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ORIGINAL ARTICLE

Large taper mechanism of HS-WEDM

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Abstract Large taper (≥ ± 5°) high-speed wire electrical discharge machining can be affected by many factors. The positioning error of wire electrode caused by guide wheels and the run-out of guide wheels are particularly important. Moreover, dielectric fluid cannot wrap the wire electrode appropriately and flow into the machining region along with the wire electrode in tilt directions. As a result, the machining accuracy and surface roughness of a large taper-cutting workpiece are worse than those of straight cutting. In order to solve these problems, this paper presents the design and improvement of two types of six-bar linkage large taper-cutting mechanisms that can realize the guide of wire electrode and the tracking spray of dielectric fluid along with the incline of the wire electrode. The first type causes angular error but no wear, whereas the second one causes wear but no angular error. The former is applied to process experiments. The experimental results show that, compared with traditional mechanisms, this new approach decreases the roundness error of the workpiece from 80 to 40 μm and the surface roughness from 4.059 to 3.495 μm under the same processing parameters. In terms of multi cutting (skim cutting), the new mechanism reduces the roundness error of taper cutting (taper ±20°, thickness 40 mm) to 25 μm and the surface roughness to 1.670 μm. An idea of intelligent servo traverse guider based on this mechanism is also proposed in this study.

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Keywords WEDM · Large taper · Servo mechanism · Guide wire intelligently · Multi cutting

1 Introduction

Wire-cut electric discharge machine can be divided into high-speed wire-cut electric discharge machine (HS-WEDM) and low-speed wire-cut electric discharge machine (LS-WEDM) by way of wire electrode's traveling. HS-WEDM usually uses molybdenum or tungsten as wire electrode, running reciprocally at the speed of around 10 m/s, while LS-WEDM uses copper as wire electrode, running unidirectionally at the speed of around 0.2 m/s. LS-WEDM is more suitable for processing parts with high precision than HS-WEDM. As an important type of high-speed wire electrical discharge machine (HS-WEDM) tool [1], taper-cutting machine tool is widely used in the processing field, such as forming cutters, tool electrode for electrical discharge machines, plastic and rubber extrusion die, wortle, splicing mold, and varieties of parts (e.g., bevel wheel and vane) [2–4]. When cutting taper parts, especially the large (≥ ± 5°) ones, the cutting effect is influenced by many factors [5, 6]. The most important of such factors are the positioning of wire electrode by guide wheels and the resulting mechanical error and run-out error [7, 8]. Dielectric liquid cannot wrap around the wire well and enter the discharge gap in large taper cutting [9], thereby resulting in poorer machining precision and surface roughness than those by straight processing [10]. Moreover, the wire electrode may be broken in the cutting process. Multi cutting is difficult for HS-WEDM taper cutting, especially large taper cutting [11].

2 Analysis of traditional large taper-cutting mechanisms

2.1 Low-speed wire electrical discharge machine (LS-WEDM) taper cutting

In LS-WEDM taper cutting, traverse guiders are moved with U and V working tables to drive the wire electrode to achieve taper-cutting movement (as shown in Fig. 1).

This process is needed to design a large transition arc in the traverse guider for its low wire moving speed (usually approximately 0.2 m/s) [12]. Soft brass wire is commonly selected as wire electrode, due to its flexibility.

2.2 HS-WEDM taper cutting

As shown in Fig. 2, for HS-WEDM, numerous sharp edges are formed on the surface of molybdenum wire from discharge pits, due to repeated use. Molybdenum is harder than the brass used in LS-WEDM, and its moving speed is as fast as 8 to 12 m/s. Thus, the service life of the traverse guider will be lower than that for the LS-WEDM tool when made of the same material [13]. If the taper cutting is conducted in a similar manner in which the traverse guider is under rigidity pull, the traverse guider will rapidly wear out and lose its position effect in a short period. Therefore, the main means to guide the wire of a HS-WEDM should be a loose contact to limit the jitter of wire electrode.

2.3 Traditional large taper mechanisms of HS-WEDM

Traditional large taper mechanisms of HS-WEDM are usually realized by the normal swinging large taper-cutting mechanism that consists of four-bar linkage. The principle and actual photograph of this mechanism are shown in Figs. 3 and 4, respectively. The upper guide wheels move in direction U by the drive of the four-bar linkage, while the upper and lower rods deflect around the axis of the lower rod. The structure of this traditional mechanism is relatively simple and can realize the taper cutting of 45°. However, positioning the wire electrode by the guide wheels causes the following phenomena.

