Investigation on orbital EDM for double-hole thin wall of integrated flexible joint

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Abstract
The thin neck structure of integrated flexible joint is the key factor to realize high-precision navigation in dynamically tuned gyroscope. The components of the thin neck structure include two adjacent circular holes and a thin-walled structure between the two holes. The thin wall is vulnerable to be deformed under the external loading which is generated by the tool when using traditional machining methods such as drilling and boring. Simultaneously, pronounced fabrication cost will occur as the cutting tools are also ready to be damaged for machining small holes based on superhard materials. To resolve above problems, a machining method is proposed for the structure of double-hole thin wall in the step-by-step orbital electrical discharge machining (EDM) by using a high rotation speed electrode. The procedure for EDM of double-hole flexible thin wall is designed, and the processing parameters of each step machining are optimized though orthogonal experiment and signal-to-noise ratio analysis. The machining experiments of double-hole thin wall of 3J33B material are proceed using the optimized parameters. The results show that the hole diameter of the double-hole flexible thin wall is 2 mm, the hole depth is 8 mm, and the average thickness of the thin wall is about 46.5 μm. The thickness range between the measured point and the average is 1.55 μm. Comparing with average thickness of 46.5 μm, the error is less than 3%, and the overall thickness is uniform relatively.

Keywords Orbital electrical discharge machining · Thin wall · Integrative flexible joint · 3J33B

1 Introduction
With the continuous progress and development of science and technology, the miniaturization and portability of devices have been the development trend of modern equipment. Microstructural systems have been widely applied in industry fields, such as aerospace and electronic, and the typical applications include dynamically tuned gyroscope (DTG), printed circuit board (PCB), and so on [1, 2]. As the key component of DTG which is mainly used in inertial navigation technology, flexible joint plays an important role in inertial system. The manufacturing accuracy of the flexible joint directly determines the performance of the inertial system. Flexible joints are typically classified as two types, combined type and integrated type. At present, developed countries are widely adopting integrated flexible joint, which is processed from a whole bar. Merits will be introduced when choosing the integrated flexible joint as it avoids the assembly error of the combined flexible joint and greatly improves the navigation accuracy and service life of the gyroscope [3].

To achieve high-precision navigation, the thin neck structure of integrated flexible joint is a critical aspect to be considered. The navigation function of gyroscope is realized mainly through deformation of the hinge in the thin neck structure [2, 4]. The thin neck structure is composed of two adjacent circular holes and a thin-wall structure between the two holes. The thickness of the thin wall is only several micron meters. The metamorphic layer and micro crack during the processing of the thin wall may lead to the damage of the thin neck [5, 6]. Therefore, high-dimensional accuracy, position accuracy, and strict stiffness are basic requirements of the thin neck structure.

Many researchers had studied how to process high-quality thin wall. Deng et al. investigated the effects of parameters on surface roughness and cutting vibration...
when dealing with micro parts with thin bottom surface and then to obtain the better surface roughness of thin bottom wall with a thickness of 80 μm in precision turn-milling machine tool by using optimized process parameters [7]. Ramaiah et al. studied the influence of the deflection and surface roughness of the thin walls at various feed rate, cutting speed, and cutting depth. The researchers optimized the machining parameters by ANOVA regression technique, manufacturing high-quality alloy thin walls with a thickness of 5 mm [8].

However, the thin wall is vulnerable to be deformed under the external loading generated by the cutting tool when using traditional machining methods such as drilling and boring [9]. In addition, in order to drill small hole on difficult-to-machine materials, the special cutting tool or bit need to adopt good wear resistance, leading to high processing cost and increasing the manufacturing difficulty of flexible joints [10–12].

EDM is a process which continuously discharge between tool electrode and workpiece in insulating working oil and removes the material by its transient local high temperature [13, 14]. Comparing with traditional machining method, EDM does not directly contact the workpiece during machining process, inducing smaller macro force. It has specific advantage in machining low stiffness micro structural parts which required high machining precision and good surface quality [15, 16]. Recently, Xu et al. designed a high-efficiency green pulse power supply with high energy used to EDM milling. The EDM milling experiments on 17–4 PH were carried out under deionized water and air were used as the inner and outer working fluids, respectively. Compared with a conventional pulse power supply, the new pulse power supply increases the energy utilization rate by more than 200% [17]. It also shows that the use of the high-efficiency green pulse power supply can contribute to processing efficient environments of EDM.

