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Micro electrical discharge machining in nitrogen plasma jet

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ABSTRACT

Dielectric, such as kerosene-based oil, deionized water or air, is an essential part of electrical discharge machining (EDM). It directly influences machining performance of the EDM process. While there is large tool electrode wear during machining in liquid dielectric, micro EDM in gas dielectric exhibits almost no tool electrode wear. However, small discharge energy, low dynamic viscosity and low debris concentration of micro EDM in gas creates narrow discharge gap, causing frequent occurrence of abnormal discharge. In this paper, nitrogen plasma jet (NPJ) is used as a dielectric to increase the discharge gap of micro EDM in gas. The machining characteristics of micro EDM in NPJ are investigated and compared with those in other dielectrics. It was found that the discharge distance, machining efficiency and surface quality are significantly improved in NPJ, compared to those in gas under the same conditions. The coaxial high-velocity air jet is helpful to reduce short circuits. Experimental results reveal that NPJ is a viable dielectric in micro EDM.

1. Introduction

Micro EDM has the ability to generate micro features in any electrically conductive material regardless of its hardness and strength. It is used to drill micro holes in diesel engine fuel injection nozzle and to generate micro molds [1]. Micro EDM can drill micro holes with diameters of 5 μm [2]. Complex 3D micro cavities have been machined using simple shaped electrodes [3,4].

Dielectric is an essential part of EDM process. In the case of liquid dielectric, (e.g., kerosene-based oil, deionized water (DIW) or mist), explosion occurs at the end of an electrical discharge due to the quick vaporization of liquid. This causes molten material to be blown into the liquid dielectric, resulting in material removal and tool electrode wear. The molten material is solidified into debris particles, and then flushed away by the liquid dielectric. In the case of gas as dielectric, molten material is directly blown out of the discharge point by compressed gas from the pipe electrode.

Properties of dielectric including dielectric strength, thermal conductivity, heat capacity and dynamic viscosity, influence the machining characteristics of EDM [5]. Usually, kerosene-based oil is used in die-sinking EDM. The discharge gap is small and machining accuracy is high. Disadvantages of kerosene-based oil include air pollution and potential fire hazard. In addition, the occurrence of abnormal discharges increases due to the increase of debris as carbon is decomposed from oil during machining. Disadvantages in DIW as dielectric differ from kerosene-based oil. When discharges occur, the polluted water has

to be removed from the working zone immediately. Otherwise, electrical chemical machining occurs. In industrial application, DIW is widely used in wire EDM because debris and polluted water can be easily flushed away along the straight wire electrode. In the 1990s, gas was proposed as a dielectric in EDM. While large tool electrode wear exists in EDM using liquid dielectric, tool electrode wear ratio (TWR) is close to zero when gas dielectric is used. Molten or vaporized material during discharges in gas is attached to the tool electrode surface to protect the tool electrode from wear [6]. In some cases, material removal rate (MRR) in gas is higher than that in oil under same machining conditions [7]. The disadvantage of EDM in gas is the narrow discharge gap, which cause frequent short circuits [8]. The rotation of electrode and the planetary movement of electrode are used to improve the unstable machining process of EDM in gas [6].

TWR is large during micro EDM in liquid dielectric. In 3D micro EDM, tool electrode diameter is usually less than 100 μm . Tool electrode wear has to be compensated to generate accurate micro cavities. Such tiny pipe electrode is unavailable on the market. To utilize the advantage of near zero TWR in gas, dielectric has to be provided from outside of the tool electrode. The discharge distance in micro EDM is several micrometers long due to small electrical discharge energy. The discharge distance has to be enlarged to use compressed gas to remove molten material from the narrow discharge gap, while avoiding short circuits. In this study, nitrogen plasma jet (NPJ) is proposed as a dielectric. The corresponding experimental equipment is developed. The machining characteristics of micro EDM in NPJ, such as the discharge

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Fig. 1. Structure of micro EDM in NPJ.

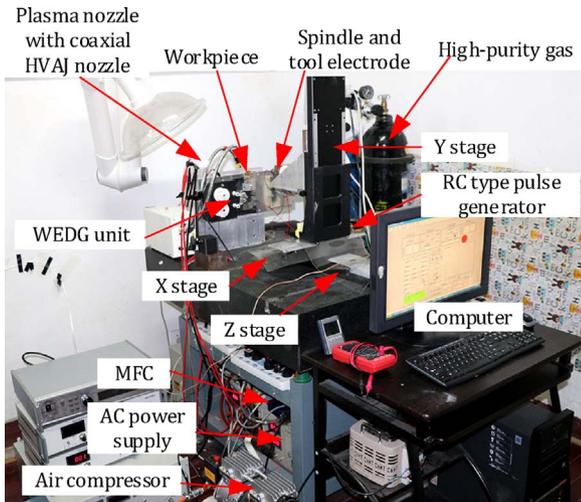
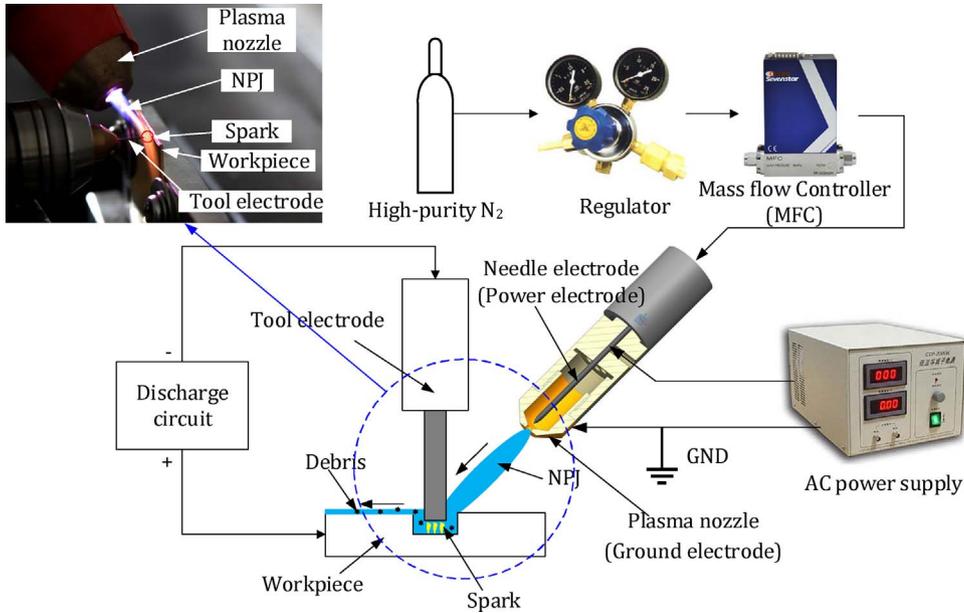


Fig. 2. Experimental equipment.

distance, MRR, TWR, surface roughness and discharge gap, are investigated and compared with those in other dielectrics. Experimental results are analyzed and discussed.

