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Enhanced Machining Performance of Micro Holes Using Electrochemical Discharge Machining with Super-High-Pressure Interior Flushing

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Micro-holes are widely used, and their machining process is vital to modern manufacturing, especially for materials that are difficult to machine. Tube electrode high-speed electrochemical discharge machining (ECDM) combines electrochemical machining (ECM) and electrical discharge machining (EDM) and is considered a promising hybrid machining method for the fabrication of micro-holes in difficult-to-machine materials. However, because of the characteristics of the hybrid process, it produces not only debris and heat but also hydroxides and bubbles. The removal of these complex machining by-products constitutes a challenge. To address this issue, super-high-pressure interior flushing, which utilises more than twice the pressure traditionally used for interior flushing, was applied to ECDM in the present study. The resultant machining technique and its performance were examined and compared with sinking machining and traditional interior flushing. The effects of various interior flushing pressures on the ECDM process were also investigated. In comparison to sinking machining and traditional interior flushing, the proposed super-high-pressure interior flushing was found to be more effective in removing the by-products of the machining process, and it was also found to enhance the machining efficiency and surface quality. The performance of the proposed machining technique was observed to vary with the diameter of the tube electrode. A Φ500 μm tube electrode allowed the use of a relatively high flushing pressure, which enhanced the material removal rate (MRR) and the removal of the machining products and also produced a small taper angle. However, the achievement of a small average hole diameter required a flushing pressure as low as possible within the range of 6–12 MPa. With Φ200 μm and Φ300 μm tube electrodes, the optimal flushing pressure for obtaining a high MRR and a small average hole diameter and taper angle was found to be 10 MPa.

Keywords: micro-hole; electrochemical machining; electrical discharge machining; super-high-pressure interior flushing; tube electrode;

1. INTRODUCTION

Micro-holes are widely used in the aerospace, automotive, electronics, optics, medical devices, and communications industries [1]. Typical examples include film cooling holes in turbine blades, holes in diesel fuel injectors, spinnerets holes, inkjet printer nozzles, and drug delivery orifices [2]. The drilling of film cooling holes, which were produced in difficult-to-machine materials, was particularly difficult, especially using traditional methods [3]. The materials employed include nickel-based superalloys and titanium alloys. The unique metallurgical properties of these materials, such as their high strength and hardness, required the use of non-traditional machining processes [4]. However, the increasing demand for higher machining efficiency and quality also poses a great challenge to the use of available non-traditional processes.

To address these issues, especially the requirement for high machining efficiency and quality, tube electrode high-speed electrochemical discharge machining (ECDM) has been proposed [5]. The process involves the use of a low-conductivity salt solution to combine high-speed electrical discharge machining (EDM) and electrochemical machining (ECM) in a unique machining process. It is thus characterised by high machining speed and surface quality. The high machining speed is achieved by high-speed electrical discharge drilling in the frontal gap, and high surface quality is obtained by electrochemical machining in the lateral gap. Tube electrode high-speed ECDM is considered a promising method for efficient machining of micro-holes with high-quality surfaces, such as film cooling holes.

However, because of the narrow machining gap in the fabrication of a film cooling hole, the flow of the work fluid is significantly inhibited. This hampers the flushing of debris and bubbles from the gap by the work fluid, especially during the machining of a deep hole [6]. The resultant accumulation of debris and bubbles in the work fluid accelerated the breakdown of the dielectric fluid, thereby increasing arc pulses. Additionally, a small machining gap makes heat dissipation difficult [7]. The resulting abnormal discharge currents and residual heat diminish the machining accuracy, generate a thick recast layer, and accelerate electrode wear [8-9]. Furthermore, poor machining stability reduces the machining speed. Thus, effective flushing is considered as vital to the success of micro-hole drilling.

To enhance flushing during drilling, several approaches have been employed by researchers, including vibration of the electrode and workpiece, orbital movement of the electrode, and the use of different flow modes of the work fluid. Prihandana et al. [10-11] found that low-frequency vibration frequently produced the shortest distance between the tool and the workpiece. It also enhances flushing and dielectric circulation between the tool electrode and the workpiece. The resultant surface roughness and tool wear rate of machining without vibration have been observed to be higher than those of machining with low-frequency vibration. Low-frequency vibration can thus be used to increase the material removal rate and decrease the surface roughness and tool wear rate. Shabgard et al. [12] found that ultrasonic vibration of the workpiece also enhanced flushing and the stability of the EDM process and increased the material removal rate (MRR) and surface quality. Rajurkar and Zhu [13] found that orbital electrode movement reduced flow disruption and improved the machining accuracy and stability. Li et al. [14] observed that a bunched electrode with multiple interior hole flushing endured higher peak currents and also increased the material removal rate and relative tool wear ratio. This was achieved by more effective flushing. Han et al. [15] found that the use of an ultrasonically vibrated electrolyte for electrochemical discharge drilling (ECDD) enhanced the machining depth by ensuring adequate flow of the electrolyte for spark generation and chip removal from the gap between the tool and the workpiece. Moreover, the shape of the bubble layer was modified by the acoustic pressure distribution in the vertical direction, which induced more active spark discharge in the vicinity of the tool surface. The machining depth was consequently clearly enhanced. Wang et al. [16] proposed that a reverse electrolyte flow pattern with vacuum extraction could prevent the occurrence of cavitation and diminish sparking and the formation of striations. Fang et al. [17] implemented pulsating electrolyte flow in ECM to improve the heat transfer, material removal rate, and surface profile. They found that a pulsating flow significantly affected the distributions of the velocity, gas fraction, and temperature near the surface of the workpiece in the flow direction.

Although the abovementioned methods have been used to enhance flushing to a certain degree, the primary determinants of the effectiveness of flushing are the flushing pressure and rate. Wang and Yan [18] investigated the effect of the flushing pressure within a certain range on electro-discharge drilling (EDD) and found that an increase in the injection flushing pressure of the dielectric fluid increased the MRR, although the enhancement was limited to a certain range. Yan et al. [19] also varied the flushing pressure for a tube electrode and observed that the material removal rate increased with increasing pressure. Wong et al. [20] investigated the effect of the flushing rate on surfaces produced by electro-discharge machining and determined an optimal dielectric flushing rate that minimised cracking and the average thickness of the recast layer. Lee et al. [21] examined the effect of dielectric flushing on the characteristics of machining and found that a low flushing pressure did not remove gaseous and solid debris after each discharge, while optimal flushing minimised the relative wear ratio. Gu et al. [22] investigated the increased discharge voltage caused by elongation of the plasma channel based on the resultant high flow rates in the narrow gap. They found that the change in the length of the plasma channel altered the resistance and consequently the discharge voltage. Munz et al. [23] examined the fundamental material removal mechanism to determine whether the flow rate directly affected the removal process. Some authors noted that the dielectric fluid serves to flush away debris and cool the electrode [24-25]. They presented direct evidence of the improvement of machining performance by flushing. The flushing pressure commonly used in traditional electro-discharge high-speed drilling is 2–4 MPa, and the machining efficiency is enhanced by the use of a lower flushing pressure.

