Experimental study on the damage law of the shape of the tool nose by the times and duration of micro-discharge

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Abstract. The micro-discharge tool setting method is to apply a certain voltage between the tool and the tool set. When the distance between the tool and the tool set is less than the discharge gap, the medium between the tool and the tool set discharges and the voltage decreases, monitoring the voltage signal and recording the machine coordinates when the voltage changes times to complete the tool setting process. In this paper, the influence of the times and duration of the discharge on the tool clearance and the shape of the tool nose during the micro-discharge tool setting process is studied. The research shows that the tool clearance is related to the discharge duration. When the duration of the discharge is less than 4s, the tool clearance becomes smaller with the increase of the times of tool setting process, and the governing tool nose damage is breakage by the discharge current impact. When the discharge duration is greater than or equal to 4s, the tool clearance becomes larger as the number of times of tool setting process increases. The burr that grows at the nose of the tool changes the nose shape. The above research provides support for the subsequent micro-discharge tool setting tool to achieve high-precision non-destructive tool setting process and optimize tool setting parameters.

1. Introduction
In the process of high-precision micro-miniature parts processing, high-precision tool setting process is an essential key to ensure machining accuracy. Due to the small size of the micro-miniature parts, the micro-tools are often used in machining. If the contact tool set is used, the contact force during the tool setting process will result in deformation or damage of the micro-tools, which affects the tool life and machining accuracy. The existing non-contact tool set in machine is laser-oriented, which does not damage the tool, but requires special protection devices and is expensive for most manufacturers. Therefore, the development of high-precision and low-cost tool set for micro-tools is an urgent need for high-precision machining of micro-miniature parts.

The Institute of Micro-Miniature Manufacturing Technology of Beijing Institute of Technology has proposed a high-precision tool setting method for micro-tools based on the micro-discharge principle, and developed a non-contact high-precision micro-discharge tool set in machine[1-2]. The micro-discharge tool set is based on the approximate analytical expression of the modified Paschen curve proposed by Go and Pohlman of the University of Notre Dame in the United States based on a large number of experimental data[3], as in equation (1). Wherein, the breakdown voltage \( V_0 \) in the uniform electric field is a function of the product of the gas pressure \( P \) and the discharge gap \( d \), which can be quantitatively described by Paschen's law, as in equation (2), where \( A \), \( B \) and \( \gamma \) are known
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constants. DFN represents the threshold electric field strength generated by field emission, as in equation (3). φ is the cathode work function. β is the geometric coefficient, and K is a fitting parameter, which has no obvious physical meaning and is difficult to determine[4-5]. As shown in Fig. 1, The modified Paschen curve under the condition of A=11.0 (m·Pa)-1, B=273.8 (V/m·Pa), γ=0.015, and P=101.325 kPa, φ=4.0 eV, β=50, K=107, the curve shows that when the gas gap is less than 5 μm, the discharge voltage is less than 200 volts, and when the discharge gap is 1 μm, the discharge voltage is only several tens of volts. Since the electric field density around the tool nose is larger and easier for discharge than the plate electrode, the discharge voltage is only a few volts when the discharge gap is 1 μm during the tool setting process. Since the voltage varies greatly with the discharge gap and the discharge gap can maintain high accuracy under a certain range of voltage fluctuations, these features make it possible to apply the micro-discharge principle in micro-tool non-contact tool setting process. The tool setting accuracy based on micro-discharge principle can reach 1 micron and the minimum diameter of the tool can reach 50nm.

\[
V_o = d\left(\frac{D_{FN} + BP}{\ln(KAPd)}\right)
\]

\[
D_{FN} = 6.85 \times 10^7 \frac{\phi^5}{\beta}
\]

Figure 1. Modified Paschen’s breakdown voltage [Eq.1], A=11.0(m·Pa)-1,B=273.8(V/m·Pa), γ=0.015, and P=101.325kPa, φ=4.0eV, β=50, K=107

However, the continuous discharge process will generate a large amount of heat at the electrode. Under the preset discharge voltage, the influence of arc on the tool nose and its law are still unclear, which restricts the application of the device. Therefore, this paper focuses on the damage and impact of the discharge duration on the shape of the tool nose and the impact of different tool setting times and discharge duration on the tool clearance, and indirectly study and analyze its impact on the accuracy of the tool set. The purpose of this study is to improve the precision of the tool setting, determine the process parameters of the micro-discharge tool setting, and optimize the tool setting process parameters for the tool life.