2. Principle of micro EDM in nitrogen plasma jet

A discharge gap in clean dielectric is smaller than that with debris due to the bridge function of debris in the discharge gap [9]. At the same time, large tool electrode wear in liquid dielectric increases the discharge gap. The discharge gap of EDM in gas is less than that in liquid dielectric because debris is directly blown away from the gap without increasing the electrical conductivity of gap [8]. The difficulty of removing molten material from the narrow discharge gap results in frequent occurrence of abnormal discharges. To enable the process of micro EDM in gas stable, it is necessary to enlarge the discharge gap.

As shown in Fig. 1, a high velocity NPJ replaces DIW or oil as the dielectric in micro EDM, which cools down the discharge area. NPJ blows away molten or evaporated workpiece material from the discharge gap and solidifies debris. During electrical discharge off-time, the high velocity NPJ helps the discharge gap to its initial conditions. While tool electrodes used in EDM in gas are mostly pipe tool electrodes with internal supplying mode, all tool electrodes used in this paper are

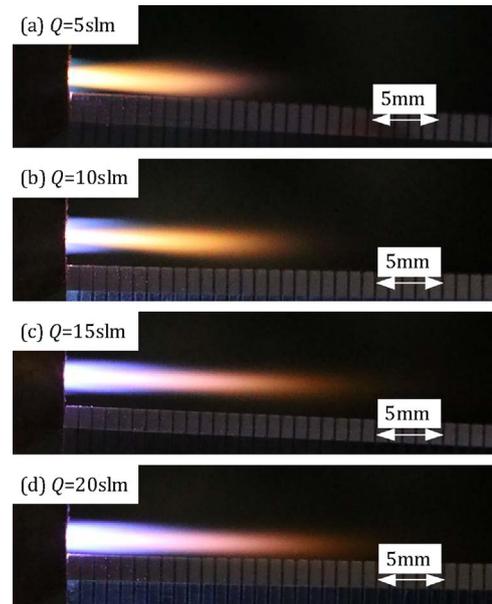


Fig. 3. NPJ under different flow rates.

cylindrical solid rods with external blowing mode.

In this study, NPJ is generated by using needle-cylinder type corona discharge with AC power supply in pure nitrogen gas, as shown in Fig. 1. Corona discharge is a weak luminous discharge, which usually occurs near where the non-uniform electric field is sufficiently large at atmospheric pressure, such as sharp needles, sharp edges, sharp points or small diameter wires [10]. When a corona discharge is initiated, the current is quite low and the voltage has no significant change [11]. Ionization takes place only locally, and the breakdown circuit is closed by displacement current in the initial stages of the corona discharge [10,11]. By increasing the discharge voltage, the gap between power electrode and ground electrode breaks down and the corona discharge transfers into the spark discharge [10]. Temperatures of this kind of plasma jet can be reduced to near room temperature values, causing no thermal damage to the workpiece material [12]. NPJ is composed of ions, free electrons, excited states atoms, molecules, free radicals and so on [12]. These particles may increase electrical conductivity of the discharge gap. Hence, the discharge gap may be enlarged, which may

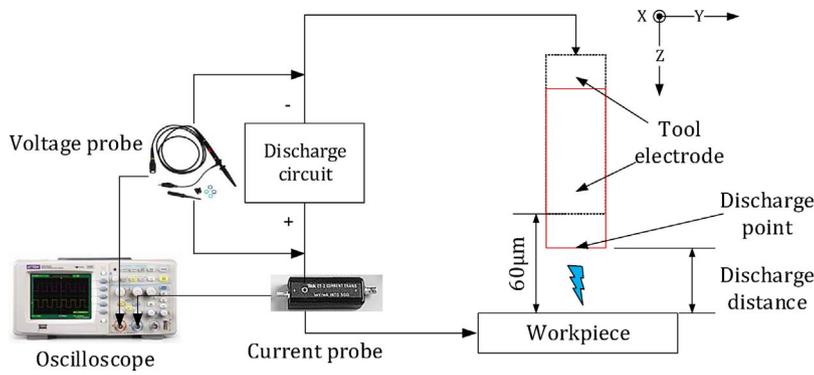


Fig. 4. Structure of discharge distance detecting experiments.

Table 1
Experimental conditions for discharge distance.

No.	Voltage (V)	Capacitance (pF)	Dielectric	Flow rate (slm)	Environment temperature (°C)	Environment humidity (%)
1	100	8200	NPJ	15	22.8	42
2			NJ	15	23.2	44
3			AJ	15	23.2	44
4			OJ	15	21.8	46
5			DIW	–	22.5	47
6	80	3300	NPJ	15	21.8	47
7			NJ	15	23	49
8			AJ	15	22.8	45
9			OJ	15	22.9	46
10			DIW	–	22	47
11		470	NPJ	15	22.1	37
12			NJ	15	23.1	50
13			AJ	15	22.9	50
14			OJ	15	21.8	48
15			DIW	–	23	50

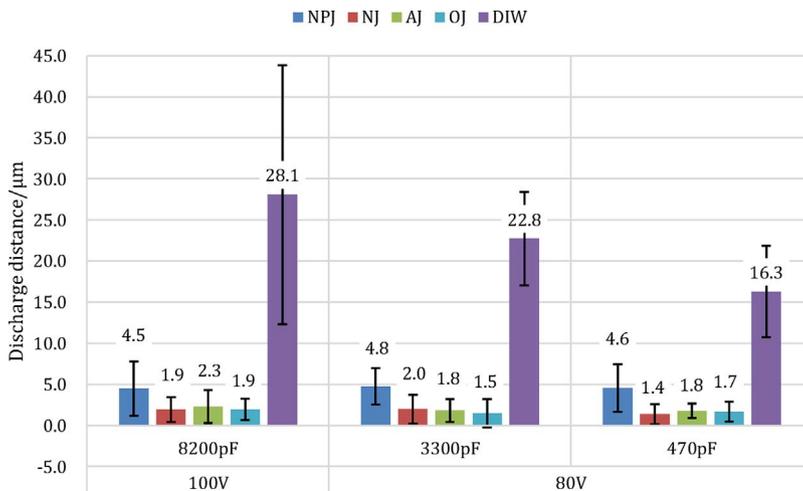


Fig. 5. Comparison of discharge distance in different dielectrics.

provide a better gap condition than micro EDM in gas.

