Research on the EDM Technology for Micro-holes at Complex Spatial Locations

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Abstract. For the demands on machining micro-holes at complex spatial location, several key technical problems are conquered such as micro-EDM power supply system’s development, the host structure’s design and machining process technical. Through developing low-voltage power supply circuit, high-voltage circuit, micro and precision machining circuit and clearance detection system, the narrow pulse and high frequency six-axis EDM machining power supply system is developed to meet the demands on micro-hole discharging machining. With the method of combining the CAD structure design, CAE simulation analysis, modal test, ODS (Operational Deflection Shapes) test and theoretical analysis, the host construction and key axes of the machine tool are optimized to meet the position demands of the micro-holes. Through developing the special deionized water filtration system to make sure that the machining process is stable enough. To verify the machining equipment and processing technical developed in this paper through developing the micro-hole’s processing flow and test on the real machine tool. As shown in the final test results: the efficient micro-EDM machining pulse power supply system, machine tool host system, deionized filtration system and processing method developed in this paper meet the demands on machining micro-holes at complex spatial locations.

1. Introduction

As the development of aviation, aerospace, automobile and biomedical engineering fields, a lot of components are developed with complex spatial location micro-hole structure [1]. Because many such kinds of components have small micro-hole aperture, low structure rigidity and special material, it is difficult to meet the machining requirements through common machining. Due to the advantages of micro-EDM machining such as high machining precision without macro cutting force during machining, it plays the irreplaceable and key role for machining such kind of components [2,3]. For the EDM forming machining of complex spatial location, five-axis combined machining can meet the machining requirements commonly. However, to complex spatial location micro-hole EDM machining, one micro-feed axis shall be designed for meeting the feeding and guiding demands of electrode wire of micro diameter [4-7]. Therefore, for such kind of components (for example: oil spray nozzle of automobile engine high-pressure common rail system, micro spray hole on aerospace divert and attitude control engine, aviation engine blade micro-hole), the six-axis EDM machining equipment with four linear axes and two rotation axes shall be developed for meeting the requirements on technique and technology. For the machining of such kind of components, this paper conducts systematic researches from the aspects of power supply system development, machine tool host design,
deionized water system development, technique test and other aspects, to conquer the technical problems of EDM machining. Development of power supply system

For the six-axis discharging machining demands on micro-EDM machining narrow pulse and high frequency, the precise micro-EDM machining power supply system developed in this paper composes of numerical control system and EDM machining control system, power amplifier unit, main circuit unit, automatic voltage regulation unit and kinematic axis drive unit. EDM machining control system mainly includes: clock control and discharging pulse signal generation part; parameters such as current and voltage setting part; special machining waveform control part (equal pulse width); micro servo clearance and discharging state (voltage and current) detection part; abnormal discharging treatment part (increasing the pulse spacing, cutting the pulse width) etc.. The power amplifier unit can amplifier the power of the machining pulse voltage and current, and composes of Vertical Metal Oxide Semiconductor (VMOS) power switching tube and prepositional drive amplification circuit. The main circuit unit includes: low-voltage machining circuit; high-voltage machining circuit; high and low voltage compound circuit; low wear circuit; super precision machining circuit etc.. The automatic voltage regulation unit provides stable machining voltage with the Pulse-Width Modulation (PWM) automatic voltage stabilizing circuit, and is capable of achieving numerical control and varied protection functions. Please see Figure 1.

![Overall framework of the power supply system](image)

Figure 1. Overall framework of the power supply system.

The machining energy of micro-EDM is provided by the pulse power supply; therefore, each circuit design is closely related with the micro-hole machining quality.

In this paper, a low-voltage automatic voltage regulation unit is designed to provide stable machining voltage for low-voltage power supply circuit. It adopts high speed PWM automatic voltage stabilizing circuit to achieve full closed-loop numerical control and varied protection functions of power output, as well as ensure the ripple factor is lower than 1%, voltage stabilizing precision reaches 0.5%, thus precisely controlling the discharging energy and improving the machining stability.

The high-voltage circuit with the principle of high speed PWM modulation is adopted to achieve high-voltage (300V) and high power voltage stabilizing power supply, and ensure the ripple factor is lower than 1% and voltage stabilizing precision reaching 1%. During the period of micro-EDM machining, it mainly works for auxiliary breakdown, which can greatly improve the breakdown rate and utilization rate of pulses, reduce the breakdown time delay, and benefit to increase the machining speed.
With the combined advantages of relaxation type pulse power supply and transistor pulse power supply, the micro and precision machining circuit, which is capable of providing small enough current and narrow enough Tr-RC pulses, is developed; thus, small discharging etch pits are produced on the machining surface, and then machining surfaces with small roughness are got, achieving the micro machining of small holes.

