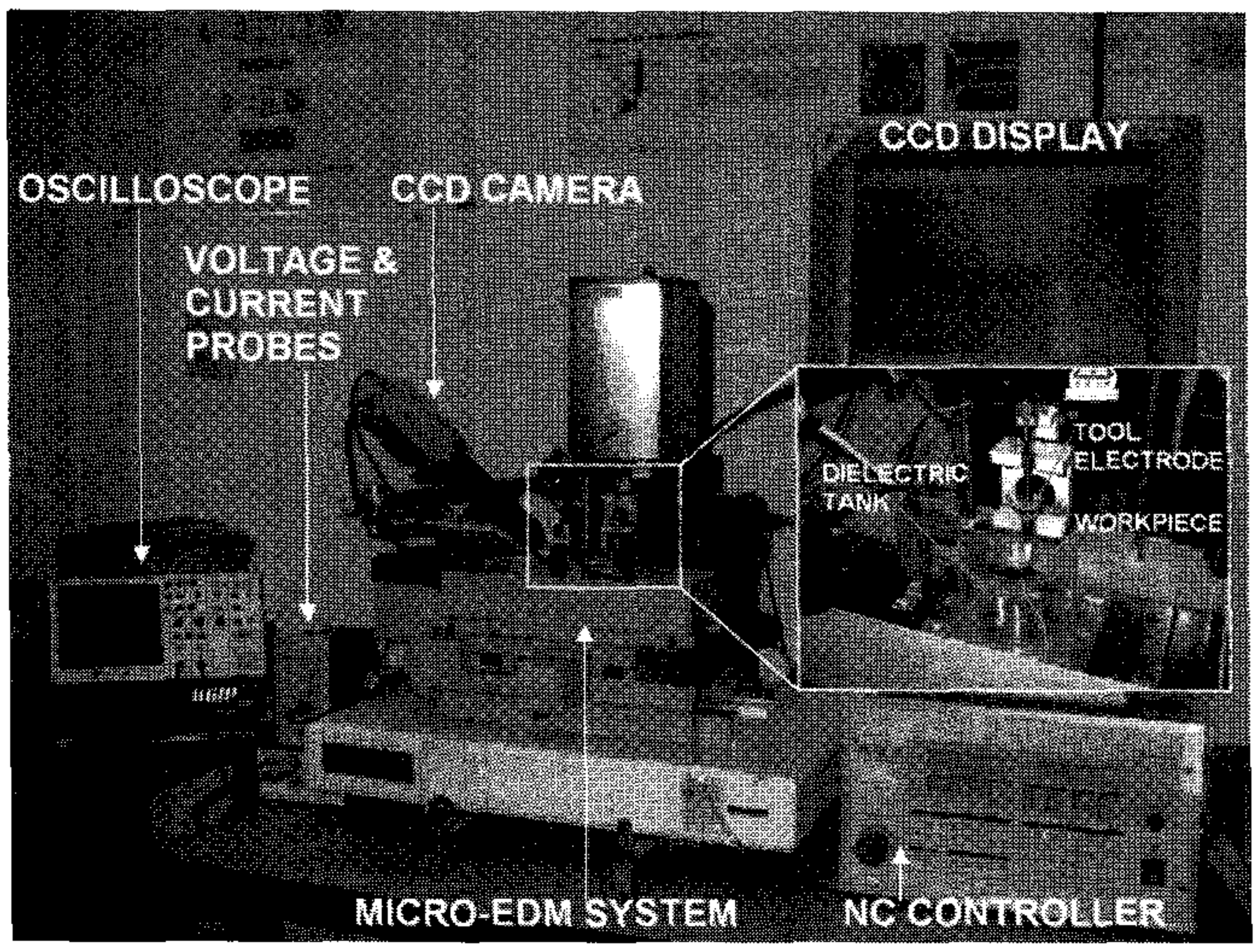

Fig. 1 Experimental setup

2.2 Materials

Machining was performed using a 300-μm diameter tungsten rod tool electrode and a workpiece made of stainless plastic mold steel with a chemical composition shown in Table 1. Each workpiece was made of two halves measuring 10 × 5 × 10 mm so that when placed together, they formed a 10 mm cube. This sandwich method was used to facilitate measurements of the micro-hole depth and the surface finish.

Table 1 Chemical composition of the workpiece material

Material	Chemical composition (%)						Reference standard
	C	Mn	Cr	Mo	V	W	
Stainless mold steel	0.38	0.5	13.6	-	0.3	-	AISI 420 MOD

The dielectric used was Idemitsu Daphne Cut HL25-S the and powder additives were silicon carbide (SiC) and aluminum oxide (Al_2O_3) nano-sized powders whose characteristics are shown in Table 2. The powder suspended in the dielectric was prepared using a two-step method in which the largest required concentration of nanopowder was added to the dielectric, and the mixture was subjected to ultrasonic agitation to facilitate particle dispersion and reduce agglomeration to achieve a homogeneous suspension. In subsequent batches, powder-dielectric mixtures with lower additive concentrations were prepared by diluting the highest concentration with an appropriate amount of additional dielectric.

