Fabrication of high accuracy micro-hole by micro-EDM under tool electrode spiral motion feed mode aided with fixed reference axial compensation

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Abstract

The accumulation of debris in the inter-electrode gap caused by inefficient flushing during the micro-electrical discharge machining (micro-EDM) process leads to severe tool electrode wear and decreases the machining accuracy of micro-holes. In this study, a novel method of tool electrode spiral motion feed mode combined with fixed reference axial compensation (FRAC) is proposed to promote the evacuation of debris and improve the machining accuracy of micro-holes. Different depths of micro-holes in titanium alloy are drilled using the tool electrode linear feed mode and tool electrode spiral motion feed mode combined with FRAC and without compensation. The process parameters are optimized and determined by means of response-surface experiments. The results show that the tool electrode spiral motion feed mode can improve the debris evacuation more effectively than the tool electrode linear feed mode. The micro-hole without a cone at the bottom can be fabricated using the tool electrode spiral motion feed mode. The introduction of FRAC method can improve the depth error of micro-holes further. A high accuracy micro-hole with a depth error of only 0.21% can be fabricated efficiently under the optimal process parameters. The tool electrode spiral motion feed mode combined with FRAC has an obvious advantage in the fabrication of high accuracy micro-holes during the micro-EDM process.

1. Introduction

In recent years, with the rapid development of modern industry, the micro holes have received more attention in the manufacture of high-end equipment in aerospace, automobile and medical industries [1], such as aero-engine turbines [2], combustion chambers [3], diesel fuel injectors [4] etc. At present, micro-holes can be machined by adopting various micro-machining methods, such as abrasive water jet drilling, laser drilling, electrochemical drilling, and micro-electrical discharge machining (micro-EDM)[5, 6]. Among them, micro-EDM has an obvious advantage in the fabrication of micro-holes on difficult-to-machine conductive materials with different hardnesses, especially titanium alloy [7, 8]. However, a continuing problem during the micro-EDM process is that a large amount of machining debris in the inter-electrode gap cannot be evacuated timely, resulting in severe tool electrode wear and decreasing the machining accuracy of micro-holes [9].

Researchers have been developing various methods to improve debris evacuation and increase the machining accuracy. Wang et al. [10] improve debris evacuation and decreased the tool electrode wear by using a helical tool electrode. Jacob et al. [11] successfully fabricated a double helical grooved tool electrode and found that the double helical grooved tool electrode performed better in debris removal than the single helical grooved tool electrode. Moreover, Kumar et al. [12] fabricated a series of micro-inclined slots on the surface of a solid cylindrical tool electrode. The results showed that the proposed tool electrode can effectively evacuate the debris existing in the inter-electrode gap and hence reduce the taper of a blind micro-hole [12]. In another study, Kumar et al. [13] drilled a series of inclined through-holes in the solid cylindrical electrode. Their experimental results indicated that the debris could be evacuated via the through-holes, which eliminated the formation of secondary sparking and resulted in a lower value of the taper angle [13]. Except for shaped electrode geometries, other methods are also used to improve the debris evacuation, i.e. ultrasonic vibration, planetary motion of tool electrode plus ultrasonic vibration and magnetic field assistance. Hirao et al. [14] applied ultrasonic vibration assistance to the tool electrode, and the debris in the machining zone was removed under the condition of high-frequency vibration. Zhao et al. [15] drilled micro-holes by using a notched tool electrode assisted by ultrasonic vibrations during the micro-EDM process. Their results indicated that both debris evacuation and machining accuracy were effectively improved. Yu et al. [16] proposed a new approach of the combination of ultrasonic vibrations and planetary motion of tool electrode in micro-EDM and found that the process of micro-EDM drilling had a tremendous improvement in the process performance, which was benefit from the debris evacuation timely. In addition, Bains et al. [17] introduced magnetic field assistance in EDM and promoted the flow of debris from the machining zone. Baseri et al. [18] used a constant magnetic field in EDM process and added TiO_2 powder to the dielectric. Their experimental results showed that debris was easy to evacuate from the machining zone under the action of a magnetic field force and the powder. Although there are many methods favorable to increasing the debris evacuation during the micro-EDM process, the fabrication of a shaped tool electrode and multi-field assistance are complex and difficult to control. So, tool electrode wear is still inevitable.