The abovementioned studies have identified the flushing pressure and rate as the primary determinants of machining speed and quality. These studies focused primarily on commonly used pressures and individual processes, such as EDM and ECM. However, the flushing conditions are more important in hybrid machining, especially a hybrid drilling process that combines EDM and ECM. In hybrid drilling, there is the high risk of jamming occurring in the machining micro-gap, where electrochemical dissolution and electrical discharge erosion take place simultaneously. This is because of the accumulation of machining by-products, including electrical discharge particles and electrochemical precipitates and bubbles. Poor flushing conditions increase the risk of the occurrence of jamming and thus diminish machining efficiency and quality.

In hybrid machining involving EDM and ECM, flushing of the machining micro-gap is still a challenging issue with regard to improving machining speed and quality. The super-high-pressure flushing is innovatively used to overcome the jamming of hybrid machining products and whereby improve the machining performances in ECDM process. Simultaneously, previous researches usually focus on the single process, like EDM or ECM, so far there have been no reports of the application of interior super-high-pressure flushing to hybrid machining. The present study was the first in which this flushing technique was applied to tube electrode high-speed electrochemical discharge machining. Considering the importance of high-speed flow to the removal of the by-products of hybrid machining and the high flow resistance that results from the narrow machining gap and small inner diameter of the tube electrode, we propose the use of super-high-pressure flushing of the gap to avoid jamming by by-products. The machining performance of the proposed interior flushing technique was compared with that of sinking machining and traditional interior flushing, which is currently used in ECDM. In addition, the effects of super-high-pressure flushing on the machining performance of ECDM, including the effects on the MRR, diameter accuracy, and surface quality, were investigated in detail.

2. PRINCIPLES OF TUBE ELECTRODE HIGH-SPEED ECDM WITH SUPER-HIGH-PRESSURE FLUSHING

Tube electrode high-speed electrochemical discharge machining is a hybrid of tube electrode high-speed electrical discharge drilling and ECM. The process employs a tube electrode as the machining tool and a low-conductivity salt solution as the work fluid in the EDM and ECM processes. The salt solution is supplied continuously from inside the tube electrode and is used as a bi-characteristic work fluid in which the EDM and ECM processes occur simultaneously.

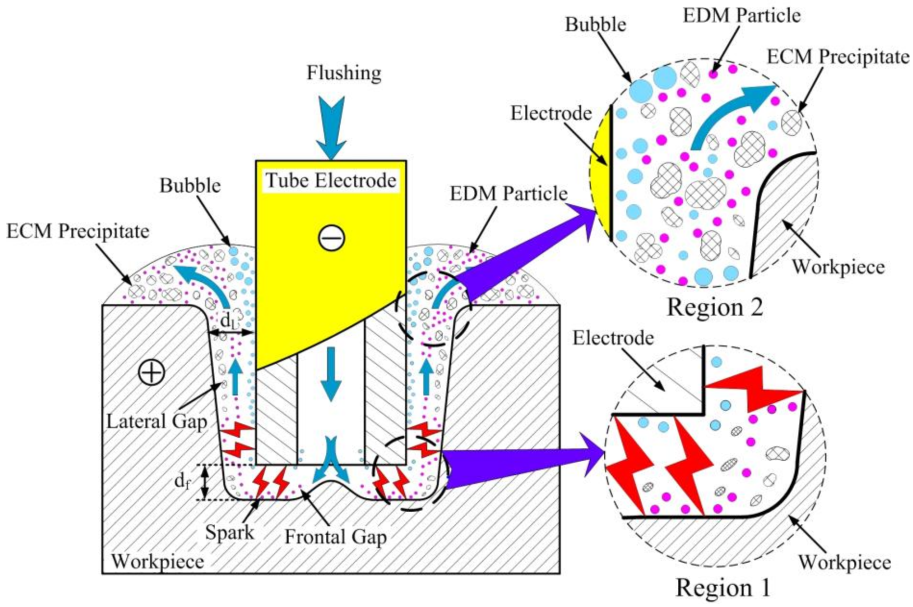


Figure 1. Mechanism of tube electrode high-speed ECDM using super-high-pressure flushing

In this study, super-high pressure in interior flushing was defined as a pressure of more than 10 MPa, which is far higher than that used in traditional flushing. The mechanism of tube electrode high-speed electrochemical discharge machining using such a high pressure is illustrated in Fig. 1.

Frontal gap. Because of the continual feeding of the tube electrode towards the workpiece, the frontal gap is always a micro-gap smaller than the theoretical maximum discharge gap of approximately 30 μm, as shown in Fig. 1. Electrochemical dissolution and electrical discharge erosion occur simultaneously in this gap, and the materials are removed rapidly to permit a high drilling speed. However, in Region 1, the accumulation of the machining products, including electrical discharge particles, electrochemical precipitates, and bubbles, in the small gap poses a high risk of jamming. As noted earlier, poor flushing conditions increase this risk and diminishing the machining efficiency and quality. Super-high-pressure flushing enhances the elimination of these by-products and increases the material removal rate. Super-high-pressure flushing in the frontal gap thus facilitates high-speed drilling.

Lateral gap. In the lateral gap, there is a transition of the material removal mechanism from EDM–ECM to pure ECM. The material removal mechanism near the forward part of the electrode is the same as that in the frontal gap, as shown in the expanded view of Region 1 in Fig. 1. Because of both the EDM and ECM processes, the lateral gap enlarges rapidly. This continues until the size of the gap exceeds the critical value for the discharge, at which point EDM is stopped and ECM becomes the exclusive machining process. Under these conditions, mass hydroxide precipitates and bubbles are generated in the lateral gap, as shown in the expanded view of Region 2 in Fig. 1. In this region, the lateral gap formed after EDM has been stopped is considered to be the initial gap for material dissolution, and the rough surface generated by EDM is removed by electrochemical dissolution in the lateral gap. However, the by-products generated in the lateral and frontal gaps combine and stagnate in the lateral micro-gap, resulting in impaired decontamination of the lateral gap and consequently secondary discharge and heat accretion. Under the prevailing high temperature, the accumulated machining by-products attach themselves to the lateral wall of the hole, and this results in poor surface quality. Hence, super-high-pressure flushing is extremely important to achieving good surface quality.

In summary, as a hybrid drilling process, tube electrode high-speed electrochemical discharge machining involves EDM–ECM, pure ECM, and a transition from EDM to ECM. Compared to traditional electro-discharge high-speed drilling, this complex machining process generates mass heat and by-products consisting of electrical discharge particles, electrochemical precipitates, and bubbles. All of these by-products are generated in a machining micro-gap only tens of microns in size. The volume of the electrochemical precipitates in particular could be up to several hundred times greater than the volume of the electrical discharge particles. The ejection of these products is thus a greater challenge in tube electrode high-speed electrochemical discharge machining than it is in traditional electro-discharge high-speed drilling. In the hybrid machining process, high-speed flow is used to remove the machining by-products. The narrow machining gap and small inner diameter of the tube electrode result in high flow resistance, and the use of super-high pressure is proposed primarily to permit high-speed flushing of the machining gap and avoid jamming of the machining by-products. Super-high-pressure flushing is vital to maintaining freshness of the work fluid, and this not only ensures that EDM can be executed in the frontal gap but also facilitates the electrochemical reaction in the lateral gap. In summary, super-high-pressure flushing refreshes the work fluid, cools the machining gap, and prevents jamming of the narrow gap by the machining by-products. The machining speed can thus be increased, and high surface quality can be achieved.