Table 2 Characteristics of the powder additives

Powder Material	Aluminum oxide (Al_2O_3)	Silicon carbide (SiC)
Particle size (nm)	40–47	45–55
Electrical conductivity ($\Omega^{-1}cm^{-1}$)	1×10^{-14}	1×10^{-6}
Concentration (g/l)	0.02, 0.04, 0.08, 0.16	0.02, 0.04, 0.08

2.3 Measurement

The dimensions of the tool electrode before and after micro-hole drilling as well as the dimensions of the resulting micro-holes were measured using an optical microscope (ROI OMIS II). In addition, the surface roughness of the micro-holes was measured using a confocal imaging profiler (PLμ, Sensofar) with a 100× magnification lens.

2.4 Machining Parameters

During the experiment, micro-holes were machined using the machining parameters shown in Table 3. The input energy setting (E) was calculated using the formula $E = 0.5CV_{oc}^2$, where C is the capacitance value corresponding to the capacitor setting and V_{oc} is the open-circuit voltage.

Table 3 Machining parameters used for the experiment

Machining parameters	Settings
Open-circuit voltage (V)	100
Capacitor setting (pF)	3300 and 220
Input energy setting (μJ)	16.5 and 1.1
Powder additives	Al_2O_3 and SiC
Powder concentration (g/l)	0.02, 0.04, 0.08, 0.16
Hole depth (μm)	150

2.5 Experimental Procedure

Before each hole was machined, the tool electrode was dressed to ensure that the rounded corners caused by electrode wear were removed and that the end face of the tool electrode was flat. The tool electrode length was then measured using the optical microscope, after which it was mounted on the micro-EDM machine and positioned directly above the mating line of the two halves of the workpiece using the NC controller. Then, the powder suspended in the dielectric was agitated with a stirrer, and micro-hole drilling to the required depth was performed. After machining, the tool electrode was removed and its length was measured again using the optical microscope. After this, the tool electrode was dressed for the next machining cycle.

3. Results and Discussion

3.1 Surface Roughness

The roughness of the machined surfaces was measured using the confocal imaging profiler. For each hole, a total of 10 surface roughness readings (Ra_i) were captured from the predetermined locations shown in Fig. 2, and the average surface roughness of the hole was calculated using

$$Ra_j = \frac{1}{10}\sum_{i=1}^{10} Ra_i \tag{1}$$

where subscript j identifies the hole and i refers to the location of the measurement.