The actual machined micro-hole depth is difficult to equal its expected depth due to the tool electrode wear. Therefore, micro-hole depth error is one of the important indicators of machine accuracy. Various tool electrode wear compensation methods have been proposed. Muralidhara et al. [19] developed an in-situ axial tool wear and machining depth measurement system to investigate the axial wear ratio variations with machining depth, and realized tool electrode wear compensation. A maximum machining depth error of 6% was observed using the proposed tool electrode wear compensation method. Ganesh et al. [20] proposed a new tool wear compensation method that integrated the micro-EDM machine to an image processing module and computer-controlled tool wear prediction algorithm. Deviation of less than 1% between the actual depth and the expected depth of the micro-hole can be obtained by the proposed novel method. Aligiri et al. [21] developed a real-time material removal volume estimator based on a theoretical electro-thermal model. The experimental and estimated results were found to be in satisfactory agreement with an average error less than 14.3% for titanium alloy workpeice material. Moreover, Nirala et al. [22] applied a modified volume removal per discharge approach in real-time. This approach realized tool electrode wear compensation by estimating real-time volume removal from the workpiece. The expected depth of the micro-hole in a brass workpeice material were successfully fabricated with an error of less than 4%. Although these tool electrode compensation methods can effectively improve the machining accuracy of micro-holes, these compensation systems are very complicated.

In our study, a novel machining method of tool electrode spiral motion feed mode combined with FRAC is proposed to improve the machining accuracy of micro-holes, with the processing parameters optimized by means of response-surface experiments. The effects of tool electrode feed mode and compensation method on the machining accuracy of micro-holes were investigated. Besides, the effects of voltage, current, frequency and tool speed on the depth error and machining time of micro-holes are also studied.

Finally, high accuracy and high efficiency micro-holes are fabricated by using the optimum processing parameters.

2. Materials And Methods

2.1. Principle of the tool electrode feed mode

Figure 1 shows the schematic diagrams of the tool electrode spiral motion feed mode and linear motion feed mode. Figure 1a shows the tool electrode spiral motion feed mode. Figure 1b shows the linear motion feed mode. The tool electrode moves in a spiral trajectory in space in the spiral motion feed mode. The tool electrode feed is controlled according to the state between the electrode and workpiece, which is similar to the linear motion feed mode. When a short-circuit signal is detected, the tool electrode is retracted, otherwise, the electrode is activated. The spiral trajectory radius R and variation distance d of each layer are the main evaluation parameters of the spiral motion feed mode. R represents the distance between the micro-hole axis and the spiral line. d is the distance between the adjacent spiral lines. The synchronized movements of tool electrode and workpiece lead to the formation of a spiral trajectory, including the outward translation and expansion movement of X-axis and Y-axis of the worktable, and the up and down linear movement of the electrode along Z-axis.

Figure 2 shows a schematic diagrams of debris evacuation under the tool electrode spiral motion feed mode (Fig. 2a) and the linear motion feed mode (Fig. 2b). The micro-EDM process produces a large number of debris particles, which is mainly evacuated from the side gap. However, most debris particles accumulate at the bottom of micro-hole under the tool electrode linear motion feed mode, which damages the shape accuracy and increases the depth error of the micro-hole. However, as can be seen from Fig. 2b that the debris can be effectively evacuated from the inter-electrode gap under the tool electrode spiral motion feed mode which provides a large side gap. Therefore, the arcing and short-circuiting in the sparking zone can be more significantly reduced under the tool electrode spiral motion feed mode than the linear motion feed mode. Thus, it can reduce tool electrode wear and further decrease the depth error of the machined micro-holes.

2.2. Tool electrode compensation method under the spiral motion feed mode

Although the tool electrode spiral motion feed mode is favourable to the reduction of tool electrode wear, such wear is still inevitable. In this study, a fixed reference axial compensation (FRAC) method based on the electric circuit signal real-time detection of electrode wear and the method of axial electrode compensation was proposed in the study, the schematic diagram of which is shown in Fig. 3. During the machining process, the tool electrode moves according to the numerical sequence and the arrow direction given in the diagram. Firstly, the tool electrode is slowly fed from the initial position to the touch position of the workpiece surface. When the tool electrode tip touches the workpiece surface, the internal electric circuit system of the machine tool forms a circuit. The trigger signal (i.e. short-circuit signal) is immediately fed back to the spindle controller and the spindle stops feeding and records the real-time coordinates including the Z-axis coordinate value. After completing electrode positioning and coordinate values recording, the tool electrode moves to the machining position and then starts processing. The expected micro-hole depth is H_e (that is the moving distance of Z-axis). When the Z-axis moves downwards to the set value, the actual depth of the machined micro-hole is only H_a due to the tool electrode wear. This results in depth error of the micro-hole. After drilling, the tool electrode returns to the initial position and then touches the workpiece again. At the same time, the real-time coordinates are recorded, including the Z-axis coordinate value. The value of tool electrode wear can be obtained through the coordinate difference of the Z-axis. As a result, the spindle can precisely compensate for the corresponding electrode axial feed in real-time and reduces the micro-hole depth error. The machining of the micro-hole continues until the electrode wear value is larger than the set value. FRAC method can further reduce the micro hole depth error and, especially, monitor the value of the electrode wear in real-time.

2.3. Experimental procedure

The machining of all the micro-holes was conducted using the micro-EDM machine tool (Sarix-200hpm). The micro-holes were cut by wire electrical discharge machining (MV1200R) to obtain their cross-sections. The cross-section morphology of the micro-holes was observed by scanning electron microscopy (Hitachi S3400N). The actual depth of the micro-holes were measured by a laser confocal microscope (Olympus OLS4100). The machining time of micro-holes was obtained using the timing system attached on the machine tool.