2. Methods of Tool Setting Experiments

In order to study the influence of discharge duration on tool shape, different tool setting times and discharge on tool clearance, the current-triggered macro-micro combined high-precision micro-motion ranging experiment method is used. The experimental device is shown in Figure 2. There are four parts: the tool module, the tool set high-precision motion unit and the signal acquisition module and the signal display module. The tool set high-precision motion unit and the tool module are respectively
placed on the substrate. The micro-motion platform in the high-precision motion unit is a six-degree-of-freedom platform with a repeating positioning accuracy of ±0.15 μm, which can realize the movement of 1 micron step to ensure that the relative motion of the tool and the tool set are micron-sized. When the tool set approaches the tool module and reaches the discharge gap ‘d’, the medium between the tool and tool set discharges. At this time, the coordinates of the micro-motion table are read by the fine-motion table control software, and the gap of the tool nose and the tool set are determined based on the discharge coordinate. The lifting platform is used to adjust the height of the tool set in the Z direction so that the tool nose can face the center of the tool block. The macro motion platform realizes the rapid approach or away movement in the X direction between the tool and the tool set, facilitating the installation and disassembly of the tool and the tool set, preventing accidental collision of the tool and tool set induced by the narrow space of the installation and disassembly process. The tool module consists of block, insulation pad and fixed block. The block ensures that the tool and the tool set are approximately at the same height in Z direction. Insulation pad insulates tool from fixed block and block, so that in the experiment, a certain voltage value can be applied to tool. The function of the fixed block is to fix tool. The signal acquisition part is a dedicated signal acquisition circuit board. Its function is to apply a voltage to tool, and ground tool set, so that a potential difference is formed between tool and tool set. The signal acquisition circuit board can get the potential difference and response to potential difference changes in a millisecond and convert the analog signal of such a potential difference into a 24V I/O pulse signal that can be recognized by the machine. When there is no discharge between tool and tool set, a 0V signal is output. When tool and tool set are discharged, a 24V signal is output. The signal display part is an oscilloscope for observing the signal output from the signal acquisition circuit to determine whether the tool is discharged between the tool and the tool set.

The tool setting process is shown in Figure 3 and Figure 4. First, tool set is installed on the micro motion platform, then it is connected to ground and the V_g on the signal acquisition circuit board. Next, the tool is placed in contact with tool set and the multimeter is used to connect to tool and tool set to ensure that the tool and the tool set are in contact. If the multimeter does not emit a beep, the two parts
are not in contact. Then the tool is requested to move by hand to the position of the tool set until the multimeter beeps. After the tool and tool set are in contact, the screw on the fixed block tightened to fix the position of the tool. Then the tool is connected to the \( V_{in} \) port of the signal acquisition circuit board. A certain relative force between the tool set and the tool causes the two parts to elastically deform. After the above steps, the gap between the tool and tool set ‘D’ is defined as \( D_1 \), and the value of \( D_1 \) should be less than 0 because of elastic deformation, as shown in the state of 1 in Figure. 4. The position of the tool at this time is referred to as the installation position. Before the experiment, we put the tool and tool set in contact by hand, instead of letting them in a separate state at the beginning and then gradually approaching until them in contact to protect the high precision micro motion platform and tool nose from collisions damage caused by overshoot or misoperation. After ensuring that the tool and tool set are in contact, the tool set is moved away from the tool in X direction by the micro motion platform in 1 micron steps, and the continuity between the tool and tool set is measured with a multimeter buzzer for each movement of 1 micron. When the multimeter buzzer does not ring, record the coordinates at this time in the 7 micro motion platform control software, at this time the distance D between the tool and tool set is defined as \( D_2 \), \( D_2 \) is theoretically equal to 0, as shown by the state 2 in Fig. 4, defining the position at this time as the critical position. On the basis of the critical position, micro motion platform is moved away from the tool 15 microns, arriving the ‘initial position’ of the tool setting process, as shown in the state of 3 in Fig. 4. The gap between the tool and tool ‘\( D_3 \)’ set is 15 microns when the tool set is in ‘initial position’. Then the signal acquisition circuit board is connected to the 24V AD power, moving the micro motion platform to make the tool set approaching the tool in 1 micron steps, and monitor the voltage waveform of the oscilloscope. When the voltage changes from 0V to 24V, we stop moving and getting the coordinates. The position the voltage becomes 24V is called as ‘discharge position’ and the tool clearance ‘\( D_4 \)’ is the difference of the coordinate of discharge position and critical position. This is the completion of a single tool setting process experiment. After each tool finds the installation position and the critical position in the first tool setting process experiment, it will not be disassembled until all experiments are done. Therefore, the process of finding the installation position and critical position is only needed in the first experiment and doesn’t repeat in the rest experiment. In addition to the first tool setting experiment, the repeated tool setting experiments will start from the initial position. After completing all the expected experiments, we move the macro motion platform to move the tool set away from tool, then remove the tool and tool set.
Begin

Install tool set

1. put the tool in contact with tool set

The tool and tool set in contact?