3. EXPERIMENTAL DESIGN

3.1. Experimental setup

The experimental system developed in this study for the investigation of tube electrode high-speed electrochemical discharge machining with super-high-pressure flushing is shown in Fig. 2. The system consists of a super-high-pressure flushing unit, a power supply, a current/voltage detection unit, and a machining cell. The high-pressure flushing unit is the core component of the system, and it produces super-high pressure using a high-pressure pump. The pressure and flux of the work fluid are measured using a piezometer and flowmeter, respectively. The flushing process is boosted in the machining region shown in Fig. 2. The work fluid flows into the inter-electrode gap from inside the tube electrode. The entire machining process is driven by a pulse generator and monitored by a signal recorder, which is capable of measuring the machining voltage and current simultaneously.

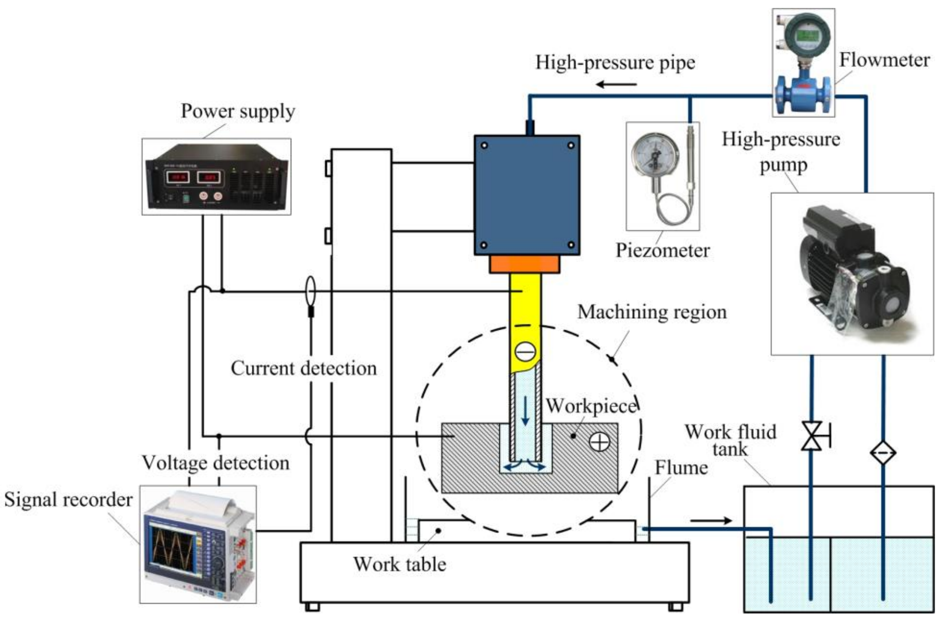


Figure 2. Schematic illustration of ECDM system with super-high-pressure flushing

3.2. Materials

DZ125L is one of the nickel-based superalloys that are most commonly used in the fabrication of turbine blades and vanes. The material has a high melting point and poor thermal conductivity, both of which are desirable properties for the purpose. However, its high stiffness and wear resistance make it difficult to achieve high efficiency and accuracy in its machining by traditional methods. In this study, a 3-mm-thick DZ125L workpiece was employed. The chemical composition of the material is summarised in Table 1. A brass tube was used as the electrode tool.

Table 1. Chemical composition of DZ125L alloy (wt%)

Composition	C	Cr	Co	W	Mo	Ta	Al	Ni
	0.07–0.12	6.50–7.50	11.50–12.50	4.70–5.20	1.00–2.00	6.50–7.50	5.60–6.20	Bal.

3.3. Machining procedures and conditions

In this study, the performance of machining with super-high-pressure interior flushing was compared with the performance of sinking machining and machining with traditional interior flushing (see Fig. 3). Sinking machining utilises a static fluid, which can be considered to have an interior flushing pressure (P) of 0 MPa. In traditional tube electrode high-speed drilling, the commonly used flushing pressure is approximately 4 MPa. In the present study, super-high pressure was defined as a pressure of approximately 10 MPa. Using a tube electrode of Φ200 μm, machining processes using the above three work fluid supply conditions were employed, and their performances were compared. The main machining parameters are given in Table 2. Holes of various diameters were drilled using various high flushing pressures to investigate the effects of high-pressure flushing on the machining performance of tube electrode high-speed electrochemical discharge machining. The machining parameters for this aspect of the study are given in Table 3.

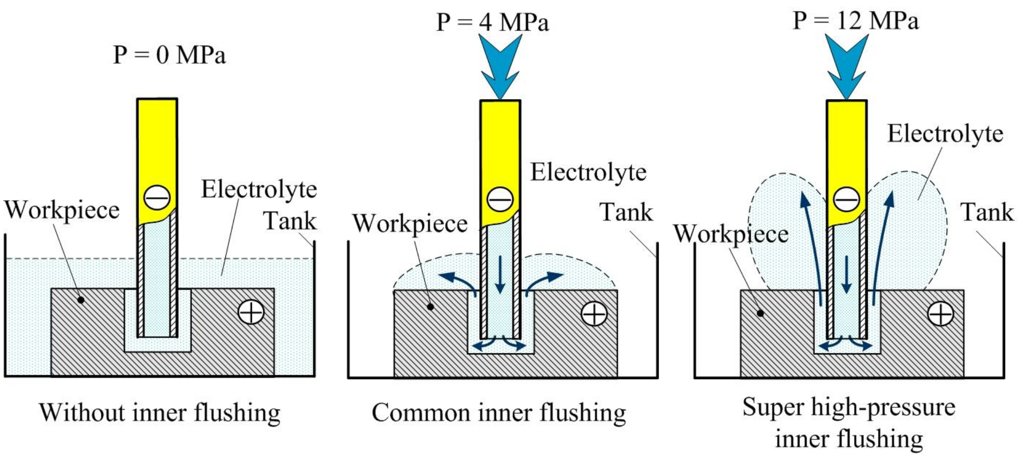


Figure 3. Schematic illustrations of different supply conditions for work fluid

The MRR is considered to be the linear material removal rate and is calculated as MRR = L/t, where *L* is the machined depth and *t* is the machining time required to drill the hole in a particular setting. The average diameter of the micro-hole is defined as $D_{average} = (D_{entrance} + D_{exit})/2$, and the taper angle θ of the hole is determined from $\tan\theta = (D_{entrance} - D_{exit})/2h$, where $D_{entrance}$ and D_{exit} are the entrance and exit diameters of the hole, respectively, and h is the thickness of the workpiece. The improvement in the machining performance of tube electrode high-speed electrochemical discharge machining achieved by super-high-pressure interior flushing was also analysed.

