Aiming at the problems of insufficient flexibility and limited size of the workpiece in traditional EDM milling, an EDM milling based on a 6-DOF serial robot is proposed in this study. To realize the rapid adjustment of the machining gap, a tool electrode servo motion device was invented and installed at the end of a 6-DOF serial robot, and a servo control strategy of the tool electrode vertical trajectory fallback was proposed. Then, to achieve the controllable thickness of every layer in EDM milling based on a 6-DOF serial robot, the servo control strategy of limited motion of the tool electrode on the basis of vertical servo control and a fix-length compensation method to compensate the tool electrode wear was proposed. Finally, to verify the correctness and effectiveness of the servo control strategy and wear compensation of the tool electrode, the trapezoidal groove structures on the plane workpiece and cylindrical workpiece were machined by EDM milling based on a 6-DOF serial robot, respectively. Also, to verify the machining ability of complex trajectories on the space surface of the workpiece of EDM milling based on a 6-DOF serial robot, three complex trajectories, such as EDM, Chinese character “China,” and “Chinese knot,” was designed and machined on the hemispherical workpiece with the radius of 38 mm. The feasibility and effectiveness of EDM milling technology based on a 6-DOF serial robot were verified, which has great market application potential.

Keywords Electrical discharge machining milling (EDM milling) · Six degree of freedom serial robot (6-DOF serial robot) · Servo control strategy · Wear compensation of tool electrode

1 Introduction

Electrical discharge machining (EDM) can fabricate conductive hard brittle materials into complex shaped parts with high precision. Although the use of die-sinking EDM, where the tool is a shaped electrode and the parts can be formed by the replication of the shaped tool electrode, is still popular in the industry today, studies to replace the electrodes that have complex geometric features with simpler tool electrodes have been active [1]. The main disadvantages of the die-sinking EDM are a longer production time of the tool electrodes and the necessity to machine mechanically shaped tool electrodes. In EDM milling, a simple cylindrical electrode is used as a tool, and the complex shaped parts can be generated by the movement of tool electrodes along a predefined path [2]. EDM milling simplifies the manufacturing process of complex shaped parts and reduces the production time and cost of tool electrodes because of the usage of a simple cylindrical tool. Thus, EDM milling technology has been applied to fabricate complex shaped parts in both the macro- and micro-domains and attracted many researchers’ attention.

In the micromachining field, micro-EDM milling has been widely used because micro cylindrical tool electrodes with a high aspect ratio can be fabricated precisely by the wire electrical discharge grinding (WEDG) [3]. Furthermore, due to the absence of cutting forces, micro cylindrical tool electrodes can be as smaller as possible to fabricate much smaller structures. Different types of microcavities such as circles, triangles [4], squares [5], channel and circular pillars [6], hemispheres, complex recesses, inclined windows, tapered sockets, narrow slots with a variable inclination, and complex shaped cavities [7] are fabricated by micro EDM milling. However, the biggest challenge for micro-EDM milling is the wear of the tool electrode. A new method to address this is developed by combining the advantage of
EDM milling and wire EDM, which is referred to as wire electrical discharge machining milling (WEDM milling) [8]. But, limited by the complex mechanical structure, WEDM milling can only fabricate very simple structures. In the field of macromachining, how to improve the machining speed of EDM milling is the main concern of researchers. Therefore, scholars have developed electrical arc machining (EAM) [9–13]. EAM milling technology is a new machining method to remove workpiece materials by using the high temperature generated by arc discharge between the tool electrode and the workpiece. Compared with the spark discharge of EDM, arc discharge has higher energy density and electro-thermal conversion efficiency, so the efficiency of EAM is much higher than that of EDM. Then, a new compound machining process employing super high-speed EDM milling and arc machining is developed for milling [9]. In summary, the researchers have conducted massive investigations on EDM milling and have greatly promoted the development of technology and industrial application. However, at present, EDM milling is mainly implemented on the 3-axis machine tool, which cannot machine complex structures on the free-form surface. Furthermore, the machining freedom and flexibility of EDM milling based on a 3-axis machine tool is poor, which limits the further application of EDM milling in high-end manufacturing.

