Experiment and Analysis of Electrode Characteristics and Electrical Parameters of Short Electric Arc Trepanning Machining of Nickel-based Superalloy

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Abstract: Nickel-based Superalloy Inconel 625 is a super-strong, super-hard typical difficult-to-machine material that can be processed with high efficiency by short electric arc machining technology. In this paper, the primary and secondary factors affecting material removal rate, electrode loss and surface quality in short electric arc trepanning machining, such as power supply voltage, electrode feed amount, electrode structure and electrode material, were studied for Nickel-based Superalloy. The test results showed that: when the power supply voltage increases, the feed rate increases, the efficiency of machining work-pieces with four material electrode tip increases accordingly, and the order of influence is graphite > ductile iron > copper > 45 steel. Among the three types of graphite electrode tips, the toothed electrode tip has the highest processing efficiency, and the through hole pin electrode has the lowest loss rate. The effect of the surface properties of the Nickel-base Superalloy after short electric arc machining is only in the heat-affected layer, less increase in hardness, which has less influence on the mechanical properties of the work-piece.

1. Introduction
Nickel-based Superalloy has good thermal fatigue properties, structural stability and fracture toughness. Therefore, it is widely used in high-precision and special industries such as aerospace. However, Nickel-based Superalloy material has a large cutting force, high cutting temperature, severe work hardening and large thermal deformation of the work piece, and is a very difficult material to be processed. Especially in the deep hole processing, the traditional deep hole trepanning method for processing Nickel-based Superalloy material has the problems of high processing difficulty, high cost, low efficiency and etc. Short electric arc machining has great advantages over traditional machining. When processing Nickel-base Superalloy with high strength, stiffness and toughness, short electric arc machining has the advantages of no cutting force, easy control of processing, high processing efficiency, low processing cost and low pollution. This paper is a detailed analysis of the factors affecting the concentration of short electric arc machining.

2. The design of short electric arc machining system and electrode structure

2.1. Short electric arc Trepanning machining system
According to the principle of short electric arc machining, the corresponding short arc trepanning machining test system was designed. Figure 1 is a schematic diagram of short electric arc machining. The work piece was clamped on the chuck, and the lathe spindle was connected to the anode.
circulation device to connect the work piece to the positive pole. The electrode tip was connected to the cathode circulation device and connected to the slide box of the lathe, so that the electrode tip was connected to the negative electrode, and insulation measures were taken between the two. When the work piece was machined, the spindle of the machine drives its rotation, and the automatic feeding system of the machine tool feed the electrode tip to the work piece. When the work piece and the electrode reached a discharge gap and the discharge was severely discharged, the high temperature generated by the arc caused the work piece surface to be rapidly melted and vaporized, and was etched away. The material was cooled by a certain pressure of water and gas mixed working medium, and was separated from the surface of the work piece, and then the electrode tip was further fed to form a new round of arc machining, thereby completing the short electrode arc trepanning processing of the work piece. One way of cooling and chip evacuation is to spray the working medium directly from the outside to the processing zone, and another is to spray the working medium from the inside of the electrode tip through the air compressor. This test was to carry out short electric arc trepanning machining test on the lathe processing machine modified by ordinary lathe. The power supply adopts DHX33A3000/28FS short electric arc cutting power supply.

Figure 1. Schematic diagram of short electric arc trepanning machining

2.2. of the tool electrode and selection of materials
The test was divided into two parts. One was to compare the influence of the electrode tips with the same structure of different materials during processing of Nickel-base Superalloy. Therefore, four materials of ductile iron, graphite, copper and 45 steel were selected as the tool electrode materials, and the same size were used. The second was to compare the influence of the electrode tips with different structures and the same material on the processing of Nickel-base Superalloy. Three electrode tip shapes of the toothed, the solid cylindrical pin-shaped, the tubular cylindrical pin-shaped were selected. In order to structural design make the working medium spray better to the machined end face, a nylon sleeve was installed outside the solid cylindrical pin-shaped electrode tip. Figure 2 shows the three structures and dimensions of the graphite material.