Previous studies presented that EDM can be used for thin-wall machining [18]. However, problems exist when choosing the EDM process to fabricate thin wall, such as a large thickness of heat-affected layer and a low shape accuracy in the hole depth direction. There are only a few studies on EDM for double-hole thin wall machining of integrated flexible joints, and it limits the application of EDM in the field of double-hole thin wall machining.

Thus, aiming at these problems, the step-by-step orbital EDM method with a high rotation speed electrode is used to machine the double-hole thin wall of integrated flexible joint in this study. The procedure of double-hole flexible thin wall is designed, and the process parameters are optimized based on orthogonal experiment and signal-to-noise ratio analysis. Moreover, the experiments of double-hole thin wall of 3J33B material with a single-hole diameter of 2 mm and a thin-wall thickness of 40 μm are carried out.

2 Prophase experiments and analysis

The double-hole flexible thin wall is mainly composed of two adjacent blind holes. The geometric tolerance of thin wall can be guaranteed only when the quality of deep blind holes is good. Therefore, the machining of the high-quality blind hole is the key to process high-quality thin wall. The preliminary experiments are carried out to study and find the processing problems of EDM for double-hole thin wall.

The EDM machine was high-speed perforating EDM machine (DS703T, Suzhou Sanguang Science Technology Co., Ltd.). The experiments were carried out on the high-elastic alloy of 3J33B, the tool electrode was a copper tube electrode with an outer diameter of 1.7 mm and an inner diameter of 1 mm, and the target depth of the blind holes was 8 mm. The process parameters were peak current of 17A, pulse duration of 36 μs, duty ratio of 0.5, and injecting liquid pressure of 3 MPa.

Due to the structure and wear of the electrode, although material removal rate (MRR) was high by EDM with injecting fluid from tube electrode, the boss remained on the bottom of blind holes due to the structure and wear of the electrode. Besides, the debris generated during the process will result in concentrated discharge which made gross lateral. With the loss of electrode, the taper of hole became larger, inducing nonuniform thin wall, as shown in Fig. 1.

The problem with electrode wear and thermal-affected layer makes one-step machining of the flexible thin wall with no boss, lesser taper, better lateral quality, and better uniform thickness to be difficult. Moreover, the gap between tool electrode and workpiece during EDM processes is difficult to measure. Thus, it is necessary to adopt a step-by-step...
machining method to solve the problems in each processing step.

Orbital EDM is a machining method that relies on the moving axis other than the machining axis of the machine tool to move periodically with a certain track [13]. Orbital EDM increases the distance between the electrode and the hole lateral, and the debris generated during EDM process can be easily flushed away from the hole; thus, the quality of lateral can be improved. The orbital radius can be changed during EDM process to expand the holes based on the material removal volume, which can develop the accuracy of the processed hole diameter and the thickness of the thin wall. In addition, the high-speed rotating electrode with orbital EDM method can remove the bottom boss and reduce the taper of the hole, as shown in Fig. 2. Therefore, this paper proposes a step-by-step orbital EDM method with a high-speed rotating electrode to process the double-hole flexible thin wall in high-elastic alloy 3J33B.

We carried out the simulation of EDM machining of double-hole flexible thin wall with high-speed rotating electrode in the past time. The effects of thermal and liquid impact on thin-wall deformation in EDM were analyzed. The simulation results showed that the influence of electrode rotation speed on the motion of discharge debris is great. The effect of liquid pressure on double-hole thin wall deformation is small. However, the electrical parameters have a great effect on the thermal deformation and surface quality of thin wall [19]. It can be seen that the processing parameters should be optimized to meet the machining requirements of thin-walled in orbital EDM.

### 3 Decision of EDM method for the double-hole flexible thin wall

#### 3.1 Procedure of EDM for the double-hole flexible thin wall

According to the prophase experiments, problems include the large hold taper, obvious roughness, and the location of the boss, which always stays at the bottom and exists by choosing EDM to machine the hole. For these problems, the processing with high MRR can be used as the first step of machining process. Then, rough machining, semi finishing, and finishing machining of holes and flexible thin wall can be processed by using orbital EDM, and the processing parameters will be optimized based on the processing objectives of each processing step.

