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# Near dry electrical discharge machining

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**Abstract**

This study investigates the near dry electrical discharge machining (EDM) process. Near dry EDM uses liquid–gas mixture as the two phase dielectric fluid and has the benefit to tailor the concentration of liquid and properties of dielectric medium to meet desired performance targets. A dispenser for minimum quantity lubrication (MQL) is utilized to supply a minute amount of liquid droplets at a controlled rate to the gap between the workpiece and electrode. Wire EDM cutting and EDM drilling are investigated under the wet, dry, and near dry conditions. The mixture of water and air is the dielectric fluid used for near dry EDM in this study. Near dry EDM shows advantages over the dry EDM in higher material removal rate (MRR), sharper cutting edge, and less debris deposition. Compared to wet EDM, near dry EDM has higher material removal rate at low discharge energy and generates a smaller gap distance. However, near dry EDM places a higher thermal load on the electrode, which leads to wire breakage in wire EDM and increases electrode wear in EDM drilling. A mathematical model, assuming that the gap distance consists of the discharge distance and material removal depth, was developed to quantitatively correlate the water–air mixture's dielectric strength and viscosity to the gap distance.


*Keywords:* Near dry machining; Electrical discharge machining; Material removal rate; Dielectric strength

## 1. Introduction

The selection and delivery of the dielectric fluid are critical to the material removal rate, surface integrity, and environmental impacts of electrical discharge machining (EDM). Dielectric fluid acts as an electrical insulation barrier in the gap between the workpiece and electrode. High-energy density EDM pulses are generated inside the dielectric fluid for material removal. The dielectric strength, defined as the maximum electric field strength that the dielectric fluid can withstand intrinsically without breakdown, is an important parameter to determine the gap distance [1]. Thermal and mechanical properties including the thermal conductivity, heat capacity, and viscosity of the dielectric fluid also influence the strength of explosions generated by EDM pulses and the subsequent melting, solidification, and heat transfer among the workpiece, electrode, and dielectric fluid [2].

Deionized water and kerosene-based oil are two commonly used dielectric fluids in conventional wet EDM. Dry EDM uses gas as dielectric fluid, and high MRR can be achieved to cut steel workpiece with the assistance of oxygen [1,3–6]. Table 1 compares the dielectric strength, thermal conductivity, heat capacity, and dynamic viscosity of air, deionized water, and kerosene/mineral oil [7–13].

High dielectric strength of dielectric fluid decreases the gap distance between the electrode and workpiece. High dielectric fluid viscosity constrains the expansion of plasma channels, focuses discharges to a smaller area, and generates larger explosive force to remove material and increase the gap distance. High dielectric fluid thermal conductivity aids the heat dissipation and reduces the thermal damage. Air has the lowest dielectric strength, thermal conductivity, and viscosity among the three dielectric fluids in Table 1. In this study, the mixture of deionized water and air is experimented as the dielectric fluid for near dry EDM. The water–air mixture properties are expected to be between those of air and deionized water.

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Table 1
Electrical, thermal, and mechanical properties of air, deionized water, and kerosene at room temperature [7–13]

| | Air | Deionized water | Kerosene/mineral oil |
|---|---|---|---|
| Dielectric strength (MV/m) | 3 [7] | 13 [8] | 14–22 [9] |
| Thermal conductivity (W/m-K) | 0.026 [10] | 0.606 [10] | 0.149 [11] |
| Heat capacity (J/g-K) | 1.04 [10] | 4.19 [10] | 2.16 [12] |
| Dynamic viscosity (g/m-s) | 0.019 [10] | 0.92 [10] | 1.64 [13] |

The debris deposition and low MRR are two problems of dry EDM [1,14]. Near dry EDM can overcome both problems. In this study, a fluid dispenser used in the minimum quantity lubrication (MQL) or near dry machining is adopted as the fluid delivery system for near dry EDM.

In this research, the work-material is aluminum 6061, denoted as Al6061. The dielectric fluid is injected by a high-pressure air stream through a nozzle to the gap between the electrode and workpiece. MRR envelopes [14–16], debris deposition, and groove width are used to compare the performance of wet, dry, and near dry EDM. In addition, EDM drilling using a tubular electrode under the wet, dry, and near dry conditions is investigated. The effects of water flow rate are studied on gap distance, MRR, and electrode wear. A mathematical model is developed to predict the gap distance based on the volumetric ratio of water in the water–air mixture.

The near dry EDM experimental setup and procedures are presented first in this paper. The MRR envelopes in near dry wire EDM are compared with those in wet and dry wire EDM. The groove width and debris deposition are examined and compared. The MRR and gap width in EDM drilling are investigated. Finally, a mathematical model and experimental validation of gap distance are presented.

## 2. Experimental setup

### 2.1. EDM machine setup

The wire EDM experiment was conducted on a Brother HS-5100 wire EDM machine using a 0.25 mm diameter brass wire electrode. For all the experiments, the axial direction wire feed speed was set at 12 mm/s, the tension force of wire was 18 N, the gap voltage $u_e$ was 45 V, the open circuit voltage $u_0$ was about 72 V, and the average pulse current $i_e$ was about 25 A. Two EDM cutting conditions, wet and near dry were tested. Results of dry wire EDM experiments conducted on the same machine have been presented in previous studies [14].

