The test of short electric arc trepanning machining and analysis of electrode machining characteristics

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Abstract. Short electric arc machining is a non-contact and inter-pole discharge processing technology, which belongs to the category of special electric processing technology. Short electric arc machining is especially suitable for processing some hard working materials with high hardness, high strength, high toughness, etc. However, it is very difficult to process the trepanning of the difficult-to-machine material. Therefore, it is a new research direction to apply the short electric arc machining technology to the trepanning machining. In this paper, the machining characteristics of the electrode are analyzed by the test of short electric arc trepanning in order to determine the effect of different electrical machining parameters on the removal rate of the workpiece material and the loss rate of electrode. Several electrode materials and different electrode structures are selected for short electric arc trepanning test in order to determine the processing characteristics of the electrode. The result shows that when the power supply voltage increases, the removal rate of the workpiece material and the loss rate of the electrode also increase accordingly. Under the same discharge voltage conditions, the removal rate of the titanium alloy TC4 by the graphite electrode is higher than that of the Ni-base high-temperature alloy In625. While, the tooth structure electrode of the same electrode material has a better processing effect.

1. Introduction

With the need of industrial production and advance in science and technology, a large number of materials (such as titanium alloys, high-strength stainless steels, and high-temperature alloys) with high hardness, high strength, high toughness, high temperature resistance and corrosion resistance are used in the field of aerospace, military and petrochemical. However, when these high-performance materials are processed by traditional machining methods, they may cause some serious problems such as high cutting temperature, large cutting force, easy-to-stick tools, and serious wear of the tools, which reduces the service life and machining efficiency of the tools, while the trepanning of the difficult-to-machine materials processing is more difficult even impossible to process. Short electric arc machining is a new type of strong arc machining method, it has the characteristics of no cutting force, operating and controlling easily in machining, any conductive material, especially for hard, super, high toughness and other difficult-to-machine materials can be processed. Therefore, the combination of short electric arc processing technology and trepanning machining has a very broad application prospect.
2. Analysis of short electric arc processing principle and discharge mechanism

Short electric arc machining is an electric cutting machining method that uses the electric corrosion phenomenon of arc discharge between the two electrodes to remove excess metal or non-metal conductive material under a certain working pressure and water-gas mixture working medium[1]. In short electric arc machining, tool electrodes are generally regarded as cathodes to connect to the negative electrode of the power supply, which can reduce the loss rate of the electrode. Short arc electric machining takes low voltage and high current pulse power, the range of supply voltage is 0-30V, the range of working current is 0-2000A, the pulse frequency is lower than the frequency used in the known machining process, the machining accuracy can reach IT8-IT12. In the process of short arc machining, when the gap between the workpiece material and the tool electrode is less than the critical distance of arc discharge, the medium between the two poles is instantaneously broken down, the voltage makes the electrons of the discharge channel to run toward the positive pole at a high speed, the positive ions run toward the negative electrode. The electrical energy becomes kinetic energy and the kinetic energy transforms into thermal energy through collision, so in the channel, the surface of anode and cathode respectively forms an instantaneous heat source, which would lead to the surface temperature of the workpiece rises sharply. When the temperature is higher than the melting point of the material, metal droplets will be generated on the surface of the anode, as the temperature will continue to rise, a small portion of metal droplets in the discharge channel will be vaporized at high temperature[2]. The metal droplets are dislodged from the workpiece by the explosive force which generates from the high temperature and pressure, the gas-liquid mixed working medium will take the metal droplets out of the processing area. The melted metal droplets that have not been stripped are cooled and condensed in the processing after being cooled by the working medium. Through the above steps, the whole process of electrical corrosion is completed. Figure 1 shows the arc discharge phenomenon during the short electric arc machining taken by the high speed camera. Figure 1a shows the beginning of the arc, at this stage, there is a bright blue arc. Figure 1b shows the second stage of the arc discharge. It can be seen from the figure that the arc moves at a high rate and forms a transparent blue filament-like arc. The third stage of the arc discharge is shown in Figure 1c, where the arc continues to elongate and generates a bright yellow spark. The fourth stage is the quenching stage. The arc reaches the critical length and extinguishes. As is shown in Figure 1 that the color of the arc gradually changes from blue to yellow. It can be known by thermodynamics that the temperature of the arc gradually decreases, the blue arc temperature is the highest. Therefore, the blue arc is mainly used to melt and etch metal[3].

