Near-Dry EDM Milling of Mirror-Like Surface Finish

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Abstract

This study investigates near-dry EDM milling as a finishing process to achieve a mirror-like surface finish. A liquid-gas mist mixture is the dielectric medium delivered through a rotating tubular electrode in the near-dry EDM milling. Near-dry EDM exhibits the advantage of good machining stability and smooth surface finish at low discharge energy input. An EDM power generator is modified by adding an electrical resistance to enable the reduction of surface roughness. Effects of dielectric fluid, electrode material and pulse energy on material removal rate and surface roughness are studied. The mirror-like surface finish with 0.32 µm $R_a$ is achieved using the kerosene mist and copper infiltrated graphite electrode with 100 µJ pulse energy.

Key words: Near-dry EDM, surface finish, mist dielectric medium.

1. INTRODUCTION

Electrical discharge machining (EDM) is a prevalent nontraditional precision machining method. The EDM machined surface is composed of discharge craters overlapping each other. To achieve a super surface finish, ultra low pulse energy1)-4) and powder mixed dielectric (PMD) EDM5)-10) are two existing methods. Both methods have their limitations.

Luo et al.1),2) demonstrated a super finished EDM surface with 0.04 µm $R_a$ by reducing the pulse energy with a very low discharge duration of $t_i$ less than 0.2 µs. Egashira et al.3) applied the ultralow discharge energy, less than 3 nJ, to conduct machining with the assistance of ultrasonic vibration. Okada et al.4) studied the radio-frequency plasma to produce a surface roughness of 0.15 µm $R_a$ on aluminum. The disadvantage of the low pulse energy method is the low material removal rate (MRR) and long machining cycle due to the frequent abnormal discharges resulting from the narrow gap distance.

The PMD EDM has been recognized as a more practical finishing process to generate very fine surface finish at relatively high MRR5),6). Powders such as graphite, silicon and aluminum suspended in the dielectric help to stabilize the machining process at low pulse energy by increasing the discharge gap distance, decreasing the stray capacitance and dispersing the discharge pulses7). However, the use of powder increases the machining cost and the consequent toxic disposal causes an environmental concern8),9). In practical applications, the powder suspended dielectric circulation system is also challenged by separating the machined debris from the useful powders and maintaining a constant powder concentration.

Near-dry EDM, first explored by Tanimura et al.11), utilizes the liquid-gas mixture as the dielectric fluid. It is found to be beneficial for the finishing process with good machining stability12). Better surface finish was achieved in near-dry EDM than that of wet and dry EDM at the same energy level. It is hypothesized that the liquid particles dispersed in the gas medium has a similar mechanism to promote the finishing process as the additive powders in PMD EDM. The dielectric disposal of near-dry EDM is cleaner than that of PMD EDM. In addition, the EDM milling configuration uses a small tubular electrode to scan over the large working area. In this case, the stray capacitance, which increases with the overlapping area between the electrode and workpiece, is no longer a constraint on the machining area, as it did in conventional die-sinking EDM1).

In this study, the near-dry EDM milling is investigated to understand the effect of dielectric fluid, electrode material and pulse energy level. Benefits and potentials of near-dry EDM milling as the finishing process are identified and discussed.

2. EXPERIMENTAL SETUP

The near-dry EDM milling experiments were conducted on a CNC die-sinking EDM machine, Vanguard 150H from EDM Solutions at Elk Grove Village, Illinois, US. Figure 1 shows the setup of the test bed. A rotary spindle, Rotobore RBS-1000, with through-spindle flushing capability is mounted on the EDM head. The mist mixture is delivered by a pulse mist spray system, AMCOL
6000 precision applicator, as in Figure 1(b), which was originally adopted in the minimum quantity lubrication (MQL) machining. The input liquid flow is set at 5 ml/min. The tested mist dielectrics and electrode materials are listed in Table 1. Negative polarity, i.e. electrode as cathode, is used in the experiment, due lower wear on cathode at low discharge pulse duration and smoother discharge crater on anode.

