Electrochemical Milling Using a Parallel Mechanism for High-speed Translation of Tool Electrodes

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Abstract
Electrochemical milling using a delta-type parallel mechanism is proposed to achieve high-speed translation of the tool electrode, which is known to improve the surface finish. Experimental results of machining a groove show that the surface roughness decreases with increasing translation speed of the tool electrode. Moreover, it is found that the high-speed translation of the tool electrode is effective at preventing electrical discharge damage of both the tool electrode and the workpiece. Large areas can be machined at high translation speeds with improved surface finish, and the machined profile accurately matches the desired profile. The experimental results indicate that there is an optimum pick feed that ensures both a better surface flatness and finish.

Key words: Electrochemical machining, Electrochemical milling, Parallel mechanism, High-speed translating, Surface roughness

1. INTRODUCTION
In electrochemical machining (ECM)\(^1\), the workpiece is electrochemically dissolved, and the dissolved metal ions form a hydroxide in the electrolyte. Hydrogen is produced at the surface of the tool electrode. During ECM, the temperature of the electrolyte increases due to Joule heating. Therefore, the electrolyte is circulated through the machining gap to remove electrochemical products and excess heat. The conductivity of the electrolyte depends on the concentration of the electrochemical products and the temperature of the electrolyte; thus, the machining gap is influenced by them. The machining gap is also dependent on the angle between the tool electrode surface and the feeding direction\(^2\). Therefore, the tool electrode must be designed with these factors in mind, in order to obtain the desired workpiece shape, entailing substantial time and cost. Another disadvantage with conventional ECM is that if the electrode has a large area, a high-capacity power source is necessary to supply a large machining current. In electrochemical milling\(^3\)-\(^5\), or numerically controlled ECM, the workpiece is machined by translating a simple-shaped tool electrode, such as a cylindrical rod, thus reducing the tooling design effort and cost. In addition, the smaller electrode requires a smaller power source compared to that in conventional ECM. However, a problem with this approach is that the surface roughness deteriorates when the tool electrode is translated. The reason for this is explained as follows\(^6\). The area under the tool electrode has a high electric potential gradient so that the current density is also high. With increasing radial distance, the current density gradually decreases. It is known that a better surface finish is obtained with a high current density; conversely, a poorer surface finish is obtained at a low current density. As the electrode is translated, the surface finish under the tool electrode rapidly becomes better owing to the high current density. However, as the tool electrode translates, these areas are machined again by the peripheral part of the tool electrode where the current density is lower, thus degrading the surface finish. For electrolyte jet machining, Kawanaka et al.\(^7\) and Natsu et al.\(^8\) proposed a high-speed translation of the electrolyte jet to solve this problem. At higher translation speeds, the workpiece does not spend much time under the periphery of the electrode; hence, the surface finish is not degraded. In the case of electrochemical milling, which uses the tool electrode, it is expected that the same effect can be obtained. In a conventional machine tool, however, fast translation of the tool electrode is limited because of the higher inertia of stages, which are stacked to allow multi-axis motion. Although Kawanaka et al. achieved a high translation speed using a linear motor stage, the electrolyte jet was translated in only one direction. On the contrary, the parallel mechanism\(^9\) has the advantage of low inertia, which enables high-speed movement of the tool electrode. Therefore, this mechanism is considered to be suitable for achieving high-speed translation of the tool electrode.

In this study, electrochemical milling that uses a parallel mechanism is proposed. First, a groove is machined, and the influence of the translation speed
is investigated. Next, the surface of the workpiece is machined by translation in the X- and Y-directions, and the influence of the translation speed on the surface quality is investigated. In addition, a translating pattern suitable for high-speed translation of the electrode is discussed.

2. MACHINING EQUIPMENT

In this study, a linear delta-type parallel mechanism is used to realize fast translation of the tool electrode. Figure 1 shows a linear delta-type parallel mechanism that has three degrees of freedom. In this mechanism, three linear actuators are arranged vertically on a frame axis at intervals of 120°. The linear actuator is connected to the end-effector by two parallel links. With the linear delta-type parallel mechanism, each actuator is capable of independent motion, allowing for rapid XYZ movement of the end-effector. Figure 2 shows the machining equipment used in this study. The linear actuator utilizes a timing belt and a stepper motor to move a carriage. The end-effector and the actuator are connected by links with spherical joints consisting of magnets and steel balls. Motion error during translation in one direction under the conditions used in this study is approximately 50 μm or less in the Z-direction. The motion error is not small enough for precise machining. Because the purpose of this study is an fundamental investigation such as influence of translation speed on the surface quality, however, the motion error has an insignificant effect on the purposes of this study. A tool electrode holder is fixed to the end effector. A cylindrical pipe tool electrode is used, and the electrolyte is pumped through the electrode during machining.

