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ORIGINAL ARTICLE

A comparative investigation on hybrid EDM for drilling small deep holes

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Abstract For the use of electrical discharge machining (EDM) to drill small, deep holes, many studies have shown that tool electrode vibration and rotation and pump forced flushing can improve machining efficiency or quality. However, these factors are usually studied separately. In this study, a hybrid, rotary, ultrasonic EDM system was developed that used these three methods simultaneously. A comparative investigation on different combinations of the three methods was conducted for drilling small, deep holes in Inconel 718 and 41Cr4 workpieces. Results showed that, compared with other combinations for precision drilling under low discharge currents, combinations including these three methods simultaneously achieved more stable machining and higher material removal rates. In addition, the applied current greatly influenced hole depth and the effects of ultrasonics. When a high discharge current was applied, the electrode vibration contribution appeared weak.

Keywords Electrical discharge machining (EDM) · Rotary ultrasonic machining · Small deep hole

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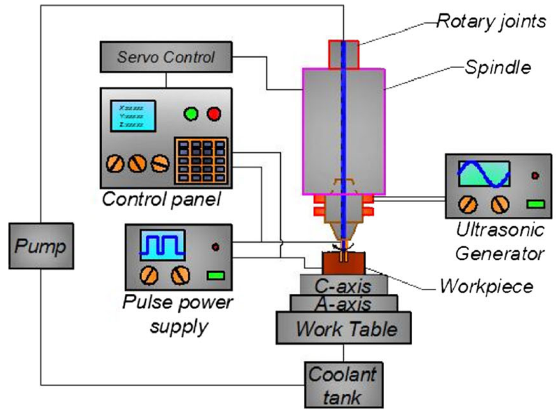
1 Introduction

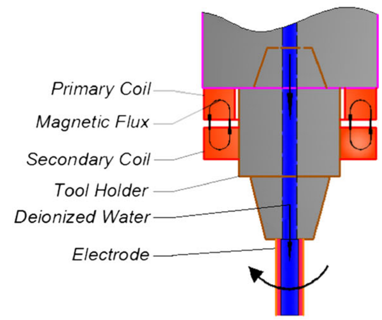
Electrical discharge machining (EDM) is a process for removing material, no matter its hardness, by means of the action of serial discharges on electrically conductive materials [1]. EDM does not make direct contact between the electrode and workpiece, as a contactless machining that is free from mechanical force. Thus, EDM has special advantages in drilling burr-free, small diameter holes [2]. However, one main problem of EDM is its low efficiency, especially in EDM drilling of small, deep holes. As hole depth increases, the debris density exceeds a certain value, which encourages abnormal discharges that cause significant electrode wear or damage and slow the material removal rate (MRR) [3].

Enhancing flushing in the discharge gap has been proven to be an effective method for improving debris elimination. In EDM flushing, a dielectric fluid is distributed through a spark gap to remove gaseous and solid debris generated during the EDM process. One important role of flushing is to stabilize discharge repetition [4]. Wong et al. have divided the flushing method into four main categories: normal flow, reverse flow, external flushing, and immersion flushing [5]. Normal flushing is also known as forced pump flushing, in which dielectric fluid is fed through the tool electrode and exits through gaps and is fit for drilling small, deep holes, because of its direct flushing effects. Wang et al. have simulated a liquid-solid two-phase flow field in a discharge gap of small hole EDM drilling and, after numerical simulation, experiments showed that MRR increases with increasing dielectric fluid pressure and velocity [6]. Ye et al. have studied the mechanism of high speed, small hole EDM drilling and found that the effective quenching ability of