The procedure for step-by-step orbital EDM of double-hole thin wall is shown in Fig. 3. The workpiece was high-elastic alloy 3J33B with a thickness of 10 mm. First, a brass tube electrode with a diameter of Ф1.5 mm was used to machine two pre-holes with a size of Ф1.7×7.8 mm, and the center of the holes was 2 mm apart in 3J33B. Then, a brass electrode with a diameter of Ф1 mm was selected to carry out step-by-step orbital EDM with optimized process parameters. The detailed processing procedures are listed as follows:

1. Parameters with the largest MRR were selected as the first rough machining parameters to remove bottom boss.
2. Parameters with the best hole taper were selected as the second rough machining parameters to expand the pre-holes and maintain the hole taper.
3. Parameters with the least flange length were selected as the semi finishing machining parameters to develop the machined surface of hole wall.
4. Parameters with the best surface roughness were selected as the finishing machining parameters to generate the flexible thin wall.

![Fig. 3 The procedure for orbital EDM of double-hole thin wall](image-url)
In addition, to machine a thin wall with uniform thickness of only tens of microns at the thin neck, the clamping error of workpiece and electrode and the manufacturing accuracy of electrode should meet the requirements of processing. Therefore, the block electrode discharge grinding technology was carried out before and during machining to reduce the eccentric and perpendicular errors caused by the manufacturing accuracy and clamping of the electrode. Meanwhile, the movement error of workbench was calibrated by the dial indicator, and compensated during the EDM process, which results in a deduction of the repeated positioning error caused by the movement of the machine tool.

4 Compensation method of electrode wear

Figure 4 shows that the electrode material is removed in radial direction during prophase experiments, which affects the diameter of the hole and the thickness of the thin wall, and the electrode wear rates (EWR) varied with the diameters of the electrodes. The electrode wear in radial direction was compensated as the following methods:

1. The EWR based on parameters for the first rough machining, the second rough machining, the semi-finishing machining, and the finishing machining was calculated. Then the electrode wear length of each machining step in radial direction can be obtained, and the diameters of the holes can be sequentially controlled.

2. As shown in Fig. 5, the rotation of the electrode and the motion of the workpiece along a circular track proceed simultaneously. If there was no eccentric error to the rotation center of the spindle after the electrode was clamped, the electrode wear in the radial direction was regarded as uniform. Therefore, as long as there was no electrode eccentric error, the electrode wear volume in the radial direction after each machining can be accurately measured and compensated by using the NC and contact sensing function of the machine tool, and the size of hole can be accurately controlled.

The loss of electrode in radial direction can be roughly calculated by the method of relative EWR in step (1). The electrode wear can be obtained accurately by the method of contact perception in step (2), and then the loss of electrode was compensated during EDM processing.

5 Parameter optimization experiments of high-elastic alloy 3J33B orbital EDM

In this work, the MRR, flanging width, taper, and surface roughness are the processing objectives. Peak current, pulse duration, pulse interval, reference voltage, level of machining time, and level of servo feed speed were used as the experimental factors, and the orthogonal experiments was designed. The signal-to-noise ratio (SNR) analysis method was used to optimize the orthogonal experiment results, and the optimized parameters were verified by experiments.

5.1 Orthogonal experiments and signal-to-noise ratio analysis

Orthogonal experiments were carried out on an EDM machine tool (HCD400K, Hanchuan Co. Ltd., with repeat position accuracy of 2 μm) with high speed motorized spindle (NR-3060S, NAKANISHI Co. Ltd., with centering precision of 1 μm), the brass electrode diameter was 1 mm, and workpiece material was 3J33B. The kerosene was chosen as working oil to avoid oxidation of 3J33B during high-temperature machining process.
In order to improve the machining efficiency, the high-speed EDM drilling machine was used to machine the pre-holes with the depth of 8 mm and the diameter of 1.7 mm, and then orbital EDM method was used to enlarge the holes. Set the radius of orbital track as 250 μm, 290 μm, 310 μm, 340 μm, 370 μm, and 400 μm in turn, and the workpiece was connected to cathode. In order to avoid accidental errors, each group of parameters was carried out 3 times. The designed orthogonal experimental table \( L_{25}(5)^6 \) of six factors (peak current \( I_p \), pulse duration \( T_{on} \), pulse interval \( T_{off} \), reference voltage \( U_s \), level of machining time \( T \), level of servo feed speed \( V \)) and five levels is shown in Table 1, and the orthogonal experimental results are shown in Table 2, including MRR, the width of flanging of hole (L), the taper of the hole wall (\( \alpha \)), and the surface roughness (Ra).