In wet EDM, the workpiece was submerged in deionized water with water jets applied from the top and bottom of the workpiece at 1 l/min flow rate to flush away the debris. An MQL fluid dispenser, model T60A-2 made by AMCOL, was used to deliver the water–air mixture. The dielectric fluid pressure was set at 0.41 MPa. The delivery of the dielectric fluid and the feed of the wire electrode are illustrated in Fig. 1.

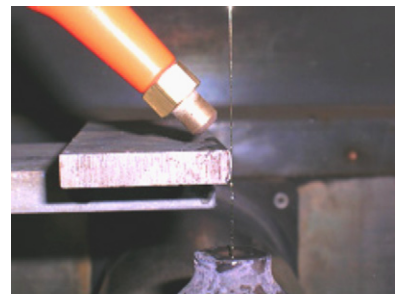

Fig. 1. The delivery of liquid–gas mixture in near dry wire EDM.

EDM drilling tests were conducted on a Gromax MD20 micro-hole EDM machine using a brass tubular electrode with 1 mm outer diameter and 0.41 mm inner diameter. The rotational speed of the tubular electrode was 120 rpm. For stable drilling under all EDM conditions, the gap voltage was set at 60 V, the pulse interval time was $t_0 = 70\,\mu s$, and the discharge duration was $t_e = 10\,\mu s$. The average pulse current varies for different experiments.

### 2.2. Wire EDM cutting

MRR envelopes, which illustrate feasible EDM process regions, have been studied by Miller et al. [15,16]. MRR envelopes of wet and dry EDM cutting of 1.27-mm-thick Al6061 are presented as the baseline data [14] for the comparison with two new envelopes of the near dry EDM. In each envelope, $t_0$ was varied to find the maximum achievable wire feed rate, which was then converted to MRR. Four levels of $t_e$ were selected: 4, 10, 14, and 18 μs, identical to those used in [14]. The upper and lower boundaries of the MRR envelope correspond to the minimum and maximum values of $t_e$ (4 and 18 μs). The specific machine limits, maximum and minimum $t_0$ (1000 and 6 μs), as well as wire breakage and short-circuit limitations, form the left and right envelope boundaries of the MRR envelope. The average pulse current $i_e$ is about 25 A. To investigate the relationship between the gap distance and dielectric fluid properties, the grooves machined at various water flow rates (0, 5, 8, 15, 21, 35, 50, 75 ml/min), as summarized in Table 2, were studied. The groove quality and groove width were examined and measured using an optical microscope at 100 × magnification. Three repeated tests were conducted in each experimental setup.

Table 2
Average gap distance in wire EDM cutting under wet, dry, and near dry conditions ($t_e = 14\,\mu s$, $t_0 = 250\,\mu s$, $u_0 = 72\,V$, $u_e = 45\,V$)

| | EDM condition | Wet | Near dry, water flow rate (ml/min) | | | | | | | Dry |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 75 | 50 | 35 | 21 | 15 | 8 | 5 | |
| | Water volumetric ratio, $\sigma$ | 1 | 0.98 | 0.75 | 0.59 | 0.42 | 0.34 | 0.22 | 0.17 | 0 |
| | Gap distance, $d$ (μm) | 43.0 | 42.7 | 41.9 | 40.9 | 38.9 | 37.6 | 33.6 | 31.4 | N/A |
| | Debris deposition problem | No | No | No | No | No | No | No | No | Yes |
| Water–air mixture properties | Dielectric strength (MV/m) | 13.0 | 12.8 | 10.7 | 9.24 | 7.59 | 6.75 | 5.57 | 5.01 | 3.00 |
| | Dynamic viscosity (g/m-s) | 0.92 | 0.92 | 0.92 | 0.91 | 0.86 | 0.80 | 0.66 | 0.56 | 0.019 |

Table 3
Average gap distance in EDM drilling under wet and near dry EDM conditions ($i_e = 10\,A$, $t_e = 10\,\mu s$, $t_0 = 70\,\mu s$, $u_e = 60\,V$)

| | EDM condition | Wet | Near dry, water flow rate (ml/min) | | | | | Dry |
|---|---|---|---|---|---|---|---|---|
| | | | 35 | 21 | 15 | 8 | 5 | |
| | Water volumetric ratio, $\sigma$ | 1 | 0.80 | 0.48 | 0.35 | 0.18 | 0.12 | 0 |
| | Gap distance, $d$ (μm) | 75 | 65.0 | 62.5 | 60.1 | 45.3 | 35.2 | N/A[a] |
| Water–air mixture properties | Dielectric strength (MV/m) | 13.0 | 11.4 | 7.86 | 7.18 | 5.50 | 4.66 | 3 |
| | Dynamic viscosity (g/m-s) | 0.92 | 0.92 | 0.85 | 0.80 | 0.57 | 0.40 | 0.019 |

[a]Significant taper, found in dry EDM drilled holes, makes the average gap distance measurement difficult.