In this study, different depths of micro-holes were drilled under the tool electrode linear feed mode and the tool electrode spiral motion feed mode. In addition, different depths of micro-holes were machined under the tool electrode spiral motion feed mode combined with FRAC and without compensation. The effects of the tool electrode feed mode and the compensation method on the depth error of the micro-holes were analyzed. Furthermore, single factor investigation and the Response Surface Method were performed to optimize the process parameters. The depth error and machining time of the micro-holes were recorded. The detail experimental conditions are shown in Table 1 and each experiment was repeated 5 times. The depth error of micro-hole is calculated through Eq. (1):

$$Depth\ error = \left| \frac{expected\ depth - actual\ depth}{expected\ depth} \right| \times\ 100\% \quad (1)$$

Table 1
Processing conditions for micro-hole fabrication

Parameters	Value
Pulse width (μs)	2
Voltage (V)	90, 100 ,110, 120, 130
Current (index)	50, 60 ,70, 80, 90
Frequency (kHz)	100, 120, 140, 160, 180
Tool speed (rpm)	100, 200, 300, 400, 500
Electrode material	Tungsten carbide
Workpiece	Titanium alloy
Working medium	Hedma111 spark oil

3. Results And Discussion

3.1. Effect of the tool electrode feed mode on the shape of micro-holes

Comparative experiments of tool electrode spiral motion feed mode and linear feed mode were carried out. Constant parameters were used to drill the micro-holes under the two feed modes, which were voltage 100 V, current 60 index, frequency 120 kHz, pulse width 2 μs and tool speed 500rpm, respectively. Figure 4 shows the shape of the micro-holes drilled under the two tool electrode feed modes. As can be seen in Fig. 4a, there are cones at the bottom of the micro-holes when using the linear motion feed mode. This is because the debris accumulated and then formed a parabolic cone in the bottom center of the micro-hole due to the vortex[23]. When the tool electrode feed mode was spiral feed, the debris can be easily evacuated from the inter-electrode gap, so the tool electrode spiral motion feed mode can effectively eliminate the bottom cone of the micro-hole. The micro-holes without the bottom cone can be obtained, which are shown in Fig. 4b.

Figure 5 shows the depth errors for the different depths of micro-holes drilled under the tool electrode spiral motion feed mode and the tool electrode linear motion feed mode. When the expected depths of micro-holes were 600, 800, 1000, 1200 and 1400μm, the depth errors of the micro-holes drilled under the tool electrode spiral motion feed mode decrease by 36.5%, 45.10%, 37.40%, 31.60% and 23.80% compared with those of the micro-holes drilled under the tool electrode linear motion feed mode. The depth error of micro-holes increased with increase of the expected depth. In another word, decrease in machining accuracy of the micro-holes with the increase of expected depth still exists under the tool electrode spiral motion feed mode.

3.2. Effect of the compensation method on the depth error of micro-holes

Micro-holes were fabricated using the tool electrode spiral motion feed mode combined with and without fixed reference axial compensation (FRAC). The same process parameters, the voltage, current, frequency, pulse width and tool speed, were used. The expected depths of micro-holes were 400, 600, 800, 1000, 1200, 1400 and 1600 µm. The depth errors of the micro-holes drilled with and without the compensation method are shown in Fig. 6. The depth errors of the micro-holes drilled with FRAC was significantly lower than those drilled without compensation. When the expected depth was 1600 µm, the actual depth of micro-hole increased from 1270.56 µm to 1592.10 µm by using FRAC. The depth error decreased from 20.59–0.494%, providing that the FRAC method can obtain high depth accuracy.

3.3. Effect of process parameters on the depth error and machining time of micro-holes

3.3.1 Effect of pulse voltage

Micro-holes were fabricated using the tool electrode spiral motion feed mode combined with the FRAC method and without compensation under different pulse voltages of 90, 100, 110, 120 and 130 V. The pulse width, frequency, current and tool speed were fixed at 2 µs, 130 kHz, 60 index, 500rpm, and the expected depth of the micro-hole was 1000 µm. Figure 7 shows the actual depth and depth error of the micro-holes. When the voltage increases from 90 V to 130 V, the depth error of micro-holes drilled with FRAC method and without compensation increases from 0.342–0.659% and from 2.76–14.02%, respectively. Too high voltage is unfavorable to the improvement of machining accuracy, because the high voltage generates large electrical spark energy, which increases the tool electrode wear. Thus, the depth error of micro-holes increases with the increase of voltage. However, it is worth noting that the depth accuracy of micro-holes fabricated with FRAC method is significantly better than that without compensation. Especially, when the voltage is 110v, the depth error of the micro-hole drilled without compensation is as high as 10.54%, while the depth error of the micro-hole machined with FRAC method is only 0.45%. The depth error decreases by 95.37%.