During EDM process, the machining efficiency and machining quality can be influenced by many factors. Even under the same machining parameters, the machining results can be different each time because of random interference. Therefore, the changes of repeatability experimental results need to be taken into account in the post-processing analysis. SNR analysis was used to analyze the influence of experimental parameters and random interference on experimental objectives.

For the experimental objectives of 3J33B in EDM, the width of flanging, taper of the hole wall, and the surface roughness are required to be quite small, and the SNR of these objectives should be calculated according to the expected small characteristic calculation by Eq. (1). On the contrary, a high value of MRR is required and should be calculated according to the expected large characteristic calculation as Eq. (2).

**Table 1** Orthogonal experimental table \( L_{25}(5)^6 \)

| No | \( I_p \) (A) | \( T_{on} \) (μs) | \( T_{off} \) (μs) | \( U_s \) (V) | \( T \) | \( V \) |
|----|---------------|------------------|------------------|-------------|------|------|
| 1  | 0.64          | 5                | 15               | 20          | 2    | 2    |
| 2  | 0.64          | 10               | 25               | 30          | 2    | 2    |
| 3  | 0.64          | 20               | 50               | 40          | 4    | 4    |
| 4  | 0.64          | 40               | 80               | 60          | 6    | 6    |
| 5  | 0.64          | 60               | 120              | 80          | 8    | 8    |
| 6  | 2             | 5                | 25               | 40          | 6    | 8    |
| 7  | 2             | 10               | 50               | 60          | 8    | 0    |
| 8  | 2             | 20               | 80               | 80          | 0    | 2    |
| 9  | 2             | 40               | 120              | 20          | 2    | 4    |
| 10 | 2             | 60               | 15               | 30          | 4    | 6    |
| 11 | 3.3           | 5                | 50               | 80          | 2    | 6    |
| 12 | 3.3           | 10               | 80               | 20          | 4    | 8    |
| 13 | 3.3           | 20               | 120              | 30          | 6    | 0    |
| 14 | 3.3           | 40               | 15               | 40          | 8    | 2    |
| 15 | 3.3           | 60               | 25               | 60          | 0    | 4    |
| 16 | 5.6           | 5                | 80               | 30          | 8    | 4    |
| 17 | 5.6           | 10               | 120              | 40          | 0    | 6    |
| 18 | 5.6           | 20               | 15               | 60          | 2    | 8    |
| 19 | 5.6           | 40               | 25               | 80          | 4    | 0    |
| 20 | 5.6           | 60               | 50               | 20          | 6    | 2    |
| 21 | 9.6           | 5                | 120              | 60          | 4    | 2    |
| 22 | 9.6           | 10               | 15               | 80          | 6    | 4    |
| 23 | 9.6           | 20               | 25               | 80          | 8    | 6    |
| 24 | 9.6           | 40               | 50               | 30          | 0    | 8    |
| 25 | 9.6           | 60               | 80               | 40          | 2    | 0    |

In order to improve the machining efficiency, the high-speed EDM drilling machine was used to machine the pre-holes with the depth of 8 mm and the diameter of 1.7 mm, and then orbital EDM method was used to enlarge the holes. Set the radius of orbital track as 250 μm, 290 μm, 310 μm, 340 μm, 370 μm, and 400 μm in turn, and the workpiece was connected to cathode.

During EDM process, the machining efficiency and machining quality can be influenced by many factors. Even under the same machining parameters, the machining results can be different each time because of random interference. Therefore, the changes of repeatability experimental results need to be taken into account in the post-processing analysis. SNR analysis was used to analyze the influence of experimental parameters and random interference on experimental objectives.