### 2.3. EDM drilling

Two sets of EDM drilling experiment were conducted. The first set was to evaluate the drilling speed and hole quality, including the shape variation and debris deposition, of wet, dry, and near dry EDM. The average pulse current was set at 10 A. The workpiece used was 1.27-mm-thick Al6061. For wet EDM, the flow rate of deionized water was 107 ml/min. For dry EDM, the air jet pressure was set at 0.62 MPa. For near dry EDM, the water flow rate and the pressure of the carrying air jet were set at 21 ml/min and 0.62 MPa, respectively. The hole quality was inspected using an optical microscope at 100× magnification.

The second set investigates the effects of water flow rates on EDM drilling speeds with $i_e$ values at 10, 12, and 15 A. Diameters of drilled holes at different water flow rates were also measured for the investigation of the relationship between the gap distance and dielectric fluid properties. The water flow rate was varied as 5, 8, 15, 21, and 35 ml/min as shown in Table 3.

## 3. Near dry wire EDM MRR and gap distance

### 3.1. MRR envelope boundaries

Fig. 2 shows three MRR envelopes which outline the feasible regions for the wet, dry, and near dry wire EDM cutting of 1.27-mm-thick Al6061. The average of three repeated test results is presented. The range of variation of three tests is within 10% of the nominal value and is consistent for all experimental conditions. For wet and dry wire EDM [14], the region of feasible MRR is bounded by the wire breakage, short circuit, and machine limits of maximum and minimum $t_e$ (18 and 4 μs) and maximum $t_0$ (1000 μs). The wet EDM has a significantly higher MRR than that of the dry EDM (21.9 mm$^3$/min vs. 0.98 mm$^3$/min). At low pulse intervals of $t_0$, frequent EDM pulses generate concentrated heat and lead to wire breakage. The minimum value of $t_0$ that can be reached at high level of $t_e$ without wire breakage, is greatly dependent on the dielectric fluid used. For wet EDM, due to the higher thermal conductivity of the bulk water than that of the water–air mixture, $t_0$ can be as low as 100 μs at $t_e = 18\,\mu s$.

For the near dry EDM using water–air mixture at a water flow rate of 5.3 ml/min, the envelope boundary falls between the wet and dry EDM. The maximum MRR is improved, from 0.98 mm$^3$/min in dry EDM, to 2.53 mm$^3$/min. The near dry EDM has a consistently higher MRR than that of dry EDM for all $t_0$ and $t_e$. However, the wire breakage, due to the lower capability of water–air mixture to relieve the concentrated heat from the wire electrode, still limits the MRR in near dry EDM at low $t_0$. Nevertheless, near dry EDM shows two advantages. First, there is no short circuit limit at the lower boundary. Second, in the region of very low-energy input ($t_e = 4\,\mu s$ and $t_0 > 150\,\mu s$), the MRR in near dry EDM is higher than that of the wet EDM.

The close up view of MRR (below 4 mm$^3$/min) vs. $t_0$ for the wet and near dry EDM is shown in Fig. 3. Three regions, designated as I–III, are identified. In Region I ($t_0 > 650\,\mu s$), the near dry EDM has higher MRR than that of wet EDM because the lower thermal conductivity and heat capacity of the water–air mixture contribute to less heat dissipation during discharge and a larger portion of

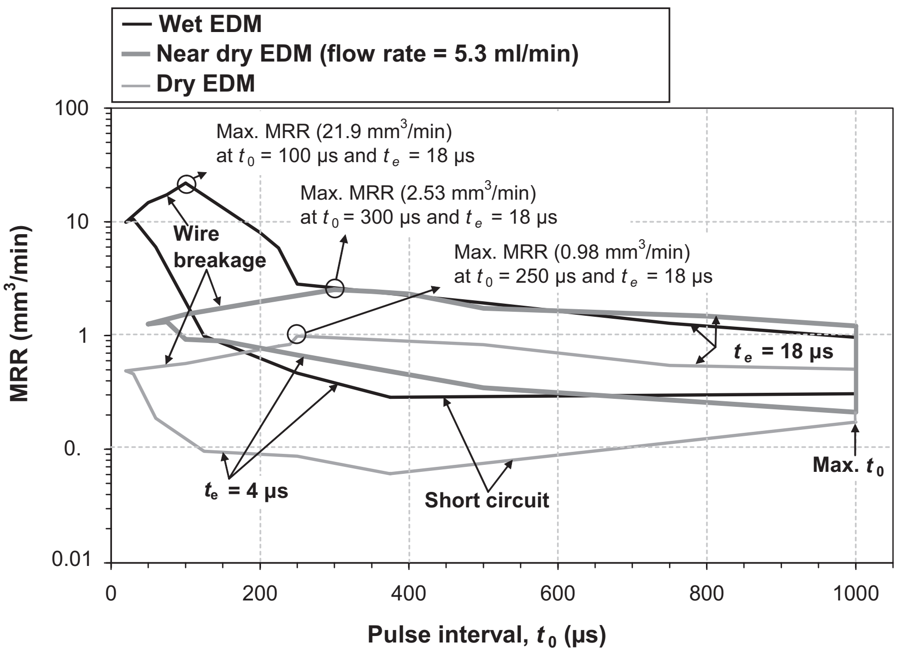


Fig. 2. Comparison of the boundaries of feasible MRR envelopes for wet, dry, and near dry wire EDM ($i_e = 25\,A$, $u_e = 45\,V$).

