Experimental Study of Tool Wear in Electrochemical Discharge Machining

Jianxiao Bian 1,2, Baoji Ma 1,3,*, Xiaofeng Liu 1 and Lijun Qi 1

1 School of Mechanical Engineering, Xi’an Technological University, Xi’an 710021, China; jxbian@ldxy.edu.cn (J.B.); xiaofengliu@163.com (X.L.); qilijun@xatu.edu.cn (L.Q.)
2 School of Mechanical Engineering, Longdong University, Qingyang 745000, China
3 Shaanxi Key Laboratory of Non-Traditional Machining, Xi’an 710021, China
* Correspondence: mabaojee@163.com; Tel.: +86-133-1920-9983

Featured Application: In this work, the problem of ECDM tool wear is investigated, which has important engineering significance for the high-precision and low-cost machining of ECDM.

Abstract: Electrochemical discharge machining (ECDM) is an emerging special processing technology for non-conductive hard and brittle materials, but it may encounter the problem of tool wear due to its process characteristics, which affects the processing accuracy. In this study, in the non-machining state, the tungsten carbide spiral cathode with a diameter of 400 µm was selected to analyze the influencing mechanism of the process parameters on tool wear, and a suitable voltage range for the processing was obtained. The influence of the cathode’s loss behavior on the film formation time and the average current of spark discharge was discussed based on the current signal. The results show that the tool wear mainly appears from the bottom to the end and edge tip of the protrusion. Loss is mainly in the form of local material melting or gasification at high temperature. In addition, the loss may shorten the film formation time, but the effect on the average current of spark discharge is small.

Keywords: ECDM; tool wear; tool cathode; film formation time; average current of spark discharge

1. Introduction

Electrochemical discharge machining (ECDM) is an emerging special processing technology, which has the advantages of high efficiency, good flexibility and low cost [1–4]. It can be used to handle non-conductive hard and brittle materials with fine structure [5,6]. With the development of micro-electromechanical system (MEMS) and microfluidics technologies, higher technical requirements are raised for the microfabrication of non-conductive materials, such as glass, ceramics, and carbon fiber-reinforced polymer (CFRP) material. ECDM has rapidly developed and been studied as an important processing method [7–9]. Especially for the micro-machining of hard and brittle material with complicated 3D structures, many studies have been conducted to improve the machining precision, such as changing the motion control approach [10], parameter optimization using the response surface method [11] and building the tool wear simulation model [12]. In the ECDM drilling test for CFRP, the factors which affect the machining precision are from various aspects, including tool wear, the stability of gas film, the electrolyte components and the CFRP machining process.

The machining process of ECDM is as shown in Figure 1. The tool electrode (cathode) and the auxiliary anode are immersed in the electrolyte, respectively, and then respectively connected to the negative and positive anodes of the pulse power supply. When a voltage is applied, the electrochemical reaction occurs, and hydrogen and oxygen are generated on the surface of cathode and auxiliary anode. The electrochemical reaction intensifies with the increase in voltage. Part of the hydrogen escapes from
the surface of the cathode, and part is fused between bubbles. When the critical voltage is reached, the generation rate of hydrogen bubble equals to its escape rate, and an insulating gas film is formed on the cathode surface via fusion. As a result, the cathode is completely separated from the electrolyte, and a potential difference is generated. Under the effect of potential difference, electric discharge occurs, and sparks are generated. The workpiece is eroded by high-temperature melting. But this process is often accompanied with the tool wear, On the one hand, the tool wear has causes the change of tool length, and the immersed depth of the cathode also changes accordingly, which results in the insufficient feed of the cathode, and the machining precision cannot be guaranteed. On the other hand, the tool wear has also led to the deterioration in the stability of the gas film, and as a result, the gas film formation time and average spark discharge current present significant fluctuations, while the fluctuation in the spark output energy affects the machining stability, which greatly affects the stability and machining accuracy [13]. Therefore, it is especially necessary to study the tool wear of ECDM.