Figure 8 shows the machining time of the micro-holes under different pulse voltages. It can be observed that the machining time with FRAC method is longer than that without compensation. It is because that FRAC method needs to perform electrode axial compensation during the micro-hole drilling process. The introduction of FRAC method increases the machining time. The machining time of micro-holes fabricated without compensation decreases from 1285s to 686s sharply with the voltage increased from 90v to 130v. The machining time of the micro-holes drilled with FRAC method decreases from 1322s to 809s firstly and then increases to 842s. The use of too high voltage does not make the machining time of the micro-holes fabricated with FRAC method decrease linearly. The increase of the voltage will lead to the increase of electrode wear, resulting in the increase of compensation number when the FRAC method is used. It means that the machining time increases. Therefore, a reasonable voltage value can effectively improve the machining efficiency and machining accuracy of micro-holes.

3.3.2 Effect of pulse current

Figure 9 shows the actual depth and depth error of the micro-holes drilled using the tool electrode spiral motion feed mode combined with FRAC method and without compensation under pulse currents of 50, 60, 70, 80 and 90 index. The pulse width, frequency voltage and tool speed were fixed at 2 μs, 130 kHz, 110 V and 500 rpm. The expected depth was 1000 μm. The effects of current and voltage on the depth error of micro-holes are similar. As can be seen from Fig. 10 that as the current increases from 50 to 90 index, the depth error of the micro-holes drilled without compensation increases from 11.36–13.90%. However, with the increases of the currents, the depth error of the micro-holes drilled with FRAC method increases from 0.413–0.580%. Similarly, a high current would generate large electrical spark energy, which would increase the tool electrode wear. Thus, the machining accuracy of micro-holes can be reduced under high current condition.

Figure 10 shows the machining time of the micro-holes drilled with different pulse currents. With the increase of the current, the machining times of the micro-holes drilled with FRAC method and without compensation decrease monotonously. It is because that the excessive current would increase the removal rate of the workpiece material.

3.3.3 Effect of pulse frequency

Figure 11 shows the actual depth and depth error of the micro-holes drilled using the tool electrode spiral motion feed mode combined with FRAC method and without compensation under pulse frequencies of 100, 120, 140, 160 and 180 kHz. When the frequency increase from 100 to 180 kHz, the depth error of the micro-holes drilled without compensation and with FRAC method increased from 10.57–12.85% and 0.152–0.256%, respectively. It can be found that the increase in the frequency leads to an increase in the depth error of the micro-holes.

When the pulse frequency is increased from 100 kHz to 180 kHz, the machining times of the micro-holes drilled without compensation and with FRAC method increase from 715s to 740s and 748s to 775s, respectively, which is shown in Fig. 12. A possible reason is that the debris evacuation may be affected with the increase of pulse frequency significantly. A high frequency provides a small pulse cycle, while the pulse width is fixed at 2 μs. The pulse interval is small in the case of high frequency. It means that the debris is hard to evacuate timely from the machining zone. As a result, an excessive arcing and short-circuiting occur easily in the sparking zone, which limits the machining accuracy and increases the machining time.

3.3.4 Effect of tool speed

Figure 13 shows the actual depth and depth error of the micro-holes drilled using the tool electrode spiral motion feed mode combined with FRAC method and without compensation under tool speeds of 100, 200, 300, 400 and 500 rpm. When the tool electrode rotation speed increases, the depth error of the micro-holes drilled without compensation decreases from 14.81–10.99%. In contrast, the depth error of the micro-holes drilled with FRAC method is below 0.43%. An increase in the rotational speed of the tool electrode results in an increase in the flow velocity of the debris and dielectric fluid. The debris in the inter-electrode gap flowed upward spirally in the flow field and was evacuated quickly. The process performance of micro-EDM is improved because of the rapid removal of debris. On the other hand, the wear of tool electrode is reduced, leading to the decrease in the depth error of micro-holes. Although the increase of tool electrode rotation speed is beneficial to the improvement of the actual depth of the micro-holes, there is still a depth error caused by electrode wear. The depth error of micro-hole can be reduced to 0.43% by using the FRAC method.

In addition, the increase of tool electrode rotation speed effectively reduces the machining time of micro-holes which is shown in Fig. 14. The machining time of the micro-holes drilled with FRAC method is reduced from 975 to 746 s with the tool electrode rotation speed increased from 100 to 500 rpm. It can also be attributed to the improvement of the workpiece material removal rate caused by the increase of tool electrode rotation speed.

3.5. Optimization of the machining parameters by Response Surface Methodology

3.5.1. Experimental detail

The process parameters of micro-holes were optimized using the Response Surface Methodology. The voltage, current, frequency and tool speed were selected as factors, each of which has three levels and is listed in Table 2. The machining time of micro-holes are selected as the results of the experimental response. Design Expert 11.0 software is used for regression and graphical analysis of data. The average values of the machining time, along with the design matrix, are shown in Table 3.