Table 2. Machining parameters for comparative experiments

Machining parameter	Value
Pulse voltage	80 V
Pulse duration T_{on}	12 μs
Pulse interval T_{off}	36 μs
Peak current	12 A
Work fluid	Sodium nitrate water solution
Solution conductivity	3 mS/cm
Tube electrode external diameter	300 μm
Tube electrode rotation	100 rpm
Work fluid pressure P	0, 4, 10 MPa

Table 3. Machining parameters for tube electrode high-speed ECDM

Machining parameter	Value
Pulse voltage	80 V
Pulse duration T_{on}	12 μs
Pulse interval T_{off}	36 μs
Peak current	12 A
Work fluid	Sodium nitrate water solution
Solution conductivity	3 mS/cm
Tube electrode rotation	100 rpm
Tube electrode external diameter	200, 300, 500 μm
Tube electrode inner diameter	100, 140, 200 μm
Work fluid pressure P	6, 8, 10, 12 MPa

4. RESULTS AND DISCUSSION

4.1. Comparison of machining performances using different machining process

In this section, the main aim is to show the advantage of super high pressure flushing machining by the comparative experiment. Munz et al.[26] has studied the effect of flushing in electrical discharge machining on machining quality and productivity, and found that high flushing pressures lead to high dielectric flow rates in the narrow gap between the tool electrode and the work piece and improve the EDM machining performance. Qu et al. [27] introduced axial electrolyte flushing into WECM for removing electrolysis products and renewing electrolyte, thus the machining productivity of WECM can improved. However, these researches usually focus on the single machining process like EDM or ECM. As the EDM and ECM hybrid machining, the TSECDD proposed by Y. Zhang, usually employed the traditional pressure about 4MPa [5]. Hence, there have been no reports of the application of super-high-pressure interior flushing to hybrid machining.

As the typical machining processes, the ECDM with static fluid and TSECDD with traditional-pressure interior flushing are chosen as the comparative objects. On one hand, the static fluid is widely used both in EDM and in ECM, and commonly studied by many researchers [28, 29]. However, these researches usually focus on the single machining process like EDM or ECM. Therefore, these experimental results cannot be used to compare with experimental results shown in this section directly. Hence the static fluid is introduced into the ECDM, and the machining performances are chosen as the comparative objects. On the other hand, the TSECDD with traditional-pressure interior flushing, which advantages have been certified by comparison with other machining process including EDM, ECM, and SEDCM [5, 30], is chosen as the other comparative object. Compared with the other two machining processes, the advantages of ECDM with super-high-pressure interior flushing including a higher flow rate of the work fluid, a higher machining speed, higher machining accuracy, and higher surface quality will be confirmed.

The work fluid was supplied to the machining gap from inside the tube electrode, and the flow rate was calculated using $F = Q/A$, where F is the flow rate of the work fluid from the tube electrode; Q is the flux of the work fluid, which can be measured; and A is the area of the hole of the tube electrode. The flow rates of the work fluid under the three supply conditions are shown in Fig. 4. For the static fluid condition, the flow rate was 0 m/s; when the traditional flushing pressure was used, the flow rate was approximately 7 m/s; and when super-high-pressure interior flushing was conducted, the flow rate was as high as 14 m/s. Hence, the flow rate achieved by super-high-pressure interior flushing was as much as twice that achieved by traditional interior flushing. This indicates that the former flushing method significantly increases the flow rate in the narrow machining gap and thus facilitates the removal of machining by-products and improves machining performance.

The machining efficiencies under the three work fluid supply conditions are compared in Fig. 4. When static fluid was applied, the MRR was only 3 μm/s, while interior flushing produced a significant improvement. Traditional-pressure interior flushing produced an MRR of almost 90 μm/s, which is approximately 30 times that of static fluid machining. However, super-high-pressure interior flushing increased the MRR to 176.471 μm/s, which is approximately twice that of traditional-pressure interior flushing and nearly sixty times that of static fluid machining.

The above observations can be explained by the fact that the static fluid almost did not remove the material from the machining micro-gap, and the maintenance of the machining by-products in the gap hampered the EDM and ECM processes, thereby reducing the machining speed. In contrast, the tube electrode interior flushing effectively refreshed the work fluid in the machining gap, thereby facilitating the EDM and ECM processes and significantly increasing the MRR. In comparison to traditional-pressure interior flushing, supper-high-pressure interior flushing removed the machining by-products from the machining gap even more effectively. The MRR values determined show that super-high-pressure interior flushing significantly increases the machining speed.

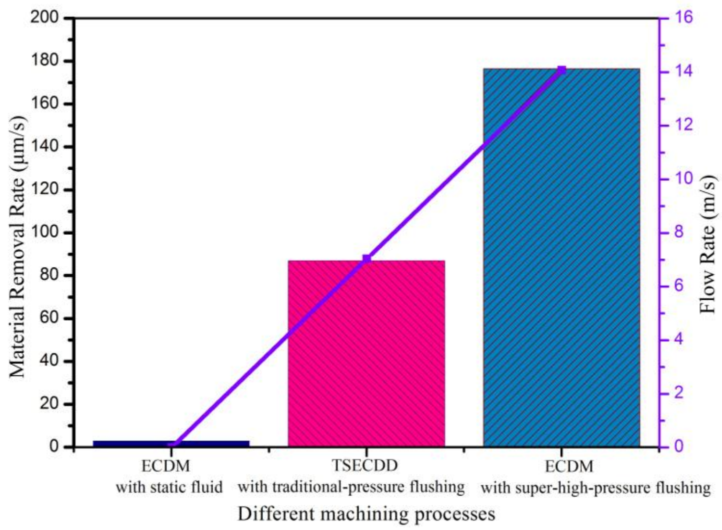
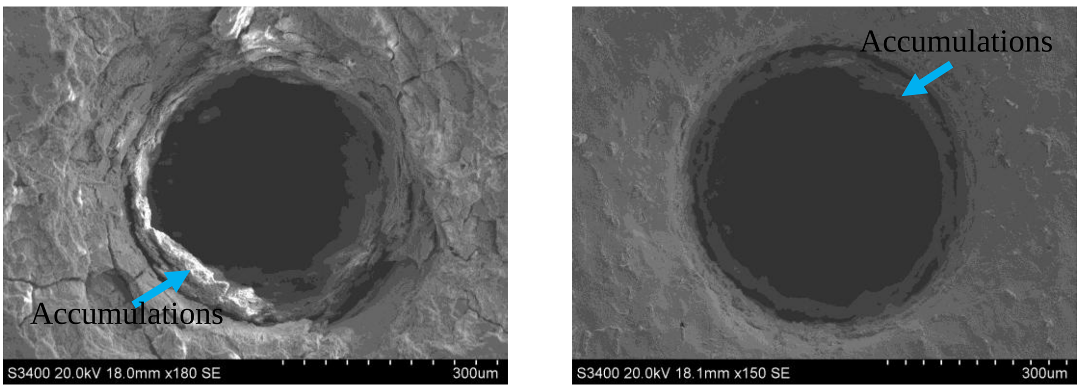


Figure 4. Comparison of MRRs and flow rates for the different machining processes