In the past 3 decades, robotic machining has attracted a great deal of research interest due to its cost advantages, high efficiency, high flexibility, and versatility of industrial robots [14]. Robotic machining is generally applied to perform tasks including drilling [15], milling [16], grinding [17], and deburring [18]. Because EDM can machine any electrically conductive parts regardless of hardness without contact force. EDM machining with robots means more advantages compared with cutting machining with robots. EDM milling with the robot will not cause mechanical vibration and does not need complex mechanical structures with great strength and stiffness. Furthermore, by using the flexibility of robots, it is possible to realize on-site processing. Mobile robot machining provides a more flexible machining mode compared to traditional machining with a fixed base. Thereby, this study proposed the EDM milling based on a 6-DOF serial robot. To achieve this, an innovative servo control principle of EDM milling based on a 6-DOF serial robot was put forward. The wear compensation of tool electrodes in EDM milling was also considered. Finally, machining experiments of the curved surface and complex trajectory were conducted to demonstrate the feasibility and superiority of EDM milling based on a 6-DOF serial robot. EDM milling based on a 6-DOF serial robot has great application potential in the machining of large difficult-to-machine parts on site.

2 Experimental setup

Figure 1 shows the schematic diagram of a self-made EDM milling system based on a 6-DOF serial robot. Figure 2 shows a picture of the experimental equipment. The machining system is mainly composed of an EDM control system, a robot control system, a 6-DOF serial robot, an end effector, a workbench, and a pulse power. The robot control system and 6-DOF serial robot are responsible for the machining trajectory motion of tool electrodes. The EDM control system and end effector are used to control the discharge state, which can be explained as follows. The end actuator is composed of a servo motor, a precision mobile platform, a connecting plate, and a fixture, as shown in Fig. 3. The cylindrical tool electrode is installed in the fixture of the end actuator. In the machining process, the discharge state detection circuit detects the voltage and current signals of the discharge gap in real-time and transmits the discharge rate, the short-circuit rate, and the open circuit rate to the EDM control system.
The EDM control system controls the servo motor of the end actuator according to the control strategy of EDM machining. Thereby, the discharge gap between the tool electrode and the workpiece can be controlled and adjusted through the end actuator. Compared with traditional 3-axis EDM milling machine tools, in our EDM milling system based on a 6-DOF serial robot, the tool electrode can be oriented in such a way that it is perpendicular to the sculptured surface, as shown in Fig. 4, which brings many benefits such as high machining speed and accuracy, convenient wear compensation of tool electrode, higher processing flexibility, and stronger processing capacity of a complex 3D surface.

Figure 5 shows the schematic diagram of EDM milling with tool electrode fixed attitude machining (a) and tool electrode variable attitude machining (b). Figure 6 shows the images of the tool electrode after EDM milling with tool electrode fixed attitude machining (a) and tool electrode variable attitude machining (b). From Fig. 6(a), it can be found that in EDM milling with tool electrode fixed attitude machining, discharges occurred between the partial area of the tool electrode edge and the workpiece. As a result, the end of the tool electrode presented a cone after machining. In EDM milling with tool electrode variable attitude machining, discharges occurred between the bottom surface of the tool electrode and the workpiece. Thus, tool electrode wear was uniform, as shown in Fig. 6(b). Thus, variable attitude milling of tool electrodes is a reasonable way to machine curved surfaces in EDM milling.

3 Servo control principle of EDM milling based on a 6-DOF serial robot

3.1 Servo control strategy of limited motion of tool electrode

EDM milling is a machining method that uses a simple electrode to do complex movements according to a NC predetermined track under the control of the NC system. EDM milling can achieve complex three-dimensional structures by scanning the two-dimensional surface with equal thickness layer by layer, as shown in Fig. 7. Based on the servo movement direction of the tool electrode, EDM milling can
be clarified into two types: EDM milling with servo motion direction along the machining trajectory shown in Fig. 8(a) and EDM milling with servo motion direction perpendicular to the machining trajectory (simply called vertical servo control) shown in Fig. 8(b). In EDM milling with servo motion direction along the machining trajectory, when a short circuit occurs in the machining process, the tool electrode retreats a certain distance along the original track to eliminate the short circuit, which has been widely used in the practical EDM milling [4]. To eliminate the short circuit in time, the response speed of the machine tool should be fast enough. However, the response speed of the 6-DOF serial robot is too slow to meet the application requirements of EDM. Thus, the servo motion direction along the machining trajectory cannot be used in EDM milling based on a 6-DOF serial robot.

To solve the above problem, a tool electrode servo motion device was invented and installed at the end of a 6-DOF serial robot, as shown and discussed in Fig. 2. Then, the servo motion direction perpendicular to the machining trajectory can be used in EDM milling based on a 6-DOF serial robot, in which the servo movement direction of the tool electrode and the scanning movement direction of the tool electrode is perpendicular to each other and their movements are independent.