3. INFLUENCE OF TRANSLATION SPEED

In order to investigate the influence of the translation speed of the tool electrode on the surface roughness, grooves were machined. Table 1 shows the machining conditions. The tool electrode is a brass pipe with an outer diameter of 3 mm and a bore of diameter 0.75 mm. The workpiece is made of carbon steel (C50). A constant voltage of 30 V was applied to the working gap. In order to investigate the influence of the tool electrode translation speed on the surface roughness of the machined groove, the translation speed was varied from 20 mm/min to 5000 mm/min. The tool electrode was translated repeatedly, and the number of the translations was changed to obtain the same machining time per unit area, regardless of the translation speed. The translation distance was 30 mm. The center of the translation motion of the tool electrode was set at the center of movable range of the equipment in X-Y plane. The initial machining gap between the tip of the tool electrode and

| Tool electrode | Brass pipe |
|----------------|------------|
| Outer diameter | 3 mm       |
| Inner diameter | 0.75 mm    |
| Workpiece      | Carbon steel (C50) |
| Applied voltage| 30 V (DC)  |
| Electrolyte    | NaNO₃ aq. 9 wt.% |
| Electrolyte supply pressure | 0.2 MPa |
| Flowrate of electrolyte | 80 mL/min |
| Initial gap distance | 50 μm |
| Translating speed, number of translating | 20 mm/min, 1 time, 100 mm/min, 5 times, 1000 mm/min, 50 times, 5000 mm/min, 250 times |
| Translating distance | 30 mm |
workpiece was set at 50 μm. The tool electrode was not fed in the Z-axis direction during machining.

Figure 3 shows the machined surface and the cross-sectional profile of grooves for translation speeds of 20 mm/min and 1000 mm/min. As the translation speed increases, a glossier surface is obtained as compared to that of the lower translation speed. Figure 4 shows the influence of translation speed on the surface roughness Ra of the machined groove for various distances from the center of the groove. The surface roughness was measured around the middle of the groove in a direction parallel to the translating direction with a sampling length of 3 mm. It is evident that the surface finish is improved by increasing the translation speed due to the phenomenon described in section 1. This is because the increased translation speed leads to a decrease in the influence of the low current-density area, thus indicating that a higher translation speed is effective in electrochemical milling, as well as in electrolyte jet machining. On the other hand, the center of the groove was machined deeply, as shown in the cross-sectional profile of Fig. 3. Here, the gap between the tip of the tool electrode and the workpiece gradually increases with time because material from the workpiece was removed by electrochemical dissolution. In our experiment, the electrolyte is pumped from the center hole of the tool electrode, and it flows out in a radial direction of the tool electrode. When the machining gap is small, the tip of the electrode is immersed in the electrolyte. However, as the machining gap becomes larger during machining, the electrode tip no longer remains submerged in the electrolyte. As a result, only the area where the electrolyte impinges on the workpiece is machined, as in electrolyte jet machining. A solution to this problem is discussed in section 4.

From the experiments, an additional effect of the speed of translation was discovered. At low translation speeds, damage to both the workpiece and the tool electrode from the electrical discharge was observed. Figure 5 shows a damaged workpiece machined at a translation speed of 20 mm/min and an applied voltage of 40 V. Discharge frequently occurred at a lower translation speed of 20 mm/min. Figure 6 shows the damage to the tool electrode from the discharge before and after machining. However, when the translation speed was increased to 1000 mm/min, damage due to discharge was not observed, and a glossy surface was obtained for the workpiece. This is because at high translation speeds, even though discharges occur, they do not last long enough to cause damage. In electrical discharge machining, when there is relative motion between the tool electrode and the workpiece, the arc column generated by the electrical discharge moves on the cathode to a greater extent than on the anode. In ECM,
because the workpiece is the anode, the arc column does not move on the workpiece, and the discharge spot on the anode remains stationary. The tool electrode is the cathode, and the discharge spot on the tool electrode moves around, owing to the relative motion between the tool electrode and the workpiece. When the discharge spot reaches the edge of the tool electrode, the discharge gap between the anode and cathode widens because of the movement of the electrode\(^{10}\). The gap distance then becomes too large to sustain a discharge, and it extinguishes. Therefore, increasing the translating speed results in less damage to the workpiece and the tool electrode. From these results, it can be said that the higher translation speed is also effective at decreasing the damage induced by the electrical discharge.

4. EFFECT OF SUBMERGED MACHINING

As described in section 3, more material was machined at the center of the groove. This is because as the machining gap increases, the material is removed only where the electrolyte jet impinges, as in electrolyte jet machining. The Z-axis movement of the electrode to compensate for the widening gap can eliminate this problem. However, this requires precise control of the Z-axis movement. Therefore, to eliminate this problem, the machining tank was filled with the electrolyte, and the workpiece was submerged in the electrolyte.

In this arrangement, even with an increased gap distance, current flow from the electrode tip is maintained, thus ensuring material removal directly under the tool electrode. Then, the influence of translation speed on the surface roughness was investigated for submerged machining. The experimental method was the same as that described in section 3. However, the applied voltage was set to 20 V, and the supply pressure of electrolyte was set to 0.4 MPa to obtain almost the same flow rate with the experiment in section 3. The other machining conditions were the same as those shown in Table 1.