For the experimental objectives of 3J33B in EDM, the width of flanging, taper of the hole wall, and the surface roughness are required to be quite small, and the SNR of these objectives should be calculated according to the expected small characteristic calculation by Eq. (1). On the contrary, a high value of MRR is required and should be calculated according to the expected large characteristic calculation as Eq. (2).

\[
LB : S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) (db) \tag{1}
\]

\[
HB : S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) (db) \tag{2}
\]

where \( S/N \) is the value of SNR, \( N \) is times of repeat experiments, and \( y_i \) is the objective value of the number \( i \) experiment, \( i = 1, 2, 3 \).

### 5.2 Optimal analysis for material removal rate

The SNR of MRR was calculated in Eq. (2). As shown in Table 3, the MRR of the 25th experiment has the largest SNR, and the machining speed is the fastest, that is, the removal speed of material is the fastest. Through analyzing results,
the changed outcomes of the experiments can be reflected by the condition of the value $R$, which is one of the influential factors. As shown in Table 4, the influence order of various factors on the MRR from high to low is peak current, pulse interval, pulse duration, level of servo feed speed, and level of machining time. In the study, the large MRR is required. Thus, the optimal parameters should be the group with the largest SNR of each factor, and the optimal parameters for MRR of 3J33B in EDM are as follows: $I_p = 9.6$ A, $T_{on} = 60$ μs, $T_{off} = 15$ μs, $U_s = 20$ V, $T$ is level 2, and $V$ is level 0.

Table 2 Orthogonal experimental results

| No | MRR (mm³/min) | L (μm) | α (deg) | Ra (μm) |
|----|---------------|--------|---------|---------|
| 1  | 0.496         | 0.473  | 0.413   | 17.49   | 16.37   | 16.42   | 0.638 | 0.617 | 0.642 | 2.495 | 2.420 | 2.520 |
| 2  | 0.397         | 0.432  | 0.363   | 15.47   | 14.64   | 15.34   | 0.687 | 0.727 | 0.646 | 3.520 | 3.880 | 3.670 |
| 3  | 0.325         | 0.313  | 0.322   | 14.28   | 14.55   | 13.38   | 0.497 | 0.565 | 0.543 | 2.955 | 2.995 | 3.025 |
| 4  | 0.247         | 0.272  | 0.238   | 14.26   | 13.27   | 15.31   | 0.448 | 0.482 | 0.453 | 3.450 | 3.350 | 3.245 |
| 5  | 0.213         | 0.221  | 0.193   | 17.67   | 18.36   | 18.54   | 0.440 | 0.411 | 0.474 | 3.325 | 4.705 | 3.965 |
| 6  | 0.339         | 0.429  | 0.366   | 10.64   | 8.11    | 9.22    | 0.597 | 0.585 | 0.604 | 3.090 | 3.160 | 3.170 |
| 7  | 0.349         | 0.437  | 0.384   | 13.31   | 11.56   | 12.26   | 0.584 | 0.616 | 0.552 | 2.770 | 2.485 | 3.125 |
| 8  | 0.318         | 0.342  | 0.373   | 15.58   | 16.54   | 15.82   | 0.393 | 0.454 | 0.424 | 3.865 | 4.295 | 4.185 |
| 9  | 0.305         | 0.302  | 0.328   | 19.16   | 18.34   | 19.43   | 0.392 | 0.431 | 0.419 | 4.365 | 4.465 | 4.430 |

Table 3 Orthogonal experimental results of MRR and its SNR

| No | MRR (mm³/min) | SNR   | No | MRR (mm³/min) | SNR   |
|----|---------------|-------|----|---------------|-------|
| 1  | 0.496         | −6.82 | 14 | 0.535         | 0.561 |
| 2  | 0.397         | −8.08 | 15 | 0.590         | 0.556 |
| 3  | 0.325         | −9.90 | 16 | 0.331         | 0.415 |
| 4  | 0.247         | −11.99| 17 | 0.390         | 0.311 |
| 5  | 0.213         | −13.64| 18 | 0.911         | 0.905 |
| 6  | 0.339         | −8.57 | 19 | 0.780         | 0.756 |
| 7  | 0.349         | −8.28 | 20 | 0.785         | 0.772 |
| 8  | 0.318         | −9.32 | 21 | 0.449         | 0.573 |
| 9  | 0.305         | −10.14| 22 | 1.542         | 1.359 |
| 10 | 0.396         | −7.99 | 23 | 1.559         | 1.634 |
| 11 | 0.336         | −9.93 | 24 | 1.810         | 1.775 |
| 12 | 0.399         | −8.25 | 25 | 1.834         | 1.799 |
| 13 | 0.378         | −8.68 |    |               |       |
The confirmation experiments were carried out, which were repeated for 3 times. The results are shown in Table 5. It can be concluded that the average degree for MRR of the optimized process parameters is increased by 20.58% compared with the result of the group with the largest MRR in the orthogonal experiments, which means that the optimized parameter group is the best scheme for MRR of 3J33B in EDM.