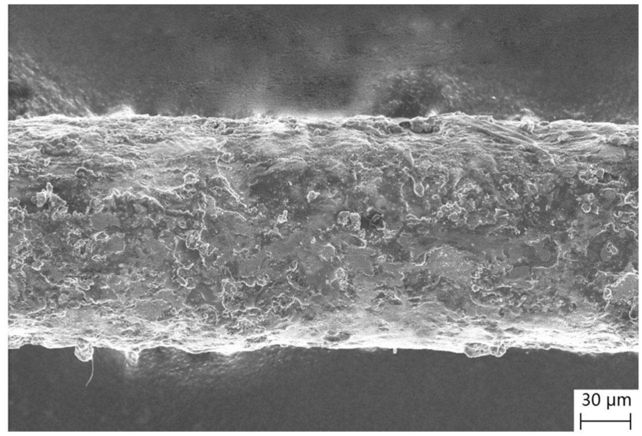


Fig. 2 Surface of molybdenum wire for HS-WEDM

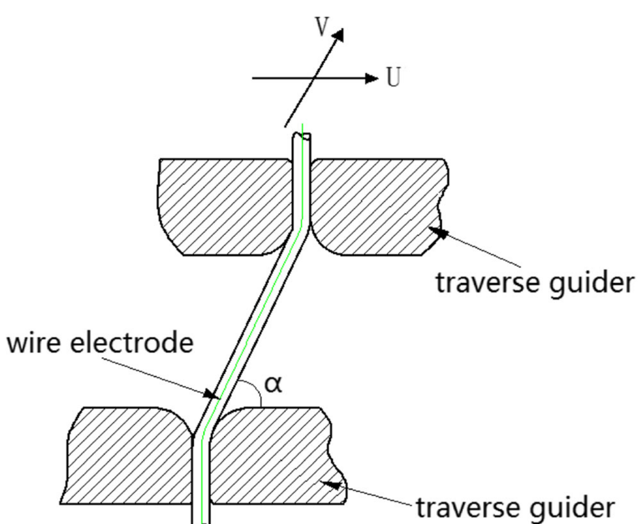


Fig. 1 Structure representation of the traverse guider of LS-WEDM taper cutting

First, the "angular error" of wire electrode in large taper cutting will occur as shown in Fig. 5. In large taper cutting, when the guide wheels move in direction U, the tangent point of wire electrode and guide wheels change from point A and C (straight cutting) to point B and D (taper cutting). This change forms an error between the actual and theoretical positions of the wire electrode, which is called "angular error" (*b* in Fig. 5). "Angular error" increases with an increase in cutting taper and wheel diameter. Although the "angular error" can be theoretically revised by the error compensation of interpolation calculation [14], the cutting accuracy is worse after the error compensation because of the instability and uncertainty of the position of the wire electrode. As a result, in precise large taper cutting, the consistency and stability of wire electrode should first be ensured to compensate for the "angular error" by software. Positioning the wire electrode with a traverse guider is currently an effective method. Second, when positioning the wire electrode using guide wheels, water nozzle is

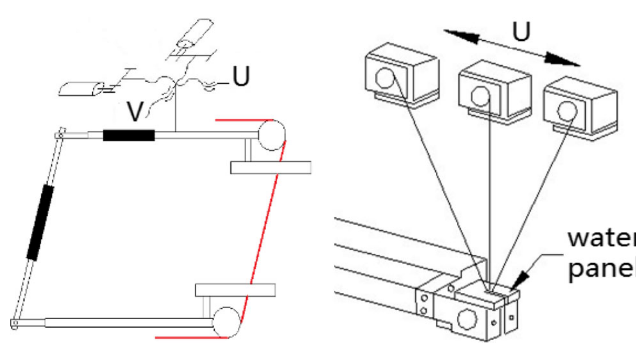


Fig. 3 Traditional four-bar linkage swinging wire frame of large taper wire electrical discharge machine (WEDM)

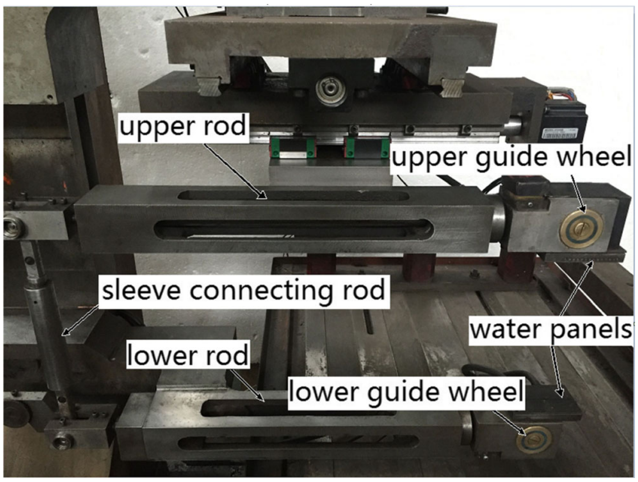


Fig. 4 Photograph of traditional four-bar linkage swinging wire frame of large taper WEDM

usually made as elongated slot in direction U with many water holes to avoid the interference with the wire electrode when it moves in direction U. In this case, the dielectric fluid spurt from the water nozzle cannot wrap the wire electrode well. Consequently, the cooling of the wire electrode cannot be ensured, and the wire electrode is disturbed as shown in Fig. 6. In conclusion, the cooling effect in the machining region is poor. Thus, the cutting accuracy and surface roughness are affected by this method.