![Figure 1. Arc discharge phenomenon.](image1)

3. Design of short arc electric trepanning system and electrode structure

3.1. Design of short arc electric trepanning system

The schematic diagram of the short arc electric trepanning system is shown in Figure 2. The range of the power supply voltage is 0-30V, and the working current can reach 2000A. The working medium adopts a water vapor mixed medium with a certain pressure. The tool electrode is connected to the cathode circulation device, the workpiece is connected with the anode circulation device. The
Insulation measures must be taken between the tool electrode and workpiece. At the beginning of processing, the tool electrode performs rotation and feed movement, the workpiece material performs a relative rotation movement, the water-emulsion mixed medium enters the working area with a certain pressure. When the distance between the tool electrode and workpiece reaches the discharge gap, there will be a violent discharge between them, which could cause the workpiece to be melted and vaporized. The etched material is removed from the workpiece surface under the action of the working medium with certain pressure.

3.2. The structure design and material selection of tool electrode

The design of the tool electrode includes two parts, the selection of electrode material and the design of the electrode structure. The structure of the tool electrode is mainly designed according to the requirements of the short arc trepanning system and the processing characteristics of the workpiece. The electrode material is mainly selected according to the conductivity, melting point and other physical characteristics of various materials. The melting point of graphite is as high as 3652°C. The conductivity of graphite is 4 times higher than stainless steel, 2 times higher than carbon steel and 100 times higher than non-metal. Moreover, the graphite electrode has good machinability and is easy to generate arc[4]. The copper has good conductivity, high compactness, soft texture, strong plasticity, high electrical conductivity, and high thermal conductivity. Therefore, after comparative analysis, it is determined that copper and graphite are more suitable as electrode materials for short electric arc trepanning machining. Figure 3 shows the structure of the electrode tip designed by Creo software. Figure 3a shows the pin-type structure of the electrode tip, which generates electric arc by the four cylindrical in the discharge processing, this structure of the electrode head has a simple structure, small discharge area and large chip space features. Figure 3b shows the tooth structure of the electrode head, which generates electric arc through the tooth-shaped end surface, with a large discharge area and high processing efficiency.

![Image](image-url)

(a) Pin-type structure
(b) Tooth structure

Figure 3. Tool electrode design.
4. Short electric arc trepanning machining test and analysis

4.1. Effect of electric processing parameters on removal rate and electrode loss rate

In the test of the short electric arc trepanning machining, the titanium alloy TC4 and Ni-base high-temperature alloy In625 whose size is Φ50mm×180mm are processed by the graphite. The single factor experiment is used in this test. We change the parameters of power supply voltage (25V, 18V, 10V) and keep other factors unchanged to analyze the influence of the power supply voltage on the removal rate and the electrode loss rate of workpiece[5]. The electrodes are toothed, with an outer diameter of 35mm and an inner diameter of 30mm. Figure 4 shows the curve of the change of material removal rate and electrode loss rate.