A the tubular cylindrical pin-shaped electrode tip  B the solid cylindrical pin-shaped electrode tip  C the toothed electrode tip

Figure 2. Three types of structure of the electrode tip
3. Test and analysis of short electric arc machining of nickel-based superalloy

In this experiment, the effects of power supply voltage, electrode feed rate, electrode structure and electrode material on the material removal rate and electrode loss of short electric arc trepanning machining of Nickel-based Superalloy Inconel 625 were studied. Firstly, the effects of the four electrode materials on the material removal rate and electrode loss rate under different voltages and feed rates were tested and compared with the conditions of the same voltage and feed rate. Secondly, the effects of three kinds of graphite electrode tips on material removal rate and electrode loss rate were studied. The processing power supply is DHX33A3000/28FS short electric arc cutting power supply. The experimental equipment was a trepanning machine tool by a common lathe. The test material was a Nickel-based Superalloy Inconel 625, and the bar material was φ50 mm×300 mm. Figure 3 is a diagram shows the process of mounting and processing of the tubular cylindrical pin-shaped electrode tip.

3.1. Analysis of processing data of electrode tips of four different materials

3.1.1. Effect of discharge voltage on material removal rate. The influence rule of discharging voltage on material removal rate and electrode loss rate under different voltages (25V, 20V, 12V) and the same feed rate (2mm/min) were studied for four different materials of the tooth tip. The test data showed in the figure 4 and 5.

![Figure 4. Relationship between discharge voltage and material removal rate](image)

![Figure 5. Relationship between discharge voltage and rate of electrode loss](image)

As can be seen from Figures 4 and 5, when the voltage increases, the material removal rate and the electrode loss rate also increases. Under the same voltage conditions, the order of influence of the electrode material on the removal rate is graphite > ductile iron > copper > 45 steel, and the electrode loss rate is from 45 steel > ductile iron > copper > graphite. Therefore, under the same voltage condition, the graphite electrode has the highest efficiency in processing the work piece and the loss of electrode is the smallest.
3.1.2. Effect of feed amount of electrode tip on material removal rate. The influence rules of feed rate on material removal rate and electrode loss rate under different feed rates (2mm/min, 4mm/min, 6mm/min) and the same voltage (20V) were studied for four different materials of the tooth tip. The test data showed in Figure 6 and 7.

The data in Figure 6 and 7 indicate that the larger the feed rate, the faster the electrode removes material, while the more the electrode is lost. The processing data of the graphite electrode of Figure 6 shows that when the feed rate is too large, the arc erosion material is not fast enough, and the loss of the graphite electrode is also small. Therefore, under conditions of excessive feed rate, the electrode tip is in contact with the work piece, resulting in a short circuit of the short arc machining system. The order of influence of the electrode material on the removal rate under the same feed rate is graphite > ductile iron > copper > 45 steel, that is, the graphite electrode has the highest processing efficiency for the work piece. The electrode loss from large to small is 45 steel > ductile iron > copper > graphite, that is, the graphite electrode has the least loss when processing the work piece. Therefore, under the same voltage conditions, the graphite electrode is the best material for the processing of short electric arc machining of Nickel-base Superalloy.

3.2. Analysis of processing data of three different structure of graphite tips

The influence rule of discharging voltage on material removal rate and rate of electrode loss under different voltages (25V, 20V, 12V) and the same feed rate (2mm/min) were studied for three structures of graphite electrodes. The test data showed in the figure 8 and 9.

It can be seen from Figure 8 and 9 that the material removal rate of the work piece of the three structures increased with the increase of the voltage, and the electrode loss is more. The order of
influence of the three electrodes on the removal rate of the work piece is toothed \( > \) tubular cylindrical pin-shaped \( > \) solid cylindrical pin-shaped. The order of electrode loss from large to small is toothed \( > \) solid cylindrical pin-shaped \( > \) tubular cylindrical pin-shaped. The toothed electrode tip has a larger discharge area, so the processing efficiency is the highest, but the electrode loss is also larger, and the working medium is not sprayed well to the machined end face of the work piece, and the processing quality is worse than the other two electrode tips. The material removal rate of the tubular cylindrical pin-shaped electrode tip is medium, and the rate of electrode loss is the lowest. Considering a comprehensive consideration, the tubular cylindrical pin-shaped electrode tip works best when processing Nickel-base Superalloy.