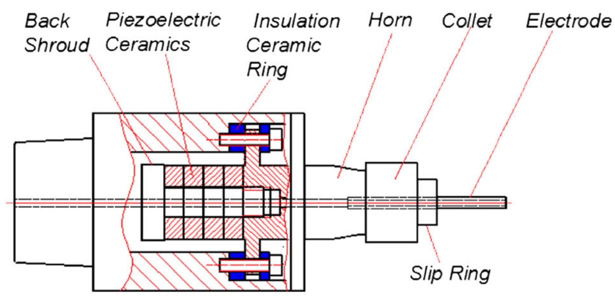
Fig. 1 Rotary ultrasonic EDM system design



(a) **Schematic diagram of rotary ultrasonic EDM system**



(b) **Contactless power transfer structure**

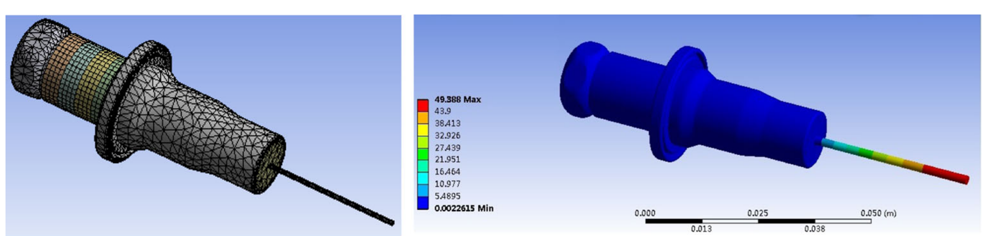


(c) **Structure of transducer**

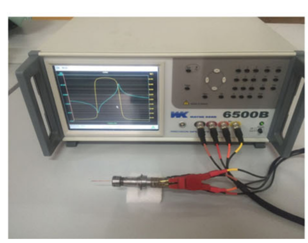
forced pump flushing reduces necessary pulse intervals and increases the effective pulse frequency [7].

In ultrasonic-assisted EDM (UEDM), high-frequency vibration is applied between an electrode and workpiece. Abdullah and Shabgard have used UEDM to drill holes on cemented tungsten carbide and reported that the MRR of UEDM was up to four times higher than that of conventional EDM [8]. In contrast, Abdullah et al. have studied UEDM effects on the thickness of the heat-affected zone and recast layer, and showed that their thicknesses decreased [9]. Huang et al. used UEDM to drill holes on Nitinol, which showed that the introduction of ultrasonic vibrations to micro-EDM of Nitinol increases machining efficiency more than 60-

Fig. 2 Determination of resonant frequency



(a) **Analysis of vibration modes by the FEM**



(b) **Resonant frequency measurement by precision impedance analyzer**

Table 1 Chemical composition of Inconel 718 (wt%)

Ni	Cr	Fe	Nb	Mo	Ti	Al	Co	C	Mn	Si	P	S	B	Cu
50–55	17–21	Bal'd*	4.75–5.5	2.8–3.3	0.65–1.15	0.2–0.8	1.0 Max	0.08 Max	0.35 Max	0.35 Max	0.015 Max	0.015 Max	0.006 Max	0.30 Max

*, Balanced

fold without significantly increasing electrode wear [3]. Gao and Liu have reported experimental results that showed that the efficiency of ultrasonic-assisted micro-EDM of stainless steel is eightfold greater than that of conventional micro-EDM [10]. Jia et al. have used UEDM to drill holes on engineering ceramics and reported that this technique is effective in attaining high MRR [11]. Shabgard et al. have studied the effects of workpiece vibration in EDM of AISIH13 tool steel with a graphite tool and found that ultrasonic workpiece vibrations significantly reduce inactive pulses and improve process stability [12].

Besides ultrasonic assistance, tool electrode rotation also serves as an effective gap flushing technique, which improves the MRR. Mohan et al. have studied the effects of rotation on EDM drilling of Al-SiC composites and showed that, increasing the tool electrode rotation speed, resulted in positive effects on MRR, electrode wear rate, and better surface roughness than when it is stationary [13]. Soni and Chakraverti have investigated EDM of titanium alloy with a rotating, solid copper-tungsten tool electrode, which, when compared with the stationary mode, found that MRR increased. Also, hole roundness is improved by rotary electrodes [14].