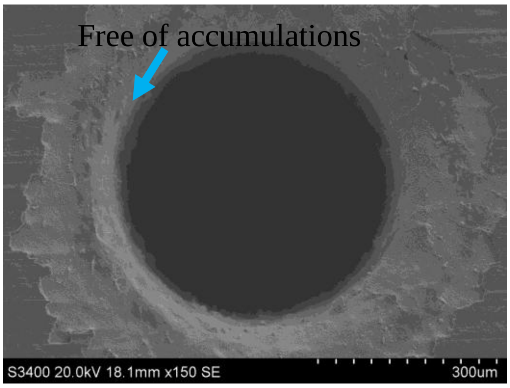
The morphologies of the hole entrances machined under the three work fluid supply conditions are illustrated in Fig. 5. When the static fluid was used, the machining by-products were not removed but rather accumulated in the lateral micro-gap, as shown in Fig. 5(a). The traditional flushing pressure improved the flushing to some extent, although a few residual by-products remained in the lateral gap, as shown in Fig. 5(b). However, as Fig. 5(c) shows, the super-high-pressure interior flushing completely removed the machining by-products, and the roundness of the hole entrance was obvious. Super-high-pressure interior flushing thus eliminates machining by-products from the lateral gap, thereby avoiding jamming. This results in higher machining accuracy, in accordance with the aforementioned analysis of the machining mechanism.

The composition of the by-products that accumulated in the lateral gap was analysed, and the results are shown in Fig. 6. The by-products included 15.73% oxygen and 8.69% carbon. This is because carbon and oxygen are produced by the oxidation of debris particles during the EDM process. During the hybrid EDM–ECM process, the oxidised debris and the flocculated hydroxides generated by the ECM process are mixed with the precipitates, which are difficult to remove from the machining gap. Hence, under poor flushing conditions, the machining by-products are more likely to adhere to the lateral surface and block the lateral gap.



(a) ECDM with static fluid

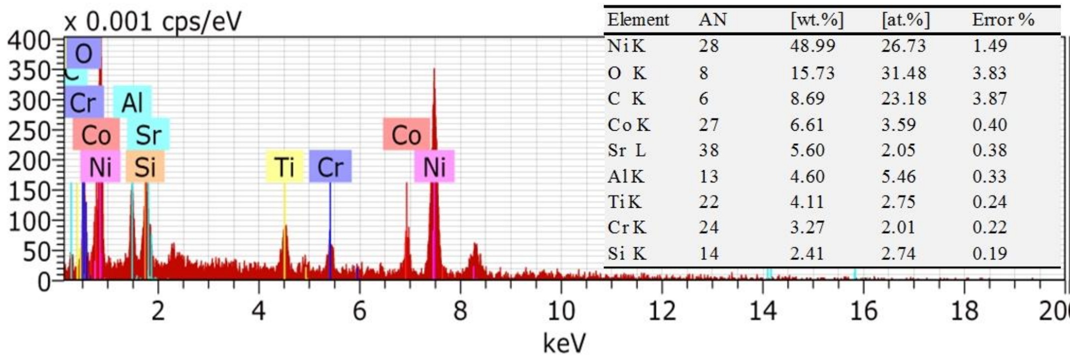
(b) TSECDD with traditional-pressure flushing



(c) ECDM with super-high-pressure flushing

Figure 5. Comparison of hole entrances for different machining processes

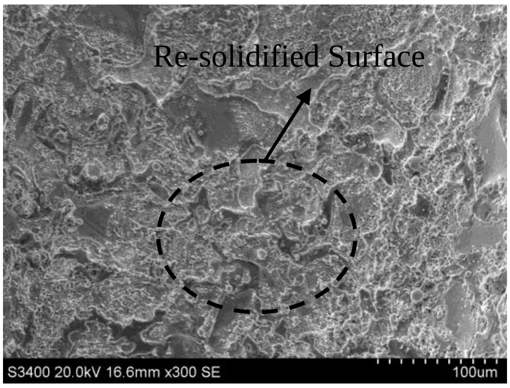
Figure 7 further compares the machined surfaces. The surface produced by static fluid machining was entirely covered by a re-solidified layer containing oxidised debris and hydroxides generated by the EDM and ECM processes, respectively. In addition, the surface was rough and contained cracks, as well as evidence of residual stress. These were the result of the absence of flushing of the work fluid from the machining micro-gap. This made it difficult for the machining by-products to escape from the micro-gap.



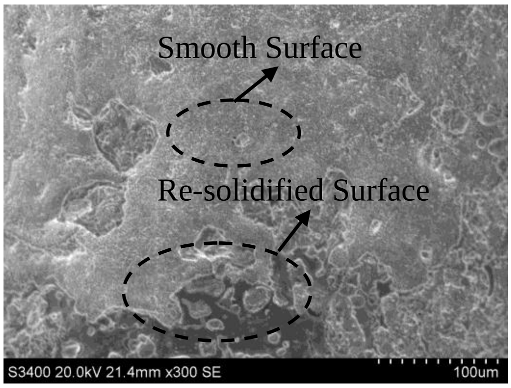
Element	AN	[wt.%]	[at.%]	Error %
Ni K	28	48.99	26.73	1.49
O K	8	15.73	31.48	3.83
C K	6	8.69	23.18	3.87
Co K	27	6.61	3.59	0.40
Sr L	38	5.60	2.05	0.38
Al K	13	4.60	5.46	0.33
Ti K	22	4.11	2.75	0.24
Cr K	24	3.27	2.01	0.22
Si K	14	2.41	2.74	0.19

Figure 6. EDX spectrum showing composition of accumulations

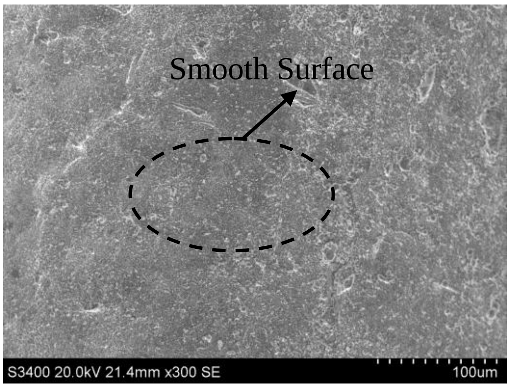
Under the prevailing high temperature, the by-products blocking the lateral gap adhered to the machined surface of the hole. In addition, the by-products in the machining gap critically weakened the electrical discharge erosion and electrochemical dissolution processes taking place on the machined surface, with the consequent secondary discharge resulting in poor surface quality. In comparison to the surface produced by static fluid machining, the surface produced by high-pressure flushing was of somewhat better quality.