4. Performance analysis of heat affected zone on workpiece surface

After short arc machining, due to the high temperature sintering of the arc, the metal structure on the surface layer of the Nickel-base Superalloy changed accordingly. The purpose of this test was to study the characteristics of short electric arc machining of Nickel-based Superalloy, analyze the changes on the surface layer structure of the work piece and the micro-hardness of the heat-affected layer. And analyze the impact of short arc machining on the mechanical properties of Nickel-based Superalloy.

Equipment used for the test: Axio Observer digital material microscope, HXD-1000TMC micro-hardness tester. Figure 10 is a metallographic diagram of the surface layer structure after processing. Figure 11 is a matrix organization of the work piece.

![Figure 10. Surface layer structure after Processing (x100)](image1)

![Figure 11. Matrix organization (x500)](image2)

The short electric arc trepanning machining is only a roughing process of the deep hole trepanning of the work piece. Since the arc machining releases the high-temperature melting material, the melted material is not removed by the working medium in time, and remains on the surface of the work piece to form a layer of recast cast structure after cooling. However, the thermal conductivity of the Nickel-based Superalloy is low, and the high temperature generated by the arc machining cannot be diffused into the interior of the work piece, so a heat-affected layer is formed between the layer of recast cast structure and the matrix organization of the work piece. The heat-affected layer is the grain refinement structure produced by the deformation and refinement of the grain of the work piece by the micro-structure of the work piece.

It is further necessary to investigate whether short arc machining changes the matrix structure of the work piece and whether it affects the mechanical properties of the material. Therefore, five points were selected between the surface layer and the matrix structure of the treated nickel-base superalloy work piece to measure the hardness of the surface layer before and after processing. The interval between each point was about 50 \( \mu m \), and the measurement data showed in Table1.

| Measuring point | Hardness/HV Before short electric arc machining | Hardness/HV After short electric arc machining | Rate of change |
|-----------------|------------------------------------------------|-----------------------------------------------|----------------|
| 1               | 221                                            | 283                                           | 21.9%          |
| 2               | 223                                            | 268                                           | 20.2%          |
| 3               | 220                                            | 253                                           | 15%            |

Table 1. Hardness change of surface layer of Nickel-base Superalloy
The measured data in Table 1 shows that the hardness gradient \( \Delta H/V/\Delta EHt=0.248HV/0.1\text{mm} \), and the material hardness change rate at the fifth measurement point, that is, near the measurement point of the substrate, is small, 0.9%. The first measurement point is that the material hardness change rate of the recast layer structure measurement point is 21.9%, so the effect of short arc machining on the work piece material is only in the heat affected zone, and the hardness is increased by about 0.248 HV for every 0.1 mm increases. The hardness is less increased, the mechanical properties of the work piece are less affected, and the subsequent processing of the work piece is less affected.

5. Conclusion
1. When the tool electrode of the four materials are used to process the Nickel-base Superalloy, as the voltage increases and the feed rate increases, the material removal rate and the electrode loss increases. Moreover, the electrode material has a great influence on the processing efficiency of short electric arc trepanning machining of Nickel-base Superalloy, wherein the graphite electrode tip has the highest material removal rate and the electrode loss is the smallest.

2. When three kinds of structure of graphite electrode tip are used to process Nickel-based Superalloy, the rules of influence of voltage and feed rate on material removal rate and electrode loss is unchanged. The material removal rate of the work piece processed by the toothed electrode tip is the highest, but the electrode loss rate is also the highest. Comprehensive analysis of material removal rate, rate of electrode loss and quality of surface machining, the solid cylindrical pin-shaped electrode tip is the best structure.

3. After the short electric arc trepanning machining of Nickel-based Superalloy, the structure of surface layer changes to form a structure of recast layer and a 343.8 \( \mu \text{m} \) heat affected layer. The hardness of the surface layer of the work piece also increases, and the hardness increased by about 0.248 HV for each 0.1 mm increases in the matrix structure from the cast layer structure to the work piece, and the hardness increases at a low speed, which does not greatly affect the mechanical properties of the work piece material.

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