Investigation of Influence of Low-level Voltage on Machining Characteristics in Pulse Wire ECM

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Abstract:
In pulse ECM, it has been found that the low-level voltage of the applied pulse influences the tool electrode wear and the machining accuracy. To attain a higher machining accuracy, the relationship between the low-level voltage and the machining accuracy was experimentally investigated in this study. It was found that a low-level voltage higher than 0V not only prevents tool electrode wear, but also improves the machining accuracy. In addition to the low-level voltage, the influence of the tool materials on the machining speed was also investigated. It was found that the different optimal low-level voltage depends on the tool material.

Keywords: ECM, pulse waveform, tool wear, machining accuracy, machining speed

1. INTRODUCTION

In recent years, the demand for micro-products and components has been increasing in various industrial fields such as precision apparatus and information communications apparatus. Therefore, techniques for producing these three-dimensional microcomponents are required.

Electrochemical machining (ECM) is a method that uses an electrolytic reaction to remove anode materials. ECM offers an advantage in that it can machine difficult-to-cut metallic materials and thus attain surfaces without any burrs or cracks, while there is no tool wear 1). Meanwhile, this method was previously regarded as being unsuitable for micromachining because the machining accuracy was low. It was recognized and reported that ECM with a pulse supply (PECM) instead of a direct current could improve the machining accuracy 2-3). Especially, microparts with complicated shapes could be machined with ultra-short pulsed ECM 4). However, tool electrode wear occurs depending on the material being used when a pulse power supply is used 5-6). This problem does not occur, regardless of the kind of material, when a direct-current power supply is used. As a desired shape is difficult to obtain owing to wear of the tool electrode during machining, it is necessary to reduce or eliminate the tool electrode wear if a higher machining accuracy is to be attained in PECM.

Endo et al. 6) reported that the use of a low-level voltage higher than 0V is effective for preventing wear to a tungsten tool electrode, and the use of a certain low-level voltage could improve the machining accuracy. However, the relationship between the low-level voltage and the machining characteristics, such as the machining accuracy and the machining speed has not been systematically investigated. Especially, the influences of the tool material and electrolyte have not yet been clarified. The low-level voltage called in this research is the offset voltage of a pulse, whose definition will be explained in chapter 2.

In this study, the influence of the low-level voltage on the machining characteristics was experimentally investigated for wire-ECM, to obtain a machining surface of a higher quality and expand the ECM application in micromachining. The optimal pulse waveform for preventing the tool electrode wear, as well as improving machining accuracy and machining speed was also investigated.

2. EXPERIMENTAL SETUP AND EVALUATION OF MACHINING CHARACTERISTICS

In this study, experiments and evaluations were performed with wire-ECM, in which a sheet workpiece is two-dimensionally machined with a fine wire electrode. Figure 1 is a schematic of the experimental setup. The sheet workpiece was mounted on a stage and fed in the +X direction toward the wire electrode for cutting. The power supply for the machining consisted of a function generator (NF Corporation, WF1965) to generate the
desired pulse signal, and a bipolar power supply (NF Corporation, BA4850) to amplify the pulse waveform to the level needed for machining. The electrolyte was supplied from a nozzle by a pump, instead of dipping the workpiece into the electrolyte, which enables stable machining due to the smooth removal of the by-products. The machining characteristics were evaluated based on the tool wear, machining accuracy, and machining speed. The tool wear was evaluated from the change in the tool shape before and after machining. If the tool was found to be thinner after machining, it was assumed that tool electrode wear occurred.

Figure 2 is a schematic of a machined groove. The machining accuracy was evaluated by the side gap-width. The side gap-width was obtained from the diameter of the wire and groove width, that is, the distance between the two parallel groove sides. As the side gap-width becomes smaller, the machining accuracy becomes higher. The machining speed was evaluated from the maximum tool feed rate, at which machining can be carried out without any electrical short-circuits. As the maximum feed rate is increased, so too does the machining speed. Figure 3 shows the waveform of the pulse voltage used in our experiments. The duty ratio is determined by Eq. (1).

The value of the higher pulse voltage is called the high-level voltage ($V_{H}$), and that of the lower one is called the low-level voltage ($V_{L}$) in this research.