During micro high frequency discharging machining, extremely high requirement is presented to the real-time monitoring under machining state, the precision and stability during feedback has direct influence on the discharging energy and machining effect. In the clearance detection system, the 12bit high speed analog to digital converter is adopted to monitor the abnormal discharging state, high speed converting time and high precision sampling result can quickly show the state of the discharging machining clearance. Super treatment capacity (30MIPS) is achieved via the most advanced programmable circuit, which is capable of detecting the pulse status within 30ns, effectively eliminating risks of harmful discharging, such as electric arc and short circuit, as well as improving the machining efficiency and surface quality.

2. Development of the host structure
The mechanical system structure design rationality of the complex spatial location micro-hole EDM machining machine tool is the key factor to achieve precise micro machining. With the method of combining CAD structure design, CAE simulation analysis (shown in Figure 2-3), modal test (shown in Figure 4), ODS (Operational Deflection Shapes) test (shown in Figure 5) and theoretical analysis [8,9], optimization design is conducted for the components and key axes of the machine tool.

![Figure 2. Machine body deformation nephogram.](image1)
![Figure 3. First-order modal vibration nephogram.](image2)
![Figure 4. PULSE system modal test interface.](image3)
![Figure 5. Sketch of ODS measure point layout.](image4)

Through the above analysis and test, casting part structures of the main components of the machine tool are optimized, and the construction of the machine tool has been improved; and the host structure is capable of meeting the EDM discharging machining requirements on complex spatial location micro-hole with aperture dispersion of ±0.003mm. The body of the machine tool is shown in Figure 6.
3. Development of deionized water filtration system

In order to achieve the precise, reliable and stable machining of micro-holes, the water circulation system shall meet the following conditions:

1. The electrical conductivity of deionized water must be lower than 0.8μS/cm;
2. The flow rate of deionized water ejected from the water spray nozzle shall be adjustable in the certain range;
3. During machining, the water temperature shall be controlled in a certain range.

According to the demands on working condition, the schematic diagram of the planned deionized water circulation system is shown in Figure 7.

The work principle of this water circulation system is: the demineralized water is sucked from demineralized water tank with the filtration pump 1, flows from the filtration system with the filter I7 or filter II8 and filter III11, and the demineralized water is filtered into the deionized water, after cooling with panel radiator 12, the water flows into the deionized water tank; deionized water is
pumped from the deionized water tank with the water spray pump 15 for precisely machining micro inverted cone holes; observing with the overflow valve 2 if the demineralized water added into the demineralized water tank has reached the requirements; the pressure meter 4 is adopted for observing the water pressure of filtration pump; the drain valve 5 is adopted for waste water drainage when replacing demineralized water; the filter selector valve 6 is adopted to control water path to cross filter I7 or filter II8; one-way valves 9 and 10 are adopted to ensure the single flow of water path and avoid interference between filter I7 and filter II8; the electrical conductivity meter 13 is adopted for detecting if the deionized water in the closed deionized water tank meets the requirements; the water level sensor 14 is adopted for detecting the deionized water level; the flow rate meter 16 is adopted for detecting the ejection flow rate of deionized water.

In order to get deionized water of high electrical conductivity, 1μm polypropylene meltblown PP filter is adopted for primary filtration; the filter structure is coarse fiber for external layer fine fiber for internal layer, loose external layer and tight internal layer. This filter is capable of removing 1μm or bigger impurity particles, including the metal particles formed during EDM machining. Polished resin is adopted for secondary filtration to replace Na+, Cl- from water with H+ and OH- radical group in the filtration material, H+ and OH- in the water are combined to produce water, thus reducing the electrical conductivity.

4. Development and test machining of process technology

The complex spatial location micro-hole machining subprogram technique flow is shown in Figure 8. Machining with reversed polarity of certain time is achieved with the electrode parameters correction, thus correcting the profile of the electrode tip, and then preparing for detection, workpiece clamping, cooling pump opening and electrode electrical contact positioning. The purpose of electrode contact positioning is to achieve automatic feed compensation of electrode with the automatic feed function and electrical contact electrode positioning function, and position the electrode and workpiece to the best place of servo hole machining through the voltage change of the electrode electrical contacting workpiece. Then, with the servo hole machining function, it is identified as open circuit, short circuit and normal machining state with the real-time acquired discharging state current, controlling the W-axis to do quick servo movement to achieve hole machining. Meanwhile, the control system will identify if it has achieved the machining depth through real-time detection, which means if it has achieved the set machining lower limit, and the machining is completed after reaching lower limit positions of the precise micro-hole machining.