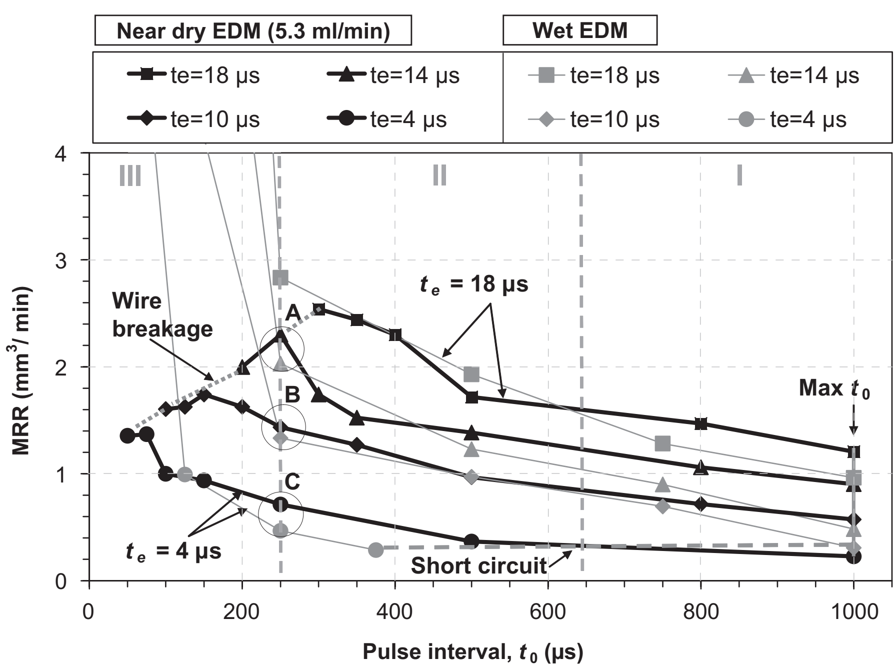


Fig. 3. Comparison of MRR performances of wet and near dry wire EDM under varied $t_0$ and $t_e$ and three regions based on near dry and wet EDM performance ($i_e = 25\,A$, $u_e = 45\,V$).

discharge energy for material removal. At the very low discharge energy setup, $t_e = 4\,\mu s$, wet EDM fails to cut due to the short circuit, but near dry EDM still works with fairly low MRR. The higher dielectric strength of the water medium generates a narrow gap distance and causes a frequent short circuit in wet EDM.

In Region II ($250\,\mu s < t_0 < 650\,\mu s$), the MRR of near dry and wet EDM is roughly the same. At the highest $t_e$ ($= 18\,\mu s$), the MRR of wet EDM starts to exceed that of near dry EDM. Under higher energy input, the higher viscosity of the water dielectric fluid in wet EDM generates larger explosion force, which contributes to the high MRR [17].

In Region III ($t_0 < 250\,\mu s$), a significant MRR difference exists between wet and near dry EDM. The MRR drops in near dry EDM and, wire breakage occurs as $t_0$ is further reduced. The dielectric fluid viscosity is critical to the MRR in Region III.

### 3.2. Effect of flow rate on MRR

The MRR in near dry EDM under 5.3 and 75 ml/min water flow rates is shown in Fig. 4. In near dry EDM, high water flow rates increases the MRR because of improved cooling, more efficient debris flushing, and higher dielectric fluid viscosity due to the higher concentration of water. It improves the MRR at low $t_0$ (below 500 μs) for all values of $t_e$, and is particularly beneficial when $t_e$ is high ($=18$ μs). The peak MRR rises to 3.9 mm$^3$/min at 75 ml/min flow rate. A much higher flow rate is required to increase the MRR because the nozzle is set near the discharge gap and thus not all water droplets are successfully delivered into the gap.

### 3.3. Gap distance and debris deposition

The groove width in wire EDM is used to estimate the gap distance. The average gap distance under the wet, dry, and near dry wire EDM and the associated dielectric strength and viscosity of the dielectric fluid are listed in Table 2. The gap distance of wet EDM is wider than that of near dry EDM. This is likely caused by the lower viscosity of the water–air mixture. Similarly, in near dry EDM, higher water flow rate generates larger gap distance. This gap distance data will be analyzed in Section 5 for the modeling of gap distance based on dielectric fluid properties in near dry EDM.

No debris deposition is observed for near dry EDM. This occurs because water–air mixture has a better flushing capability than the air jet in dry EDM.

## 4. Near dry EDM drilling

### 4.1. Wet, dry, and near dry EDM drilling

Optical micrographs of top and cross-sectional side views of EDM drilled holes and the drilling time under the wet, dry, and near dry conditions are shown in Fig. 5. The dry EDM takes 428 s to drill a hole through the 1.27-mm-thick Al6061. This is very long compared to the 11 and 13 s drilling time for the wet and near dry EDM, respectively. The dry EDM also has a severe debris deposition problem, which subsequently creates a tapered hole. The taper in wet EDM also exists but is not as significant as in dry EDM. The smallest taper exists in holes drilled by near dry EDM, which generates a straight hole with sharp edges.