Different from the micro EDM in NPJ, in which the material is removed by electrical discharges, material removal in normal plasma jet machining is by sputtering reaction or etching reaction. Both reactions are non-thermal process. In sputtering reaction, material is removed in atom form by bombarding highly energetic ions in the plasma [13]. Material removed by etching reaction is based on a “dry” chemical reaction between the chemically reactive plasma jet and workpiece material. The plasma jet used in this process is normally fed by reactive gases, such as sulfur hexafluoride (SF₆), carbon tetrafluoride (CF₄) and nitrogen trifluoride (NF₃) [14].

3. Experimental equipment and parameters

3.1. Experimental equipment

To investigate the machining characteristics of micro EDM in NPJ, experiments are carried out on a set of self-developed micro EDM equipment. Fig. 2 shows the experimental equipment. It consists of a pulse generator, set of XYZ stages of 200 mm travel distance with the unidirectional repeatability of 1 μm to control the tool electrode movement, high precision spindle with 1 μm radial runout to hold the tool electrode, set of wire electrical discharge grinding (WEDG) unit, and set of NPJ generator.

After a tool electrode is machined using WEDG unit of the

Table 2
Parameters of groove machining.

Conditions	Values
Pulse generator	RC pulse generator
Flow rate of NPJ and gas jet	15slm
Tool electrode material	Tungsten
Workpiece material	Brass H62
Tool electrode diameter	$65 \pm 5 \mu\text{m}$
Total electrode feed depth	$30 \mu\text{m}$
Layer thickness	$1 \mu\text{m}$
Tool electrode travel distance	$500 \mu\text{m}$
Rotation speed	600 rpm
Environment temperature	$20 \pm 5 \text{ }^\circ\text{C}$
Environment humidity	$40 \pm 15\%$

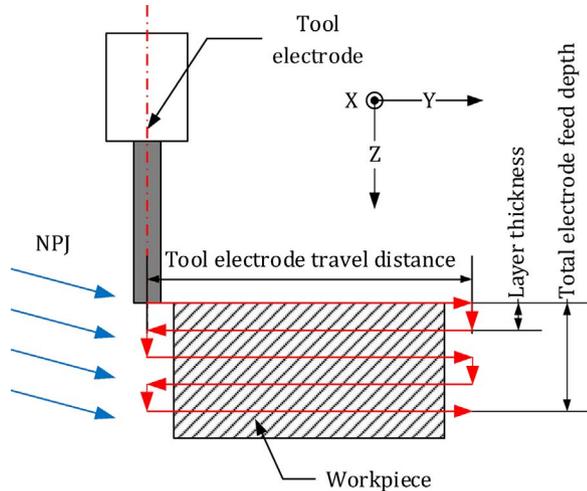


Fig. 6. Tool path for groove milling.

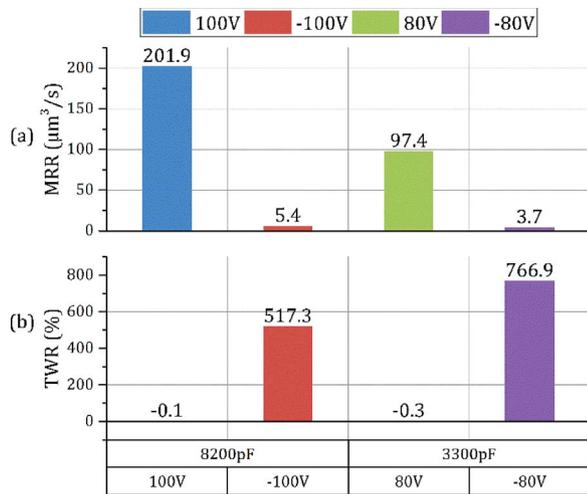


Fig. 7. TWR and MRR under different polarities in NPJ.

experimental equipment, it is controlled to move along a designated tool path. The machining time is recorded. The dimensions of machined feature in X-Y plane are measured using an optical microscope. A reference point on the workpiece surface is electrically contacted before and after machining. The position difference is defined as the tool electrode wear length. The machined depth of micro feature and the machined surface roughness are measured using an interferometer.

3.2. NPJ generator and parameters

NPJ generator consists of one set of high voltage AC power supply (CTP-2000 K made by Nanjing Suman Plasma Technology Co., Ltd), regulator (YQD-6 made by Shanghai Regulator Factory Co., Ltd), mass flow controller (CS200 made by Beijing Sevenstar Electronics Co., Ltd), high-purity nitrogen (purity: 99.999%, provided by Dalian Special Gases Co., Ltd), home-made needle electrode, and home-made plasma nozzle, as shown in Fig. 1. The needle electrode is connected to the high voltage output of the AC power supply. The needle electrode is ground into a sharp tip. The plasma nozzle is connected to the low voltage output of the AC power supply and grounded. The inner diameter of the plasma nozzle outlet is 3 mm. A high coaxiality between the needle electrode and the plasma nozzle outlet has to be ensured. The applied voltage (root mean square value) of the needle electrode is set to 1.86 kV. The frequency of the AC power supply is adjusted to 40–50 kHz. When pure nitrogen gas flows through the powered needle electrode and the grounded plasma nozzle, corona discharge occurs. Under the same applied voltage and frequency of AC power supply, the length of NPJ is controlled by MFC. Experimental results show that the length of NPJ varies with the flow rate. However, the length of NPJ increases very slowly when the flow rate of NPJ is larger than 15 standard liters per minute (slm), as shown in Fig. 3. Therefore, the flow rate of NPJ is set to 15slm with the consideration of experiment cost, space limitation and electrical discharge avoidance between the NPJ nozzle and the tool electrode during EDM. The temperature of NPJ was measured using a thermometer at the axial distance of 5 mm, 10 mm and 15 mm away from the outlet of plasma nozzle, respectively. It was all around 30 °C. In this study, the axial distance between the outlet of plasma nozzle and machining area is around 7 mm.

4. Experimental results and discussion

Extensive experiments are carried out to investigate the machining characteristics of micro EDM in NPJ, such as the discharge distance, MRR, TWR, surface roughness, discharge gap and composition analysis of machined surface. Experimental results are compared with those in DIW, nitrogen jet (NJ), air jet (AJ) and oxygen jet (OJ).

4.1. Discharge distance in different dielectrics

The structure of discharge distance detecting experiments is shown in Fig. 4. A digital oscilloscope (ATTEN® ADS1202CE) with current probe (Tektronix® CT2) and voltage probe (ATTEN® P6200) are used to detect the discharge signal. The rising edge of the current signal detected by the oscilloscope is considered as the occurrence of electrical discharge because the current probe is more sensitive than the voltage probe.