In this paper, this paper takes the machining of precise reverse taper micro-hole of high-pressure common rail system and injector head in aerospace field as example to verify if the micro-hole EDM machining equipment and process technology developed in this paper can meet the micro-hole machining demands of complex spatial location, the micro-hole EDM machining equipment adopted in this paper is shown in Figure 9, the oil spray nozzle of high-pressure common rail system is shown in Figure 10, the injector head in aerospace field is shown in Figure 11. Records of the inside and outside diameters of the finished oil spray nozzle’s micro-holes are shown in Table 1, and records of the outside diameters of the finished injector head’s micro-holes are shown in Table 2.

As shown in Table 1, the max outside aperture of reverse taper micro-holes in oil spray nozzle of the high-pressure common rail system is 0.224mm, minimum is 0.220mm; the max inside diameter is 0.241mm, minimum is 0.245mm. The dimensional tolerance range of micro-holes is in the range of ±0.003mm. As shown in Table 2, the max diameter of micro-holes in injector head in aerospace field is 0.173mm, minimum diameter is 0.168mm. The dimensional tolerance range of micro-holes is in the range of ±0.003mm.
Figure 8. Technique flow of fully automatic machining control.
Figure 9. Micro-hole EDM equipment.

Figure 10. Finished oil Spray Nozzle.

Figure 11. Injector head.

Table 1. Test records of oil spray nozzle

| Hole No. | Out-Dia (mm) | In-Dia (mm) | Taper (mm) | Vert Ang. Degree | Dev. Degree | Hor Ang. Degree | Dev. Degree | A-dim (mm) | Dev. (mm) | D-dim (mm) | E-dim (mm) | Tan Dev. (mm) |
|----------|--------------|-------------|------------|-----------------|-------------|----------------|-------------|------------|-----------|------------|------------|-------------|
| 1        | 0.223        | 0.244       | -0.021     | 77.2            | -0.3        | 35.1           | -0.1        | 1.07       | 0.01      | 0.73       | 1.16       | 0.00        |
| 2        | 0.223        | 0.242       | -0.019     | 77.3            | -0.2        | 71.2           | 0.0         | 1.07       | 0.01      | 0.73       | 1.16       | -0.03       |
| 3        | 0.223        | 0.242       | -0.019     | 77.1            | -0.4        | 143.0          | -0.4        | 1.07       | 0.01      | 0.73       | 1.15       | -0.02       |
| 4        | 0.221        | 0.245       | -0.021     | 76.8            | -0.7        | 179.2          | -0.4        | 1.07       | 0.01      | 0.73       | 1.15       | 0.01        |
| 5        | 0.220        | 0.245       | -0.025     | 77.2            | -0.3        | 215.2          | -0.4        | 1.07       | 0.01      | 0.73       | 1.16       | 0.05        |
| 6        | 0.220        | 0.243       | -0.023     | 77.3            | -0.2        | 287.1          | -0.6        | 1.08       | 0.02      | 0.73       | 1.16       | 0.06        |
| 7        | 0.223        | 0.241       | -0.018     | 77.4            | -0.1        | 323.0          | -0.8        | 1.08       | 0.02      | 0.73       | 1.16       | 0.03        |
| 8        | 0.224        | 0.242       | -0.019     | 77.0            | -0.5        | 359.7          | -0.2        | 1.07       | 0.01      | 0.73       | 1.16       | 0.00        |

Mean 0.223 0.243 -0.021 77.2 -0.3 -0.4 1.07 0.01 0.01

Range 0.004 0.004 0.008 0.5 0.5 0.7 0.01 0.01 0.09

NomR 0 0 0 0 0 0 0 0 0

Sigma 2.289 1.261 3.227 0.2 0.2 117.1 0.2 0.00 0.00 0.00 0.00 0.03

Table 2. Test records of injection holes

| No. | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|-----|----|----|----|----|----|----|----|----|
| diameter (mm) | 0.17 | 0.169 | 0.171 | 0.17 | 0.173 | 0.168 | 0.171 | 0.17 |
5. Summary
Based on the technical characteristics of EDM technology for micro-holes at complex spatial locations, in this paper, the micro-hole EDM power supply system is developed. And the host construction is developed with the method of combining theoretical analysis, CAD optimization design, CAE simulation analysis, modal test and ODS test. And the deionized water filtration system is developed according to the demands on micro-hole reliable machining. Based on these studies, the fully automatic machining control technique flow of the complex spatial location small hole is developed. Finally, the tests are conducted with the typical components (Oil spray nozzle of the high-pressure common rail system, injector head in aerospace field) of complex spatial location micro-hole. The test results show: the efficient micro-EDM pulse power supply system, host construction of the machine tool, deionized filtration system and machining process method developed in this paper can meet the demands on machining micro-holes at complex spatial locations.

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