Table 2
Factors and levels of the Response Surface Methodology experiments

Factor symbol	Parameter	Levels		
		-1	0	+1
A	Voltage (V)	100	110	120
B	Current (index)	70	80	90
C	Frequency (kHz)	100	120	140
D	Tool speed (rpm)	300	400	500

Table 3
Design of experimental matrix and results

	Process parameters				Measured values
	A: Voltage (V)	B: Current (index)	C: Frequency (kHz)	D: Tool speed (rpm)	Machining time (s)
1	100	70	100	300	822
2	120	70	100	300	796
3	100	90	100	300	784
4	120	90	100	300	784
5	100	70	140	300	851
6	120	70	140	300	819
7	100	90	140	300	812
8	120	90	140	300	806
9	100	70	100	500	783
10	120	70	100	500	784
11	100	90	100	500	741
12	120	90	100	500	778
13	100	70	140	500	811
14	120	70	140	500	795
15	100	90	140	500	774
16	120	90	140	500	806
17	100	80	120	400	802
18	120	80	120	400	798
19	110	70	120	400	821
20	110	90	120	400	786
21	110	80	100	400	815
22	110	80	140	400	824
23	110	80	120	300	851
24	110	80	120	500	802
25	110	80	120	400	812

	Process parameters				Measured values
	A: Voltage (V)	B: Current (index)	C: Frequency (kHz)	D: Tool speed (rpm)	Machining time (s)
26	110	80	120	400	798
27	110	80	120	400	796
28	110	80	120	400	818
29	110	80	120	400	803
30	110	80	120	400	826

3.5.2. Analysis of the machining time

The results of the quadratic model for machining time are given in Table 4. When the p-value of the model is lower than 0.05, the model is considered to be statistically significant [24]. According to the data shown in Table 4, factor B (current), factor C (frequency), factor D (tool speed), the interaction effect of factor A (voltage) with factor B (frequency) and the interaction effect of factor A (voltage) with factor D (tool speed) have a significant effect on the depth error. The bigger the F value is, the more significant the effect of factor on the depth error will be. Thus, the significance of the factors in descending order is D > C > B > AB > AD.

Table 4
Model variance analysis for machining time

Source	Sum of squares	df	Mean square	F-Value	Prob > F	
Model	12954.99	14	925.36	9.44	< 0.0001	significant
A	10.89	1	10.89	0.1110	0.7436	
B	2473.39	1	2473.39	25.22	0.0002	
C	2473.39	1	2473.39	25.22	0.0002	
D	3500.06	1	3500.06	35.69	< 0.0001	
AB	1156.00	1	1156.00	11.79	0.0037	
AC	72.25	1	72.25	0.7368	0.4042	
AD	870.25	1	870.25	8.87	0.0094	
BC	25.00	1	25.00	0.2549	0.6209	
BD	49.00	1	49.00	0.4997	0.4905	
CD	0.2500	1	0.2500	0.0025	0.9604	
A^2	683.05	1	683.05	6.97	0.0186	
B^2	420.32	1	420.32	4.29	0.0561	
C^2	27.59	1	27.59	0.2813	0.6036	
D^2	272.91	1	272.91	2.78	0.1160	
Residual	1470.88	15	98.06			Not significant
Lack of Fit	766.05	10	76.60	0.5434	0.8074	
Pure Error	704.83	5	140.97			
Cor Total	14425.87	29				

Figure 15 shows the effects of interaction factors on the machining time. It can be observed that as the voltage increases from 100 to 120v, the machining time of micro-holes increases slightly. In addition, the machining time of micro-holes decreases with the increase of current and tool electrode rotation speed. The increase of the current (from 70 to 90 index) and the increase of the tool electrode speed (from 300 to 500 rpm) did not increase the compensation number. In this condition, the effect of the current and tool electrode speed on the machining time of the micro-holes drilled with FRAC method is similar to that of the micro-holes drilled without compensation. Therefore, voltage of 100 V, current of 90 index, frequency of 100 kHz and tool speed of 500 rpm are selected in order to drill the micro-holes with high accuracy and high efficiency.

3.5.3. Fabricating micro-holes with high accuracy and efficiency using optimization parameters.

Using the optimization parameters, the cross-sections of the micro-holes drilled under the expected depth of 1000μm, 1200μm and 1400 μm are shown in Fig. 16. Obviously, there is no cone existing at the bottom of the micro-holes. The actual depth, depth error and machining time of micro-holes are shown in Table 5. The depth error of the micro-hole with a depth of 1000 μm is only 0.210% under optimal process parameters, whose accuracy is better than the micro-holes drilled using the FRAC method under non-optimal process parameters. And the machining efficiency under optimal process parameters improves significantly. When the expected depths were 1000 μm, 1200 μm and 1400 μm, the depth errors of the micro-holes decreased by 97.9%, 97.8%, and 98.3% compared with those of the micro-holes drilled without compensation. By using the optimized process parameters, micro-holes with higher machining accuracy and efficiency are successfully achieved.