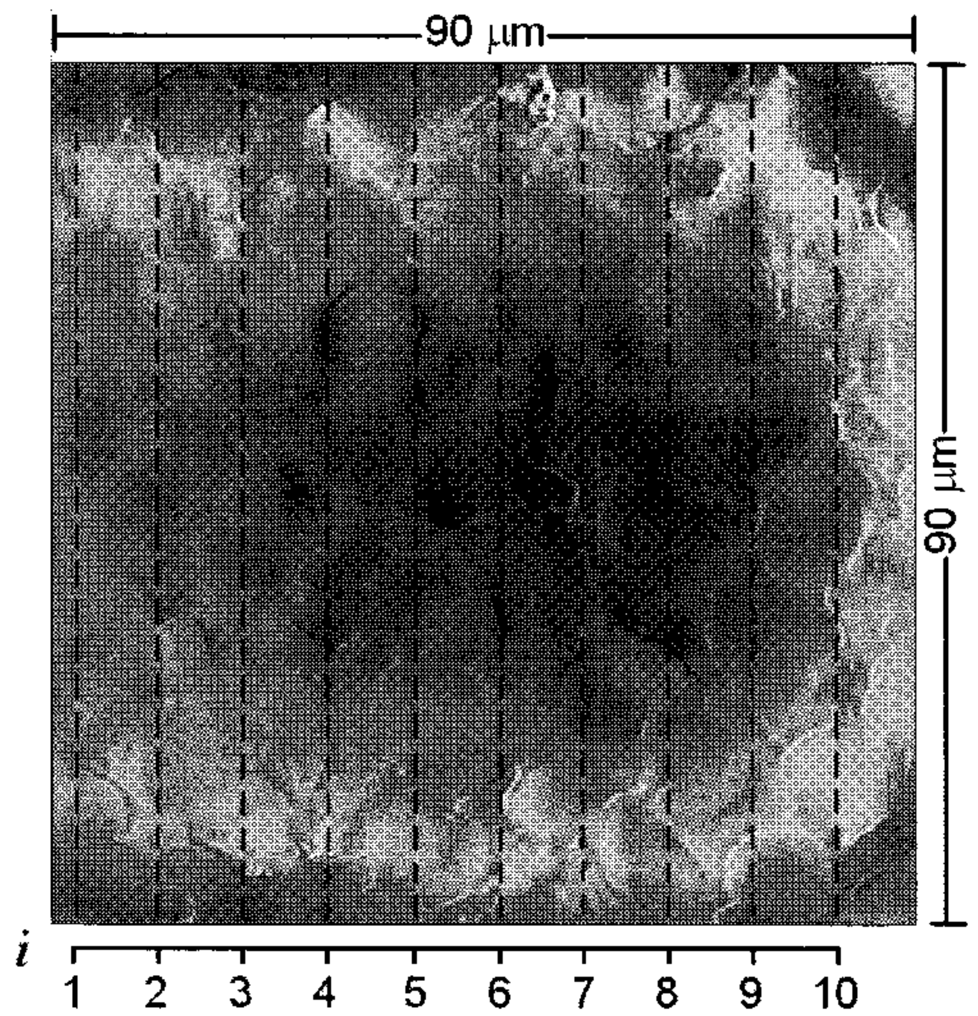

Fig. 2 Locations of the surface roughness measurements

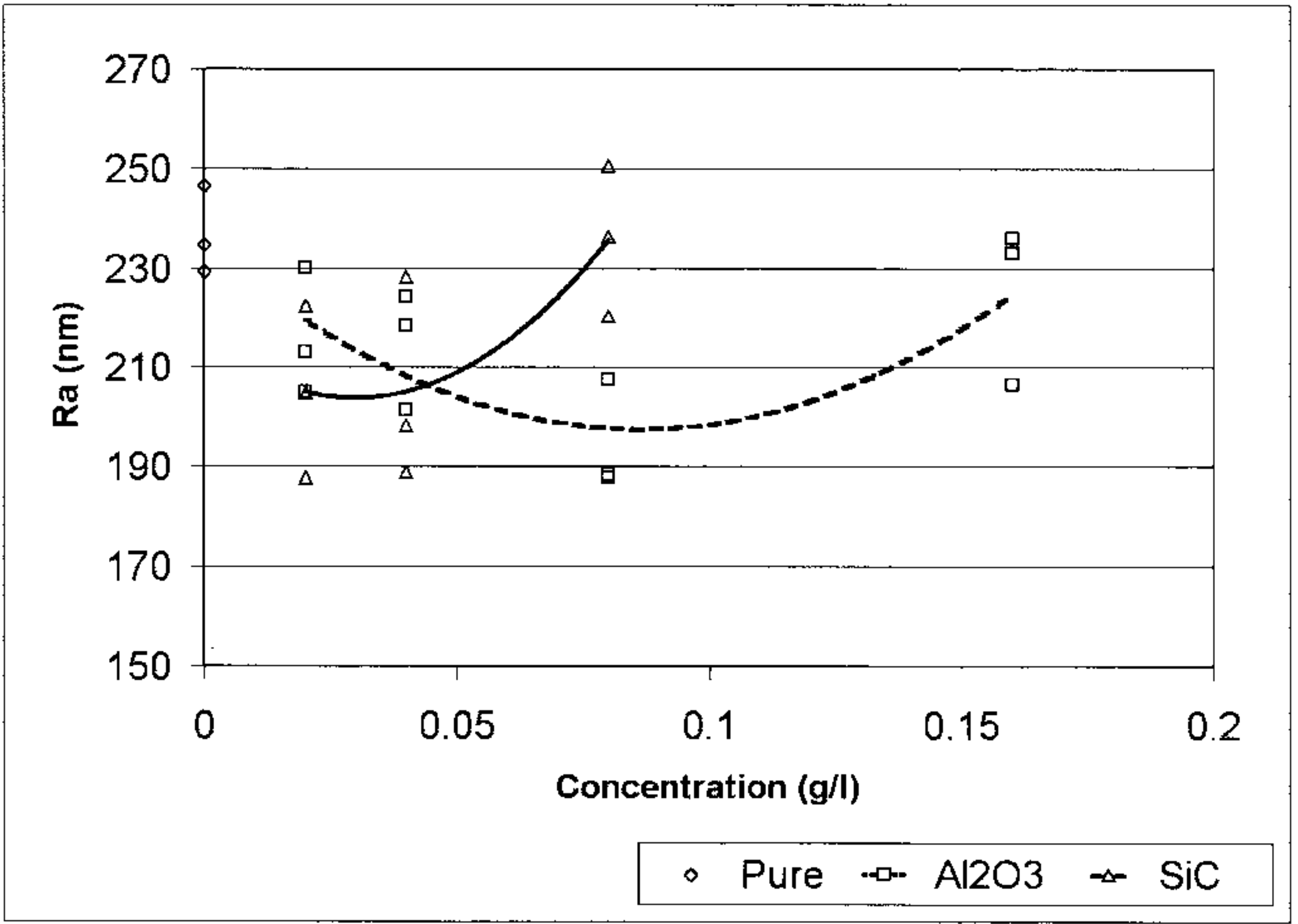

Fig. 3 *Ra* as a function of additive concentration for an energy of 16.5 μJ

The values of Ra_j for all the machined holes at input energy settings of 16.5 μJ and 1.1 μJ are shown in Figs. 3 and 4 respectively. A second-order best-fit polynomial line of second was drawn through the data points to estimate the trends of the variations.