Some researchers have combined more than one flushing method in their studies of hybrid EDM. Mohan et al. have combined a rotary tool electrode and forced pump flushing to drill holes in Al-SiC composites and, compared to a rotary solid electrode, the rotary tube electrode was found to produce a higher MRR [15]. Yan and Wang have compared three flushing methods, including forced pump, suction, and external flushing, in EDM drilling and their results showed that, under the same conditions, the MRR of forced pump flushing was almost equal to the MRR with suction flushing and external flushing had the lowest MRR [16]. In rotary electrode EDM, Wang and Yan have used a copper electrode with an eccentric hole for drilling holes in a Al2O3/6061Al composite and showed that increased pump flushing pressure of dielectric fluid results in a higher MRR [17]. Zhao et al. have used ultrasonic vibrations and a rotary single-notch electrode to drill holes in a titanium alloy, producing drilled holes < 0.2 mm in diameter and with a depth/diameter ratio of > 15 [18].

It was concluded that ancillary methods, including ultrasonic vibration and rotation of the tool electrode and forced pump flushing, all have effects on flushing and debris elimination. However, they are usually studied separately. In this study, a new hybrid EDM system was developed that included the simultaneous application of these three flushing methods. Then, a comparative investigation was performed to identify the optimal combination of methods using different combinations of the system's three methods in the drilling of small, deep holes.

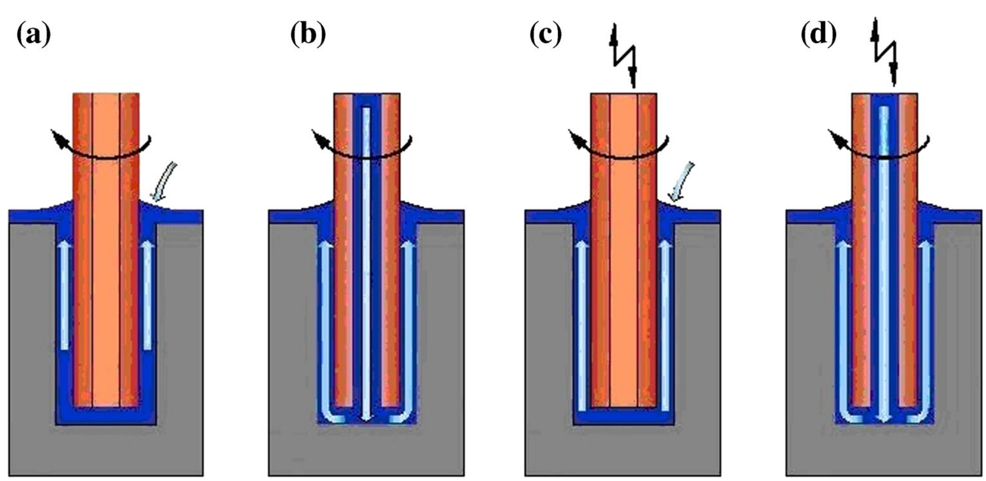


Fig. 3 Flushing modes (A mode, external flushing; B mode, forced pump flushing; C mode, external flushing + vibration; and D mode, forced pump flushing + vibration)

Table 2 Process parameters

Workpiece material	Inconel 718 block (50 × 50 × 15 mm)
Tool electrode	Copper tube Outside diameter, 1.0 mm; inside diameter, 0.5 mm
Polarity	Positive (workpiece), negative (electrode)
Dielectric fluid	Deionized water
Rotational speed (rpm)	1000
Voltage (V)	100
Current (A)	1,12
Pulse-on time (μs)	40
Pulse-off time (μs)	50
Feed rate (mm/min)	6,48
Depth of drilling (mm)	15
Frequency (kHz)	24.8–27.2