3. INFLUENCE OF LOW-LEVEL VOLTAGE ON TOOL WEAR

3.1 Cause of tool wear and preventive measures

As shown in Fig. 4, the tool wear is thought to be caused by an undershoot of the total current ($I$) flowing through the circuit as the pulse falls. The current flow in an ECM cell can be represented by an equivalent circuit, as shown in Fig. 5. The electrical elements in the equivalent circuit are described as follows. $R_c$ represents the charge-transfer resistance, which is an indicator or the difficulty of the electrolytic reaction; $R_s$ is the solution resistance of the electrolyte; $C_{dl}$ represents the double-layer capacity, formed between the electrode surface and the electrolyte, which influences the rise speed of the voltage over $R_c$; $R$ is the limiting resistance in the case of a short-circuit, and is also used to measure the total current flowing through the circuit.

\[
Duty\, ratio = \frac{T_{V_H}}{T_{V_H} + T_{V_L}} \tag{1}
\]
In PECM, the electric charge accumulated in the double-layer capacitance during the pulse on-time will discharge during the pulse off-time. As a result, the current flows in the reverse direction, which means that the tool electrode changes from being a cathode to an anode during that period. This reverse current generated during the pulse-off time causes the tool wear. In this study, a method for preventing tool wear by reducing this reverse current by increasing the low-level voltage was examined.

### 3.2 Relationship between low-level voltage and tool wear

To investigate the relationship between the low-level voltage and the tool wear, the tool shapes were observed before and after machining without any workpiece feed. The low-level voltage was 0 V or 2 V. If the tool shape did not change after machining for 10 min, it was deemed that there was no tool wear.

Several kinds of materials were selected and used in experiments, for the following reasons. Tungsten (W) and copper (Cu), which have lower standard electrode potentials, are regarded as being prone to wear. On the other hand, gold (Au), which has a higher standard electrode potential, and titanium (Ti) on the surface of which a passive film always forms, are regarded as being highly wear-resistant materials. A sodium nitrate solution (NaNO₃ aq) and sodium chloride (NaCl aq) solution were used as electrolytes because they are easy to handle due to their neutral pH. The tool wear was investigated under eight different combinations of tool material and electrolyte. The other experimental conditions are listed in Tables 1 and 2.

**Table 1 Experimental conditions**

| Tool                  | Wire (φ100 μm) |
|-----------------------|----------------|
| Workpiece             | SUS 304 plate (t = 100 μm) |
| Electrolyte           | NaNO₃ aq, NaCl aq 10 wt% |
| Initial gap-width     | 20 μm           |

**Table 2 Applied pulse**

| High-level voltage    | 10 V            |
|-----------------------|-----------------|
| High-level pulse width | 100 μs          |
| Low-level pulse width  | 100 μs          |
| Duty ratio            | 50 %            |
| Rise/Fall time        | 7 ns            |

By observing the tool electrode after machining, we found that, for a low-level voltage of 0 V, tool wear occurred in the following three combinations; W wire with NaCl aq, Cu wire with NaCl aq, and W wire with NaNO₃ aq. However, for a low-level voltage of 0 V under the other five conditions, tool wear did not occur, although the color of the wire surface changed. The color change is assumed to be a result of the oxidation of the coating film. In contrast, for a low-level voltage of 2 V, neither tool wear nor color change occurred regardless of the conditions.

Fig. 6 shows images of the W and Ti wire electrode before and after machining using NaCl aq.

![Fig. 5 Equivalent circuit of ECM](image)

![Fig. 6 Observations of tool electrode before and after machining for 10 min](image)
Figure 7 shows the current waveform during machining when using a W tool electrode. As shown in Fig. 7, for a low-level voltage of 2 V, the undershoot of the current becomes much smaller than that when the low-level voltage is 0 V. In addition, Fig. 8 shows the total quantities of electricity during a low-level pulse width. The quantity of electricity was obtained by integrating the measured current value from 100 μs to 200 μs (see Fig. 7). As shown in Fig. 8, for a low-level voltage of 2 V, the negative amount of electricity is reduced to 25% relative to the case with a low-level voltage of 0 V. Based on this result, we can conclude that the raised low-level voltage can efficiently prevent tool electrode wear by reducing the reverse current.

4. RELATIONSHIP BETWEEN LOW-LEVEL VOLTAGE AND MACHINING ACCURACY

Chapter 3 described how a raised low-level voltage prevents tool electrode wear. However, a raised low-level voltage means that the current waveform approaches direct current. Therefore, there is the risk of reducing the machining accuracy. Therefore, the relationship between the low-level voltage and the machining accuracy was investigated by changing the low-level voltage from 0 V to 6 V while fixing the high-level voltage at 10 V. The feed rate was set to 120 μm/min, and the feed amount was set to 1020 μm. NaNO₃ aq was used as the electrolyte. When machining with a W wire electrode and a low-level voltage of less than 2 V, the machining failed to be completed due to the breakage of the wire electrode caused by the tool wear.