![Figure 4. Curve of material removal rate and electrode loss rate.](image)

It can be seen from Figure 4 that as the voltage keeps increasing, the removal rate of the workpiece material continues to increase, the loss of the electrode tip also increases. Under the same discharge voltage conditions, the removal rate of titanium alloy TC4 is higher than Ni-base high-temperature alloy In625, while the loss rate of graphite on discharge processing of titanium alloy TC4 is higher than that when Ni-base high-temperature alloy In625 is processed. When the discharge voltage is increasing, the electric field strength between the two poles is also continuously enhanced, the energy accumulated in the discharge channel is also correspondingly enhanced, so the removal rate of the workpiece material per unit time is improved. Since titanium alloy TC4 has lower density and thermal conductivity than Ni-base high-temperature alloy In625[6], and high-temperature alloy has high thermal stability, so under the same discharge voltage conditions, the removal rate of the titanium alloy TC4 is higher than that Ni-base high-temperature alloy In625, at the same time, the loss rate of the graphite-processed titanium alloy TC4 is relatively high.

4.2. Short electric arc trepanning test of different structure electrodes

Two kinds of structures of copper are chosen to do the test of short electric arc trepanning machining. The tooth structure electrode is represented by A, whose size is Φ35mm. Pin-type structure electrode head is represented by B, the size of cylindrical rod is Φ6mm. The workpiece material is stainless steel (0Cr17Ni4Cu4Nb) whose size is Φ60mm×150mm. Table 1 shows the data of the test, The depth of trepanning, the removal rate of the workpiece material and the loss rate of the electrode are compared between the two structure electrodes after processing, then the test data is analyzed and processed.

| Voltage (V) | Feed rate (mm·s⁻¹) | Time (s) | Trepanning depth (mm) | Electrode loss rate (g·min⁻¹) | Material removal rate (mm³·s⁻¹) |
|------------|-------------------|---------|----------------------|-----------------------------|-------------------------------|
|            |                   | A       | B                    | A                           | B                             |
| 10         | 2                 | 60      | 3.71                 | 0.4                         | 293.4                         |
|            |                   |         |                      | 0.86                        | 1.44                          |
|            |                   |         |                      | 293.4                       | 313.4                         |
| 10         | 4                 | 60      | 4.14                 | 1.63                        | 75.1                          |
|            |                   |         |                      | 0.99                        | 1.99                          |
|            |                   |         |                      | 75.1                        | 333.4                         |
| 10         | 6                 | 60      | -                    | -                           | -                             |

Table 1. Discharge performance of copper in different structural forms.
The test shows that under the same electric processing parameters, the trepanning depth of the tooth structure electrode is deeper than that of the pin-type structure electrode when they process the stainless steel. In terms of material removal rate, the removal rate of pin-type structure electrode is higher than that of tooth structure electrode. At the same time, the loss rate of the pin-type structure is higher than that of the tooth structure. Because the short electric arc machining uses the electric corrosion phenomenon of arc discharge between the two electrodes to remove the excess metal [7], the energy per unit area at the tip of the tooth structure is relatively concentrated when discharging, the discharge area is larger. However, the pin-type structure of the electrode head is round, the energy during discharge is more dispersed than that of the tooth structure. Therefore, when the same workpiece material is subjected to electric discharge machining, the electrode material of the tooth structure has a better effect in trepanning processing. As the pin-type structure electrode has a better effect on removing the electro-sintering residue and scouring the cooling liquid, so the removal rate of the pin-type structure electrode for stainless steel is higher than the tooth structure electrode, and the loss rate of pin-type structure is higher than the tooth structure electrode.

5. Conclusion

1. In the process of short electric arc trepanning, with the increase of discharge voltage by using graphite, the removal rate of the workpiece material and the loss rate of the electrode also increase accordingly.

2. In the process of short electric arc trepanning, under the same conditions, the removal rate of the titanium alloy TC4 is higher than that of the Ni-base high-temperature alloy In625.

3. When the copper electrode of different structural forms is processed in short electric arc trepanning, the electrode of the tooth structure has a deeper degree for the workpiece material. In addition, the pin-type structure electrode has a high removal rate of the workpiece material, but the electrode loss rate of the pin-type structure is also relatively large. so the tooth structure electrode is more suitable for short electric arc electric trepanning processing.

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