To reduce the pulse energy for smooth surface finish, the EDM power generator was modified. A power resistor was serially connected in to the discharge circuit, as shown in Figure 2(a). The applied resistance lowered the output discharge energy. The resistance was varied in the experiment from 1 kΩ to 50 kΩ in order to reduce the pulse energy. The current and voltage waveforms were monitored using an Agilent Infinium 54833A digital oscilloscope. As shown in Figures 2(b) and (c), the discharge current, \( i_d \), was reduced from 4 to 1 A, in a sampled pulse. It is also observed the open voltage, \( u_0 \), also drops from 80V to 60V. This is not an expected output by inserting the resistance. Since the open voltage is not a main factor influencing the pulse energy and resultant crater morphology, this question is set aside in this paper.

AISI H13 tool steel was the work material. The surface roughness was measured using a Taylor Hobson Form Talysurf Intra profilometer with a 2 µm stylus tip radius. The workpiece was weighed before and after machining to quantify the MRR. An Olympus PME 3 optical microscope was used to inspect the machined surface and discharge crater.

### 3. RESULTS AND DISCUSSION

#### 3.1 Effect of dielectric fluid

Figure 3 compares the surface roughness, MRR and micrographs of the machined surfaces of four different near-dry EDM dielectric fluids. The surface finish is about the same, between 0.85 to 0.9 µm \( R_a \), for the four dielectric fluids. Although previous study \(^{12}\) reported that the water mist with nitrogen generates the smoothest surface finish, the long machining time induces severe electrolysis corrosion and deteriorated surface finish on the water mist machined surface, as shown in Figure 3. The individual discharge crater created by the water mist is finer than those of kerosene mist, but the electrolysis causes the blackened and rugged surface. The nitrogen medium was effective in preventing the water electrolysis by isolating the oxygen content at high pulse energy input\(^{12}\). It was also reported by Tanimura\(^{13}\) that water did not cause any electrolysis problem in near-dry EDM. However, as the discharge gap distance decreases and the machining time increases with the reduction of pulse energy, the arcing and short circuiting occur more frequently and provoke the water electrolysis in this study. This indicates that the electrolysis is
an obstacle to implement the water mist for super finishing near-dry EDM.

Kerosene mist with air Kerosene mist with nitrogen Water mist with air Water mist with nitrogen

Figure 3. (a) Surface roughness and MRR and (b) micrographs of the discharge craters for four near-dry EDM dielectric fluids ($t_i = 4 \mu s$, $i_e = 4 A$, $u_e = 45 V$, copper infiltrated graphite electrode).

Kerosene mist exhibits the advantages of shiny surface, high MRR and moderate surface finish. Even though kerosene mist generates larger and deeper craters than water mist, it could be overcome by further reducing the pulse energy to yield the desired smooth surface. Comparing the gas media in kerosene mists, air obviously enhances the MRR while the surface is slightly rougher than that of nitrogen. The nitrogen medium, which was used for preventing oxidation or electrolysis², does not contribute much to improve the surface finish, since little oxidation or electrolysis occurs while using the kerosene mist. Considering the high MRR and easy availability of air, kerosene mist with air is chosen as the dielectric fluid for further investigation.

3.2 Effect of electrode material

The results of surface roughness and MRR for the three electrode materials in near-dry EDM are shown in Figure 4. The copper infiltrated graphite electrode has the advantage of good surface finish and moderate MRR over the graphite and copper electrode materials.

Among the three materials, graphite has the highest MRR but the surface finish is the worst. As shown in Figure 5(a), the machining marks are observed as deep craters with deposition of overflowed molten material at the crest. This indicates that a large amount of heat is generated in the discharge melting the material, but the bubble explosion force is not strong enough to eject all the molten material. Such discharge pulse is close to the status of arcing. The frequent arcing could have been induced by the flaking of graphite electrode due to the thermal shock.

Figure 4. Machining performance of different electrode materials ($t_i = 4 \mu s$, $i_e = 4 A$, $u_e = 45 V$, kerosene mist with air).

Figure 5. Optical micrographs of discharge craters generated by three electrode materials
The copper electrode generates a clean surface, as in Figure 5(c), but the MRR is unacceptably low. At low pulse energy input, the gap distance between the electrode and workpiece is small. This requires a servo system with a high sensitivity to maintain the proper gap distance. Otherwise, the system will switch between the open and short circuit and thus lower the MRR significantly. When machining using the copper electrode, this situation occurs frequently.