(a) ECDM with static fluid



(b) TSECDD with traditional-pressure flushing



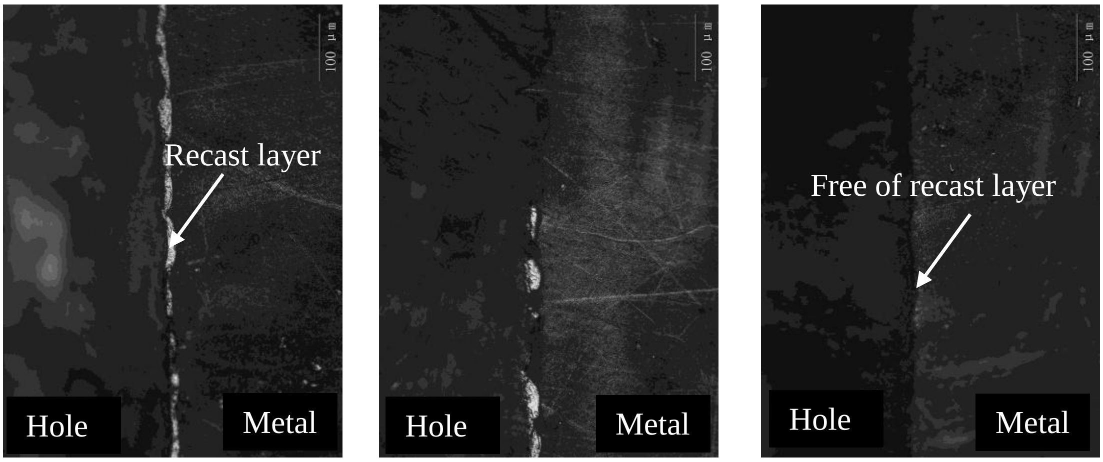
(c) ECDM with super-high-pressure flushing

Figure 7. Comparison of machined surfaces produced under the different machining processes

However, there were still surface defects in some areas, as shown in Fig. 7(b). This indicates that while high-pressure flushing improves the quality of the machined surface, the occurrence of some surface defects is unavoidable. Figure 7(c) shows a scanning electron microscopy (SEM) photograph of the surface machined using super-high-pressure interior flushing. The remarkable improvement in the surface quality is obvious, and there are no surface defects, such as cracks, voids, or metal globules. This confirms that super-high-pressure interior flushing eliminates blockage of the machining micro-gap by the by-products and continually refreshes the work fluid. Thus, secondary discharge is avoided, and surface defects are rectified by the efficient electrochemical ion dissolution that takes place in the refreshed work fluid. The excellent surface finish demonstrates the effectiveness of super-high-pressure interior flushing.

After cutting, polishing, and etching, the cross sections of the recast layer were analysed under a metallographic microscope. Figure 8 shows the results for the different work fluid supply conditions considered. The surface produced by static fluid machining was entirely covered by a re-solidified layer (Fig. 8(a)). This resulted from the high concentration of complex machining by-products in the work fluid. This increased the bad discharge, resulting in reduction of the electrochemical dissolution and consequently thickening of the recast layer formed by the EDM process and poorer elimination by the ECM process. In addition, the absence of pressure flushing of the machining micro-gap and the prevailing high temperature resulted in the re-deposition of hybrid machining by-products on the surface. In contrast, the use of tube electrode interior flushing improved the removal of the recast layer.

However, as shown in Fig. 8(b), there was still some recast layer material on the surface machined with traditional high-pressure flushing. In the case of tube electrode high-speed ECDM with supper-high-pressure flushing, the recast layer was completely eliminated, as shown in Fig. 8(c). This is consistent with the previous results obtained regarding the surface quality. Tube electrode high-speed ECDM with super-high-pressure flushing was thus confirmed to be more effective in producing micro-holes without a recast layer.



(a) ECDM with static fluid (b) TSECDD with traditional-pressure flushing (c) ECDM with super-high-pressure flushing

Figure 8. Comparison of recast layers for different machining processes

In summary, in a hybrid machining process involving simultaneous electrochemical dissolution and electrical discharge erosion, the removal of machining by-products and generated heat is the greatest challenge because of the effects these have on machining performance. The experimental results indicate that the use of static fluid in the drilling of micro-holes by tube electrode high-speed ECDM not only results in poor shape accuracy but also increases the machining time. Micro-holes produced using static-fluid hybrid EDM–ECM also have defects, including the presence of a recast layer, cracks, and residual stress. These defects result from poor removal of the machining by-products and heat. While the use of interior flushing improves the machining performance to some extent, the removal of the by-products is still unsatisfactory. The use of super-high-pressure interior flushing completely solves these problems, resulting in significantly improved tube electrode high-speed ECDM machining efficiency and surface quality.

4.2. Effect of interior flushing pressure on machining performance

As the experimental results confirm, super-high-pressure interior flushing enhances the performance of tube electrode high-speed ECDM, including the machining speed and geometric precision of the machined shape. This section describes the results of the analysis of the effect of the magnitude of the flushing pressure on the machining performance.

4.2.1 Effect of flushing pressure on flow rate

The variation in the flow rate with the flushing pressure is illustrated in Fig. 9. The flow rate of the work fluid increased almost linearly with increasing flushing pressure for the three different inner diameters of the tube electrode.

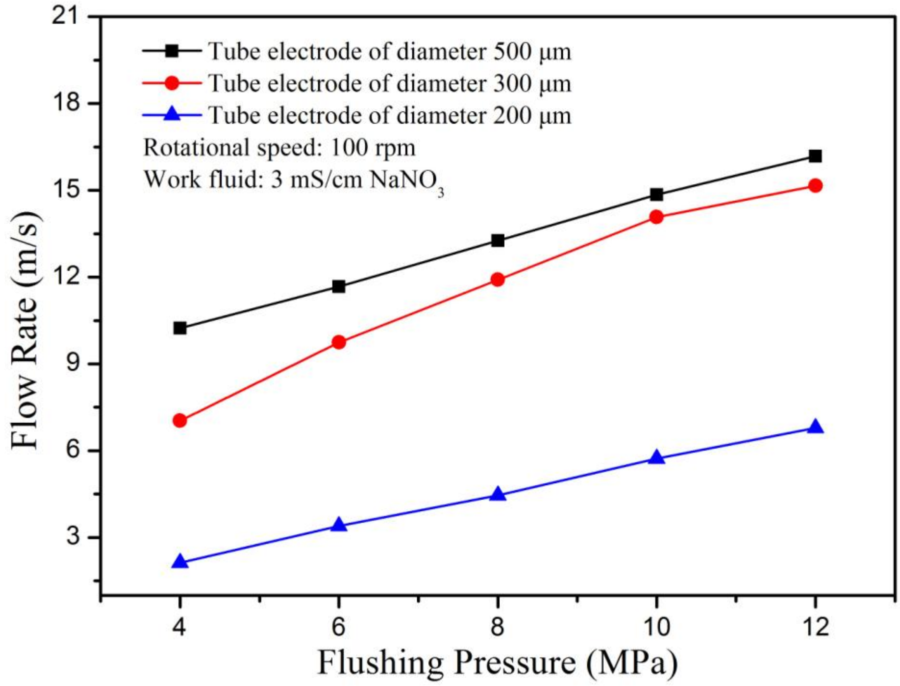


Figure 9. Effect of flushing pressure on flow rate of work fluid

In addition, the flow rates for the Φ300-μm and Φ500-μm tube electrodes were always far higher than those for the Φ200-μm tube electrode. At low flushing pressures, especially for the Φ200-μm tube electrode, the flow rates of the work fluid through the tube electrode and narrow machining gap were very low, and this probably caused jamming of the gap by the machining by-products. The observations indicate that increasing the flushing pressure can significantly increase the flow rate of the work fluid through both the tube electrode and the narrow machining gap, thereby improving the removal of the machining by-products. The flushing pressure should therefore be as high as possible.