The electrode wear in near dry EDM is 3.7 mg per hole, which is larger than the 2.7 mg per hole in wet EDM. The higher thermal load on the electrode in near dry EDM likely causes the higher electrode wear. The same phenomenon also exists in near dry wire EDM. As shown in Fig. 3, at low $t_0$ the wire breakage due to electrode wear limits the MRR in near dry wire EDM.

### 4.2. Effects of water flow rate and pulse current on gap distance

Effects of water flow rate and pulse current $i_e$ on the MRR in near dry EDM drilling are shown in Fig. 6. The efficiency of near dry EDM drilling improves with a higher water flow rate under all three levels of $i_e$. The MRR is low at $i_e = 10$ A due to the low-energy input. The highest energy input ($i_e = 15$ A), however, does not generate the highest MRR as expected. This is caused by the debris flushing problem at high-energy input. The medium level of

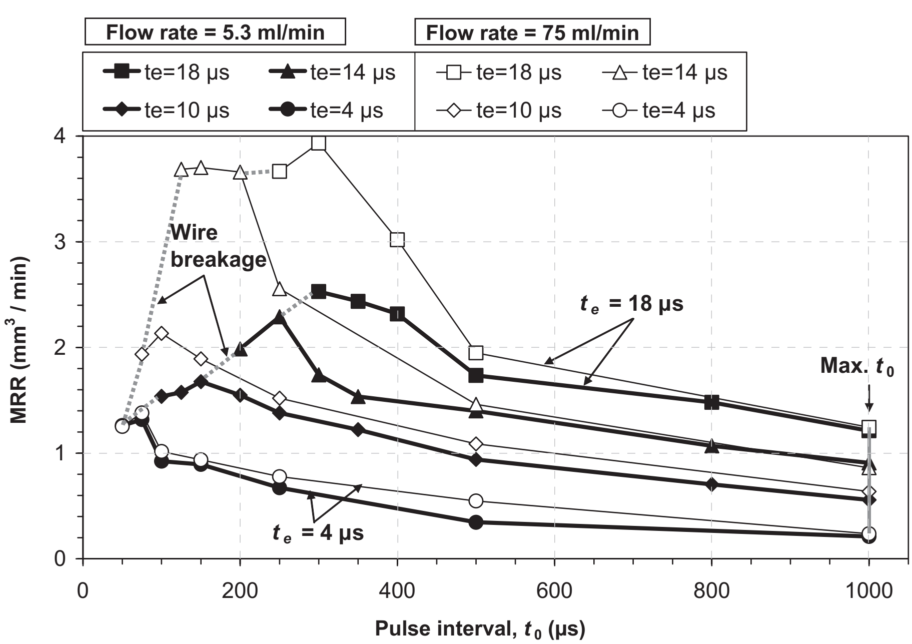


Fig. 4. MRR envelopes of near dry wire EDM cutting at two deionized water flow rates (5.3 and 75 ml/min, $i_e = 25$ A, $u_e = 45$ V).

