Development of Multi Micro Holes Synchronous Rotating and Vibration EDM Machine Tool

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Abstract. In order to solve the problem of low efficiency of single electrode discharge machining, complex process and limited machining quality of group electrode array hole machining technology in traditional micro EDM machine tools, a multi-micro-hole synchronous rotating and vibration EDM machine tool was developed. The machine tool is composed of a mechanical platform and a control system. It can realize multi-electrode independent micro-energy pulse discharge, real-time detection of each electrode gap state and servo feed adjustment, and synchronous rotation assisted vibration of each electrode. The mechanical platform of the machine tool consists of servo feed mechanism, vibrating mechanism and multi-electrode synchronous rotating mechanism. The structure optimization and stability analysis are carried out by ANSYS finite element analysis software to ensure that the design of each part of the machine tool is reasonable and reliable. The control system is composed of motor control module, servo motion control module and pulse power module. It uses STM32F103RCT6 MCU to detect the machining state in real time and coordinate the work of each module, and uploading the processing data to upper computer. The Experimental tests show that the machine tool has high machining efficiency, stability and precision, and high degree of automation.

1. Introduction

Micro-EDM technology has a wide application prospect in the fields of advanced industry with its high precision, high surface quality and no macro-force[1]. At present, single electrode discharge machining is widely used in micro-EDM machine tools, For parts with multiple micro-holes, only hole-by-hole machining can be used, but the machining efficiency is low. To solve the problem of the low efficiency of electric discharge machining, the micro-hole of the array electrode processing technology is studied by Harbin Institute of Technology[2]. The group electrode is processed by a micro-array hole according to the anti-copy principle of the electric spark, and the array hole is processed by a fine single-electrode[3]. The application of the group electrode technology greatly improves the processing efficiency of the micro-holes, but also has the technical defects that: A single electrode can not be controlled by independent discharge, if an electrode is short-circuited, the concentrated energy discharge will cause the short circuit electrode to burn out. Then the electrode can
not be rotated, and the rotation function can not be used to improve the chip removal, so the depth to diameter ratio of the hole processing is limited.

With the rapid development of power electronics technology, automatic control technology and innovative design concept, precision, refinement, intelligence and efficiency will become the development direction of EDM technology in the future\cite{4}. Based on the present research situation and future development direction of EDM, a multi-micro-hole synchronous rotating and vibration EDM machine tool is proposed in this paper, which can realize multi-electrode independent micro-energy pulse discharge and assist electrode rotating vibration technology to improve the machining efficiency and machining accuracy of multi-micro-hole machining.

2. Structure of Machine Tool

The structure of the machine tool (Fig. 1) is mainly composed of mechanical platform and control system. It can realize multi-electrode independent micro-energy pulse discharge, real-time detection of each electrode gap state and servo feed adjustment, and synchronous rotation assisted vibration of each electrode. The mechanical platform part is mainly composed of servo feed mechanism, vibration mechanism and multi-electrode synchronous rotation mechanism, the design of each part of the machine tool is reasonable and reliable. The control system is composed of motor control module, servo motion control module and pulse power supply module. It uses STM32F103RCT6 MCU to detect the machining state in real time and coordinate the work of each module, and uploading the processing data to upper computer.

![Figure 1. Overall frame diagram of machine tool.](image-url)
3. Design of Mechanical Platform

3.1. Z-axis servo feed mechanism.

The multi-micro-hole synchronous EDM machine tool adopts a stepping motor to drive a sliding table guide rail to perform longitudinal feeding motion, it can realize the full-step fast back-off when the micro-feeding and the interval lifting knife are subdivided during processing. Stepping motor is an open-loop control motor which converts electric pulse signal into angular displacement or line displacement[5]. it can achieve the purpose of accurate positioning and regulating speed. The stepping motor is driven by MD5-HF 14 five-phase stepping motor driver. The high precision sliding table guideway adopts ball wire rod to transform the rotating motion of stepping motor into linear motion, and the effective stroke is 100mm. The upper and lower ends of the guideway are equipped with a limit switch, which plays the role of travel and limit protection.

3.2. Vibrating mechanism

The introduction of the vibration processing in the EDM can promote the chip removal, improve the processing environment and improve the processing efficiency and optimize the processing quality[6]. The vibration mechanism is mainly composed of vibration motor, support plate, suspension frame, spring support rod, hinge, vibration shaft and self-lubricating copper sleeve. The vibration motor is installed on the support plate, and the excitation force is obtained by using the centrifugal force produced by the high speed rotation of the shaft and eccentric block. The support plate is fixedly connected to the suspension frame by four spring support rods, and the spring has the function of buffering and releasing energy. The support plate is connected with the vibration shaft through a hinge to buffer the transmission of the motor exciting force. The vibration rod and the lower disc are fixed by a hexagonal nut to transmit the exciting force of the motor to the electrode by the lower disc to realize the vibration-assisted machining.