Yes

Fix the tool

2. move the tool set to critical position

3. move the tool set to initial position

Connect the signal acquisition circuit board to power

The tool set approach the tool in 1 micron step

The voltage in oscilloscope change from 0 to 24

Yes

4. record the discharge gap D_e

No

Experiment times ‘n’ =100

Yes

End

Figure 3. the schematic view of the experiment process
3. Results and discussion

According to the above experimental method, the influence of different tool setting times and discharge duration on the shape of the tool nose is studied. The size of the experiment tools, and the tools nose are shown in the figure 5. The side cutting edge angle of the tool $\kappa_{g}$ is 93˚, the back rake angle $\gamma_{o}$ is 0˚, the back clearance angle $\alpha_{g}$ is 7˚, the cutting edge angle $\varepsilon_{g}$ is 55˚, and the nose radius of the tool is 0.1mm. The cutter of the entire tool is 10*10*100mm³ and the length of the tool nose is 10mm.

Firstly, the experimental research on the tool clearance $D_{4}$ and the shape of the tool nose before and after the tool is carried out under the experiments of multiple tool setting times and multiple discharge duration. The purpose is to explore the influence of the tool setting times $n$ to the tool clearance $D_{4}$ and the effect of discharge duration $T$ on the shape of the tool nose. The specific parameters of the experiment are shown in Table 1. 6 tools as is shown in Figure 5 in total have been used in the experiment, the shape and surface state of which has been observed under the microscope. As shown in Figure.7. After the observation, the experiment starts. The 6 tools are divided into 6 groups of experiments, which are respectively recorded as G1, G2, G3, G4, G5 and G6. The discharge duration $T$ of each group is set to be less than 1 s, 1 s, 2 s, 3 s, 4 s, 5 s, respectively. The tool setting times of all group are equal to 100. The tool setting experiment is carried out according to the flow of Figure.3, and the tool clearance $D_{4}$ of every tool setting experiment is recorded. After completing 100
repeated tool setting experiments, record the data and observe the shape and state of the tool nose using a microscope, and record the image as shown in Figure.7.

Table 1. The parameters of the experiments

| Experiment group parameters | G1  | G2  | G3  | G4  | G5  | G6  |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| Discharge duration, T/s     | <1  | 1   | 2   | 3   | 4   | 5   |
| Temperature                 | 24℃ |     |     |     |     |     |
| Humidity                    | 16.5%RH |     |     |     |     |     |
| Atmospheric pressure        | 1011Pa |     |     |     |     |     |
| Tool setting times, n       | 100 |     |     |     |     |     |
| VCC                         | 24V |     |     |     |     |     |
| Vin                         | 3.5V|     |     |     |     |     |
| The steps of micro motion   | 0.001 mm |     |     |     |     |     |
| The speed of macro motion   | 5 mm/s |     |     |     |     |     |

The tool used in the experiment was a carbide tool, and the dimensions of the blade are shown in Figure 2. After the experiment was completed, the position of the tool was recorded and the change of the position of the tool with the number of times of the tool was made, and the nose of the blade was observed using a laser confocal microscope of Olympus.

Figure 6 shows the relationship between the tool clearance D4 and the tool setting times n of the 6 group of experiments. It can be seen from the figure that the G1 has the most stable tool clearance. Among the 100 experiments, the tool clearance is 0.002mm only 2 times, and the other 98 times are 0.001mm. The tool clearance of G2 stabilized at 0.002mm in the first 80 times, and then changes to 0.003mm. In G3 group, the tool clearance of the first 40 times experiments was stabilized at 0.001 mm, and then the tool clearance was stabilized at 0 mm. The G4 group's discharge gap is divided into three sections. At the first 30 times experiments, the tool clearance is stable at 0.001mm. At the 31-70th experiments, the discharge gap is stable at -0.002mm. After 70 times experiments, the discharge gap changes to -0.003mm. The G5 discharge gap is also divided into three sections, At 0-20 times experiments, the discharge gap is 0.001m. The discharge gap is 0.002mm at the 21-50 times experiments and at the last half of the 100 times experiments, tool clearance is 0.003mm. The G6's tool clearance is divided into a number of small segments. The tool clearance increases 0.001mm with an average of 9 times experiments. The tool clearance of the first experiment is 0.001mm. After 100 times experiments, the tool clearance has been increased to 12mm.