2 System setup

This system adopted three methods that could be applied simultaneously, including tool electrode ultrasonic vibration, tool electrode rotation, and forced pump flushing (Fig. 1a). For the design of the ultrasonic vibration system, the ultrasonic vibration could be applied to a tool electrode or workpiece, such that, for a workpiece, the item should be firmly fixed to a vibrating worktable. Unfortunately, because of the workpiece shape complexity, different workpiece parts might produce different vibration amplitudes or directions that can lead to uncertainty in the applied vibration. Comparatively speaking, it is more reasonable to apply ultrasonic vibration to the tool electrode, especially for EDM drilling. The tool electrode was fixed to an ultrasonic transducer that was attached to a spindle, such that the electrode could vibrate and rotate simultaneously. Therefore, ultrasonic power was transferred to the rotary transducer. At present, power transfer devices mainly use contact structures, such as carbon brushes or slip rings. Overall, these structures have some shortcomings that might shorten the device's lifetime, i.e., vibration, abrasion, and sparking at high rotation speeds. To ensure tool rotation precision, a contactless power transfer device was adopted here, which was based on transformer theory. A pair of coupled coils was used with a stationary primary coil and connected to an ultrasonic generator (Fig. 1b). The secondary coil was fixed to a tool holder and connected to a transducer in the tool holder, which rotated with the tool holder. This structure was compact and relatively independent of the ultrasonic vibration system. In addition, a forced pump flushing was achieved in this hybrid EDM system by choosing an electric spindle with an inner coolant function.

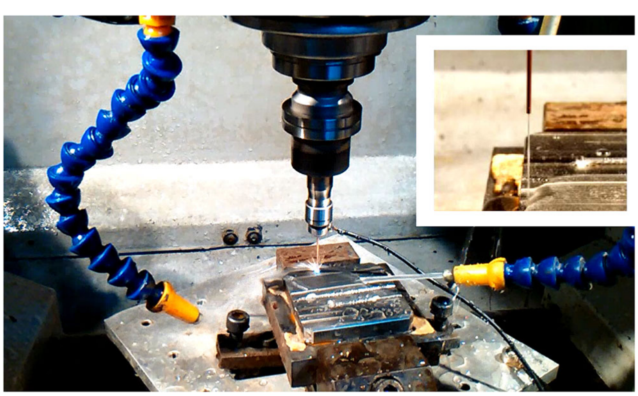


Fig. 4 Experimental set-up

The transducer structure consisted of a back shroud, piezoelectric ceramic, horn, and electrode (Fig. 1c). The electrode was attached to the horn through an ER collet (Standard No. DIN 6499). The whole vibration structure was installed in a HSK32 tool holder and used two ceramic rings as insulation. Precision processing was performed on the ceramic rings, horn flange, and tool holder to ensure accurate assembly. The slip ring was used in the power supply of the EDM pulse generator, which was fixed on the collet clamping nut. The dielectric fluid flowed through the inner coolant tube in the tool holder and out of the tube electrode.

The dimensions of the tool electrode, as a part of the vibration system, affected the resonant vibration frequency of the system. In EDM, the electrode wears down and its length decreased, such that the system's resonant frequency changed with the tool electrode wear. In addition, if the output frequency of the ultrasonic generator was not correspondingly adjusted, the electrode end's vibration weakened, which was unfavorable, as a stable vibration being important throughout the process. The finite element method (FEM) was used to simulate the vibration mode and obtain the resonant frequency for tool electrodes with different lengths (Fig. 2a). A precision impedance analyzer (65120B; Wayne Kerr Electronics, London, England) was used to measure the resonant frequency and revise results from FEM (Fig. 2b). Finally, an accurate, revised model was established to predict the resonant frequency during the machining process.