The open voltage of discharge circuit is initially set to 5 V. The tool electrode is fed towards the workpiece in step size of $1 \mu\text{m}$ until a rising edge of the current signal is detected by the oscilloscope. This position is defined as zero point in Z-axis, as shown in Fig. 4. First, the tool electrode moves to the starting point $60 \mu\text{m}$ above the workpiece surface and a desired open voltage and capacitance are set. Then the tool electrode is fed toward the workpiece in the step size of $1 \mu\text{m}$ until an electrical discharge is detected. The distance between the tool electrode and workpiece surface at this position is defined as the discharge distance. This process is repeated 16 times under each condition. The measured discharge distances are recorded and averaged.

Experiments of discharge distance are carried out in NPJ, NJ, AJ, OJ and DIW. Workpiece material is brass H62. Tool electrode material is tungsten. Experimental conditions are listed in Table 1. The average values and standard deviations of discharge distance are shown in Fig. 5.

In Fig. 5, it can be seen that the average discharge distances in DIW are much larger than those in other dielectrics under the same

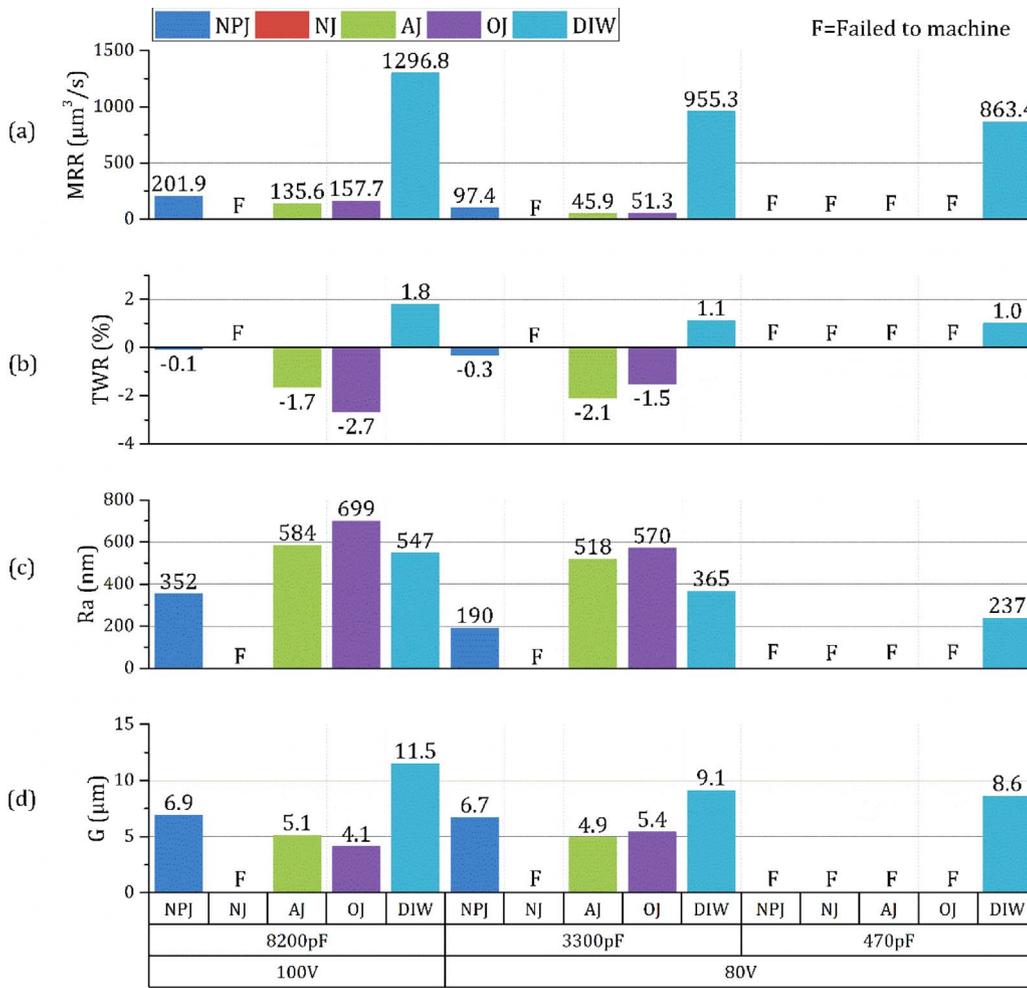


Fig. 8. Machining performance in different dielectrics.

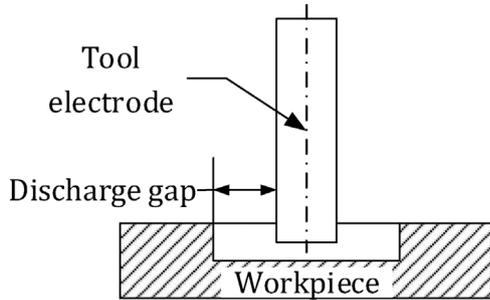


Fig. 9. The definition of discharge gap.

conditions. The average discharge distances in NPJ are larger than those in AJ, NJ and OJ. The difference of average discharge distance in AJ, OJ, and NJ is smaller than 1 μm , which is within the unidirectional repeatability of moving stage.

The variations of environment temperature and environment humidity are below 2 $^{\circ}\text{C}$ and 15%, respectively, as shown in Table 1. The process of discharge distance detection is less than 10 min and thermal deformation caused by temperature variation is dismissible. Humidity of the machining area is mainly determined by the humidity of gas supply rather than the environment humidity. The purity of gas supply used to generate NPJ, NJ and OJ are all 99.999%. A filter regulator (SMC[®] AW20-02BG) and a micro mist separator regulator (SMC[®] AWM20-01BC) are connected to the output circuit of an air compressor in series to filter solid impurities and vapor existing in AJ. Therefore, the difference of humidity among NPJ, NJ, OJ and AJ is very small.