Table 6
Actual depth, depth error and machining time of the micro-holes with different expected depths

Expected depth	Ha (actual depth)	Depth error	Machining time
1000μm	997.9μm	0.210%	734s
1200μm	1196.8μm	0.267%	816s
1400μm	1396.1μm	0.280%	936s

4. Conclusions

In this study, a novel micro-EDM method with tool electrode spiral motion feed combined with fixed reference axial compensation (FRAC) has been proposed to fabricate high-accuracy micro-holes. Single factor and Response Surface Method experiments were conducted to study the effect of process parameters on the depth error and machining time of the micro-holes. subsequently, the optimized process parameters were used to fabricate high-accuracy micro-holes. The following conclusions can be drawn:

1. The tool electrode spiral motion feed mode has a better debris evacuation capability than the linear motion feed mode. Micro-holes without cones can be successfully machined under the tool electrode spiral motion feed mode.

2. The FRAC method can reduce the depth error of micro-holes. The depth errors of all the micro-holes drilled under tool electrode spiral motion feed mode combined with FRAC are less than 0.659%.

3. The increase in pulse voltage, current, and frequency leads to an increase in the depth error of the micro-holes. The increase of tool electrode rotation speed can decrease the depth error of the micro-holes.

In addition, the machining time of the micro-holes drilled with FRAC method has no obvious increase compared with that drilled without compensation.
4. The machining efficiency and accuracy of the micro-holes are improved under the tool electrode spiral motion feed mode combined with FRAC method using the optimized process parameters.

Declarations

Author contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by all authors.

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Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval

Not applicable to this section.

Consent to participate

The authors are agreeing to participate.

Consent for publication

The authors give their consent for publication in this journal.

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

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Figures

Figure 1

Schematic diagram of tool electrode feed modes: (a) spiral motion feed mode, and (b) linear motion feed mode

Figure 2

Schematic diagram of debris evacuation under (a) linear motion feed mode and (b) spiral motion feed mode