3 Experiments and discussion

Several experiments were performed using this new hybrid EDM system. The initial workpiece material was Inconel 718, a nickel-based super alloy (Table 1), which

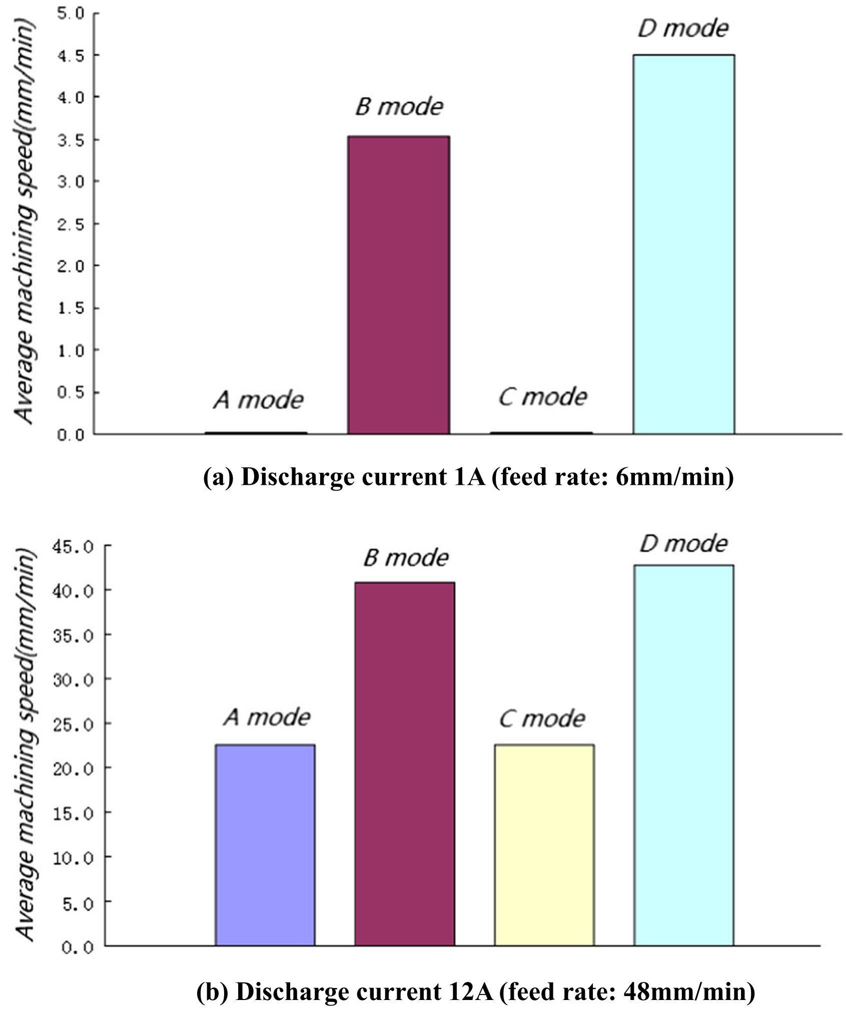


Fig. 5 Average machining speed versus the flushing mode

is a typical hard-to-machine material and used extensively in the aerospace industry. In the experiments, four modes of flushing were introduced, including external flushing, forced pump flushing, external flushing + vibration, and forced pump flushing + vibration (modes A–D, respectively), and tests for each mode were performed under low and high discharge currents (1 and 12 A, respectively; Fig. 3). The rotating electrode was applied in all tests to ensure hole roundness. Experimental process parameters in experiments and the experimental set-up are shown in Table 2 and Fig. 4, respectively.

The average machining time illustrated the effect of flushing modes on machining efficiency under a low discharge current (Fig. 5a). In A and C modes, full-thickness holes were not obtained, so the machining speed was close to zero. In B and D modes, through holes were made successfully, and in D, the highest machining speed was observed. The average machining speed illustrated the effects of flushing modes on machining efficiency under high discharge current (Fig. 5b). In A and C modes, complete holes were not drilled and the machining speed was also close to zero. In B and D modes, through holes were drilled successfully, with almost equal machining speed.