3 Principle of servo large taper-cutting mechanisms with six-bar linkage

In HS-WEDM large taper cutting, influenced by the bearing accuracy and the change in tension of wire electrode, positioning of the wire electrode by the guide wheel is not stable. In addition, the servo water-spraying and wire-electrode wrapping cannot be achieved efficiently through the water nozzles. To

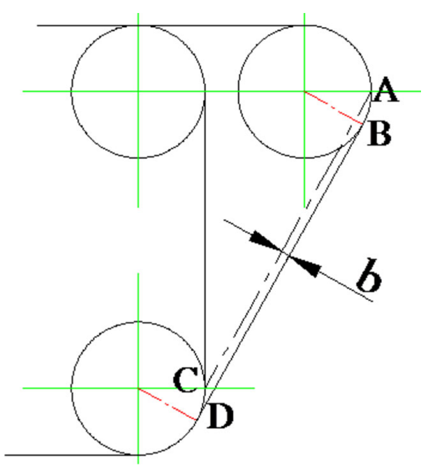


Fig. 5 Schematic of the "angular error" caused by the positioning of guide wheel in direction U

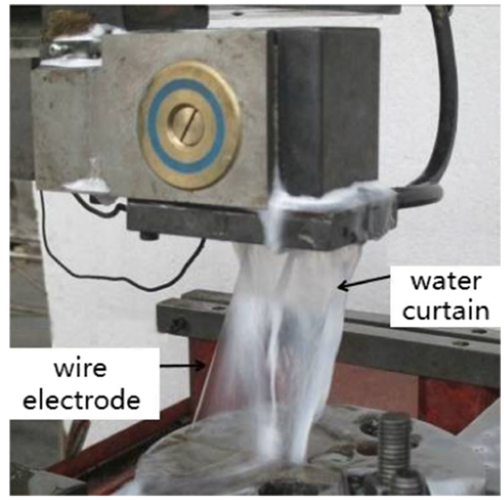


Fig. 6 Phenomenon of unilateral water curtain when wire electrode moves in direction U

solve these problems, two types of six-bar linkage large taper-cutting mechanisms that can realize the servo guide of wire electrode and the tracking spray of dielectric fluid, are designed in this study. The structures of these two types of six-bar linkage large taper-cutting mechanisms are relatively complex.

3.1 Mechanism that causes "angular error" but no wear

The principle of the first mechanism that causes "angular error" but no wear is shown in Fig. 7.

The transmission process in direction U of these servo large taper-cutting mechanisms with six-bar linkage is as follows. When motor U works, upper linear axis 7 moves forward or

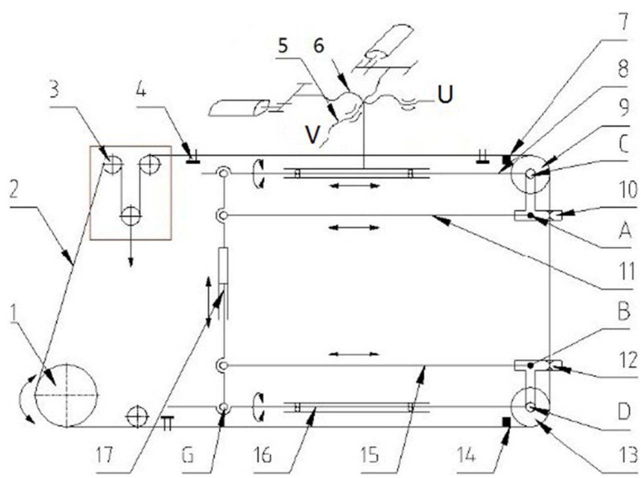


Fig. 7 Schematic of the servo large taper-cutting mechanisms with six-bar linkage. *1*—wire cylinder; *2*—wire electrode; *3*—constant tension unit; *4*—zirconia fork; *5-V*—leading screw; *6-U*—leading screw; *7*—upper linear axis; *8*—upper conductive lump; *9*—upper guide wheel; *10*—upper traverse guider; *11*—upper connecting rod; *12*—lower traverse guider; *13*—lower guide wheel; *14*—lower conductive lump; *15*—lower connecting rod; *16*—lower linear axis; *17*—sleeve connecting rod