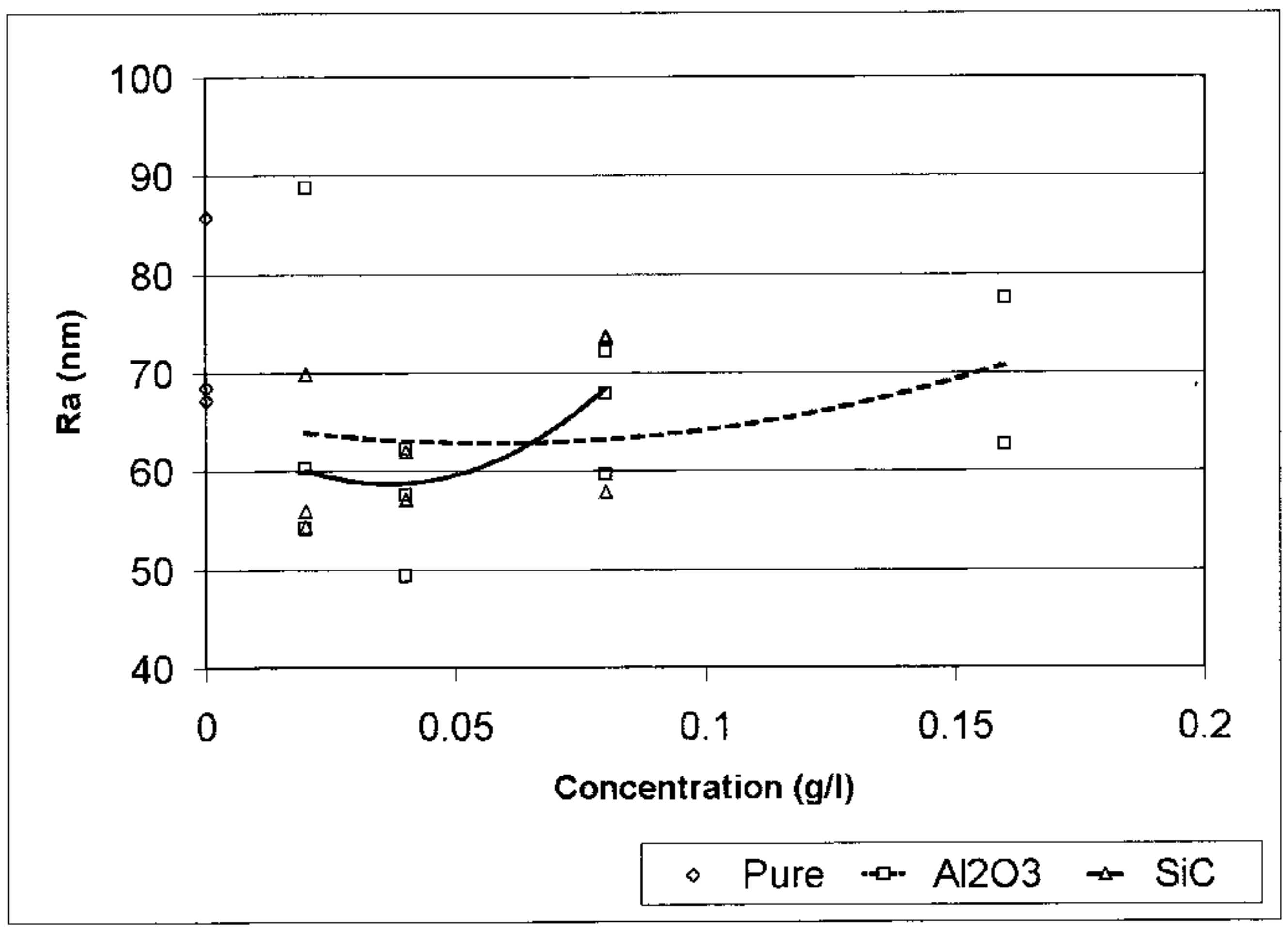

Fig. 4 *Ra* as a function of additive concentration for an energy of 1.1 μJ

The manner in which *Ra* varied with the additive concentration can be observed in Figs. 3 and 4. For an input energy setting of 16.5 μJ, the smallest *Ra* was achieved between 0.02–0.04 g/l of SiC additive and at about 0.08 g/l of Al_2O_3 additive. For an input energy setting of 1.1 μJ, the smallest *Ra* was achieved at about 0.04 g/l for both SiC and Al_2O_3 additives.