Under low discharge current, the most effective flushing mode was D. Videography of EDM with these four flushing modes under low discharge current showed that

Table 3 Chemical composition of 41Cr4 steel (wt%)

C	Si	Mn	S	P	Cr	Ni	Cu
0.37–0.44	0.17–0.37	0.50–0.80	0.030 Max	0.030 Max	0.80–1.10	0.030 Max	0.030 Max

Table 4 Process parameters

Workpiece material	41Cr4 cylinder (diameter, 20 mm; length, 150 mm)
Tool electrode	Copper tube Outside diameter, 1.0 mm; inside diameter, 0.5 mm
Polarity	Positive (workpiece), negative (electrode)
Dielectric fluid	Deionized water
Rotation speed (rpm)	300
Voltage (V)	40
Current (A)	2,4,8,16,30
Pulse-on time (μs)	40
Pulse-off time (μs)	50
Feed rates (mm/min)	25
Feed range of Z-axis (mm)	250
Frequency (kHz)	16–28
Flushing pressure (Mpa)	1.0

the discharge efficiency was low in A and C modes (Suppl. videos). As the tool electrode frequent was moving backward, because of short circuits when reaching certain depths, holes could not be made. In these two modes, as forced pump flushing was not applied, forced pump flushing was concluded to be the dominant factor in debris elimination under low current. In B, consecutive discharge sparks were observed, but only a few short circuits occurred. In D, the number of short circuits decreased and the discharge efficiency increased. Compared to B, the average machining time in A was shortened by ~ 22%.

Under a high discharge current, through holes still were not achieved in A and C modes due to frequent electrode moving backward, which meant that forced pump flushing was also

Table 5 Process parameters of machined holes

	①	②	③	④	⑤	⑥	⑦	⑧	⑨
Ultrasonic	Off	On	On	Off	On	On	On	Off	Off
Current (A)	16	30	16	30	8	8	30	4	30

the dominant factor for debris evacuation with a large current. However, the machining efficiency in D was similar to that in B. Ultrasonic vibration appeared unhelpful in increasing discharge efficiency.

From the experimental results above, forced pump flushing was concluded to be very important in EDM drilling of deep holes because of its effective debris removal. Under the same feedrate, ultrasonic effects on machining efficiency were influenced by current. The effects of current on EDM drilling with ultrasonic vibration were investigated in another group of experiments, in which 41Cr4 was selected as the workpiece material, as a typical hard-to-machine material. The chemical composition of 41Cr4 steel and experiment process parameters are shown in Tables 3 and 4, respectively. Partially machined holes and their process parameters are shown in Fig. 6 and Table 5.

In these experiments, the feed range was 250 mm and holes were drilled as deep as possible (Fig. 7) Notably, deep holes using ultrasonics could not be machined under a 2 A discharge current because of frequent electrode moving backward. Without ultrasonics, deep holes could not be machined with 2 and 4 A for the same reason. With an 8 A current, the deepest hole, with a diameter of < 1.1 mm and a depth to diameter ratio of > 100 was obtained with ultrasonic assistance. The depth was approximately twofold deeper than without ultrasonics. With a 16 or 30 A current, hole depths were