In 1968, Kurafuji and Suda [14] applied the spark discharge generated in the electrolysis process in the hole machining of non-conductive glass material for the first time. Since then, many studies on the ECDM process have been conducted. Yang et al. [15] observed the loss and machining over-cutting of tungsten carbide, tungsten and 304 stainless steel cylindrical cathode materials with the diameter of 200 μm in the 5 mol/L KOH electrolyte and under the speed of 500 rpm and a voltage of 28–46 V. They pointed out that the corner of the tool electrode has the highest current density, which increases in wear near the corner. The degree of wear is related to the melting point and thermal conductivity of the cathode material. By comparing the performances of three materials, it is found that when the tungsten carbide material is used as the cathode, it results in smaller overcutting and lower tool wear. Behroozfar and Razfar [16] studied the loss of brass, steel and tungsten carbide cathodes with different melting points at a high voltage, and used the tungsten carbide cathode for the micro-machining of ceramics. They believed that the loss may be tool loss caused by the increase in the surface temperature of the electrode, and this rise in temperature was triggered by discharge. The tungsten carbide and steel with higher melting points can be used to reduce the tool loss at high voltage. Ziki and Wüthrich [17] conducted a quantitative analysis of the tool loss and thermal expansion of three different tool electrode materials (tungsten, steel and stainless steel) and measured the thermal expansion of the tool electrode. According to their research results, stainless steel has the highest tool expansion rate and less tool loss, the surface temperature of the electrode can be controlled by applying pulse voltage, and the machining accuracy can be improved by using stainless steel. Kim et al. [18] studied the effect of pulse voltage on the heat-affected zone (HAZ) of the copper cathode with 250 μm diameter in the 25 wt%
KOH electrolyte and the 40 V voltage. According to the experimental results, they drew the conclusion that the derivation of the shape and size in hole machining will increase with a smaller diameter tool. In addition, the wear rate of the auxiliary anode (graphite) was also studied in their work. In summary, the researchers believed that tool wear is mainly caused by the melting or gasification of the partial material of cathode, due to a rise of surface temperature. The severity of wear was related to the melting point and thermal conductivity of cathode material.

A review of relevant literature shows that there has been no extensive research on the tool wear for ECDM. During ECDM machining, on the one hand, the immersion depth (Z axis) of the cathode and the surrounding electrolyte environment will change. On the other hand, the cathode will contact the anode, which will change the state of spark discharge. As a result, it becomes difficult to analyze tool wear. We aim to reveal the influence mechanism of machining parameters on tool wear, such as voltage, frequency, duty cycle, spindle speed, and the electrolyte concentration. In this paper, in the non-machining state (the CFRP workpiece exists and the cathode immersion depth is fixed), a spiral tungsten carbide cathode of 400 µm in diameter was selected, and its tool wear is discussed. The voltage range suitable for machining was obtained. Combined with the current signal, the relationship among the tool wear, the gas film formation time and the average current of spark discharge was investigated. The study of the tool wear can provide a theoretical basis for the promotion and application of the ECDM process, which has certain engineering significance for the high-precision and low-cost machining of ECDM.

2. Experimental Settings

2.1. Experimental Equipment

The ECDM experimental system includes a power supply system, a machine tool system, a microelectrode system, and a machining control and monitoring system. The power supply system uses AN12010D-M single-pulse power supply (Ansi, Wuxi, China), which can provide 0–120 V voltage, frequency within 10 KHz and 0–100% duty cycle. The machine tool system is composed of a three-axis simultaneous machining platform, an air floatation test bed, a high-speed electric spindle, and fixtures. The air floatation test bed can maintain the stability of the machining platform and ensure the accuracy of the spindle at high speed. The microelectrode system includes a spiral tungsten carbide electrode, electrolytic cell, electrolyte, fixture, and a lifting platform. The machining control and monitoring system consist of the MP-C154 motion control card, A622 current probe (Tektronix, Shanghai, China), TBS1104 digital storage oscilloscope (Tektronix, Shanghai, China) and a B013 Supereyes (SuperEye, Shenzhen, China). The current probe was used to monitor the current signal in a real-time manner, and the data were output from oscilloscope. The key performance indicators of the digital storage oscilloscope include the 100 Mhz bandwidth, four channels and the 1 GS/s sampling rate. Supereyes is a portable digital microscope with 13 million pixels, which can achieve 1–2000 magnification. It is mainly used for process observation, image capturing, and tool (tool immersion depth) setting. As shown in Figure 2, the experiment was conducted in an environment with a constant temperature of 20 ± 0.3 °C. The tool wear was observed using a NOVA NANOSEM 450 scanning electron microscope (Hillsboro, OR, USA). The BSM-220.4 electronic balance (Zhuojing, Shanghai, China) was used to measure the amount of the cathode weight loss, which has an accuracy of 0.0001 g. Vernier caliper was used to measure the cathode length loss, and the precision was 0.02 mm.
Figure 2. ECDM experimental system: (a) the schematic diagram; and (b) the actual view.