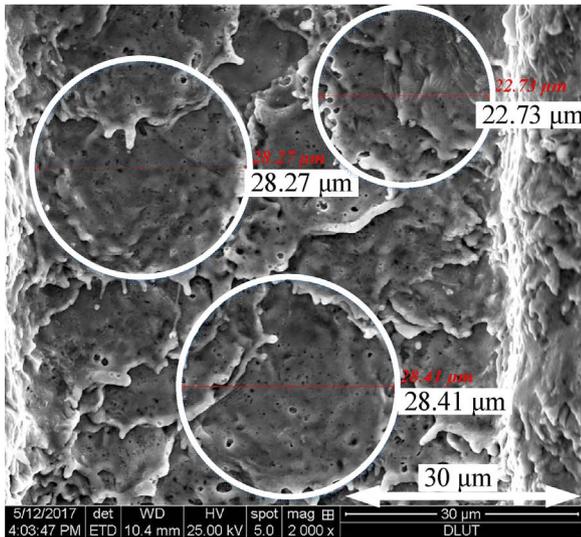
It was reported that the discharge gap in air-water mixture dielectric decreases abruptly with the decrease of water volumetric ratio due to the abrupt drop of the dynamic viscosity of the air-water mixture dielectric [5]. The dynamic viscosity of air, nitrogen or oxygen is much lower than DIW [15]. NPJ can be regarded as a kind of locally ionized nitrogen, which dynamic viscosity is approximate to that of nitrogen. Low dynamic viscosity of NPJ or gas jet results in smaller discharge distance in NPJ and gas jet than in DIW. Debris and some other impurities in NPJ or gas jet are much less than in DIW due to the low density of NPJ or gas jet [8]. Therefore, the discharge distance in NPJ or gas jet is smaller than in DIW.

Discharge distance in NPJ is larger than that in gas jet, which may be caused by the increase of electrical conductivity. It was reported that discharge gap increases with the increase of electrical conductivity [16–18]. However, it is very difficult to measure the electrical conductivity of NPJ [19–21]. The electrical conductivity of NPJ and other dielectrics can be estimated by the following equation [16]:

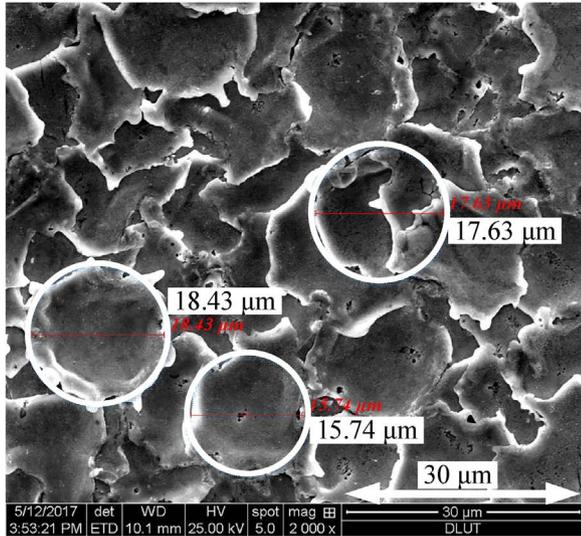
$$\sigma = nqu \quad (1)$$

where, σ is the electrical conductivity; n is the density of current carrier; q is the quantity of electric charge of single current carrier; u is the mobility of current carrier. There is almost no current carrier in gas jet due to the absence of ions and electrons. The density of current carrier (n) in NPJ is much higher than in gas jet because NPJ is obtained by corona discharge. Thus, the electrical conductivity in NPJ is higher and the discharge distance is larger than those in gas jet.

The measured discharge distances in Fig. 5 vary in large range, especially in DIW. The discharge distance is measured using electrical contact method. The error may be caused by the positioning error of



(a) In NPJ



(b) In DIW

Fig. 10. Discharge craters in NPJ and DIW under open voltage of 100 V and capacitance of 8200pF.

moving stage, stray capacitance between the tool electrode and workpiece, and surface contact condition of tool electrode and workpiece. In DIW, the impurity (e.g., particles and bubbles) on the workpiece and resistivity of DIW may trigger electrical contacting signal.

4.2. Effect of polarity

Polarity significantly affects MRR and TWR of micro EDM. Negative tool electrode is generally used in micro EDM with liquid dielectric [22]. The polarity of tool electrode is also negative when the dielectric is gas [6,7,23]. To investigate the influence of polarity on MRR and TWR of micro EDM in NPJ, experiments of groove machining are carried out. The machining conditions are listed in Table 2. The open voltages are 80 V and 100 V, respectively. The capacitance values are 8200 pF and 3300pF, respectively.

The tool path of groove machining is designed, as shown in Fig. 6. A groove is machined layer-by-layer. At the beginning of each layer machining, the tool electrode is fed into the workpiece with one-layer thickness. NPJ is provided from the side of solid electrode at a certain flow rate. Molten material is easily blown away from the working area

to the open surrounding.

Fig. 7 shows TWR and MRR under different polarities in NPJ. In Fig. 7, “-voltage” means that the tool electrode is connected to positive and the workpiece is connected to negative. All results indicate that normal machining process is available when the tool electrode is connected to the negative, and the workpiece to the positive. Otherwise, only the tool electrode wear occurs.

4.3. Influence on machining performance

To study the machining characteristics of micro EDM in NPJ, groove machining is carried out in different dielectrics such as NPJ, NJ, AJ, OJ and DIW. The groove is machined layer-by-layer under the machining parameters listed in Table 2. Other parameters are shown in Figs. 8 and 11.

The results of MRR in different dielectrics are summarized in Fig. 8(a). It can be seen that machining is unavailable in NJ. In experiment, it was observed that short circuit occurs frequently in NJ due to the narrow gap. All machining in NPJ, AJ and OJ are available except for the experiments under open voltage of 80 V and capacitance of 470pF. A large discharge distance in NPJ leads to higher MRR than those in gas jet under the same discharge energy. It is easier to form a spark column in NPJ than those in gas jet because existing of ions and electrons in NPJ. This helps to obtain a higher MRR in NPJ than in gas jet [24]. Heat generated by oxidation reaction enhances material removal of the EDM process [6]. It is reported that the oxidized particle has the capability to reattach less on the workpiece helps the material removal and flushing in the EDM process [25]. Therefore, machining in AJ or OJ is available compared to that in NJ. The more oxidation reaction in OJ than that in AJ leads to a higher MRR in OJ than that in AJ. In the case of open voltage of 80 V and capacitance of 470pF, the machining is unavailable in gas jet even in NPJ, although the average discharge distances in NPJ under different discharge energy are very close as shown in Fig. 5.

Fig. 10 shows that diameters of discharge craters in NPJ are much larger than those in DIW under the same discharge energy. It is because that diameters of spark column in micro EDM in NPJ are larger than those in DIW, since spark column expands more easily in dielectrics without liquid than in liquid dielectric [8]. Therefore, the discharge energy density of micro EDM in NPJ or gas jet is smaller than that in DIW under the same discharge energy. This might be the reason that all of machining in NPJ, AJ and OJ under the conditions of open voltage of 80 V with capacitance of 470 pF failed.

MRRs increase with an increase of discharge energy in all dielectrics. MRRs in DIW are much larger than those in NPJ and gas jet. This is due to the larger discharge energy density and discharge distance in DIW than those in NPJ or gas jet. The pressure wave of gaseous bubbles generated by quick vaporization of liquid dielectric during electrical discharge is large enough to blow the molten material from the discharge area effectively, resulting in higher MRRs in DIW than in NPJ or gas jet.