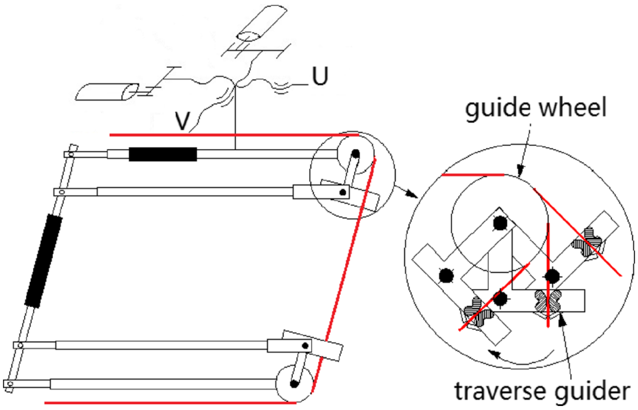


Fig. 8 Schematic of the motion of servo traverse guider when the taper mechanism moves in direction U

backward by the drive of gears and leading screw. At this time, the entire upper linear axis 7 and lower connecting bar 15 take the back endpoint G of the lower wire frame as the rotating center and move forward or backward. The upper connecting bar 11 moves forward or backward with the upper linear axis 7. The upper traverse guider 10 rotates around center C clockwise or anticlockwise by the drive of turning point A. At the same time, the lower connecting rod 15 moves forward by the drive of the sleeve connecting rod 17, and the lower traverse guider 12 rotates around center D clockwise or anticlockwise by the drive of turning point B. Such motion can ensure that the upper and lower traverse guiders rotate at the same angle. Hence, the V-groove of hard locating block inside the traverse guider will constantly coincide with the wire electrode. The distance between the upper connecting rod 11 and the lower connecting rod 15 will inevitably increase or decrease. This change can be compensated for by the automatic elongation or shortening of sleeve connecting rod 17. The elongation of the wire electrode is compensated for by constant tension unit 3 at the motion, and the input of electricity to the wire winding system is achieved by upper and lower conductive lumps 8 and 14.

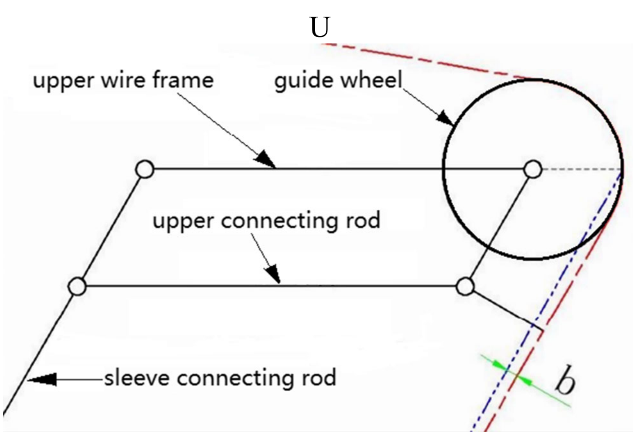


Fig. 9 Local diagram of the large taper mechanism that causes "angular error" but no wear

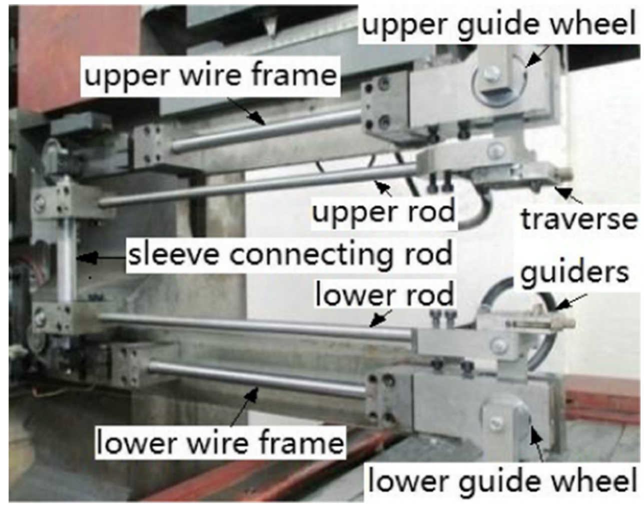


Fig. 10 Real device of the follow-up guide and spray mechanism

Theoretically, no wear is generated between wire electrode and traverse guider because the direction of the wire electrode constantly keeps coincidence with the limiting slot of the traverse guider (Fig. 8). On the one hand, this mechanism cannot eliminate the "angular error" (Fig. 9) caused by the motion of guide wheel in direction U. On the other hand, this mechanism can effectively confine the electrode wire vibration when the wire electrode is traveling through the traverse guider, and the wire traveling stability can be improved. In addition, the dielectric fluid ejected from the water nozzle on the traverse guider can always wrap the wire electrode well and easily enter to the machining gap with wire traveling. Therefore, good washing, cooling, and deionization performances can be achieved, which contribute to high cutting precision, high cutting efficiency, and good surface quality. The mechanism and machining process are depicted in Figs. 10 and 11, respectively.