2.2. Materials

According to the previous research literature [19–22], the tungsten carbide electrode was selected. According to the research of Fang et al. [23], in wire electrochemical discharge machining (WECDM), when a spiral electrode was used, the axial updating speed of electrolyte was accelerated, and the uniformity of the slit width in the depth direction was enhanced. Liu studied the machining locality of the spiral electrode in the WECDM process, and fabricated a series of kerfs with 138 μm wide [19]. For this reason, the spiral electrode was selected. Secondly, tool wear is related to the cathode size. In order to better compare the tool wear, a spiral tungsten carbide electrode with a 400 μm diameter was selected (Aoshi, Shenzhen, China). This spiral electrode has the shape of a two-edged drill. Table 1 shows the geometric dimensions and physical properties of the tool electrode. The workpiece is made of carbon fiber-reinforced polymer (CFRP) composite material (Hengjing Shenzhen, China), using the laminated plate and plain weave fabric. The fiber volume was 65%, the base material was epoxy resin, and the size was 25 mm × 25 mm × 1 mm.

Table 1. Geometric dimensions and the physical properties of the tool electrodes.

| Parameters                  | Values                                      |
|-----------------------------|---------------------------------------------|
| Geometric dimensions        | ![Diagram of geometric dimensions]           |
| Melting point               | 3140(°C)                                    |
| Hardness                    | 92(HRA)                                     |
| Thermal conductivity        | 50.2(W/K·m, at 20 °C)                       |
According to the principle of electrochemical discharge machining, as the power is turned on, the system will undergo an electrochemical reaction. Hydrogen and oxygen are generated at the cathode and anode, respectively. The chemical equations is:

\[
\text{Cathode: } 2H_2O + 2e^- \rightarrow 2(OH)^- + H_2 \uparrow \quad (1)
\]

\[
\text{Anode: } 4(OH)^- - 4e^- \rightarrow 2H_2O + O_2 \uparrow \quad (2)
\]

In ECDM, alkaline solution is usually used as the electrolyte. In this research. The electrolyte used in the ECDM experiment was 5-15-25 wt% sodium hydroxide (Zhiyuan, Tianjin, China). In addition, \( Fe^{2+} \) in the solution may combine with other ions, or migrate to the cathode and deposit. When \( Fe^{2+} \) is combined with hydroxide ion, then:

\[
Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \downarrow \quad (3)
\]

\( Fe(OH)_2 \) has little solubility in water, which will precipitate. In order to prevent the interference of other ions with the experimental reaction process, the electrolyte was prepared using the sodium hydroxide solute and deionized water in proportion. The auxiliary anode used in the experiments is cylindrical graphite of Ø10 mm.

2.3. Experimental Procedure

In order to ensure the accuracy of the experiment and avoid unexpected effects, each experiment was repeated three times and the average values are reported in the results. In order to ensure that the electrochemical system was composed of cathode, workpiece, electrolyte and the auxiliary anode in actual machining, the CFRP workpiece was set up in this experiment. However, the CFRP workpieces were not machined in the study on tool wear. Among the experimental parameters, the immersion depth is the immersion depth of the cathode, which refers to the distance between the surface of the electrolyte and the bottom of the cathode. The immersion depth of the auxiliary anode is the height of the auxiliary anode immersed in the electrolyte in the electrolytic cell, and the auxiliary anode is not completely immersed in the electrolyte. The experimental parameters are as shown in Table 2. The experimental procedure is as follows:

(a). Use deionized water to prepare the sodium hydroxide electrolyte, and cool it to room temperature; record the weight of the tool electrode.

(b). Fix the auxiliary anode in the electrolytic cell and connect to the anode of power supply; clamp the tool electrode onto the principal axis (Z axis) and connect to the cathode of the power supply. Fix the workpiece on the support plate.

(c). In order to ensure the immersion depth is 2 mm, control the feed of cathode in the Z axis direction. Using Supereyes to observe the distance between the cathode and the surface of the electrolyte, when the bottom of the cathode contacts the surface of the electrolyte, feed downward for 2 mm. Then, turn on the air pump and the pulse power in sequence, check the voltage and current signals, and store the data with an oscilloscope.