5.3 Optimal analysis for flanging width of hole

When using EDM fabrication method, the working oil will experience vaporization, expansion, and explosion. Under these physical loading, the removed metal will be thrown out from the hole by the generated heat source. However, part of removed metal will be cooled by the flowing working oil and solidified again, attached to the raised recast layer around the orifice, forming the flanging as shown in Fig. 6. Figure 7 illustrated that since the width of flanging is not uniform, 8 positions around the orifice were measured, and the average value was calculated as flanging width of hole.

The optimal parameters of minimum flanging width were obtained by SNR analysis. As shown in Fig. 8, the optimal parameters should select the group with the largest SNR of each factor, so the optimal parameters for the smallest flanging width are as follows: $I_p = 2$ A, $T_{on} = 5$ μs, $T_{off} = 25$ μs, $U_s = 60$ V, $T$ is level 6, and $V$ is level 4. Through the comparative experiments, it is found that the average value of flanging width using the optimized process parameter is reduced by 10.19% compared with that in the previous experiment. In addition, based on the SNR analysis, the single-objective optimizations of hole wall taper and surface roughness were also carried out, and the optimal parameters for each processing were obtained as shown in Table 6. Through the comparative experiments, it is found that the taper and surface roughness of the optimized process parameters is reduced by 7.50% and 25.61%, respectively.

Furthermore, the experimental results showed that the thickness of recast layer increased with the increase of peak current, which had the same trend as the influence of peak

| Level | $I_p$ (A) | $T_{on}$ (μs) | $T_{off}$ (μs) | $U_s$ (V) | $T$ | $V$ |
|-------|-----------|---------------|---------------|-----------|-----|-----|
| 1     | -10.08   | -7.91         | -3.56         | -4.64     | -5.08 | -4.12 |
| 2     | -8.86    | -6.04         | -4.00         | -5.68     | -4.70 | -6.15 |
| 3     | -7.52    | -4.93         | -5.05         | -5.53     | -6.83 | -6.05 |
| 4     | -4.68    | -5.03         | -6.52         | -6.39     | -5.57 | -6.98 |
| 5     | 2.56     | -4.66         | -9.44         | -6.35     | -6.40 | -5.28 |
| R     | 12.64    | 3.25          | 5.88          | 1.75      | 2.13  | 2.86  |

| MRR (mm³/min) | Average MRR (mm³/min) | SNR |
|---------------|------------------------|-----|
| No. 1 | No. 2 | No. 3 |       |
| Confirmation experiment | 2.210 | 2.157 | 2.309 | 2.230 | 6.94 |
| Group 24 | 1.834 | 1.799 | 2.140 | 1.924 | 5.61 |

Fig. 6 Morphology for flanging of 3J33B hole

Fig. 7 Schematic diagram for measurement of flanging
current on surface roughness. Other studies showed that the thickness of metamorphic layer in surface increased with the increase of roughness of machined surface [20, 21], and it can be concluded that reducing the surface roughness of EDM can also reduce the thickness of machined metamorphic layer.

6 Results analysis for EDM machining of double-hole thin wall based on optimized process parameters

Using the optimized parameters for each step machining, the experiments of high-speed rotating electrode orbital EDM for thin wall were carried out. The morphologies of holes and thin wall in thin-wall structure are observed using scanning electron microscopy (SEM, Merlin Compact, Carl Zeiss AG, Germany). As show in Fig. 9, there are no obvious cracks and very small width of flanging at the orifice. The tiny flanging may be removed by electrochemical machining (ECM).