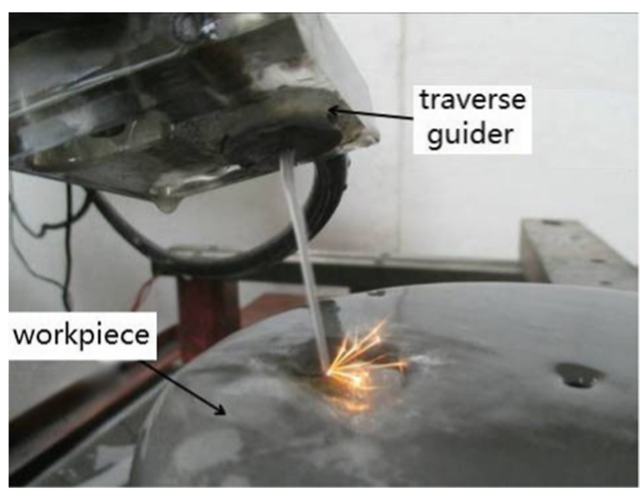


Fig. 11 Process site of the follow-up guide and spray mechanism

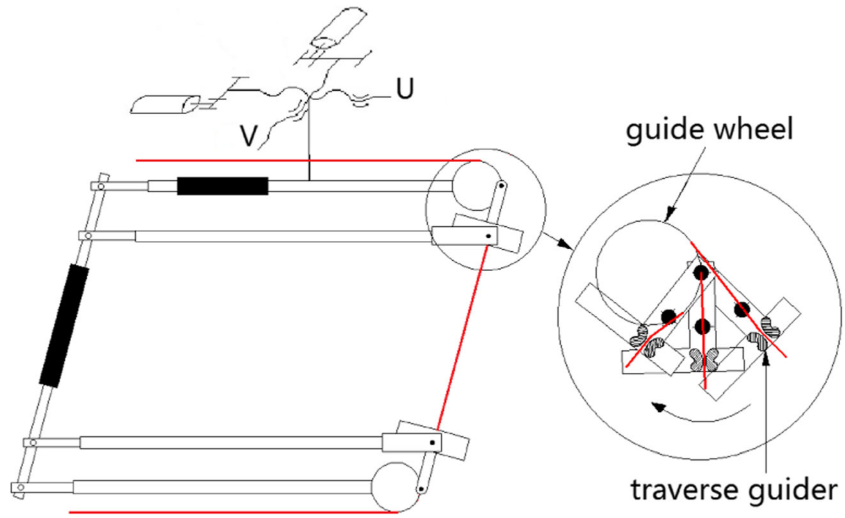


Fig. 12 Picture of the six-bar linkage wire-guiding mechanism that causes wear but no "angular error"

3.2 Mechanism that causes wear but no "angular error"

The "angular error" of the first mechanism occurring on the guide wheel incurs an effect on the machining accuracy of large taper cutting. To eliminate this effect, a six-bar linkage mechanism of large taper cutting with water-spraying and wire-guiding servo devices is designed, which causes wear but no "angular error." The principle is that the upper and lower traverse guiders rotate on the front radium points of the upper and lower guide wheels, respectively, as presented in Fig. 12. The local sketch of this wire-guiding mechanism is shown in Fig. 13. The limiting function of the traverse guider allows the actual and theoretical positions of the wire electrode between the upper and lower traverse guiders to coincide. Thus, the "angular error" in large taper cutting is eliminated. The water nozzle can also realize the function of tracking spray. The picture of this mechanism and the head of the taper-cutting device are shown in Figs. 14 and 15, respectively. The rotation center of this mechanism is situated on one side of the head of the taper-cutting device. Accordingly, only unilateral support guide wheels are allowed. This large taper-cutting mechanism theoretically eliminates the "angular error." Nevertheless, when the mechanism is working under the function of traverse guider, the deviation of wire electrode from the theoretical position to the actual position is small. The distance from the traverse guider to the front radium point of the guide wheel is short. Consequently, serious abrasion occurs between the wire electrode and traverse guider, which will eventually harm the traverse guider. The front endpoint also needs to be located precisely on the rotation axis, and it is thus difficult to process, assemble, and adjust.