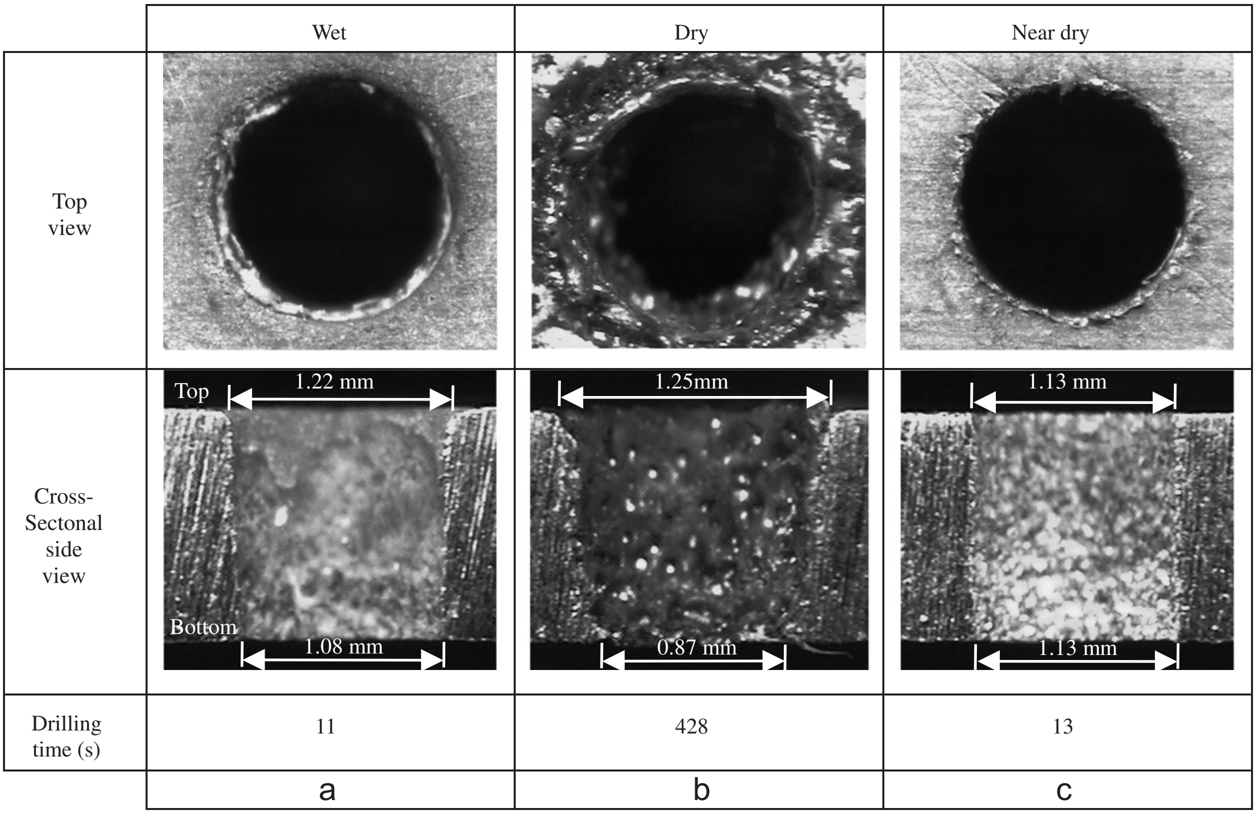


Fig. 5. Optical micrographs on holes drilled on 1.27 mm Al6061: (a) wet, (b) dry, and (c) near dry EDM conditions ($i_e = 10$ A, $t_e = 10\,\mu$s, $t_0 = 70\,\mu$s, $u_e = 60$ V).

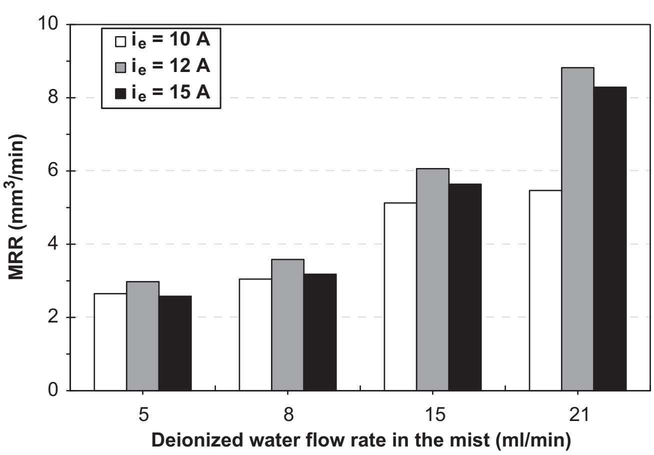


Fig. 6. The effect of deionized water flow rate and discharge current on the MRR of EDM drilling ($t_e = 10\,\mu$s, $t_0 = 70\,\mu$s, $u_e = 60$ V).

$i_e$ ( = 12 A) has the highest MRR by balancing the debris flushing and power input. The measured average gap distance is calculated using the difference between the average hole diameter and electrode diameter. Table 3 lists the average gap distance in wet, dry, and near dry EDM at five water flow rates. Following the same trend observed in Table 2 for the wire EDM, higher water flow rate corresponds to larger gap distance. A model is developed in the following section to investigate the effect of dielectric strength and dynamic viscosity on the gap distance.

## 5. Modeling of near dry EDM gap distance

### 5.1. Mathematical modeling

A mathematical model is developed to predict and understand the effect of an air–water mixture on the gap distance in near dry EDM. The model is based on four assumptions:

1. The gap distance, $d$, is assumed to be affected primarily by the dynamic viscosity and dielectric strength of the dielectric fluid [1]. The effect of dynamic viscosity and dielectric strength on $d$ can be decoupled into $d_1$ and $d_2$, which are the gap distance contributed by discharge distance and material removal depth, respectively.
2. The critical distance at which the applied gap voltage will cause the breakdown in the dielectric fluid is $d_1$. The discharge distance $d_1$ is assumed to be inversely proportional to the dielectric strength, $S_m$, in the unit of MV/m, i.e. $d_1 = \alpha/S_m$, where $\alpha$ is a constant.
3. The dynamic viscosity affects the magnitude of explosive force and material removal depth in the dielectric fluid. The distance $d_2$ is proportional to the dynamic viscosity $\eta_m$ of the water–air mixture, i.e., $d_2 = \beta\eta_m$, where $\beta$ is a constant.
4. Values of $\eta_m$ and $S_m$ are not readily available but they are expected to be between those of air and deionized

water and dependent upon the concentration of water in the mixture dielectric fluid. The viscosity and dielectric strength of air, $\eta_a$ and $S_a$, and water, $\eta_w$ and $S_w$, are available, as shown in Table 1. Values of $\eta_m$ and $S_m$ can be predicted using the following formula:

$$S_m = (S_w - S_a)\sigma^m + S_a, \quad (1)$$

$$\eta_m = (\eta_w - \eta_a)(1 - (1 - \sigma)^n) + \eta_a), \quad (2)$$

where $\sigma$ is the volumetric ratio of water in the air–water dielectric fluid and $m$ and $n$ are the exponent coefficients to be solved by curve fitting the experimental data. In Eqs. (1) and (2), the water–air mixture properties are bounded between those of the air and water at $\sigma = 0$ (100% air) and 1 (100% water), respectively.

The validity of these assumptions is evaluated in EDM experiments. Values of $\sigma$ can be calculated based on the flow rate of water and air. Details of the calculation of $\sigma$ are summarized in the Appendix.