The copper infiltrated graphite electrode combines the advantages of both copper and graphite electrode materials, as shown in Figure 5(b). The graphite content, once dispersed into the discharge gap at a comparatively small amount, can help to initiate the discharge at low pulse energy input. The copper content increases the thermal conductivity, which relieves the thermal shock on the electrode. Copper also has enough toughness to hold the electrode material together in near-dry EDM. The arcing can thus be reduced by reducing the flaking of graphite powder. Smooth discharge craters, as shown in Figure 5(c), are generated.

The copper infiltrated graphite electrode is used in the following experiments for further surface finish improvement.

### 3.4 Mirror-Like Machined Surface

Figure 6 demonstrates the machined pockets with the mirror-like surface finish using a tubular electrode with 3 mm outside diameter. Reflection of the electrode tip can be observed.

Figure 6. Illustration of the mirror-like machined surface.

The four steps from roughing to final finishing are summarized in Figure 7. The pulse energy is reduced by applying higher resistance as the machining proceeds. The discharge current and discharge voltage are monitored using an oscilloscope. Since \( i_e \) and \( u_e \) alters, the pulse energy is calculated using Equation (1) to characterize the pulse energy for each step.

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E = i_e \cdot u_e \cdot t_i
\]

The surface finish is smoothed effectively as the pulse energy decreases. As shown in Figure 7(b), the small pulse energy reduces the depth of the discharge crater and the molten material overflow. Currently, the best surface finish achieved is 0.32 \( \mu m \) \( R_a \) with a pulse energy of 100 \( \mu J \) by applying a 50 k\( \Omega \) resistor in the discharge circuit. At this energy level, the test with wet EDM was failed because of low machining stability. Frequent electrode servo retraction was observed. This is because an extremely small discharge gap distance is required to initiate the discharge in liquid kerosene medium. High sensitivity and quick response of the servo system are thus necessary for maintaining the small gap distance. Otherwise, the machining status could easily deteriorate to the switching between the open and short circuit\(^1\).

### 3.5 Discussion

The current near-dry EDM result is compared
with work by Pecas and Henrique\textsuperscript{10}, who also studied the EDM polishing of AISI H13 tool steel. They reported that with a 32 cm\textsuperscript{2} machining area, 0.50 µm $R_a$ is the limit for conventional EDM using the kerosene dielectric while the silicon powder mixed dielectric is able to lower the surface roughness to 0.20 µm $R_a$ with the pulse energy less than 10 µJ. The polishing by near-dry EDM milling already exceeds the conventional die-sinking EDM and is promising when compared to PMD EDM, if the same low pulse energy is used.

The potential of near-dry EDM has not yet been fully explored due to the limitation of the minimum pulse duration. In this study, the EDM generator is only capable of producing 4 µs pulse duration, as shown in Figure 2. In general, pulse duration close to or lower than 1 µs is expected for the finishing EDM\textsuperscript{1,10}. With lower pulse duration, the expansion of the plasma channel can be restricted, resulting in smaller discharge crater size and finer feature. In this study, the discharge crater depth is reduced but the crater diameter remains about the same due to the constant pulse duration, as shown in Figures 2(b) and (c). As reported by Luo\textsuperscript{1} and Tao and Shih\textsuperscript{12}, among the three factors influencing the pulse energy, the pulse duration has the most significant effect on surface finish in super finishing EDM. Therefore, by reducing the pulse duration, the surface finish is expected to be further reduced in near-dry EDM.

4. CONCLUSIONS

Near-dry EDM as a super finishing process was explored in this study. Kerosene mist with air, coupled with a copper infiltrated graphite electrode was found to produce the best overall results in near-dry EDM finishing. Advantages and potentials of near-dry EDM milling were identified. The near-dry EDM had good machining stability and its surface finish was very good at relatively long pulse duration and high pulse energy level.

Further exploration of the near-dry EDM milling as a super finishing process is being carried out at the University of Michigan. Lowering of the pulse duration (< 0.5 µs) and pulse energy (< 10 µJ) will be implemented to drive towards even better surface finish. The electrode wear mechanism will be studied and compensated for the precision EDM milling process. Effect of gas-liquid composition on MRR and surface roughness will be investigated.

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