To observe the uniformity of the overall thickness of the thin wall, the thin wall was cut into two sections along a parallel line at certain distance from the center line of two holes by WEDM. Then, the denture base resin was injected into the hole, gradually polishing the section to the thinnest part of the thin wall to observe the thickness uniformity. The section morphology of the thin wall is shown in Fig. 10a, and there is no obvious deformation from the top to the bottom with a good uniformity of thin wall. The thickness of recast layer is shown in Fig. 10b, and the thickness of melting layer is small, with an average value of 4.2 µm. However, the thin wall is slightly damaged due to the polishing process, and it is difficult to evaluate the surface quality of the thin wall in the hole. Thus, the inner wall of the single hole processed with the optimal parameters was observed. As shown in Fig. 11a, there is no crack on the wall, no boss at the bottom of the hole, and less discharge debris in the hole. The surface roughness was measured by using a laser scanning confocal microscope (LEXT OLS3000 Microscope, Olympus Corp.) as shown in Fig. 11b, and the roughness was about 0.61 µm.

In order to calculate the thickness of thin wall, the segmented radial cutting method was adopted to observe the radial sections of thin wall at different depths. This method can reduce the deformation of thin wall caused by WEDM. The workpiece was splitted into 3 mm and 7 mm away from the upper surface by WEDM, the diameters of the double holes on the plane of each workpiece and the distance between them was measured by digital microscope, and then the thickness of the thin wall can be calculated.

The measurement results of thickness of thin wall are shown in Table 7. It can be seen from Table 7 that the overall thickness of the thin wall is relatively uniform, and the average thickness at the orifice, hole depth of 3 mm, and hole depth of 7 mm are 46.12 µm, 45.79 µm, and 47.52 µm, respectively. Comparing with average thickness of 46.5 µm, error is within 3%, which meets the processing requirements of thickness uniformity. However, it is not the target value of

| Table 6 Optimal parameters of taper and surface roughness |
|----------------------------------------------------------|
| Parameter       | $I_p$ (A) | $T_{on}$ (µs) | $T_{off}$ (µs) | $U_s$ (V) | $T$ | $V$ |
| Optimal parameters for taper | 5.6 | 40 | 15 | 30 | 0 | 4 |
| Optimal parameters for surface roughness | 0.64 | 5 | 80 | 40 | 4 | 8 |
40 μm; the reasons may be that the electrical contact sensing accuracy of the EDM machine is low, and the measured electrode diameter is inaccurate, inducing in inaccurate calculation of electrode radial loss and orbital radius. Even the dial indicator measurement was added to avoid the movement error of the machine tool, the movement error was accumulated due to multiple movements, resulting in the difference between the theoretical value and the actual value. It is possible to reduce the deviation by using an EDM machine with higher repeat positioning accuracy.

Table 7 Measurement results for thickness of thin wall

| No | Thickness of orifice (μm) | Thickness at hole depth of 3 mm (μm) | Thickness at hole depth of 7 mm (μm) |
|----|--------------------------|-------------------------------------|-------------------------------------|
| 1  | 46.39                    | 45.75                               | 48.05                               |
| 2  | 45.62                    | 46.72                               | 47.09                               |
| 3  | 46.36                    | 44.89                               | 47.42                               |
7 Conclusions

In this paper, the orbital EDM machining for double-hole flexible thin wall for high-elastic alloy 3J33B was studied. The single-objective optimization was adopted for each machining step, and the experiments for orbital EDM of thin wall based on optimal process parameters were carried out. The conclusions are shown as follows:

1. A high-speed rotating electrode step-by-step orbital EDM method for double-hole flexible thin-wall machining is proposed, and the processing procedure is designed.

2. Using the optimal process parameters for each step machining, the MRR of EDM machining for 3J33B elastic alloy was increased by 20.58%, the width of flanging was reduced by 10.19%, the taper of hole was reduced by 7.50%, and the surface roughness was reduced by 25.61%.

3. The double-hole thin-wall structure was processed, which its thin neck with an average thickness of about 46.5 μm, its single hole with the diameter of 2 mm, and depth of 8 mm. The difference between the thickness range of the three measured points and the average value was 1.55 μm, compared with average thickness 46.5 μm, the error was less than 3%.

Author contribution Yang Liu: Conceptualization, investigation, methodology, writing—original draft preparation, Yunlong Du: Writing-review, editing, validation, Weifeng Li: Investigation, validation, Yerui Feng: Data curation, Yongfeng Guo: Writing-review, funding acquisition, project administration, supervision.

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Declarations

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