To ascertain the significance of the change in *Ra* at these additive concentrations, an ANOVA study was performed on the *Ra* values generated using the machining conditions shown in Table 4. The comparison was made with respect to the *Ra* values generated in a pure dielectric.

Table 4 Machining conditions used for comparison

s/n	Input energy (μJ)	Additive	Concentration (g/l)
1.	16.5	Al_2O_3	0.08
2.	16.5	SiC	0.04
3.	1.1	Al_2O_3	0.04
4.	1.1	SiC	0.04

The ANOVA study assumes that the experimental data follows a theoretical F-distribution so that a test ratio for each source of variation can be determined and expressed as an F-value. The F-value is then compared with a control limit value F(critical) specified for type I error probability (α = 0.05). The source of variation is

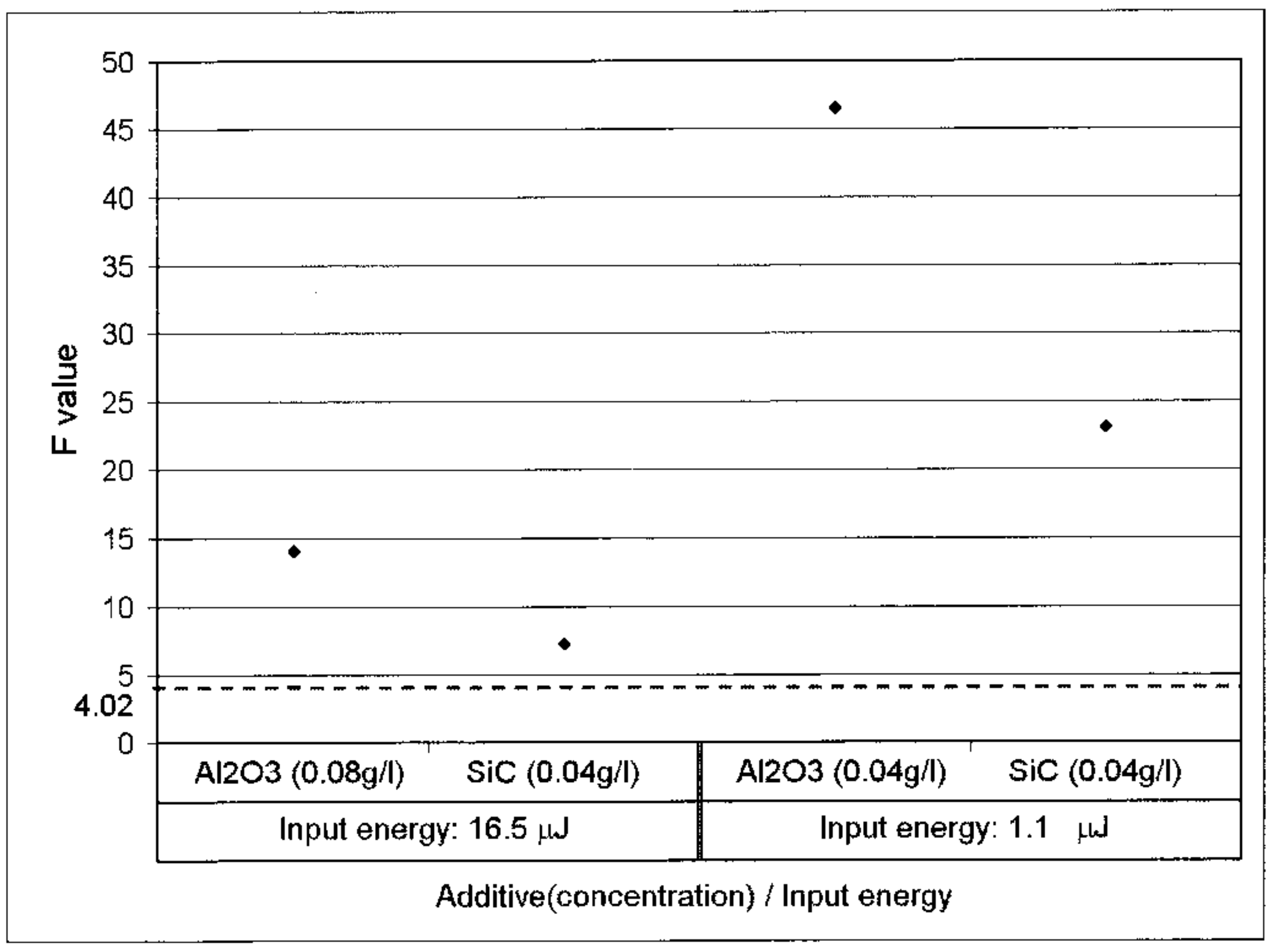

Fig. 5 Results of the ANOVA study on *Ra* values

considered statistically significant when its F-value is greater than F(critical), while an F-value smaller than F(critical) implies an absence of statistically significant variance for the corresponding source of variation. Figure 5 shows the results of the ANOVA study.