(d). After the experiment is finished, take out the tool cathode, weigh the tool cathode and record the data after air drying. Observe the surface morphology of the cathode using a scanning electron microscope.
Table 2. Experimental parameters.

| Parameters                        | Values                                                      |
|-----------------------------------|-------------------------------------------------------------|
| Cathode material                  | Ø400 µm spiral tungsten carbide                            |
| Auxiliary anode                   | Ø10 mm cylindrical graphite                                 |
| Voltage (V)                       | 28–44 step 1; 44–64 step 2                                 |
| Immersion depth (mm)              | 2                                                          |
| Processing time (s)               | 200                                                        |
| Rotating speed (rpm)              | 1000, 2000, 3000                                           |
| Electrolyte concentration (wt% NaOH) | 5, 15, 25                                               |
| Frequency (Hz)                    | 500, 1500, 2500                                            |
| Duty cycle (%)                    | 30, 50, 70                                                 |

3. Results

Table 3 lists the amount of cathode weight loss and the length loss under the experimental parameters, and Figure 3 shows the SEM images of the tool electrode under the different experimental parameters. Figure 4 presents a sample of a dynamic current signal at the voltage of 52 V. In this set of current signals, the power supply outputs two signal pulses. The t1 stage is mainly a process in which the electrochemical reaction occurs, the bubbles are generated, and they combine with each other to form the gas film. During this process, the current is large and unstable. This period of time is called the gas film formation time. When the voltage is applied, the circuit forms a loop, and the current instantly reaches a high value. At the same time, a large number of bubbles are generated on the electrode surface due to the electrochemical reaction. The generation of bubbles will squeeze out the electrolyte around the tool electrode, which is equivalent to increasing the impedance between the tool electrolyte and the electrolyte, and the current will gradually decrease as a result. For pulsed power supplies, there is a period for gas film formation at the beginning of each pulse cycle. The formation time of gas film is directly related to the machining efficiency [24]. t2 is the spark discharge stage. At this stage, due to the potential difference between the tool electrode and the electrolyte, discharge occurs, which generates sparks. It can be seen from Figure 4 that it is a disordered spark discharge state, and the current is mainly concentrated in the range of 200–300 mA. The average current is 256.3 mA. The average current affects the quality and efficiency of electrochemical discharge machining to a certain extent.

Table 3. Weight loss of cathode (Y) and the length loss of cathode (Z) in the ECDM process.

| A  | 28  | 32  | 36  | 40  | 44  | 48  | 50  | 52  | 54  | 56  | 58  | 60  | 62  | 64  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| V  | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| Z  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |

| B  | 500 | 1500 | 2500 | 500 | 500 | 70  |
|----|-----|------|------|-----|-----|-----|
| C  | 52 V, 50%, 15 wt%, 2000 rpm | 52 V, 1500 Hz, 15 wt%, 2000 rpm |
| Y  | 6.6 | 7.2  | 9.7  | 2.6 | 6.6 | 12.5|
| Z  | ~0  | ~0   | ~0   | ~0  | ~0  | ~0  |

| D  | 5   | 15   | 25   | 1000 | 2000 | 3000 |
|----|-----|------|------|------|------|------|
| E  | 52 V, 1500 Hz, 50%, 2000 rpm | 52 V, 1500 Hz, 50%, 15 wt% |
| Y  | 1.4 | 6.6  | 8.5  | 7.5  | 6.6  | 8.6  |
| Z  | ~0  | ~0   | ~0   | ~0   | ~0   | ~0   |

\[1\] A: voltage; B: frequency; C: duty cycle; D: electrolyte concentration; E: rotating speed.
Figure 3. SEM image of the tool electrode under different experimental parameters.

Figure 3. Cont.
From the findings, changes in the voltage in the cathode present a trend. Figure 4. Current signal sample.

Figure 3. SEM image of the tool electrode under different experimental parameters.