TWR is greatly influenced by the dielectric. TWRs of groove machining are summarized in Fig. 8(b). It can be seen from Fig. 8(b) that TWRs in DIW increases with an increase of discharge energy. TWRs in NPJ and gas jet tend to be negative. This is because of the molten material deposited on the tip of tool electrode before being removed from the narrow gap, protecting the tool electrode from wear. However, large TWR has to be compensated to achieve the accuracy requirement. Due to the large discharge distance, TWRs in NPJ as shown in Fig. 8(b) are less than 0.3%, which is quite smaller than absolute values of TWRs in DIW and gas jet.

The results of surface roughness are shown in Fig. 8(c). The surface roughness increases with an increase of discharge energy. The surface roughness in NPJ is lower than that in DIW, which may be caused by the molten material flattened by blowing of NPJ and lower discharge energy density in NPJ. The most drastic oxidation reaction in OJ caused

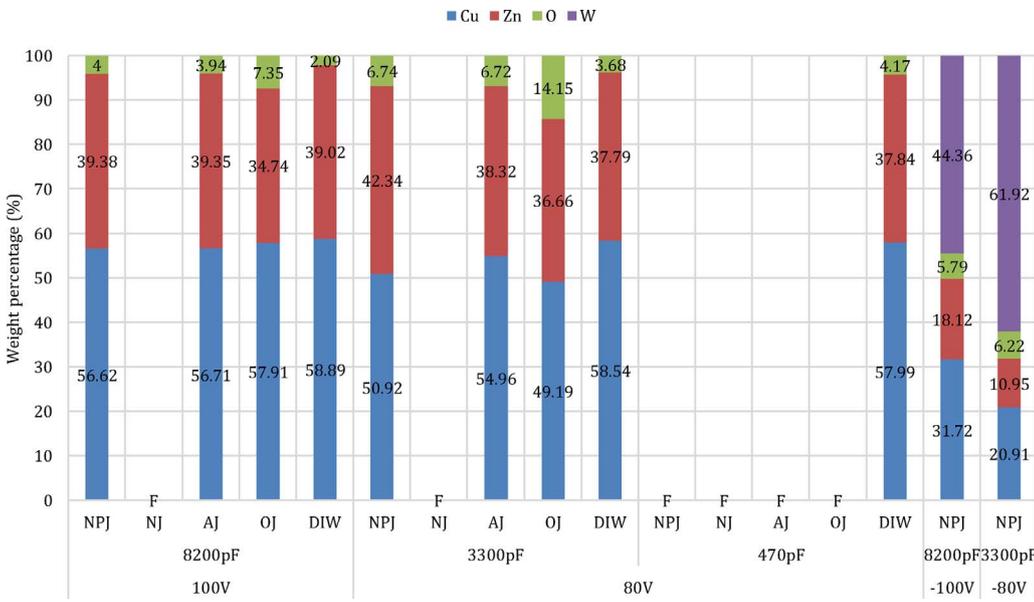


Fig. 11. Material composition analysis results for groove milling experiments.

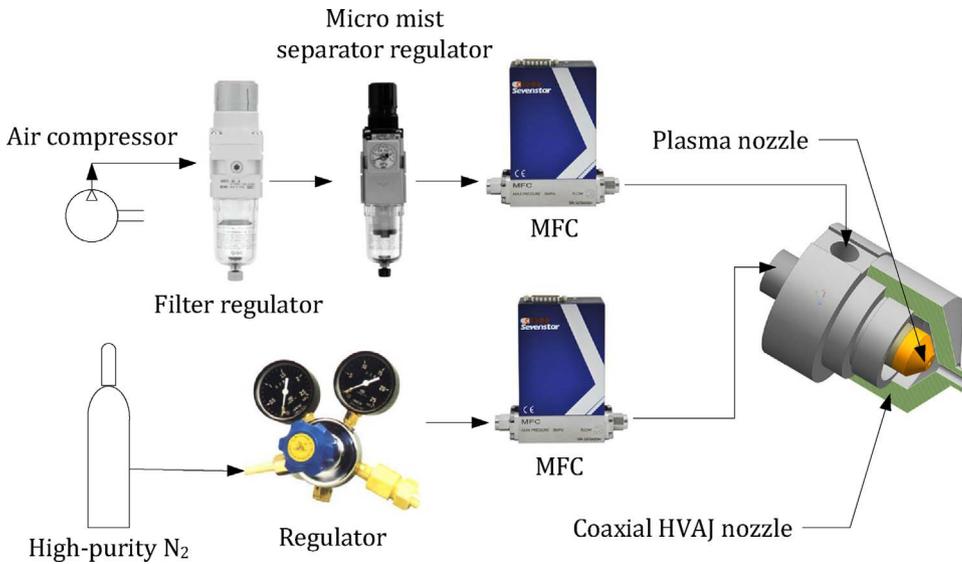


Fig. 12. NPJ with coaxial HVAJ.

the highest surface roughness among NPJ, AJ and OJ. A large discharge distance in NPJ results in lower surface roughness than that in AJ.

Fig. 8(d) shows the results of the discharge gap (G) between the side wall of the machined groove and the tool electrode. The definition of the discharge gap is shown in Fig. 9. The discharge gap is calculated by the following equation:

$$G = (W - d)/2 \quad (2)$$

where, G is the discharge gap; W is the width of the groove; d is the diameter of the tool electrode. It can be seen from Fig. 8(d) that the discharge gap in DIW are larger than those in other dielectrics under the same conditions. The discharge gap in NPJ is larger than those in AJ and OJ. These results coincide with results of discharge distance in Fig. 5. The debris is removed easily from a large discharge gap, leading to stable machining process, resulting in high MRR and good surface quality.

The compositions of workpiece material brass H62 are Cu and Zn. The material composition of machined surface is analyzed using an energy dispersive x-ray spectroscope (EDS). The measured results are summarized in Fig. 11. It is clear that tungsten is deposited on the workpiece surface when the polarity of tool electrode is positive.

Otherwise, there is no tungsten detected on the machined surface. In micro EDM in NPJ, nitrogen cannot be found on the machined surface. A certain amount of oxygen is found on the machined surface from the elemental oxygen in the atmosphere. Oxygen on the machined surface in OJ is the highest among all dielectrics under the same conditions.