In Fig. 5, the F(critical) value is shown as a horizontal dotted line with a magnitude of 4.02, and the data points represent the F-values for the different variances when compared to the *Ra* generated in a pure dielectric. Data points located further away from the F(critical) value indicate a stronger degree of significance or insignificance for the points above and below the dotted line, respectively. Thus, it is clear that the use of additives in the appropriate concentrations results in a statistically significant reduction in *Ra* values for both input energy settings employed.

$$Ra_{k,ave} = \frac{1}{n}\sum_{j=1}^{n} Ra_j \tag{2}$$

To estimate the percentage reduction in *Ra* as a result of machining at the two input energy settings with dielectrics having suspended powder concentrations of Al_2O_3 (0.08 g/l), Al_2O_3 (0.04 g/l) and SiC (0.04 g/l), the average *Ra* value (Ra_{ave}) for each machining condition listed in Table 4 was calculated using where *k* represents the machining condition shown in Table 4, and *j* and *n* identify the individual holes and the total number of holes machined using machining condition *k*.

Table 5 compares the average *Ra* values achieved with that generated while machining in a pure dielectric. The largest percentage reduction in surface roughness was 24.1% when 0.04 g/l of Al_2O_3 was used for machining at an input energy setting of 1.1 μJ.

Table 5 Comparison of average *Ra* values

s/n	Input energy (μJ)	Additive	Concentration (g/l)	Ra_{ave} (nm)	% reduction
1.	16.5	Nil	0	239.8	--
2.	16.5	Al_2O_3	0.08	194.0	19.1
3.	16.5	SiC	0.04	205.4	14.3
4.	1.1	Nil	0	70.5	--
5.	1.1	Al_2O_3	0.04	53.5	24.1
6.	1.1	SiC	0.04	58.4	17.2

3.2 Machining Over-cut

With the reduction in surface roughness achieved using the machining conditions shown in Table 4, an analysis on changes in the over-cut was also performed at the same machining conditions.

The amount of machining over-cut was calculated using measurements of the tool electrode wear, desired hole depth, and actual hole depth, which are related to each other as shown in Fig. 6. The electrode wear was calculated using the electrode length before and after micro-hole drilling. The actual hole depth (Z_{hole}) was measured using the optical microscope, while the desired hole depth (Z_{set}) represented the ideal hole depth achieved when machining without the occurrence of electrode wear and without considering machining over-cut. The amount of over-cut was calculated using