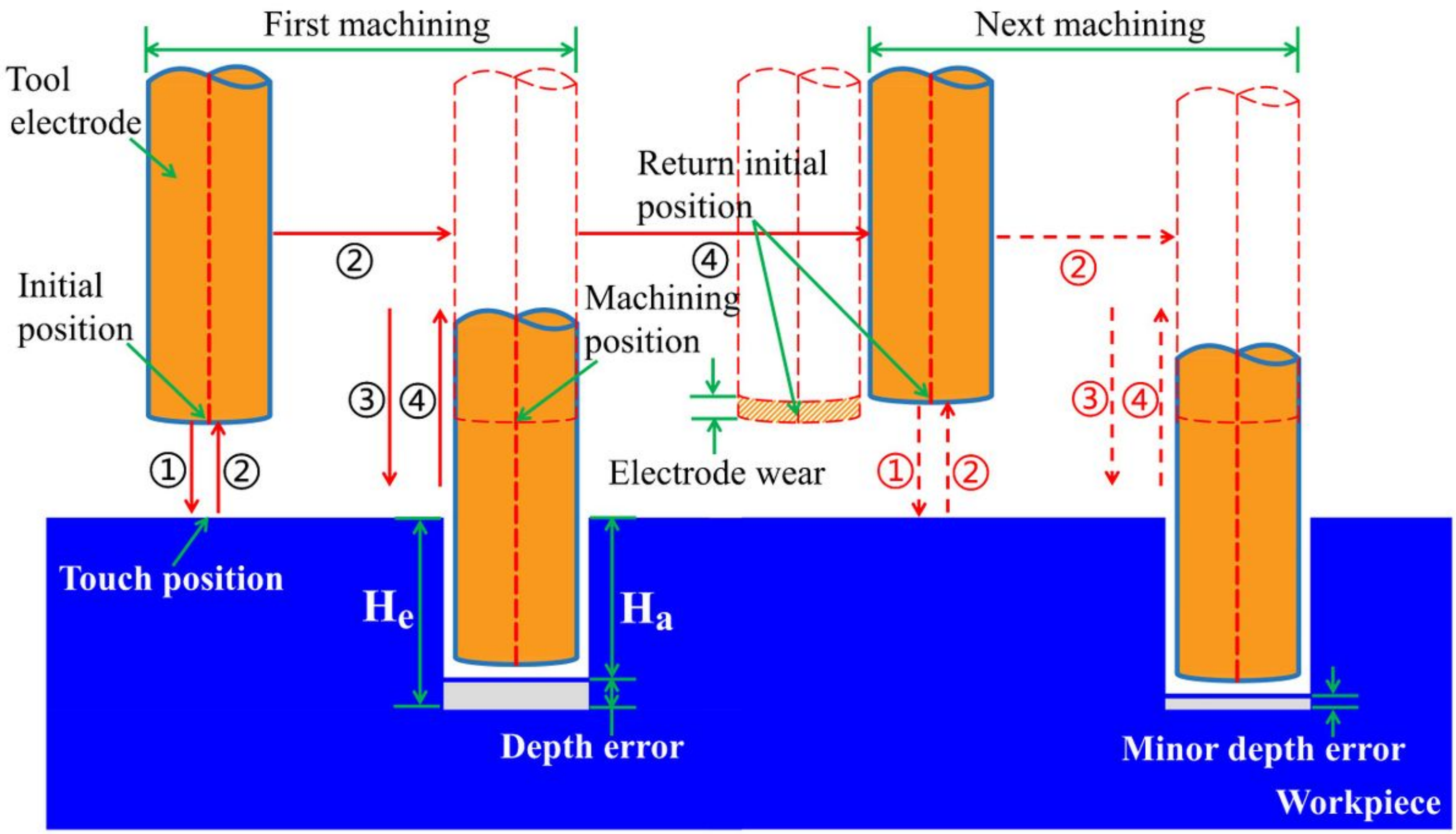

Figure 3

Figure 4

Shape of the micro-holes drilled under different tool electrode feed modes: (a) linear motion feed mode, and (b) spiral motion feed mode

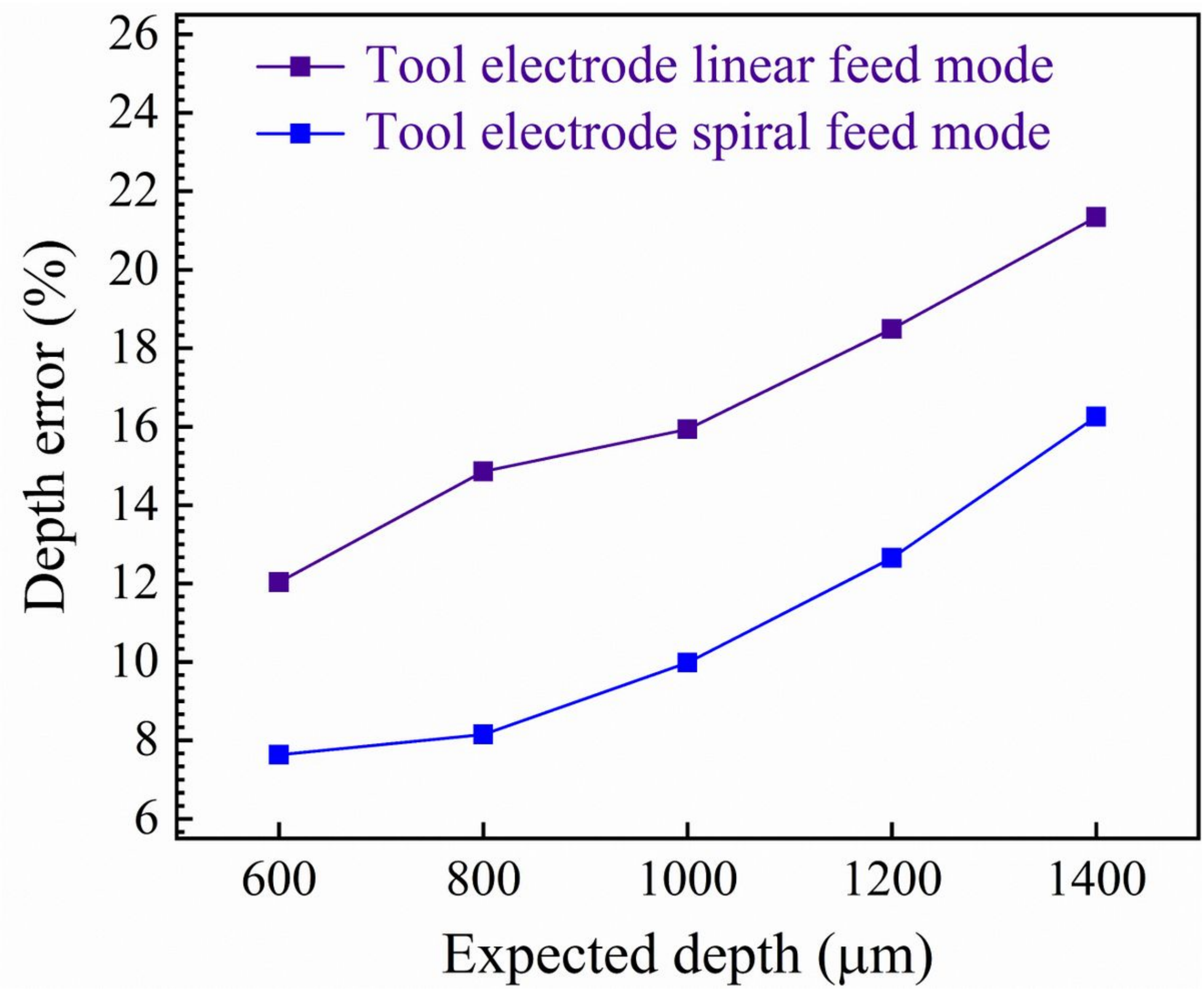

Figure 5

Effect of the tool electrode spiral motion feed mode and the linear motion feed mode on the depth error of micro-holes