5. NPJ aided with coaxial high-velocity air jet

MRR of micro EDM is mainly influenced by two factors, discharge energy and debris removing. However, the flow rate of NPJ is not large enough to effectively blow away debris in micro EDM with NPJ. It is too expensive to increase the flow rate of NPJ. Therefore, a coaxial high-velocity air jet (HVAJ) is added to assist debris removal. The inner diameter of outlet of coaxial high-velocity gas nozzle is 3 mm. In this study, the flow rate of coaxial HVAJ is set to 47.5slm. NPJ aided with coaxial HVAJ is designed, as shown in Fig. 12.

To investigate the effect of coaxial HVAJ, experiments of discharge distance are carried out. The workpiece material is brass H62 and the tool electrode material is tungsten. Other experimental conditions and results are summarized in Fig. 13. The average discharge distances in NPJ with HVAJ (Fig. 13) are slightly lower than the average discharge

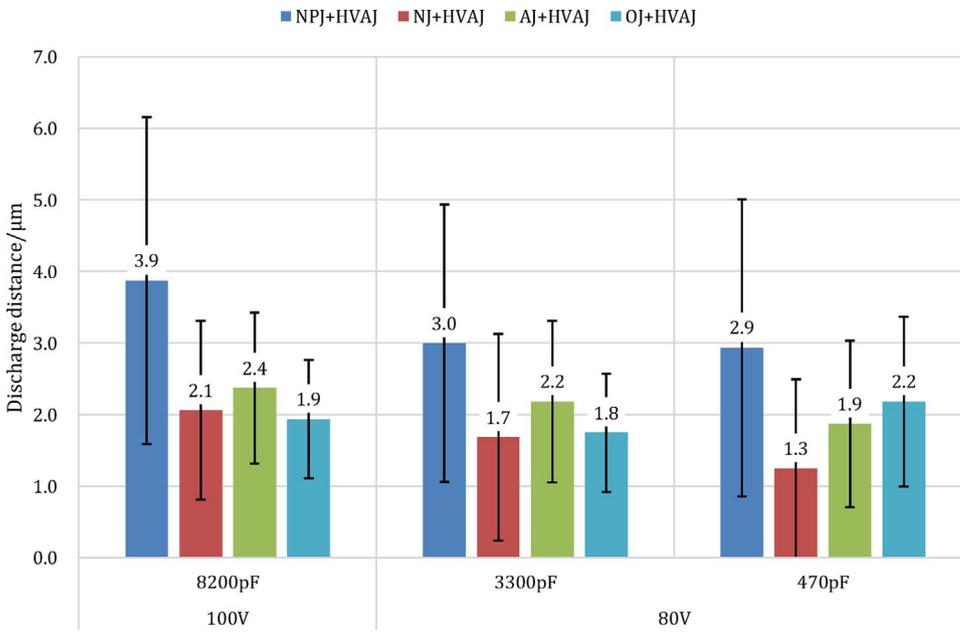


Fig. 13. Discharge distance in different jets with HVAJ.

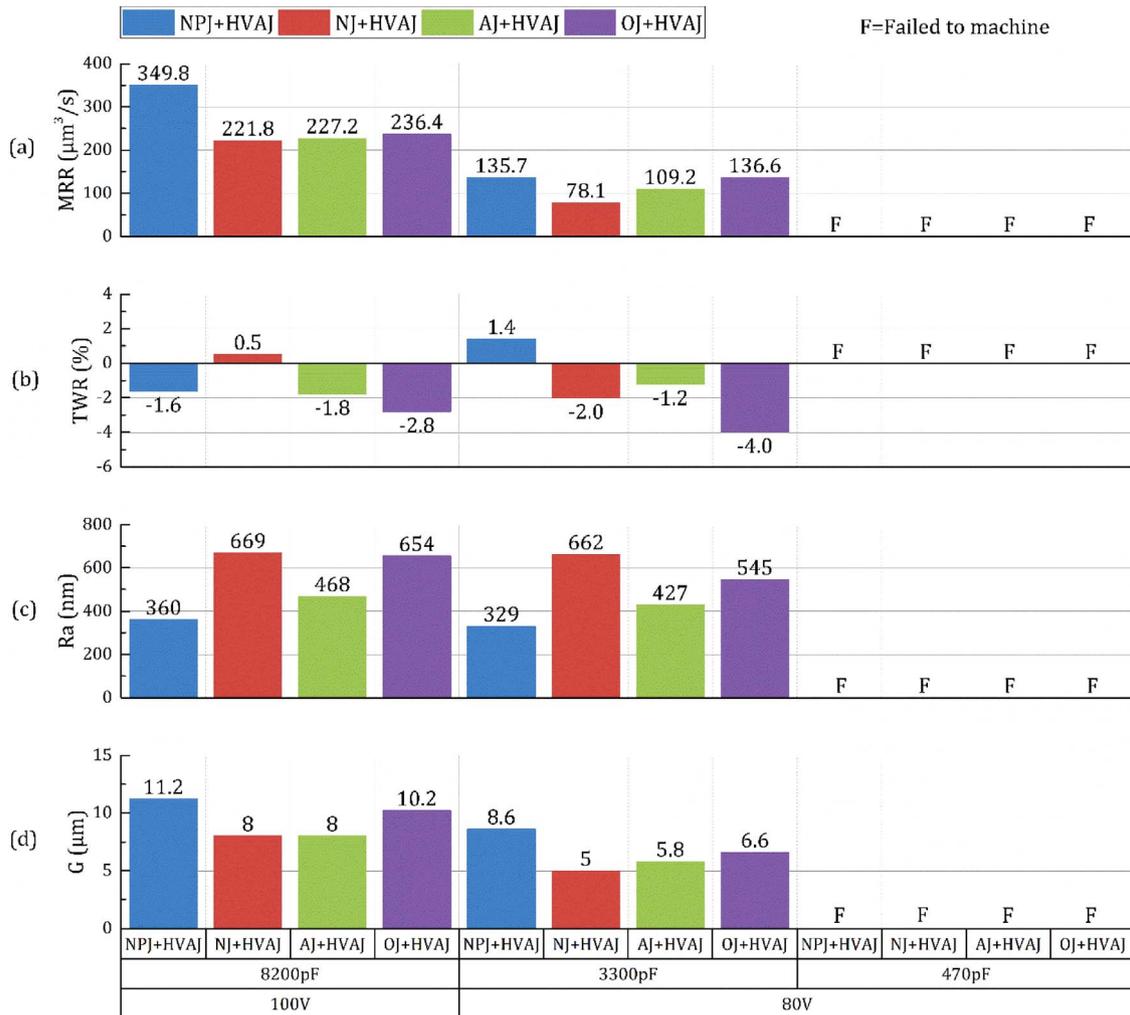


Fig. 14. Machining performance in different jets with HVAJ.