Of the above six groups of experiments, only the tool clearance D4 of the G1 did not change with the increase of the tool setting times. The tool clearance of other five groups varies with the tool setting times. Moreover, it can be seen from the figure 6 that when the discharge duration is 1s<T<4s, the tool clearance is gradually becoming smaller, and when T≥4s, the trend of tool clearance changes is gradually increasing. The gas atmosphere and potential difference during the experiments remain unchanged, so it is only possible that the change in the shape of the tool nose causes a change in the tool clearance. Therefore, it can be concluded that with the increase in tool setting times, the changes of the tool clearance D4 is related to the discharge duration T. When T<1s, the tool clearance D4 does not change with the tool setting times. When 1s<T<4s, the tool clearance D4 decreases. The tool clearance D4 gradually increases as the tool setting times increases, when T≥4s.
Figure 6. the tool clearance change with experiment times

Figure 7 is the photomicrograph of the shape of the nose before and after the experiments. The actual discharge position should be at the right side of the tool nose because the tool nose head to right. It can be seen from the photo in Figure 7(a), (b) that the G1 group emerges a little blackening at the right end of the tool nose after the experiments and the contour of tool nose changes from a complete arc to several separate boundaries. After 100 times of tool setting experiments of the G2 group in Figure 7(c), (d), the protrusion of the original tool edge arc has disappeared, and a row of pits separated from each other appears at the right end of the tool edge arc. For G3 group in Figure 7(e), (f), part of the tool nose arc appears the overall rearward movement and at the rear of the contoured rearward, a severely ablated black pit appeared. In the G4 group in Figure 7(g), (h), the right side of the tool nose has a larger overall rearward movement than G3, and the entire right half of the tool nose has moved backwards. The right side profile of the G5 group didn’t move backwards in Figure 7(i), (k), but the pits were also very noticeable, and two small burrs of up to 20 μm were grown on both sides of the nose. The contour of the tool nose of the G6 group in Figure 7(k), (l), was completely changed, and a black giant columnar structure of up to 60 μm was grown.

From the above results, after 100 times experiments, the discharge current will damage the tool nose. The condition and extent of the damage is related to the discharge duration T. When T<4s, the influence of the discharge current on the tool is mainly caused by the impact of the current, which forms pits and breakage on the tool surface. When the discharge time is short, the tool nose damage is mainly the pit caused by the discharge arc impact, and when the discharge time increases, the pits become gradually larger and larger, and finally join together to form an overall back shift of the tool nose profile. When the discharge duration T is greater than or equal to 4s, the effect of the discharge current on the tool is no longer the pit caused by the arc impact, but the growth of burrs caused by the huge energy brought by the continuous action of the current changes the shape of the tool nose.
Figure 7. The tool nose under laser confocal microscope before and after the experiments. (a) The tool nose of G1 before experiment; (b) the tool nose of G1 after 100 times experiments; (c) the tool nose of G2 before experiment; (d) the tool nose of G2 after 100 times experiments; (e) the tool nose of G3 before experiment; (f) the tool nose of G3 after 100 times experiments; (g) the tool nose of G4 before experiment; (h) the tool nose of G4 after 100 times experiments; (i) the tool nose of G5 before experiment; (j) the tool nose of G5 after 100 times experiments; (k) the tool nose of G6 before experiment; (l) the tool nose of G6 after 100 times experiments.
As the breakdown discharge time increases, the shape of the nose changes to a different extent. This is because during a brief discharge, the impact of the arc has a large influence on the nose, the nose is broken by the arc, finally resulting in the nose becoming shorter. At the same time, the discharge gap \(d\) is not changed, so the tool set move closer to the tool, which makes the \(D_4\) become smaller. In the process of long-term continuous discharge, the heat generated by the arc has a great influence on the tool nose, and the heat is not easily diffused at the tool nose, eventually causing the heat to accumulate on the tool nose, at the same time, the edge of the tool is gradually broken due to the impact of the arc, resulting in an alternating distribution of the spikes and the pits. The growth of the spikes always follows the direction of the arc, which causes the length of the nose to increase, and the actual discharge gap \(d\) is fixed, which leads to a change in the discharge position. As a result, the \(D_4\) is increased.

4. Conclusion
In this paper, the experimental study on the difference of tool clearance \(D_4\) and the damage of the shape of the tool nose before and after the tools are carried out under the conditions of multiple tool setting times and multiple discharge duration. The purpose of the experiment was to investigate the effect of tool setting times \(n\) on the tool clearance \(D_4\) and the effect of the discharge duration \(T\) on the shape of the tool nose. The conclusions obtained from the experimental results are as follows:

1. With the increase in the tool setting times, the change of the tool clearance \(D_4\) is related to the discharge duration \(T\). When \(T<1\)s, the tool clearance \(D_4\) does not change with the change of the tool setting times. When \(1<s<T<4\)s, the tool clearance \(D_4\) decreases. The tool clearance \(D_4\) gradually increases as the tool setting times increases, when \(T\geq4\)s.

2. After 100 tool setting experiments, the discharge current will damage the tool nose. The condition and extent of the damage is related to the discharge duration \(T\). When \(T<4\)s, the influence of the discharge current on the tool is mainly caused by the impact of the current, which forms pits and breakage on the tool surface. When \(T\geq4\)s, the effect of the discharge current on the tool is no longer the pit caused by the current impact, but the growth of burrs caused by the huge energy brought by the continuous action of the current changes the shape of the tool nose.

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