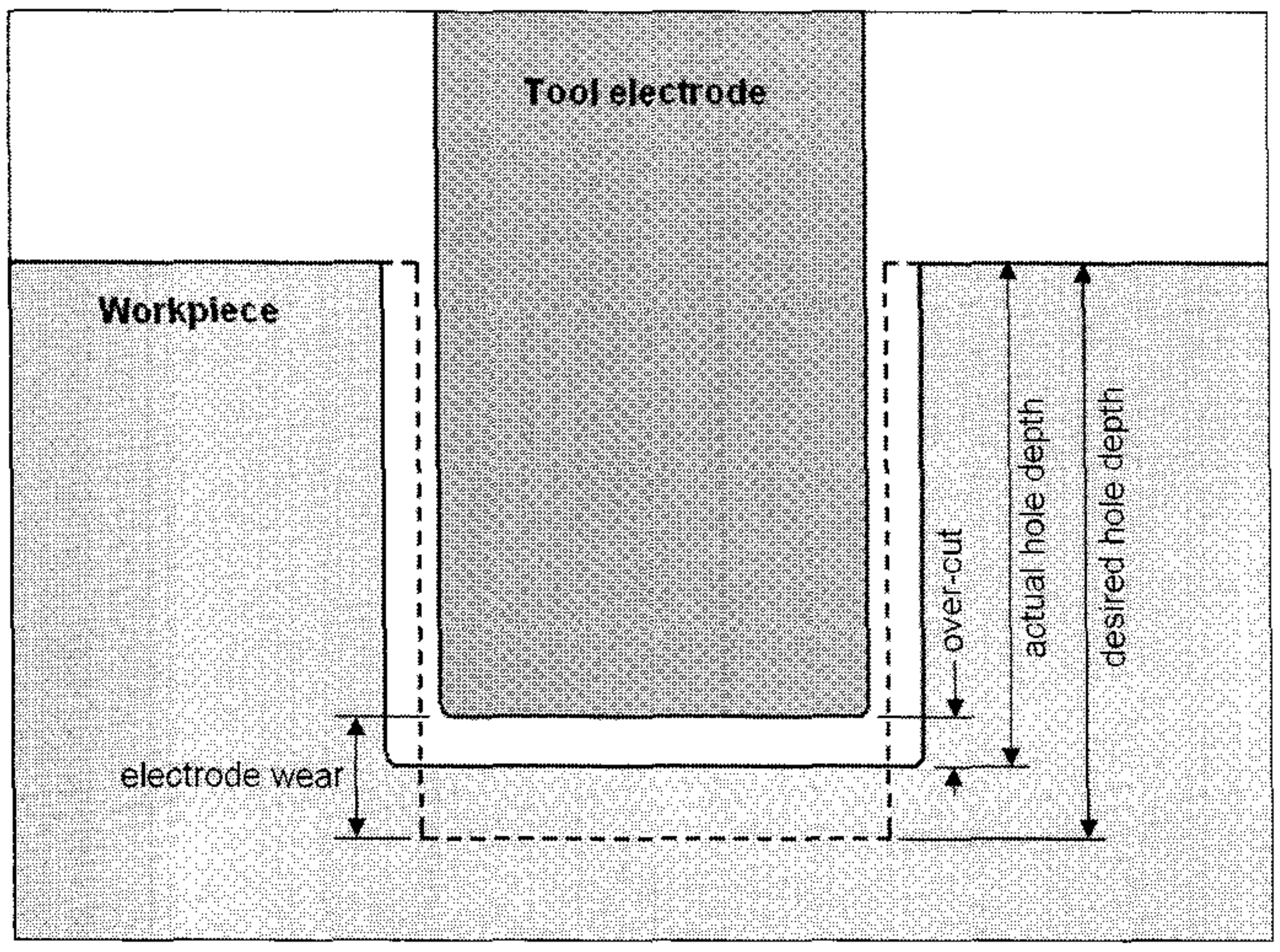

Fig. 6 Determination of machining over-cut

$$d_{gap} = \left(L_{initial} - L_{final}\right) - \left(Z_{set} - Z_{hole}\right) \tag{3}$$

where d_{gap} is the amount of over-cut, $L_{initial}$ is the electrode length before machining, L_{final} is the electrode length after machining, Z_{set} is the desired hole depth (150 μm), and Z_{hole} is the measured hole depth.

The calculated values of machining over-cut are plotted in Fig. 7. Based on the distribution, the addition of Al_2O_3 and SiC additives to the dielectric did not result in a change in the over-cut values compared to that obtained when machining using a pure dielectric.