3.3. Multi-electrode synchronous rotating mechanism

The electrode rotation can promote the throw of the processing chip and reduce the short-circuit condition of the discharge gap, meanwhile, It also can effectively improve the processing efficiency and the finish of the surface of the workpiece to be processed[7]. This machine tool is mainly composed of the upper disk, lower disk, rotating motor, synchronous pulley(×4), synchronous belt and the electrode device(×3). The electrode device is composed of three parts including an electrode, an electrode jacket and a fixed brush. The three electrode clamping sleeves are installed on the lower disk at intervals of 60°. Each jacket and the lower disk are connected by deep groove ball bearing, which can rotate freely. And each jacket transmitted with the rotating motor through the synchronous belt is fixed with a synchronous belt wheel, The fixed brush is equipped with a wire, which is responsible for transmitting the micro-energy pulse generated by the pulse power supply to the electrode.

4. Structural Reliability Analysis Based on ANSYS

4.1. Stress analysis of upper and lower disk

The stress analysis of ANSYS on the connection hole is based on the fourth strength theory, i.e. the distortion energy theory. This theory holds that yield failure of materials is caused by the energy of shape change [8]. When the specific energy of shape change at a point inside the part exceeds the limit of yield stress in a single direction, the yield failure occurs. And the stress calculation formula is as follows:

\[
\sigma \leq \frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right] \leq [\sigma]
\]  

(1)

Where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are the stresses in X, Y and Z directions respectively, and \( [\sigma] \) is the yield limit of the material.

The upper disc is made of steel 45 and is equipped with a brush and a rotating motor. The stress analysis is shown in Fig. 2(a). Since the mass of the rotating motor is relatively large, and the mass of
the electric brush is relatively small, the stress at the connection hole between the motor shaft and the upper disk is relatively concentrated, and the maximum stress is about 0.02Mpa. The stress value is less than the yield limit of the steel 45(355Mpa), so the upper disc design meets the strength requirements.

The lower disk is equipped with vibration shaft, electrode, upper and lower disk connecting rod and other parts, and its stress analysis is shown in Fig. 2(b). In the actual machining, in addition to the parts and components installed in the lower disk, the upper disk vibration should also be driven by the upper and lower disk connecting rod, so the stress at the installation hole of the upper and lower disk connecting rod is more concentrated, and the maximum stress value is 0.07Mpa. The stress value is less than the yield limit of steel 45(355Mpa), so the lower disk design also meets the strength requirements.

4.2. ANSYS fatigue analysis

Fatigue is the phenomenon that the structure cracks under the repeated action of a force lower than its limit load. ANSYS fatigue analysis adopts Miner fatigue damage hypothesis, that is, the fatigue fracture of parts is the cumulative effect of internal micro-cracks on material damage. When the number of stress cycles reaches a certain value, the material will reach the fatigue limit\[9\]. When the machine tool vibrates, it produces sinusoidal force and is subjected to symmetrical cyclic load. Based on S-N curve of materials, structural fatigue calculation was carried out to obtain the life analysis of suspension and vibration axis, as shown in Fig. 3(a) and Fig. 3(b) respectively. The suspension frame structure of the machine tool is prone to fatigue fracture because of the bending moment of the horizontal part under the action of stress. Under the action of vibration force, fatigue failure is easy to occur in the thickness of the connecting part between the shaft hole and the pin shaft. In practical machining, due to the uncertainty of external load and the frequent start and stop of vibrating motor, the actual life is smaller than that of theoretical analysis. So in order to improve the life of suspension frame and vibration shaft, we can improve the fatigue strength of the structure by heat treatment and eliminate the stress concentration point of parts in some way.
5. The Design of the Control System

5.1. Servo motion control

We choose MD5-HF14 five-phase stepping motor driver to drive the stepping motor. The driver has the functions of automatic downflow and self-diagnosis, it also has the function of subdivision drive, which can realize low speed rotation and high precision control. For a five-phase stepping motor with a basic stepping angle of 0.72°, the control accuracy can reach 0.00288/1 step. In addition, the driver uses optical coupling input to resist external interference. The drive has four inputs and one output, including CW, CCW, HOLD, DIV/SEL, ZERO, which connects to the five GPIO pins of processor STM32F103. The driver has two input modes: single pulse and double pulse, which are selected by 2/1clk switch on the driver. In monopulse mode, CW input pulse signal and CCW input rotation direction signal. In double pulse mode, CW input forward pulse signal and CCW input reverse pulse signal. Hold is the excitation OFF control signal of stepping motor, and the high level is effective. DIV/SEL is the resolution selection signal, the resolution set by MS1 is selected at low power, and the resolution set by MS2 is selected at high power. MS1 and MS2 are two resolution settings switches on the drive. ZERO is the origin excitation output signal used to confirm the position of the motor shaft, the connection between the drive and the STM32F103 is shown in Fig. 4.