In EDM milling, the thickness of every layer must be controllable. In EDM milling with servo motion direction perpendicular to the machining trajectory, the servo motion of the tool electrode can affect the thickness of every layer because the direction of servo motion is along the direction of layer thickness. Thus, the controllable thickness of every layer is the key to EDM milling based on a 6-DOF serial robot. To guarantee that the layered thickness is controllable, we proposed the servo control strategy of limited motion of the tool electrode on the basis of vertical servo control, as shown in Fig. 9. In this servo control strategy, we set the upper and lower limit planes of the tool electrode motion, which were the UU′ and DD′ planes. That is, the tool electrode can only do the servo motion in the area between the UU′ and DD′ planes whose distance is ΔG which was 100 μm in these experiments. After the tool electrode finishes one layer, the tool electrode feeds down one layer thickness δ and the UU′ and DD′ planes also feed down one layer thickness δ.
3.2 Wear compensation of tool electrode

EDM milling faces a well-known problem: the wear of tool electrodes. Due to the long machining path, the electrode wear becomes important. It appeared to be necessary to compensate for this wear so as to generate an accurate geometry in the machining process. Thus, this study used a fix-length compensation method to compensate for the tool electrode wear [19]. In this method, the tool electrode compensates downwards for a constant length $\xi$ every time when it mills a fixed distance $L$, as shown in Fig. 10.

According to the geometric relationship, the compensation distance $L$ can be expressed by Eq. (1).

$$ L = \frac{T}{\Psi} \xi v $$

(1)

where $v$ is the scanning speed of tool electrode, $T$ is the total machining time, $\Psi$ is the wear length of tool electrode, which can be expressed by Eq. (2):

$$ \Psi = \frac{V \cdot \text{REWR}}{S} $$

(2)

where $V$ is the workpiece material removal volume, $S$ is the sectional area of tool electrode, REWR is the relative electrode wear ratio, which is the ratio of tool electrode wear volume to the workpiece material removal volume.

Then, combining Eqs. (1) and (2), the compensation distance $L$ can be expressed by Eq. (3):

$$ L = \frac{T \cdot S}{V \cdot \text{REWR}} \xi v $$

(3)

The machining parameters used in this study are shown in Table 1.

Figure 11 shows the comparison of discharge current waveform in EDM without wear compensation and with wear compensation. From the figure, it can be found that the current waveform density in EDM without wear compensation was sparer than that in EDM with wear compensation.

This is because the discharge gap became larger as the tool electrode was worn, decreasing the discharge rate. Thus, this experiment demonstrated that the tool electrode compensation method improved the machining state.

4 Machining experiments of EDM milling based on a 6-DOF serial robot

4.1 EDM milling of trapezoidal groove

To verify the correctness and effectiveness of the servo control strategy and wear compensation of the tool electrode, the trapezoidal groove structures on the plane workpiece and cylindrical workpiece were machined with a 3 mm diameter tool electrode by EDM milling based on a 6-DOF serial robot, respectively, as shown in Fig. 12. Firstly, through the experiment of the EDM milling plane, the REWR, which was 8.2% under the experimental conditions shown in Table 1, was obtained. In the machining experiment of trapezoidal groove on the plane workpiece of high-speed steel, the sectional area of tool electrode $S$ was 7.065 mm$^2$, the workpiece material removal volume $V$ was 275 mm$^3$, and the total machining time $T$ was 5008 s, and the compensation value $\xi$ was 5 $\mu$m. Then, the compensation distance $L$ can be calculated by Eq. (3), and $L$ was 1.57 mm. The EDM milling results of the trapezoidal groove on the plane workpiece without and with wear compensation of the tool electrode are shown in Fig. 13(a), (b), respectively. From Fig. 13(a), it can be found that the distance between the bottom surface and the top surface of the trapezoidal groove was only 3.2 mm, which was far less than the actual 5 mm. Furthermore, the included angle of the side of the trapezoidal groove was 35.7°, which was also far less than the actual 45°. But, from Fig. 13(b), it can be found that after considering the wear compensation of the tool electrode, the distance between the bottom surface and the top surface of the trapezoidal groove was 5.1 mm, which was close to the actual 5 mm. Furthermore, the included angle of the side of the groove was 43.8°, which was also close to the actual 45°.

![Fig. 10 Schematic diagram of fix-length compensation method](image-url)

| Table 1 Experimental conditions |
|---------------------------------|
| **Open voltage**                | 110 V |
| **Discharge current**           | 15 A  |
| **Pulse frequency**             | 2 kHz |
| **Pulse duration**              | 25%   |
| **Tool electrode**              | Copper (+) |
| **Dielectric liquid**           | EDM oil |
| **Workpiece**                   | High speed steel, 45 steel, 304 stainless steel (−) |
| **Scanning speed of tool electrode** | 0.2 mm/s |
| **Layer thickness $\delta$**    | 100 $\mu$m |
the trapezoidal groove was 45.6°, which was also close to the actual 45°. This experiment verified the correctness and effectiveness of the servo control strategy and wear compensation of the tool electrode.