Figure 4. Current signal sample.
4. Discussion

4.1. Tool Wear

In electrochemical discharge machining, when the voltage does not reach the critical voltage, there are not enough bubbles generated by the electrochemical reaction to form an insulating gas film on the cathode. When the critical voltage is reached, the generation rate and escape rate of the bubbles are equal, which can form an insulating gas film on the cathode and discharge to generate sparks. In general, more electrochemical energy can be provided by increasing the voltage, thus resulting in more frequent spark discharges. However, tool wear may also occur. Therefore, the cathode critical voltage of 28 V was chosen as the starting voltage in the experiment. Within the range of 28–64 V, the cathode weight loss is shown in Figure 5a. It can be seen that when the voltage is below 44 V, the cathode has almost no loss. On the one hand, the negative cathode weight loss may be caused by measurement error due to the impurities attached to the cathode when it is exposed to air. On the other hand, according to the study of Nasim Sabahi and Mohammad Reza Razfar [25], in the sodium hydroxide electrolyte, granular or flocculent particles may condense on the cathode surface after the cooling of electrolyte, and this may also cause an increase in the weight of the cathode, as shown in Figure 6b,c. This phenomenon was also found at high voltage, as shown in Figure 6d. Above 44 V, the cathode weight loss increases sharply with the increase in voltage. Similarly, with the increase in frequency, duty cycle and electrolyte concentration, the cathode weight loss shows an increasing trend, but no linear relationship seems to be presented between the speed and the cathode weight loss, and the variation range of the cathode weight loss is very small. The cathode length loss is shown in Figure 5b. It can be seen that at low voltages, the cathode length almost does not change; when the voltage exceeds 58 V, the cathode length presents significant reduction. The shortening of the cathode changes the immersion depth.

As can be seen from Figure 3, the tool wear mainly occurs at the end and the bulge part of the edge, and the loss is diffused from the edge tip to the root. This phenomenon is consistent with the findings of Jiang et al. [6]. They pointed out that a higher current density will be generated near the edge of the tool electrode, and more severe wear is expected to occur at the edge of the tool electrode. From the perspective of energy, high voltage provides more energy, and the energy transferred to the cathode in the form of thermal energy through spark discharge will also increase. When the local temperature of the cathode reaches the melting point, local melting and even the vaporization of material may occur. However, the spark discharge is denser at the end of the cathode and at the part with the edge bulge. Therefore, the tool wear is more likely to occur at these locations, as shown in Figure 6e,f. In addition, the tungsten carbide cathode is manufactured with powder metallurgy. Behroozfar and Razfar [16] pointed out that the surface temperature of tool electrode will rise to 2800 °C at the voltage of 50 V. At high temperatures, the tungsten carbide material may melt and remain in the electrolyte in the form of powder. There is also less debris remaining on the electrode surface. Therefore, at higher voltages (>56 V), there is dense concave shape loss in the spiral inner concave of the cathode.

When the duty cycle increases, the spark discharge time $t_2$ will also increase accordingly, and more energy will be transferred to the cathode. More severe tool wear has occurred in this case. The input energy decreases with the increase in frequency. According to the research by Zhang et al. [26], the critical voltage is proportional to frequency. At lower pulse frequencies, the critical voltage will increase sharply, and more energy is required to generate spark discharges. Therefore, in the process of increasing frequency, the energy required to generate spark discharges declines. According to the law of energy conservation, more energy may be transferred to the cathode, and loss occurs. The increase in electrolyte concentration also lowers the critical voltage. Although the spindle speed is conducive to the discharge of products in electrochemical discharge machining and the improvement of machining accuracy, it has almost no effect on the critical voltage [26]. In the case of constant energy, theoretically, the application of speed causes the bubbles on the cathode surface to generate a centrifugal force in the opposite direction to the surface tension. Large bubbles are more likely to fall off the surface of
the cathode under the effect of buoyancy and centrifugal force, resulting in instantaneous conduction among the electrolyte and the electrode and the generating electrolytic current. According to the research of Cheng et al. [24], if there is electrolytic current generated between the electrolyte and the electrode due to the defect of gas film, it has almost no effect on the tool electrode. Therefore, the spindle speed has little effect on the tool wear.

The relationship between the voltage and tool wear is shown in Figure 5. (a) the cathode weight loss; and (b) the cathode length loss.