distances in NPJ without HVAJ (Fig. 5). However, discharge distances in NPJ with HVAJ are still larger than those in gas jet with HVAJ. The differences of average discharge distance in gas jet with HVAJ

compared to those in the same gas jet without HVAJ are all within 1 μm, as shown in Figs. 5 and 13. It indicates that the addition of HVAJ results in no significant change of discharge distance. The density of

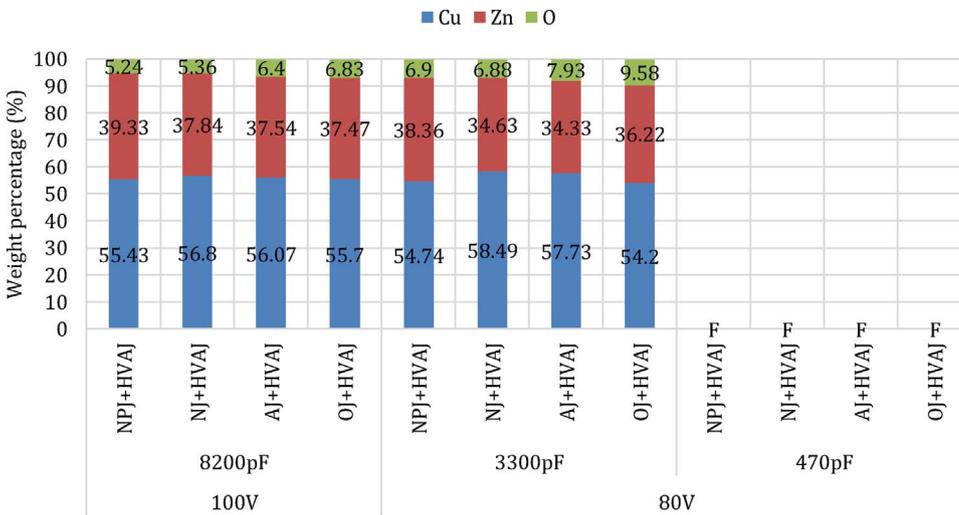


Fig. 15. Material composition analysis results in different jets with HVAJ.



Fig. 16. 'DUT' machined by micro EDM in NPJ with HVAJ.

ions and electrons in NPJ decreases when HVAJ is added to NPJ, resulting in the decrease of electrical conductivity. Therefore, the discharge distances in NPJ with HVAJ are slightly lower than those in NPJ without HVAJ under the same conditions.

To study the influence of the coaxial HVAJ on machining performance of micro EDM, grooves are machined under the same conditions in Table 2. Other machining parameters are shown in Figs. 14 and 15. All MRRs in Fig. 14(a) increase due to the coaxial HVAJ, compared to the MRRs in Fig. 8(a). Machining becomes available when coaxial HVAJ is added to NJ. Molten material during discharge is efficiently removed as the dielectric flow rate is increased by the coaxial HVAJ. Machining is still unavailable under open voltage of 80 V and capacitance of 470 pF due to low discharge energy.

Results of TWR are shown in Fig. 14(b). It can be seen that TWRs are small and randomly distributed due to small material removal amount of workpiece and small tool wear. Some factors such as the thermal deformation, repeated positioning error of moving stage and measurement errors might be reasons for errors of TWR.

Surface roughness is shown in Fig. 14(c). Similar to those in Fig. 8(c), the values of surface roughness machined by micro EDM in NPJ with coaxial HVAJ are smaller than those machined by micro EDM in gas jet with coaxial HVAJ. This is because the discharge distance in NPJ with coaxial HVAJ is larger than those in gas jet with coaxial HVAJ because of electrical particles, such as ions and electrons, in the gap. However, the values of surface roughness in micro EDM in NPJ with coaxial HVAJ are larger than those in NPJ only. It may be due to the oxygen in HVAJ involved in machining, resulting in poor surface roughness. It is consistent with the reported results [26]. The weight percentage of oxygen element on the machined surface in NPJ with

HVAJ (Fig. 15) is slightly higher than those in NPJ without HVAJ (Fig. 11) under the same conditions. The flow rate of gas jet aided with HVAJ is much larger than gas jet only, resulting in lower surface roughness than that in gas jet only under the same conditions.

Results of discharge gap are shown in Fig. 14(d). It can be seen that the discharge gaps in NPJ with HVAJ are larger than those in gas jet with HVAJ under the same conditions. Discharge gaps in NPJ or gas jet with HVAJ shown in Fig. 14(d) are larger than those without HVAJ under the same conditions shown in Fig. 8(d). This might be caused by the vibration of tool electrode because the flow rate of NPJ or gas jet increases from 15slm (without HVAJ) to 62.5slm (with HVAJ).

Fig. 15 shows material composition of the machined surface. Compared to results in Fig. 11, it can be seen that the oxygen weight percentage increases in all machined surface except OJ. The coaxial HVAJ adds oxygen in the machining area, reducing the percentage of oxygen in OJ.

Based on experimental results above, it is clear that the gap condition of micro EDM in NPJ is improved significantly when aided with coaxial HVAJ. Letters 'DUT' were machined. The voltage is set to 80 V and capacitance is 3300pF. Total tool electrode feed depth is 20 μm . The diameter of electrodes is $90 \pm 5 \mu\text{m}$. Other parameters are listed in Table 2. Machining results are shown in Fig. 16. It takes 6 h 15 min to machine the letter D; 7 h 45 min for U; and 4 h 36 min for T. There is little debris recast on the machined bottom surfaces. Debris is also accumulated on the edges of the letters. Each tool electrode length after machining is increased by less than 3 μm .

6. Conclusions

In this paper, NPJ was proposed as the dielectric in micro EDM. It was found that the discharge distance increases significantly due to the presence of electrical particles, such as ions and electrons, in the gap. The molten material is more efficiently removed in micro EDM with NPJ than with gas jet. This results in increased MRR and decreased surface roughness. To set the polarity in micro EDM in NPJ, the tool electrode is connected to the negative and the workpiece to the positive. Otherwise, there is no material removal of the workpiece. Tool electrode wear can be ignored due to the deposition of molten material during discharges. The material compositions of machined surface in NPJ are similar to those in DIW. No nitrogen element was found on the machined surface by micro EDM in NPJ. To further increase machining efficiency, coaxial HVAJ was proposed in micro EDM in NPJ and in gas jets, such as NJ, AJ and OJ. The increase of dielectric flow rate in the narrow gap enhances material removal, leading to significant increase of MRR. Machining of micro EDM in NJ becomes available with the assistance of HVAJ. Some micro features have been machined

successfully by micro EDM in NPJ with coaxial HVAJ.

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