In the machining experiment of trapezoidal groove on the cylindrical workpiece of 45 steel with the experimental conditions shown in Table 1, the workpiece material removal volume $V$ was 374.8 mm$^3$, and the total machining time $T$ was 6965 s. Then, the compensation distance $L$ can be calculated by Eq. (3), and $L$ was 1.558 mm. The EDM milling results of the trapezoidal groove on the plane workpiece without and with the wear compensation of the tool electrode are shown in Fig. 14(a), (b), respectively. From Fig. 14(a), it can be found that the distance between the bottom surface and the top surface of the trapezoidal groove was far less than the actual 5 mm. But, from Fig. 14(b), it can be found that after considering the wear compensation of the tool electrode, the distance between the bottom surface and the top surface of the trapezoidal groove was 4.8 mm, which was close to the actual 5 mm. It should be noted that, limited by the installation accuracy of the worktable fixture of self-made equipment, in the machining of the curved workpiece, the lower positioning error of the workpiece resulted in lower machining accuracy than the plane workpiece shown in Fig. 13. However, this problem can be solved by designing and manufacturing high-precision fixtures in the future.
4.2 EDM milling of complex trajectory on the space surface workpiece

To verify the machining ability of complex trajectories on the space surface of the workpiece by EDM milling based on a 6-DOF serial robot, three complex trajectories, such as EDM, Chinese character “China,” and “Chinese knot,” were machined with tool electrodes of 2 mm diameter, 2 mm diameter, and 3 mm diameter, respectively, under the experimental conditions shown in Table 1. The material of the hemispherical workpiece with a radius of 38 mm was 304 stainless steel. The machining result presented in Fig. 15 shows that in the EDM milling of complex trajectory on the space surface using a 6-DOF serial robot, the tool electrode can be always perpendicular to the tangent plane of the workpiece surface, which ensures the machining accuracy of complex trajectory. The generation principle of the complex trajectories was explained as follows. Firstly, the hemispherical workpiece was established by CATIA 3D modeling software; the second step was to draw the plane sketch of the complex trajectories by using the sketch drawing function of CATIA software; the third step used the generative shape design (GSD) function of CATIA software to project the plane sketch drawn in the previous step onto the hemispherical workpiece surface; step 4 used the GSD function of CATIA software to discrete the curve projected on the hemispherical workpiece surface in the previous step into a certain number of track path points; the 5th step was to export the position information \((x, y, \text{ and } z)\) of the track path points generated in the previous step through the digitized shape editor of CATIA software; the last step was to solve the attitude information of the tool electrode \((\alpha, \beta, \text{ and } \gamma)\) through the position information of the tool electrode \((x, y, \text{ and } z)\). Specifically, the mathematical principle was to ensure that the axis of the tool electrode was perpendicular to the normal surface of the surface at any position. The experimental results demonstrated that EDM milling based on a 6-DOF serial robot is feasible and effective in the machining of complex trajectories on the space surface.

5 Conclusions

This paper proposed EDM milling based on a 6-DOF serial robot. The research results were summarized below:

1. To solve the problem that serial robot cannot meet the rapid response requirements of EDM for real-time adjustment of discharge gap, a tool electrode servo motion device was invented and installed at the end of a 6-DOF serial robot, and a servo control strategy of tool electrode vertical trajectory fallback was proposed to realize the rapid adjustment of machining gap.

2. To achieve the controllable thickness of every layer in EDM milling based on a 6-DOF serial robot, the servo control strategy of limited motion of the tool electrode on the basis of vertical servo control and a fix-length compensation method to compensate the tool electrode wear was proposed.

3. To verify the correctness and effectiveness of the servo control strategy and wear compensation of the tool electrode, the trapezoidal groove structures on the plane workpiece and cylindrical workpiece were machined by EDM milling based on a 6-DOF serial robot, respectively. This experiment verified the correctness and effectiveness of the servo control strategy and wear compensation of the tool electrode.

4. To verify the machining ability of complex trajectories on the space surface of the workpiece of EDM milling based on a 6-DOF serial robot, three kinds of complex trajectories were designed and machined on the hemispherical workpiece with a radius of 38 mm.
Author contribution Xiaoming Yue: conceptualization, investigation, validation, visualization, writing—original draft, and funding acquisition. Zhiyuan Chen: data curation and visualization. Zuoke Xu: formal analysis and methodology. Jing Liu: project administration, supervision, resources, and writing—review and editing.

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