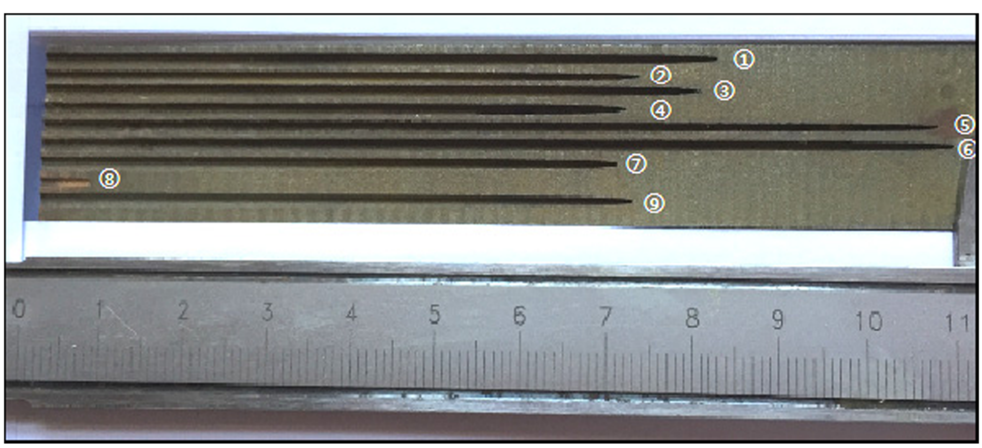


Fig. 6 Machined holes

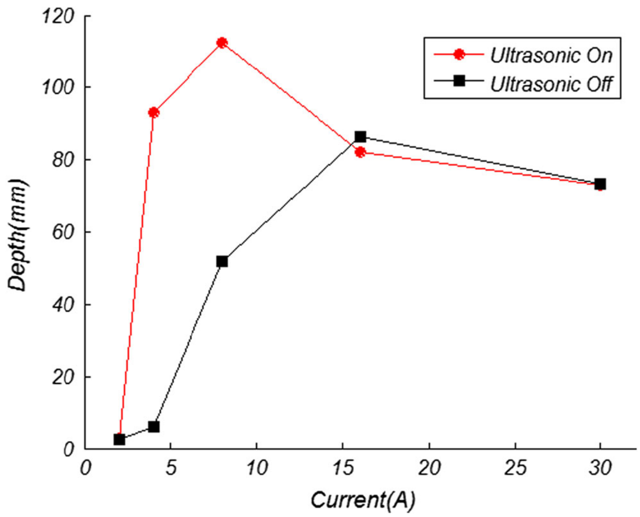


Fig. 7 Depth of holes under different currents

almost the same with or without ultrasonics. However, compared to the depth with an 8 A current, depths were decreased, which was due to higher electrode wear rate when larger currents were used.

The average machining speed increased with increased current, both with and without ultrasonic assistance (Fig. 8). Under a 4 A current, deep holes were drilled with ultrasonics, but the machining speed was 0.56 mm/min, which was quite slow. Under a relatively low current, drilling holes was found to be difficult while with a 30 A current, the machining speed with ultrasonics was almost equal to that without ultrasonics. Therefore, ultrasonic assistance was judged to be little helpful for increasing the machining speed using a large current.