The various factors of the two wire-guiding devices, including manufacturing assembly difficulties, precision requirement, and the requirement of large taper mechanism for a stable long-term cutting, are considered. Although the wire-

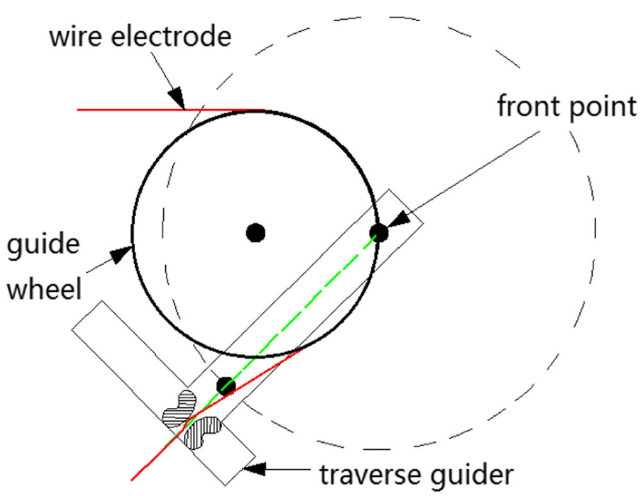


Fig. 13 Local sketch of the traverse guider that causes wear but no "angular error"

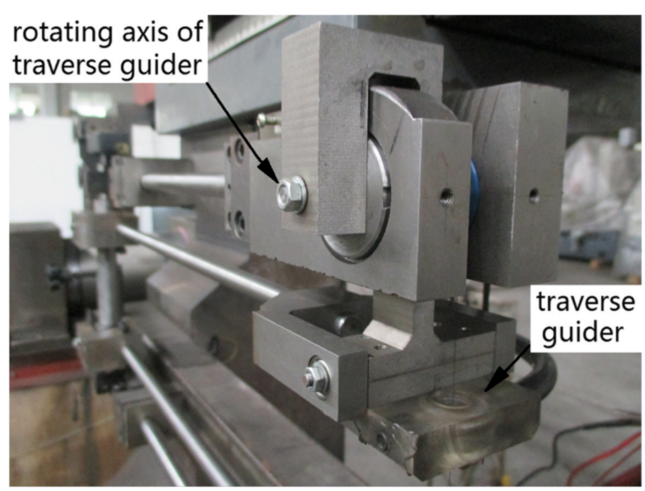


Fig. 14 Physical picture of the wire-guiding mechanism that causes wear but no "angular error"

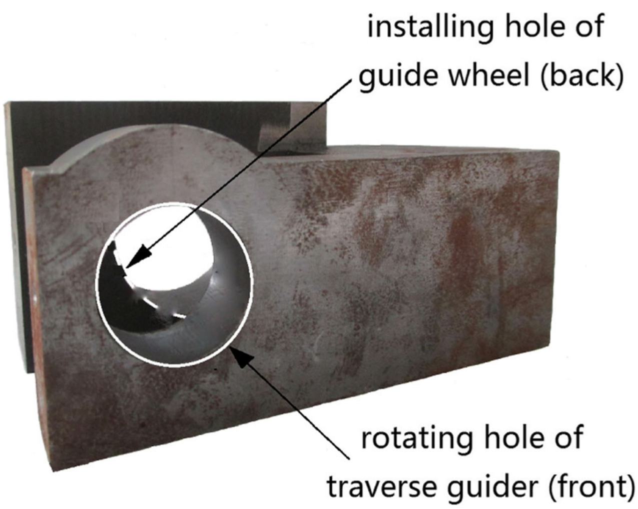


Fig. 15 Head of the taper-cutting wire-guiding device that causes wear but no “angular error”

guiding mechanism that causes wear but no “angular error” eliminates the angular error theoretically, the service life of traverse guider is greatly reduced. Accordingly, the wire-guiding mechanism that causes “angular error” but no wear is selected for production.

4 Processing technology of the large taper water-spraying and wire-guiding servo mechanism

Experiments are conducted by using a traditional large taper-cutting mechanism and well-designed servo mechanism.

4.1 Effect of machining precision

The cutting material is a 40-mm-thick Cr12. The shape after processing is a cone with a bottom diameter of 40 mm and a conicity of ±20°. Table 1 shows the test parameters.

Table 1 Experimental conditions

Item	Value or condition
Electrode wire	Diameter: Ø0.18 mm Length: 300 m
Working fluid	JR1A: 1:20
Wire speed	12 m/s
Cutting parameter	Pulse width: 20 μs Duty cycle: 1:5 PA tubes: 3 Average cutting current: 3.5 A

Table 2 Roundness error of cutting workpieces of different mechanisms

Mechanism	Traditional mechanism	Servo mechanism
Roundness error	43	40
	46	37
	43	39

The accuracy of the cutting workpieces is shown in Table 2.

When using traditional mechanism for large taper cutting, the yield of dielectric fluid that flows into the machining region is unstable. Surface burning exists when the dielectric fluid is too little, while wire vibration increases when the dielectric fluid is too much, leading to a rugged surface. Given that the wire electrode of the servo mechanism for large taper cutting is constantly vertical through the traverse guider, the vibration caused by the run-out of guide wheel and the disturbance of working fluid are eliminated by the limiting function of the traverse guider. Therefore, the space stability and consistency of the wire electrode can be ensured, and the machining precision of the parts is improved compared with the traditional mechanism.