Figure 6. Cont.
voltage, and the bubble generation rate increases significantly, which significantly shortens the gas film formation time. With the further increase in voltage, the shortening of gas film formation time becomes significantly shortened. This is because the electrochemical reaction intensifies with the increase in voltage. The data collected at the beginning of the experiment are represented by Start, and End is the data collected after 200 s, which can reflect the change in the gas film formation time. When the voltage is low, the gas film formation time is long; as the voltage increases, the gas film formation time will be significantly shortened. This is because the electrochemical reaction intensifies with the increase in voltage, and the bubble generation rate increases significantly, which significantly shortens the gas film formation time. With the further increase in voltage, the shortening of gas film formation time becomes slower and eventually stabilizes. The trend in the gas film formation time before and after machining is consistent. From another perspective, according to Wüthrich et al. [27], the gas film formation time is related to the time required by the local heating of electrolyte, which also depends on the resistance between the electrodes (local temperature of the electrolyte). At high voltages, the spark discharges become more intense, and the conductivity of the electrolyte is enhanced with the increase in the local temperature of the electrolyte, leading to the decrease in resistance between the electrodes. As a result, the gas film formation time is shortened. This is also consistent with the experimental results.

**Figure 6.** Partial view of the tool wear under different voltages: (a) the base tool; (b) 28 V, 500 Hz, 50%, 15 wt%, 2000 rpm; (c) 28 V, 500 Hz, 50%, 15 wt%, 2000 rpm; (d) 52 V, 500 Hz, 50%, 15 wt%, 2000 rpm; (e) 52 V, 500 Hz, 50%, 15 wt%, 2000 rpm; and (f) 58 V, 500 Hz, 50%, 15 wt%, 2000 rpm.

**4.2. Film Formation Time**

Figure 7 shows the comparison of the gas film formation time before and after machining with the increase in voltage. The data collected at the beginning of the experiment are represented by Start, and End is the data collected after 200 s, which can reflect the change in the gas film formation time before and after the tool wears to a certain extent. It can be seen from Figure 7 that when the voltage is low, the gas film formation time is long; as the voltage increases, the gas film formation time will be significantly shortened. This is because the electrochemical reaction intensifies with the increase in voltage, and the bubble generation rate increases significantly, which significantly shortens the gas film formation time. With the further increase in voltage, the shortening of gas film formation time becomes slower and eventually stabilizes. The trend in the gas film formation time before and after machining is consistent. From another perspective, according to Wüthrich et al. [27], the gas film formation time is related to the time required by the local heating of electrolyte, which also depends on the resistance between the electrodes (local temperature of the electrolyte). At high voltages, the spark discharges become more intense, and the conductivity of the electrolyte is enhanced with the increase in the local temperature of the electrolyte, leading to the decrease in resistance between the electrodes. As a result, the gas film formation time is shortened. This is also consistent with the experimental results.

**Figure 7.** Relationship between the voltage and film formation time before and after machining.
When the cathode has loss after 200 s of machining, it can be seen from Figure 7 that the gas film formation time generally shows a decreasing trend, but the reduction is not significant. Zhang et al. [26], in their conclusion, stated that the critical voltage also increases with the increase in the diameter of the tool electrode. According to this conclusion, the critical voltage of the cathode after loss is reduced, and the energy required to generate spark discharges has also decreased. At the same critical voltage, the voltage is inversely proportional to the gas film formation time. Lowering its critical voltage will shorten the gas film formation time. Although the gas film formation time is shortened and the spark discharge time is increased in the same cycle according to the results, its processing efficiency is improved, but due to the small reduction, the improvement of processing efficiency is limited. Moreover, the loss of the cathode affects the machining accuracy.

4.3. Average Current of Spark Discharge

The magnitude and stability of the average current of spark discharge reflects the spark machining ability and the stability of gas film. As can be seen from Figure 8, the average current of spark discharge shows a trend to decrease slightly and then increase as the voltage increases. According to the research of Wüthrich et al. [27], it is known that in the process of electrochemical discharge, the current of the electrochemical reaction is much higher than the spark discharge current. When the voltage is low, the system has not entered the spark state of stable discharge, and the spark discharge is mixed with the electrochemical reaction. Therefore, the average current of the spark discharge is higher. During the gradual increase in voltage, the ratio of electrochemical reaction gradually decreases, the average current also decreases accordingly, and the average current slightly decreases. When the voltage continues to increase, the average current begins to increase gradually, and the spark discharge also becomes more intense.