4.2.2 Effect of flushing pressure on MRR

The effect of the magnitude of the interior flushing pressure on the MRR is illustrated in Fig. 10. The variation in the MRR with the flushing pressure is dependent on the tube electrode diameter. For the Φ500-μm tube electrode, the MRR increased linearly from 69.767 to 111.111 μm/s as the flushing pressure increased from 6 to 12 MPa. For the Φ300-μm tube electrode, the MRR also increased as the flushing pressure increased from 6 to 10 MPa and then began to decrease. For the Φ200-μm tube electrode, the MRR initially increased slightly and then decreased, with the maximum

MRR corresponding to a pressure of 10 MPa. It can thus be assumed that as the flushing pressure increases, the by-products in the machining gap are more easily washed away, resulting in significant enhancement of the MRR. A higher flushing pressure is thus favourable to the MRR. However, for a small tube electrode (for example, one with a diameter of Φ200 μm), the inner diameter is only 50–60 μm, and an overly high flushing pressure will shake the soft tube structure, resulting in poor machining stability. Overly powerful flushing is thus not suitable for Φ200-μm and Φ300-μm tube electrodes, for which optimal MRR and flushing can be achieved using a pressure of 10 MPa.

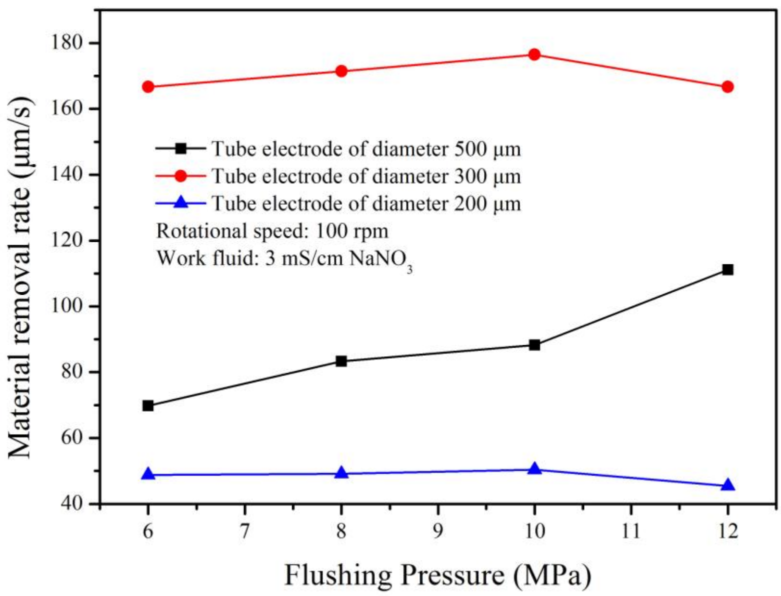


Figure 10. Effect of flushing pressure on MRR

4.2.3 Effect of flushing pressure on average hole diameter

Figure 11 shows the effect of the magnitude of the flushing pressure on the average hole diameter. When a tube electrode with a diameter of Φ500 μm was used, the hole diameter increased as the flushing pressure increased, up to 12 MPa. For the Φ300-μm and Φ200-μm electrodes, the average hole diameters initially increased with the flushing pressure and then decreased, with the peak diameters corresponding to pressures of 10 and 8 MPa, respectively. These results can be explained by the fact that a higher flushing pressure, up to 12 MPa, effectively flushed the machining heat and by-products from the narrow gap, including debris, gas bubbles, and hydroxides. The better refreshment of the work fluid and decontamination of the narrow lateral gap enhanced both the electrochemical dissolution and electrical discharge erosion rates, thereby increasing the lateral gap of the EDM and ECM processes. However, for a small-diameter tube electrode, an excessively high flushing pressure will cause instability of the rotation of the electrode, resulting in poor flushing and a decreased hole diameter. For the purposes of machining, the diameter range should ideally be as small as possible. Thus, a lower flushing pressure should be used for a Φ500-μm tube electrode, while the pressure for Φ300-μm and Φ200-μm tube electrodes should be set to 12 MPa.

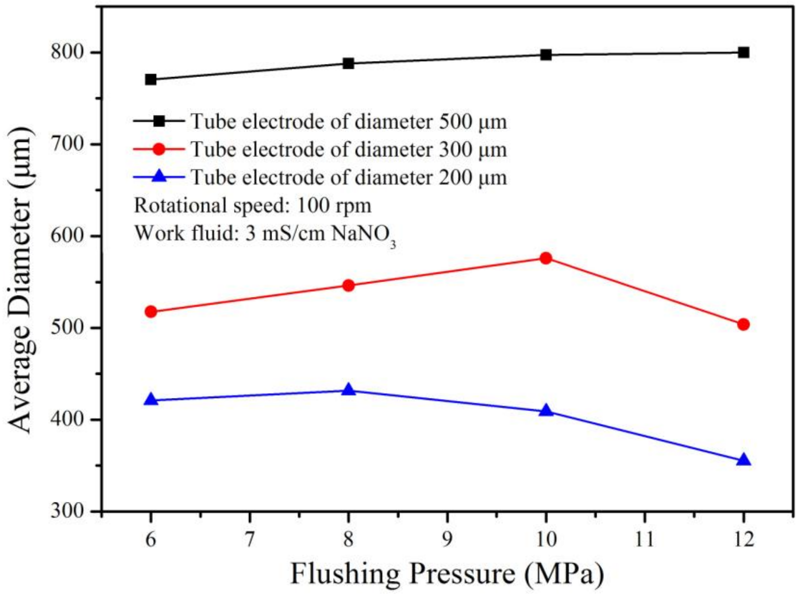
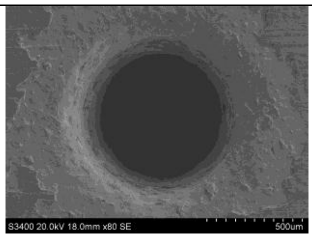
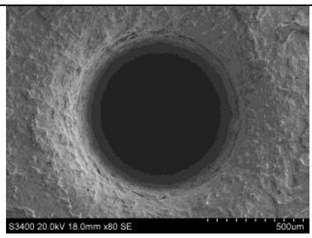
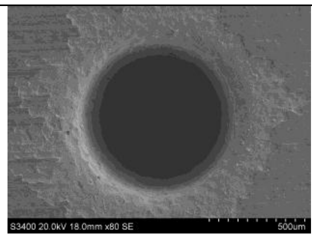
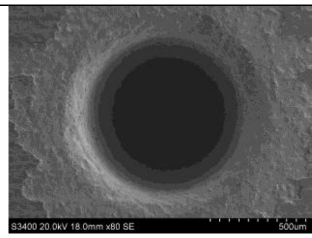
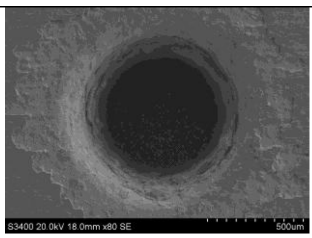
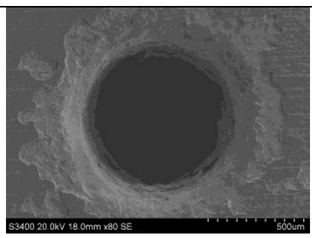
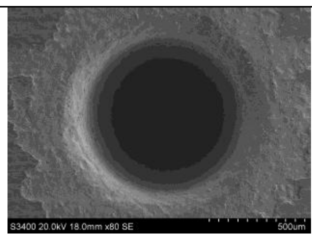
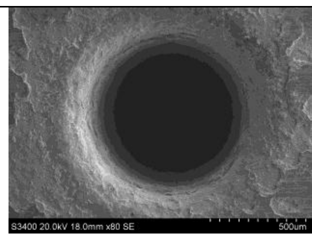