4.2 Effect on large taper multi cutting

The cutting material is 40-mm-thick Cr12. The shape after processing is a cone with a bottom diameter of 40 mm and a conicity of ±20°. The test parameters are shown in Table 3.

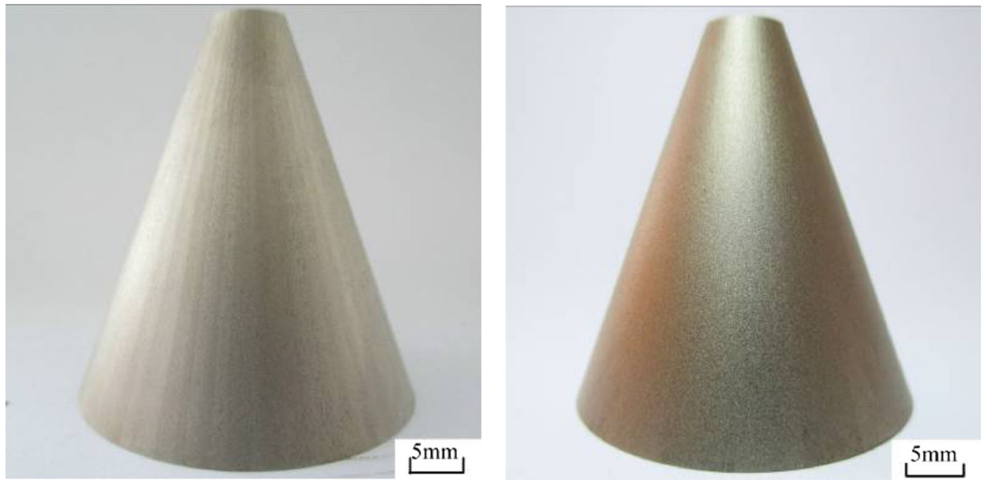
The surface texture of the workpieces of multi cutting is shown in Fig. 16.

The surface roughness and precision of the workpieces cut by the two mechanisms are shown in Tables 4 and 5, respectively.

Figure 17a shows the wire electrode along a closed kerf in the main cutting. The resultant force of discharge

Table 3 Electrical parameters of multi cutting

Power parameters	Main cutting	First trimming	Second trimming
Pulse width (μs)	20	7	5
Duty ratio	1:5	1:10	1:13
PA tubes	3	1	1
Average current (A)	3.5	0.5	0.3



(a) Surface texture of the workpiece cut by the traditional mechanism

(b) Surface texture of the workpiece cut by the servo mechanism

Fig. 16 Cutting surfaces of the parts cut by different large taper-cutting mechanisms. **a** Surface texture of the workpiece cut by the traditional mechanism. **b** Surface texture of the workpiece cut by the servo mechanism

on the wire electrode is symmetrical, and therefore, the vibration of the wire electrode is restrained. From Fig. 17b, we can see, in first or second trimming, the kerf becomes open and the resultant force of discharge on the wire electrode becomes asymmetrical. As a result, the vibration of the wire electrode is no longer restrained. The traditional large taper-cutting mechanism cannot keep the wire electrode stable and cannot restrain its vibration. While using servo mechanism, the spraying direction of the dielectric fluid keeps parallel with the wire electrode in large taper machining. The traverse guider confines the vibration of the wire electrode to maintain the consistency of wire spatial position in the multi cutting process. Therefore, multi cutting can be conducted with high repeated positioning accuracy, and the surface quality and precision can be significantly improved.

5 Invention of an intelligent traverse guider

As mentioned above, the main approach for guiding the wire electrode of HS-WEDM should reduce the wire vibration. The large taper mechanism that causes “angular error” but no wear will only eliminate the wear between traverse guider and wire electrode and realize free traction under an ideal condition. However, the machining and assembling errors in the manufacture of the large taper mechanism, which are finally reflected in the relative position of the traverse guider and wire electrode, will inevitably lead to contact wear between the traverse guider and wire electrode in WEDM large taper cutting. The difference in relative position is imperceptible in large taper manufacturing and machining.

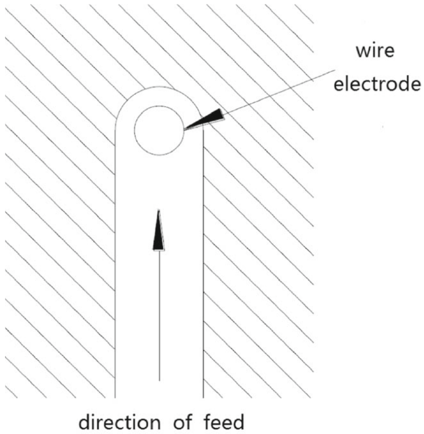
Therefore, this study proposes a new means of guiding wire electrode intelligently. Through this approach, we can intuitively judge the contact condition of the limiting contact surface of wire electrode and traverse guider by an indicator light. Figure 18a shows the principle of this mechanism, and Fig. 18b is the local sketch. The guide of wire electrode is achieved by two conductive eccentric rods (the soleplate is non-conducting). When the wire electrode runs at a low speed, the two eccentric rods are adjusted until they reach the critical point of contact and non-contact