However, the effect of tool wear on the average current of spark discharge does not seem to show a certain pattern, and the variation range before and after the loss is also very small. The average current decreases between 62 V and 64 V. In the experiments at these two voltages, the cathode showed significant loss, which led to the shortening of the blade length, and the depth of cathode immersed in electrolyte also changed accordingly, which reduces the average current as a result. Finally, the tool wear has little effect on the average current of spark discharge, which mainly depends on the voltage.

![Figure 8](image_url)  
*Figure 8. Relationship between the voltage and average current of the spark discharge before and after machining.*
5. Conclusions

In this study, the mechanism of the effect of the process parameters on tool wear was analyzed. By using the current signal, the influence of tool wear on the film formation time and the average current of spark discharge is discussed. The conclusions drawn from the experimental results are summarized as follows:

1. The tool wear increases sharply as the voltage increases. It is also directly proportional to frequency, duty cycle, and electrolyte concentration, but the speed has little effect on tool wear.
2. Tool wear mainly appears from the bottom upward to the tip and the bulge part of edge. The loss is mainly in the form of local melting or the vaporization of the material at a high temperature.
3. The gas film formation time is significantly shortened with the increase in voltage, and the tool wear will cause the gas film formation time to decrease.
4. In the process of voltage increase, the average current of spark discharge presents a rule of slight decrease first and then a sharp increase. The tool wear has little effect on the average current of spark discharge.

Author Contributions: Formal analysis: J.B.; investigation: J.B.; project administration: J.B.; writing—original draft preparation: J.B., X.L.; writing—review and editing: B.M., L.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by Open Research Fund Program of Shaanxi Key Laboratory of Non-Traditional Machining (Grant No. SXTZKFJJ202004), and the Doctoral Foundation Project of Longdong University (Grant No. XYBY1905).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tarlochan, S.; Akshay, D. Developments in electrochemical discharge machining: A review on electrochemical discharge machining, process variants and their hybrid methods. *Int. J. Mach. Tool Manuf.* 2016, 105, 1–13.
2. Pankajkumar, G.; Akshay, D.; Pradeep, K. Developments on electrochemical discharge machining: A review of experimental investigations on tool electrode process parameters. *P. I. Mech. Eng. Part B J. Eng.* 2015, 229, 910–920.
3. Li, J.; Li, H.; Hu, X.; Niu, S.; Xu, G. Simulation Analysis and Experimental Validation of Cathode Tool in Electrochemical Mill-Grinding of Ti6Al4V. *Appl. Sci.* 2020, 10, 1941. [CrossRef]
4. Shrivastava, P.K.; Dubey, A.K. Electrical discharge machining–based hybrid machining processes: A review. *P. I. Mech. Eng. Part B J. Eng.* 2013, 228, 799–825. [CrossRef]
5. Sundaram, M.; Chen, Y.J.; Rajurkar, K. Pulse electrochemical discharge machining of glass-fiber epoxy reinforced composite. *CIRP Ann.-Manuf. Tech.* 2019, 68, 169–172. [CrossRef]
6. Jiang, B.; Lan, S.; Ni, J.; Zhang, Z. Experimental investigation of spark generation in electrochemical discharge machining of non-conducting materials. *J. Mater. Process. Tech.* 2014, 214, 892–898. [CrossRef]
7. Liu, J.W.; Yue, T.M.; Guo, Z.N. Grinding-aided electrochemical discharge machining of particulate reinforced metal matrix composites. *Int. J. Adv. Manuf. Tech.* 2013, 68, 2349–2357. [CrossRef]
8. Wang, D.; He, B.; Cao, W. Enhancement of the Localization Effect during Electrochemical Machining of Inconel 718 by Using an Alkaline Solution. *Appl. Sci.* 2019, 9, 690. [CrossRef]
9. Beranoagirre, A.; Urbikain, G.; Calleja, A.; López de Lacalle, L.N. Hole Making by Electrical Discharge Machining (EDM) of γ-TiAl Intermetallic Alloys. *Metals* 2018, 8, 543. [CrossRef]
10. Sanchez, J.A.; de Lacalle, L.L.; Lamikiz, A.; Bravo, U. Dimensional accuracy optimisation of multi-stage planetary EDM. *Int. J. Mach. Tools Manuf.* 2002, 42, 1643–1648. [CrossRef]
11. Chaudhari, R.; Vora, J.J.; Mani Prabu, S.S.; Palani, I.A.; Patel, V.K.; Parikh, D.M.; de Lacalle, L.N.L. Multi-Response Optimization of WEDM Process Parameters for Machining of Superalastic Nitinol Shape-Memory Alloy Using a Heat-Transfer Search Algorithm. *Materials* 2019, 12, 1277. [CrossRef] [PubMed]
12. Sanchez, J.A.; Plaza, S.; Lopez de Lacalle, L.N.; Lamikiz, A. Computer simulation of wire-EDM taper-cutting. *Int. J. Comput. Integr. Manuf.* 2006, 19, 727–735. [CrossRef]
13. Kamaraj, A.B.; Jui, S.K.; Cai, Z.; Sundaram, M.M. A mathematical model to predict overcut during electrochemical discharge machining. *Int. J. Adv. Manuf. Tech.* 2015, 81, 685–691. [CrossRef]