![Figure 4. Hardware Circuit Diagram of stepping Motor Control](image)

In order to control the stroke and limit protection of the electrode and to avoid electrode damage, a limit switch is installed on the upper and lower parts of the slide guide rail. The connection with microcontrollers is shown in Fig. 5.

![Figure 5. Limit circuit diagram](image)

5.2. Electrode Rotation and Vibration Control

The output current of STM32F103 microcontrollers is too small to drive the motor directly, so the current needs to be amplified through the chip L298. L298 is a single chip integrated high voltage, high current, two-way full-bridge motor drive chip, which is used to drive inductance load[10]. Output PWM from one channel timer of STM32F103 microcontrollers can change the motor speed by changing the duty cycle of PWM wave. Pins 5, 7, 10 and 12 of L298 are the steering control end of the motor. Here, pin 5 and 12 are fixedly connected to high level, and 7, 10 are fixedly connected to low level, so that the motor rotates normally. The rotary motor drive control diagram is shown in Fig. 6.
The duty ratio of the PWM output waveform is controlled by the single chip microcomputer to speed the motor. The principle is that the on-time of the switch tube in one cycle is t, and the period is T, so the average voltage across the motor is as follows:

\[ U = V_{cc} \times \left( \frac{t}{T} \right) = \alpha V_{cc} \]  

(2)

where \( \alpha = t/T \) is PWM duty cycle and \( V_{cc} \) is power supply voltage. The speed of the motor is proportional to the voltage at both ends of the motor, that is to say, the speed of the motor is proportional to the duty cycle of PWM. The larger the duty cycle is, the higher the speed of the motor is.

5.3. Impulsing Power Source

The pulse power supply is divided into two parts: pulse discharge module and gap detection module. The pulse discharge module is controlled by STM32F103RCT6 microcontrollers. It mainly uses the PWM output function of its timer to set the reference threshold of the gap voltage and control the switching elements in the discharge control loop to realize the independent control of micro-energy discharge of each electrode. So as to realize the closed-loop control of the system, the clearance status detection module detects the voltage value of the clearance in real time and feeds back to the microcontrollers, which determines the current clearance status and drives the stepper motor to adjust the machining clearance by Z-axis servo feeding.

6. Processing Experiment and Analysis

The micro-hole EDM machine built in the laboratory is shown in Fig. 7. The three-electrode synchronous EDM is carried out by applying different vibration frequency and rotating speed to the machine tool. Working for 200 hours without abnormal conditions, the processing effect is good.

Test conditions: the processing voltage is 100V, the working fluid medium is mechanical oil, the electrode is connected to the positive electrode, the electrode material is 0.1mm tungsten steel, the workpiece is connected to the negative electrode, the workpiece material is 3mm stainless steel. The output cycle of the processor is 2083.3ns, the PWM signal wave with duty cycle of 30%, that is, the pulse width time is 625.0ns, and the interpulse time is 1458.3ns. In order to analyze the effects of machining voltage, electrode rotation speed and vibration amplitude on the machining efficiency of micro holes, a number of experiments were designed as shown in Table 1 (taking the micro holes with machining depth of 3mm as an example). Through the analysis of the experimental results, it can be seen that the larger the machining voltage, the larger the duty cycle of vibration pulse (the larger the
amplitude), the larger the duty cycle of rotating pulse (the larger the rotating speed), the shorter the processing time, the higher the machining efficiency.

| Test number | Processing voltage/V | the vibration pulse duty cycle/% | Rotating pulse duty cycle/% | Test index Process time/s |
|-------------|----------------------|---------------------------------|---------------------------|--------------------------|
| 1           | 80                   | 50                              | 50                        | 878                      |
| 2           | 90                   | 50                              | 50                        | 745                      |
| 3           | 90                   | 60                              | 50                        | 623                      |
| 4           | 90                   | 70                              | 50                        | 456                      |
| 5           | 100                  | 50                              | 50                        | 667                      |
| 6           | 100                  | 50                              | 60                        | 543                      |
| 7           | 100                  | 50                              | 70                        | 429                      |

7. Conclusion
In this paper, a synchronous rotating vibration EDM machine with multiple microholes can be used in the machining of complex workpiece with multi-microhole array. The mechanical platform of the machine tool is optimized by ANSYS simulation to ensure the high structure reliability, it also can realize the function of electrode servo feed and multi-electrode synchronous rotating vibration. In the control system, the motor control module is coordinated by STM32F103RCT6 single chip microcomputer, the servo motion control module and the pulse power supply module detect the machining state in real time and adjust the machining parameters to realize the closed loop machining control. The machining experiments show that the machine tool can realize the stable discharge machining of multi-electrode EDM and improve the machining efficiency.

8. Acknowledgments
This work was financially supported by the key R&D plan of Shandong Province fund (Project No.:2017GGX30124).

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