Figure 11. Effect of flushing pressure on average hole diameter

The SEM photographs of the hole entrances for different work fluid supply pressures are shown in Fig. 12. The variations in the hole diameter in this figure agree with those in Fig. 11. Moreover, examination of the inner surface around the entrance reveals the accumulation of the machining by-products under lower flushing pressures. With increasing flushing pressure, the by-products were removed. However, excessively high pressures are not beneficial to the removal of the by-products when using a small-diameter tube electrode. A comprehensive analysis of Figs. 11 and 12 reveals that, to obtain a smaller hole diameter and better removal of the by-products, the flushing pressure should be set to approximately 10 MPa.

	P = 6 MPa	P = 8 MPa	P = 10 MPa	P = 12 MPa
Φ500 μm				
Φ300 μm				

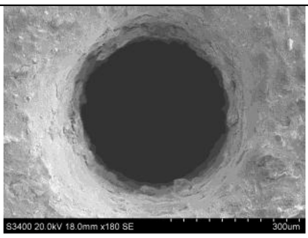
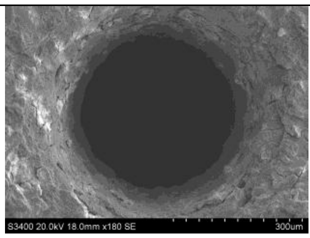
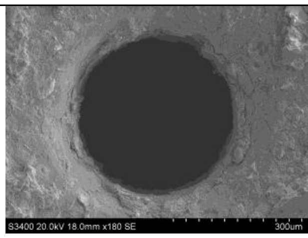
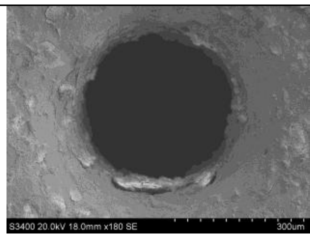
Φ200 µm				

Figure 12. SEM photographs of holes machined using different flushing pressures

4.2.4 Effect of flushing pressure on taper angle

The variation in the taper angle with the flushing pressure is shown in Fig. 13. The taper angle decreased sharply with increasing flushing pressure for the Φ500 µm tube electrode. In the cases of the Φ300-µm and Φ500-µm electrodes, the angle decreased almost linearly with increasing flushing pressure between 6 and 10 MPa and thereafter tended to increase. This indicates that increasing the flushing pressure can improve the uniformity of the material removal from the lateral gap through better refreshment of the work fluid. Moreover, the higher the machining speed is under high flushing pressures, the shorter the machining duration is between the entrance and exit of the lateral gap, and this reduces the taper angle. Hence, to obtain the smallest possible taper angle when using a Φ500-µm tube electrode, the flushing pressure should be as high as possible, while for Φ300-µm and Φ200-µm electrodes, the flushing pressure should be set to 10 MPa.

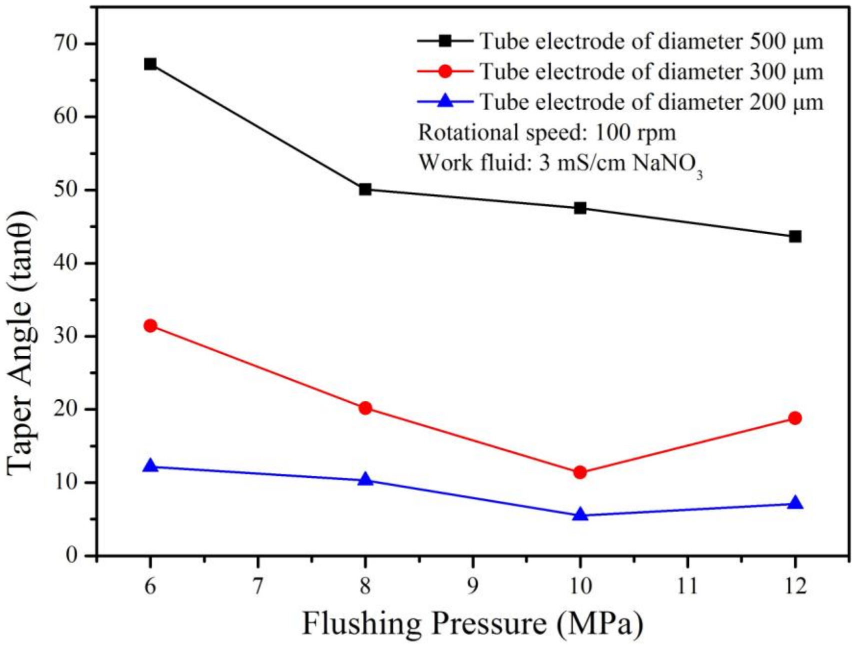


Figure 13. Effect of flushing pressure on taper angle

5. CONCLUSIONS

In this study, super-high-pressure flushing was applied to tube electrode high-speed ECDM for the first time. The machining performance achieved was examined and compared with the performance of sinking machining and traditional interior flushing. The effects of different interior flushing pressures on the tube electrode high-speed ECDM process were also investigated. The following are the conclusions drawn from the results of the study.

1. Super-high-pressure interior flushing significantly increases the flow rate of the work fluid in the narrow machining gap, thereby facilitating removal of the machining by-products. To enhance the removal, the flushing pressure should be made as high as possible.
2. The use of a static fluid for micro-hole drilling by tube electrode high-speed ECDM not only diminishes the shape accuracy but also increases the machining time. The use of traditional interior flushing improves the machining performance to some extent, but the removal of the machining by-products remains unsatisfactory. Super-high-pressure interior flushing removes the machining by-products and the generated heat more effectively. It also increases the MRR to up to 176.471 μm/s when a Φ500 μm tube electrode is used. This is almost twice the value achieved by the traditional interior flushing pressure and nearly sixty times that achieved by static fluid machining. The machining efficiency and surface quality is thus significantly improved by super-high-pressure interior flushing.
3. For a Φ500 μm tube electrode, a higher flushing pressure increases the MRR. However, for Φ200 μm and Φ300 μm tube electrodes, the optimal flushing pressure for enhanced MRR is 10 MPa.
4. Overall, to achieve a smaller hole diameter and better removal of the machining by-products, the flushing pressure should be set to approximately 10 MPa.
5. To obtain the smallest possible taper angle when using a Φ500 μm tube electrode, the flushing pressure should be as high as possible, while for Φ300 μm and Φ200 μm tube electrodes, the optimal flushing pressure is 10 MPa.

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