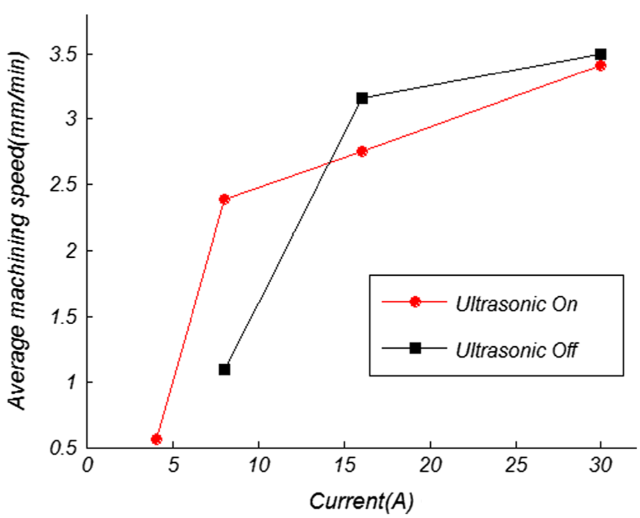


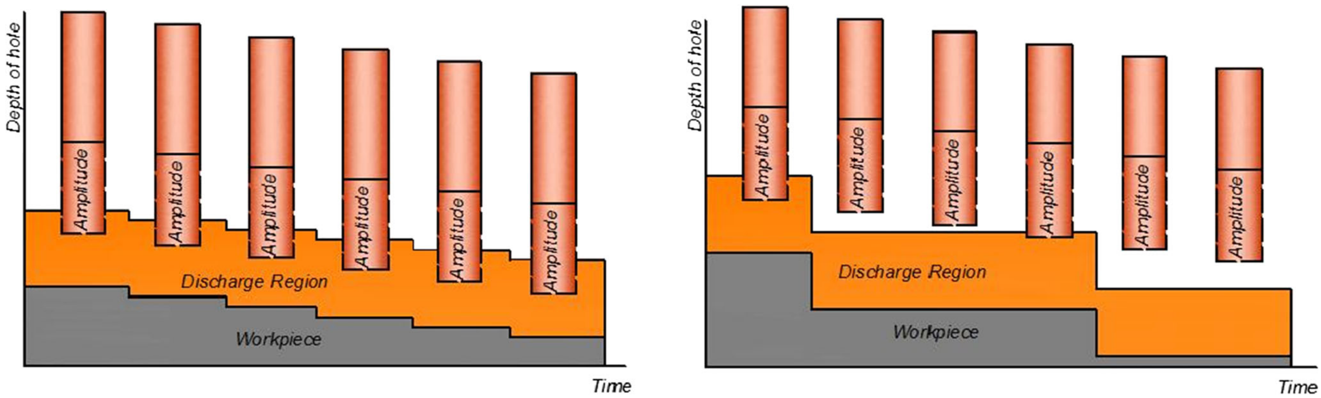
Fig. 8 Machining speed under different currents

The effects of ultrasonic assistance were explained here based on workpiece erosion by discharge sparks, such that, under low current, erosion by discharge sparks was low. Even with ultrasonic assistance, after a series of discharges, a hole could not be machined. When the current was increased to or above a certain level, erosion by discharge sparks increased, and, thus, material removed effectively. Furthermore, when ultrasonics were applied, the distance between the electrode and workpiece was relatively stable and always within the discharge region (Fig. 9a). This effect was because discharge most likely occurred in the closest position of the tool while vibrating [19]. The tool was assumed to move toward the workpiece during every vibration in UEDM, improving the probability of discharge. Vibrations increased the opportunity of discharge, and thus, directly increased the number of discharges. However, under a large discharge current, erosion by discharge sparks was large, such that the distance between the electrode and workpiece changed greatly, reaching beyond the distance of likely discharge (Fig. 9b). To discharge again, the electrode needed to feed forward until it reached the discharge region once again. Under this condition, the effects of vibration were equivalent to lengthening the electrode by the amplitude of vibration. Therefore, the discharge efficiency did not increase with ultrasonics when a large discharge current was used.

4 Conclusions

A hybrid, rotary, ultrasonic EDM system, which combined ultrasonic vibration and rotation of the tool electrode and forced pump flushing, was developed and employed in a comparative investigation into different flushing modes during EDM of an Inconel 718 steel workpiece. Small, deep hole drilling experiments were then carried out on a 41Cr4 steel workpiece. The following results are obtained:

1) Four flushing methods, including external flushing, forced pump flushing, external flushing with vibration, and forced pump flushing with vibration, were investigated. The results showed the importance of forced pump flushing in drilling deep holes; it being absolutely essential to eliminate debris efficiently and ensure the progress of deep hole drilling.
2) The effect of ultrasonic electrode vibration was influenced by the discharge current. The combination of ultrasonic vibration and the proper current was very important in the machining speed and hole depth. When a high



(a) Suitable discharge current **(b) Large discharge current**

Fig. 9 Distance change between electrode and workpiece in UEDM

current, the machining speed and hole depth was almost equal to those without ultrasonic vibration.

3) For drilling small, deep holes, a good alternative appeared to be to incorporate vibration and rotation of the tool electrode with pump-forced flushing into one EDM system.

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