Figure 6

Effect of FRAC method on the actual depth and depth error of micro-holes

Figure 7

Actual depth and depth error of micro-holes drilled under different pulse voltages

Figure 8

Machining time of micro-holes drilled under different pulse voltages

Figure 9

Actual depth and depth error of micro-holes drilled under different pulse currents

Figure 10

Machining time of micro-holes drilled under different pulse currents

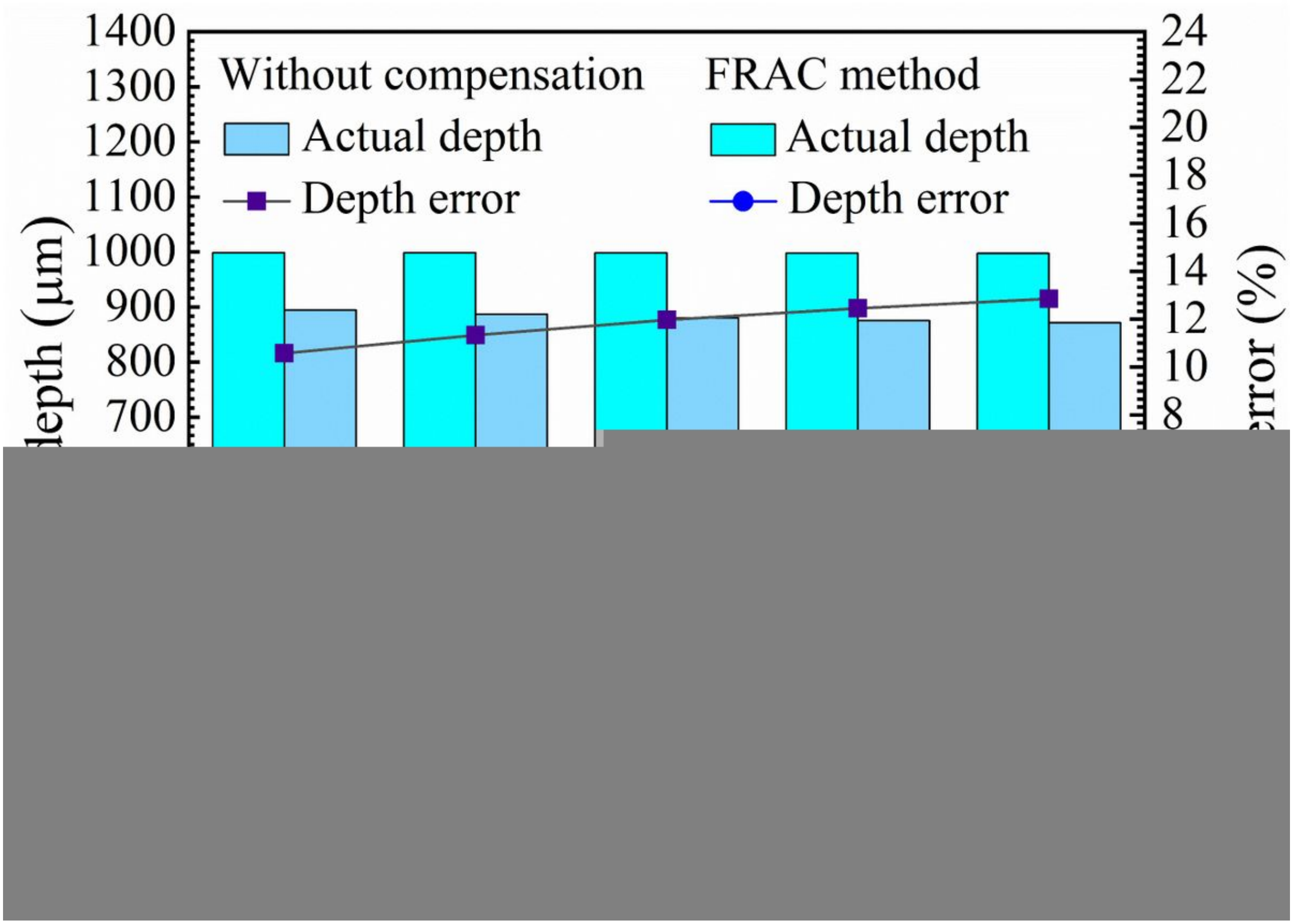

Figure 11

Actual depth and depth error of micro-holes drilled under different pulse frequencies

Figure 12

Machining time of micro-holes drilled under different pulse frequencies

Figure 13

Actual depth and depth error of micro-holes drilled under different tool speeds

Figure 14

Machining time of micro-holes drilled under different tool speeds

Figure 15

Effect of processing parameters on the machining time of micro-holes.

Figure 16

Cross-section of the micro-holes drilled with the optimized process parameters.