The gap distance $d$ can be expressed as

$$d = d_1 + d_2 = \frac{\alpha}{S_m} + \beta\eta_m. \quad (3)$$

Substituting $\eta_m$ and $S_m$ from Eqs. (1) and (2), the $d$ can be expressed as

$$d = \frac{\alpha}{(S_w - S_a)\sigma^m + S_a} + \beta((\eta_w - \eta_a)(1 - (1 - \sigma)^n) + \eta_a). \quad (4)$$

In Eq. (4), $m$, $n$, $\alpha$, and $\beta$ are four unknown variables, which can be determined by curve fitting the experimental data. Values of viscosity and dielectric strength of air ($\eta_a$ and $S_a$) and deionzied water ($\eta_w$ and $S_w$) are known. Experimental measured values of $d$ under different water flow rates in wire and drilling EDM are summarized in Tables 2 and 3.

### 5.2. Parameters for EDM gap distance model

The curve fitting toolbox in Matlab is utilized to calculate $\alpha$, $\beta$, $m$, and $n$ using the experimental data of $d$ and $\sigma$ for both the wire and drilling EDM. Reasonable approximation in curve fitting is achieved, as illustrated in Fig. 7 for wire EDM and in Fig. 8 for EDM drilling. For the wire EDM, $\alpha = 4.5 \times 10^{-6}$ V, $\beta = 4.6 \times 10^{-5}$ m$^2$s/g, $m = 0.90$, and $n = 5.0$. For the EDM drilling, $\alpha = 0.10 \times 10^{-6}$ V, $\beta = 7.7 \times 10^{-5}$ m$^2$s/g, $m = 0.82$, and $n = 4.7$.

### 5.3. Discussions and model validation

Since the viscosity and dielectric strength are the intrinsic properties of the dielectric fluid, they should be independent of the EDM setups. The values $m$ and $n$ are used in Eqs. (1) and (2) to estimate the viscosity and dielectric strength of the air–water mixture for the wire and drilling

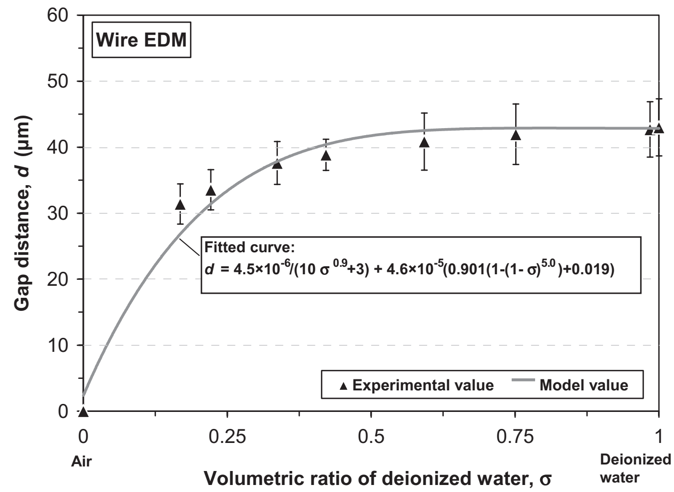


Fig. 7. Experimental measured and model predicted gap distance $d$ vs. volumetric ratio of water $\sigma$ for wire EDM cutting.

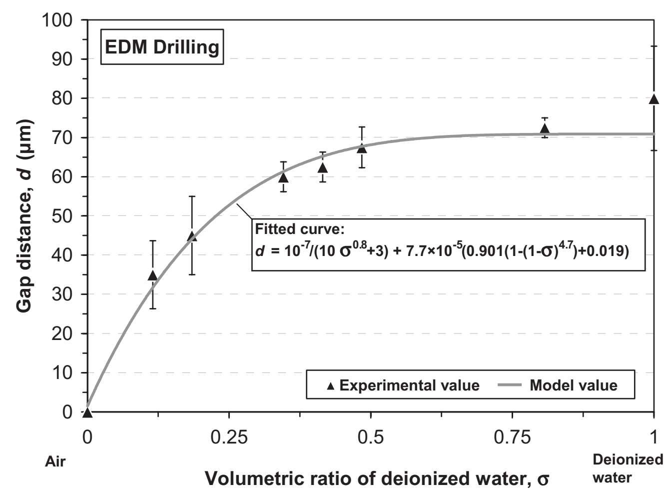


Fig. 8. Experimental measured and model predicted gap distance $d$ vs. volumetric ratio of water $\sigma$ for EDM drilling.

EDM. Hence, it is expected theoretically that $m$ and $n$ should be the same for wire and drilling EDM. The closely matched modeling results of $m = 0.90$ and 0.82 and $n = 5.0$ and 4.7 for the wire and drilling EDM, respectively, indicates the validity of the model. Fig. 9 plots the estimated viscosity and dielectric strength of the air–water mixture at different level of water volumetric ratio. Good match has been observed for the estimated properties yielded from the two independently developed models, wire EDM model and EDM drilling model. It indicates that the model estimated liquid–gas mixture property is independent of the EDM setup, either wire EDM or EDM drilling, but only dependant on the liquid volumetric ratio. Thus, the theoretical model is indirectly validated.