As shown in Fig. 9, for a low-level voltage higher than 3 V, the side gap-width tends to increase, that is, the machining accuracy decreases. The reason for the drop in accuracy is thought to be that a higher low-level voltage causes the waveform to approach a conventional DC voltage waveform. In addition, in the case of a Ti electrode with a low-level voltage of 2 V, as well as in the case of a Cu electrode with a low-level voltage of 3 V, the machining accuracy improved relative to the case with a low-level voltage of 0 V. In contrast, in the case of an Au electrode, the side gap-width barely changes as the low-level voltage is increased from 0 V to 3 V.

5. RELATIONSHIP BETWEEN LOW-LEVEL VOLTAGE AND MACHINING SPEED

In PECM, it should be possible to achieve a faster feed rate when the low-level voltage is increased, due to the average current being correspondingly higher. Therefore, a higher machining accuracy may be obtained, because the amount of time required for the wire electrode to pass a unit length decreases and the side and front gap-width become smaller. On the other hand, the machining accuracy drops when the low-level voltage is set too high as mentioned in the former chapter. Therefore, there may exist an optimal low-voltage for the machining accuracy.

Thus, experiments were carried out to find the maximum feed rate and the corresponding side gap-
width, when using different low-level voltages.

Figure 10 shows the relationship between the low-level voltage and the maximum feed rate and side gap-width. From Fig. 10(a), we can see that the maximum feed rate increases with the low-level voltage. As shown in Fig. 10(b), there is a minimum side gap-width for the raised low-level voltage, except when using an Au electrode. Therefore, to realize micro-machining with a higher degree of accuracy, it is effective to raise the low-level voltage to an optimal value.

6. INVESTIGATION OF THE OPTIMAL PULSE WAVEFORM

This study set out to investigate the optimal pulse waveform for wire-ECM. The optimal pulse waveform is defined as that pulse waveform which prevents tool wear and improves the machining accuracy while increasing machining speed. Therefore, an evaluation function J, shown with equation (2), including the feed rate and side gap-width is adopted and used to evaluate the pulse waveform.

\[ J(V_l) = \frac{F_M(V_l)}{G_S(V_l)} \]

Here, \( F_M \) : Maximum feed rate [\( \mu m/min \)]
\( G_S \) : Side gap-width [\( \mu m \)]
\( V_l \) : Low-level voltage value [V]

The results shown in Fig. 10 were then used and calculated using Eq. (2). The results are shown in Fig. 11. The evaluation value of Fig. 11 was standardized by the value at the minimum low-level voltage, 0V, for the corresponding tool material. As shown in Fig. 11, a value of 4V is the optimal low-level voltage for the evaluation of all materials except Cu.

7. CONSIDERATION OF REASON FOR ACCURACY IMPROVEMENT

It was found that the machining accuracy was improved when a suitable low-level voltage was set, because the side gap-width became smaller, except when using an Au electrode. The reason for this accuracy improvement is thought to be because the side gap-width became smaller due to a reduction in the machining amount. This reduction in the machining amount is probably caused by an increase in the electrical resistance, due to bubbles that are generated between the electrodes.

The gap during ECM was observed using a high-speed camera (Photron, FASTCAM Mini UX100). Figure 12 shows the setup used for filming. Machining was performed by dipping the wire electrode and workpiece in electrolyte. Figure 13 shows the gap area when using low-level voltages of 0V and 4V. As shown in Fig. 13, for a low-level voltage of 4V, the amount of bubbles was greater...
than that in the case of a low-level voltage of 0 V. This difference in the amount of bubbles is thought to be the reason for the improvement in the accuracy as the low-level voltage is raised in PECM.

The bubbles which are generated while the low-level voltage is applied cause an increase in the resistance between the electrodes. The amount of material removed from the workpiece and the side gap-width will decrease as the resistance increases and, thus lead to an improvement in the machining accuracy. When using an Au electrode, it is assumed that the machining accuracy is barely affected because the standard electrode potential of the Au is higher than that of other metals. In other words, an electrolytic reaction does not occur when the low-level voltage is applied because of the higher standard electrode potential.

8. CONCLUSIONS

In this paper, the influence of the low-level voltage on the machining characteristics was experimentally investigated for wire-ECM. The results can be summarized as follows:

(1) It was found that a raised low-level voltage not only prevents tool electrode wear, but also improves the machining speed regardless of the materials being used.

(2) In the case of W and Ti electrodes, the optimal low-level voltage is 2 V.

(3) The machining accuracy improvement with a raised low-level voltage is probably caused by an increase of the resistance in the gap due to the bubbles generated by the low-level voltage.

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