14. Kurafuji, H. Electrical discharge drilling of glass I. *Ann. CIRP* 1968, 16, 415–419.

15. Yang, C.K.; Cheng, C.P.; Mai, C.C.; Wang, A.C.; Hung, J.C.; Yan, B.H. Effect of surface roughness of tool electrode materials in ECDM performance. *Int. J. Mach. Tools Manuf.* 2010, 50, 1088–1096. [CrossRef]

16. Behroozfar, A.; Razfar, M.R. Experimental Study of the Tool Wear during the Electrochemical Discharge Machining. *Mater. Manuf. Process.* 2015, 31, 574–580. [CrossRef]

17. Ziki, J.D.; Wüthrich, R. Tool wear and tool thermal expansion during micro-machining by spark assisted chemical engraving. *Int. J. Adv. Manuf. Tech.* 2011, 61, 481–486. [CrossRef]

18. Kim, D.J.; Ahn, Y.; Lee, S.H.; Kim, Y.K. Voltage pulse frequency and duty ratio effects in an electrochemical discharge microdrilling process of Pyrex glass. *Int. J. Mach. Tools Manuf.* 2006, 46, 1064–1067. [CrossRef]

19. Liu, Y.; Wei, Z.; Wang, M.; Zhang, J. Experimental investigation of micro wire electrochemical discharge machining by using a rotating helical tool. *J. Manuf. Process.* 2017, 29, 265–271. [CrossRef]

20. Nguyen, K.H.; Lee, P.A.; Kim, B.H. Experimental investigation of ECDM for fabricating micro structures of quartz. *Int. J. Precis. Eng. Manuf.* 2015, 16, 5–12. [CrossRef]

21. Liu, Y.; Zhang, C.; Li, S.; Guo, C.; Wei, Z. Experimental Study of Micro Electrochemical Discharge Machining of Ultra-Clear Glass with a Rotating Helical Tool. *Processes* 2019, 7, 195. [CrossRef]

22. Kang, X.; Tang, W. Micro-drilling in ceramic-coated Ni-super alloy by electrochemical discharge machining. *J. Mater. Process. Technol.* 2018, 255, 656–664. [CrossRef]

23. Fang, X.L.; Zhang, P.F.; Zeng, Y.B.; Qu, N.S.; Zhu, D. Enhancement of performance of wire electrochemical micromachining using a rotary helical electrode. *J. Mater. Process. Technol.* 2016, 227, 129–137.

24. Cheng, C.P.; Wu, K.L.; Mai, C.C.; Yang, C.K.; Hsu, Y.S.; Yan, B.H. Study of gas film quality in electrochemical discharge machining. *Int. J. Mach. Tools Manuf.* 2010, 50, 689–697. [CrossRef]

25. Sabahi, N.; Razfar, M.R. Investigating the effect of mixed alkaline electrolyte (NaOH + KOH) on the improvement of machining efficiency in 2D electrochemical discharge machining (ECDM). *Int. J. Adv. Manuf. Tech.* 2017, 95, 643–657. [CrossRef]

26. Zhang, Z.; Huang, L.; Jiang, Y.; Liu, G.; Nie, X.; Lu, H.; Zhuang, H. A study to explore the properties of electrochemical discharge effect based on pulse power supply. *Int. J. Adv. Manuf. Tech.* 2016, 85, 2107–2114. [CrossRef]

27. Wüthrich, R.; Spaelter, U.; Bleuler, H. The current signal in spark-assisted chemical engraving (SACE): What does it tell us? *J. Micromech. Microeng.* 2006, 16, 779–785. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).