Table 4 Surface roughness of the workpieces cut by two mechanisms

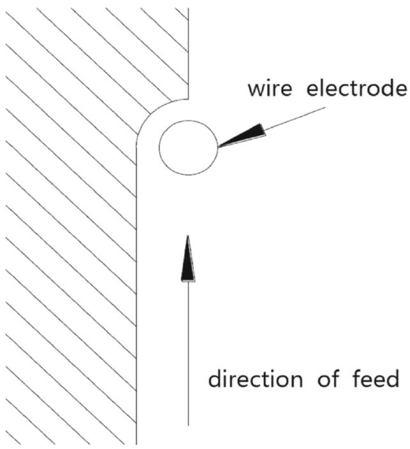
Cutting times	1	3
Traditional mechanism	4.059	1.793
Servo mechanism	3.495	1.670

Table 5 Roundness error of the workpieces cut by two mechanisms

Cutting times	1	3
Traditional mechanism	83	50
Servo mechanism	40	25

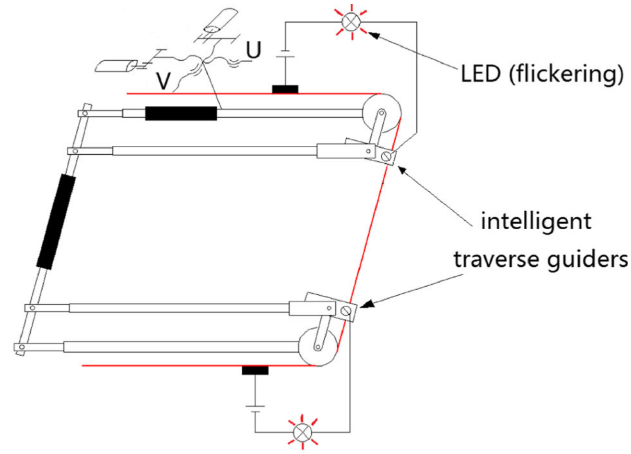


(a) Main cutting

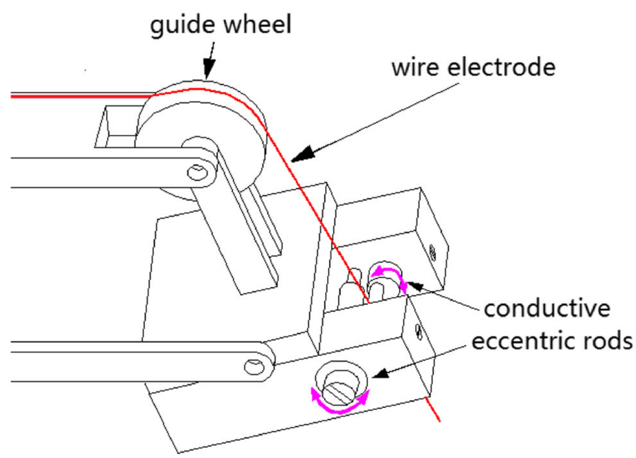


(b) First or second trimming

Fig. 17 Discharge conditions of wire electrode in large taper multi cutting. **a** Main cutting. **b** First or second trimming



(a) Principle of an intelligent traverse guider



(b) Local sketch of an intelligent traverse guider

Fig. 18 Schematic of an intelligent traverse guider. **a** Principle of an intelligent traverse guider. **b** Local sketch of an intelligent traverse guider

with the wire electrode. The mutual spatial position of the wire electrode and eccentric rods can be judged by the flicker of a light-emitting diode in the attached circuit. The position of the eccentric rods is then fixed to limit the vibration of the wire electrode. As a result, the wear between the limiting rods and wire electrode is greatly reduced, and their service life is prolonged. The spatial state of the wire electrode and eccentric rods can be adjusted intuitively, which can provide a visualized suggestion for manufacture and assembly. This device can also improve the accuracy of HS-WEDM large taper cutting. The application of this device will be gradually perfected in further research.

6 Conclusion

This study analyzed the positioning of wire electrode in traditional large taper WEDMs, evaluated the deficiency of traditional large taper wire-guiding mechanisms, and designed two large taper servo wire-guiding mechanisms. The wire-guiding mechanism that causes “angular error” but no wear was adopted. This study also proved that this mechanism can greatly improve the surface roughness and accuracy of large taper cutting and is suitable for HS-WEDM large taper multi cutting. To further improve the accuracy and stability of the spatial positioning of wire electrode and to reduce the friction and wear between wire electrode and traverse guider, this study proposed an intelligent approach for wire guiding.

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