## 6. Concluding remarks

In this study, MRR envelopes of near dry wire EDM at two flow rates were compared with those of wet and dry

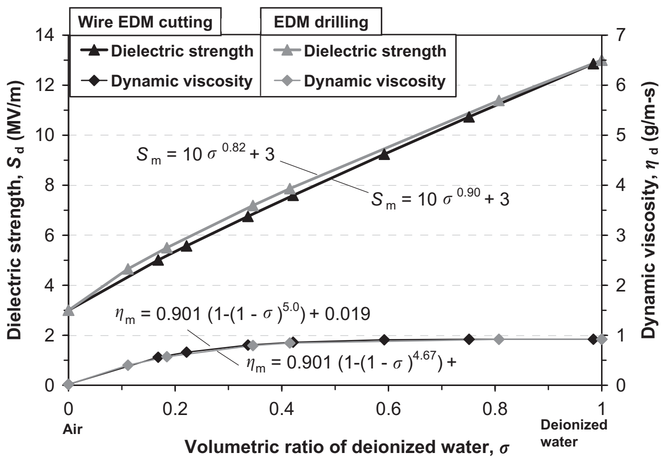


Fig. 9. Estimated values of dielectric strength $S_m$ and dynamic viscosity $\eta_m$ vs. volumetric ratio of water $\sigma$ calculated from the wire EDM and EDM drilling.

EDM. Near dry EDM improved the MRR and eliminated the problem of debris deposition. It was observed that floating metallic debris was effectively collected and burning fumes were greatly suppressed with the application of water–air mixture. The same benefits were also observed in near dry EDM drilling, which achieved better hole consistency with almost no taper.

A mathematical model predicting the gap distance based on the dielectric strength and dynamic viscosity of the water–air mixture was proposed and validated for both wire and drilling EDM. The semi-empirical model provided a quantitative prediction of the gap distance and gained better insight into wet, dry, and near dry EDM.

Research is continuing at the University of Michigan to study the combination of additional liquids such as hydrocarbon oil, and gases such as nitrogen, oxygen, and helium, in near dry EDM. The goal is to tailor unique properties of the EDM dielectric fluid to achieve machining efficiency and quality improvements, such as high MRR and fine surface roughness in near dry EDM.

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## Appendix

The estimation of the volumetric ratio of water, designated as $\sigma$, delivered into the discharge gap is presented. The air and deionized water are pressurized within separate tubes and then merge together to be delivered through a nozzle (in wire EDM), or a tubular electrode (in EDM drilling) to the discharge gap. The actual air flow rate is difficult to measure. The Bernoulli equation with head loss [18], as shown in Eq. (A.1), is utilized and the volumetric air flow rate at the tube exit can then be known by multiplying the air tube exit area with the air velocity at tube exit.

$$\frac{\Delta p}{\rho} = k\frac{V^2}{2} + h_{\mathrm{lT}}, \tag{A.1}$$

where $\Delta p$ is the pressure drop within the air tube, $\rho$ is the air density, $k$ is the kinetic energy coefficient, $V$ is the air velocity at the tube exit, and $h_{\mathrm{lT}}$ is the total head loss, which is caused by friction and abrupt cross-section change. In this study, the effect of cross-section change is neglected and only the friction factor is considered. The total head loss can be represented as [18]

$$h_{\mathrm{lT}} = f\frac{L}{D}\frac{V^2}{2}, \tag{A.2}$$

where $f$ is the friction factor, $L$ is the air tube length, and $D$ is the air tube diameter.

In this study, the pressure drop $\Delta p$ is 0.11 MPa, the air density $\rho$ is 1.17 kg/mm$^3$, and the value of $k$ is 1.08 for turbulent pipe flow. The value of $f$ is estimated to be 0.06 for both wire and drilling EDM using experimentally created charts [18]. The diameter and length of the air tube are 4 and 1200 mm, respectively. On knowing $\Delta p$, $\rho$, $L$ and $D$, and assuming reasonable values for $k$ and $f$, the air velocity, $V$, is solved from Eqs. (A.1) and (A.2). Thus, the continuous air flow rate, $Q_a$, can be estimated based on $V$ and the outlet area, $A_o$.

$$Q_a = VA_o = \sqrt{\frac{2\Delta p}{\rho\left(k + f\frac{L}{D}\right)}}\left(\pi r_o^2\right), \tag{A.3}$$

where $r_o$ is the radius of the nozzle outlet.

Since the water–air mixture is supplied in pulses, the volume of air, $q_a$, carrying the water droplets through the nozzle is

$$q_a = \delta t Q_a, \tag{A.4}$$

where $\delta t$ is the time duration for each pulse. In each pulse, the volume of water is designated as $q_w$. It can be measured using a container and a stopwatch to measure the amount of water collected in a specific period of time. The volume of water divided by the number of pulses in the time duration is $q_w$. The volumetric ratio of water $\sigma$ is

$$\sigma = \frac{q_w}{q_w + q_a}. \tag{A.5}$$

The resulting air velocity is about 97 m/s, and thus the time duration of each ejected dielectric fluid shot is very short, 0.2 ms, which makes $q_a$ very small, about 200 mm$^3$. The value of $\sigma$ is calculated and the results are summarized in Tables 2 and 3.

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