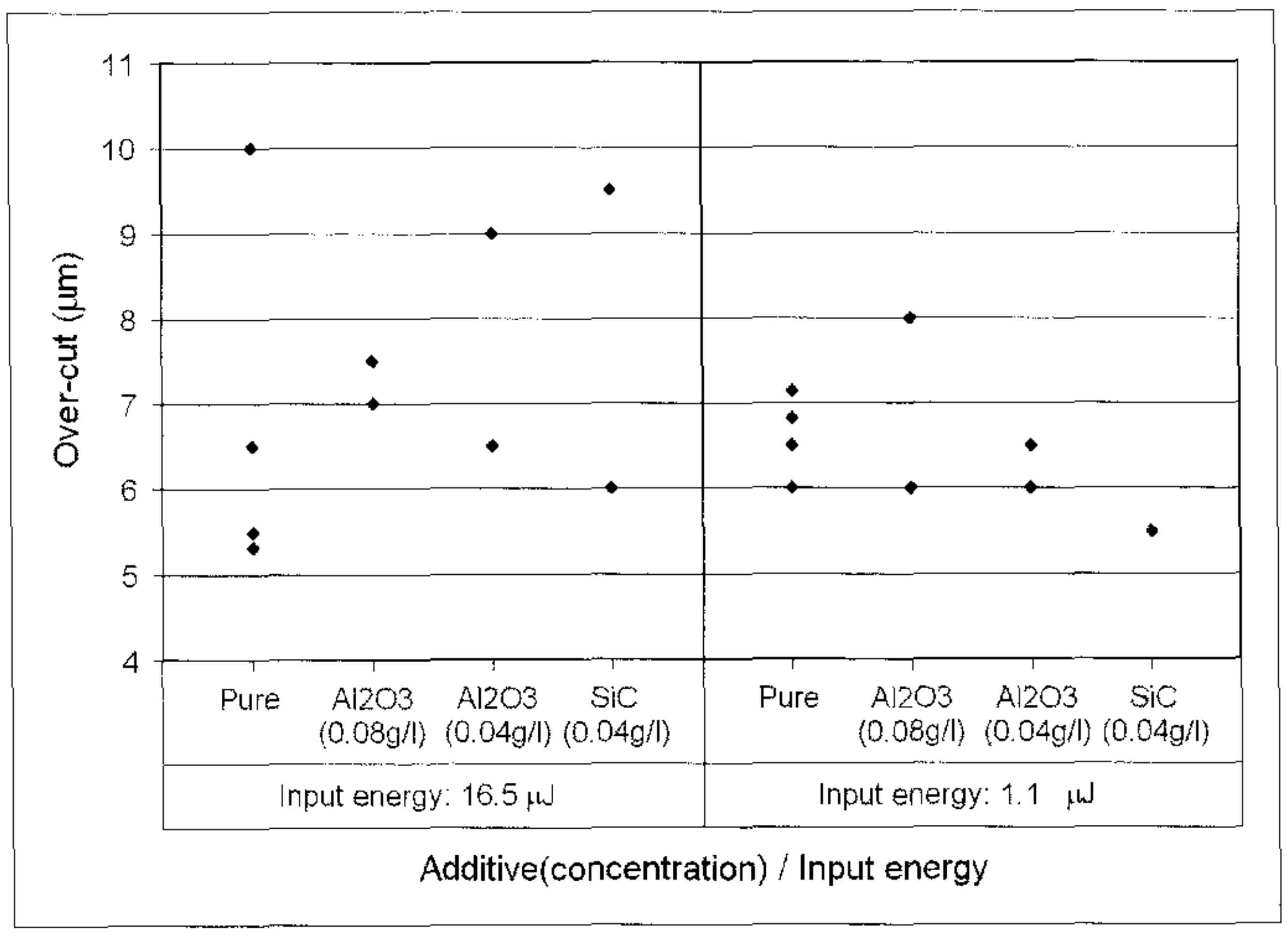

Fig. 7 Distribution of over-cut for various machining conditions

3.3 Benefits of Using Nanopowders for PSD Micro-EDM

The use of SiC and Al micropowders for micro-slit machining[9] resulted in a 26–28% reduction in surface roughness values. In addition, a maximum slit expansion of 110 μm was reported and attributed to the optimal conductivity and suspension of the Al micropowder-kerosene mixture. In the present experiment, the use of SiC and Al_2O_3 nanopowders resulted in a 14–24% reduction in average surface roughness values without a noticeable change in over-cut values compared to that obtained when machining using a pure dielectric.

Thus, the use of nanopowders in PSD micro-EDM provides the benefits of a reduced surface roughness while maintaining a geometrical accuracy of the PSD micro-EDM process comparable to that of micro-EDM using a pure dielectric. Furthermore, since the discharge gap distance in micro-EDM is in the range of a few microns, the use of nanopowders ensures they remain properly suspended in the discharge gap.

4. Conclusion

This study has provided a new insight into the use of semi-conductive SiC and non-conductive Al_2O_3 nanopowders in PSD micro-EDM. Through micro-hole drilling at different discharge energy settings, the changes in the surface roughness and discharge gap distance as a result of using powder suspended in dielectrics were measured and compared to corresponding results obtained when machining in a pure dielectric. The variation in *Ra* values showed that the minimum surface roughness values were achieved when 0.08g/l of Al_2O_3 or 0.04 g/l of SiC were used with a machining input energy setting of 16.5 μJ, and when 0.04 g/l of Al_2O_3 or SiC were used with a machining input energy setting of 1.1 μJ. Furthermore, an ANOVA study on the *Ra* values generated at these additive concentrations showed that a statistically significant reduction in surface roughness was achieved through the use of powder suspended dielectrics. The percentage reduction in average surface roughness values ranged from 14% when 0.04 g/l of SiC was used for machining at an input energy setting of 16.5 μJ, to 24% when 0.04 g/l of Al_2O_3 was used for machining at an input energy setting of 1.1 μJ. In addition, estimates of discharge gap distances using the length of electrode wear and the corresponding depth of micro-holes machined with these additive concentrations showed that the use of powder-suspended dielectrics did not change the gap distance.

Additive powder sedimentation was observed while performing the PSD micro-EDM experiments. Such powder sedimentation may reduce the amount of powder particles flowing into the discharge gap since the effective concentration of additives in the dielectric is reduced. The flow of powder particles into the discharge gap may also be restricted due to the occurrence of powder particle agglomeration, which increases the effective particle size. To address these issues related to the use of PSD micro-EDM, an investigation into the use of ultrasonic field assistance is proposed as future work.

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