Figure 7 shows the machined surface and the cross-sectional profile of grooves with translation speeds of 20 mm/min and 5000 mm/min. Machining the submerged workpiece resulted in a groove with a flat bottom-surface. The glossiness of the surface increased with higher translation speeds of 5000 mm/min. Figure 8 shows the influence of translation speed on the surface roughness \(Ra\) of the machined groove for various distances from the center of the groove. It is evident that the surface finish was improved by increasing the translation speed. In conventional electrochemical milling, with a tank full of electrolyte installed on an axis stage, high-speed translation of the stage is relatively difficult because of the high inertia of the
arrangement. With the parallel mechanism proposed in this study, only the end-effector and electrode move; they have a relatively small inertia and can therefore easily translate at high speeds, even for submerged machining, which is suitable for electrochemical milling.

5. LARGE-AREA MACHINING USING HIGH-SPEED TRANSLATION

5.1 Influence of translation speed

The surface of the workpiece was machined with an X-Y translation of the electrode, and the effect of translation speed on the surface quality was investigated. First, the tool electrode was translated repeatedly in the X-direction for the same Y position. The tool electrode was then moved to the next Y position with a pick feed of 3 mm, and the tool electrode was translated again in the X-direction. This process was repeated until a sufficient area (approximately 20 mm × 20 mm) of the workpiece surface was machined. Table 2 shows the machining conditions. The translation speed was varied at 50 mm/min and 5000 mm/min, and the number of translations was adjusted such that the machining time per unit area was maintained constant regardless of the translation speed. The initial gap distance between the electrode tip and workpiece was set at 50 μm. The electrode was not fed in the Z-direction. The workpiece was submerged in the electrolyte.

Figure 9 shows the optical microscope image of the machined surface, the 3D topography, and the profile in Y-direction at translating speeds of 50 mm/min and 5000 mm/min. The images from the optical microscope show that the glossiness of the machined surface with the higher translation speed of 5000 mm/min is better than that with the 50 mm/min translation speed. From the 3D topographies and profiles of the machined surface with a translation speed of 5000 mm/min, it is noted that ridges were formed periodically on the machined surface. This is due to the pick feed of the tool electrode in the Y-direction.

5.2 Influence of the pick feed

5.2.1 Calculation of machined profile

As described in the previous section, ridges were formed on the machined surface. In order to obtain a flat surface, the influence of the pick feed was analytically investigated. First, a groove was machined at a translation speed of 5000 mm/min with 100 translations, and the groove profile was measured. The other machining conditions were the same as those shown in Table 2. The profiles of the machined surface in Y-direction (pick feed direction) with the translations of the tool electrode were calculated by superimposing the measured groove profiles for various pick feeds. In fact, the current distribution is affected by the shape of the workpiece surface because the machining gap is dependent on the workpiece shape. However, if the roughness of the workpiece surface and the machining depth are small, the influence of the workpiece shape on the current density distribution is small and can be ignored. In the calculation of the machined profile, the pick feeds were set at 0.3, 2.4, 2.7, and 3 mm. For a pick feed of 0.3 mm, the translating number was decreased to one tenth of the other pick feeds in order to obtain almost the same machining depth. Therefore, the groove depth with a pick feed of 0.3 mm for the calculation was set at one tenth of the measured groove depth, which was obtained with the translating number of 100 times.

Figure 10 shows the profile of the groove machined at a translation speed of 5000 mm/min with 100 translations. Figure 11 shows the calculated profiles for various pick feeds. For a large pick feed of 3 mm, ridges are formed on the
machined surface, as material removal around the edge of the tool electrode is small. Decreasing the pick feed to 2.7 mm reduces the ridge height, and a flatter surface is obtained. Further, reducing the pick feed to 2.4 mm results in valley formation on the machined surface because the material removal around the edge of the tool electrode is increased. These results indicate that a 2.7 mm pick feed is an optimal value for obtaining a flat surface. On the other hand, when the pick feed is further decreased to 0.3 mm, a flatter surface is obtained. However, as described in the next section, when the pick feed is too small, a glossy surface is not obtained in the experiment.

5.2.2 Experimental investigation

The influence of the pick feed was experimentally investigated. With pick feeds set to 0.3, 2.4, 2.7, and 3 mm, the other machining conditions remained the same as those used in section 5.1. Figure 12 shows an optical microscope image of the machined surface, the 3D topographies, and the area roughness $S_a$ with various pick feeds. Figure 13 shows the profiles of the machined surface at various pick feeds. The machined profiles are almost identical to the calculated profiles shown in Fig. 11. These results indicate that the machined profile can be calculated by superimposing the groove profile. When the pick feed was 0.3 mm, an almost flat surface was obtained. However, from the optical microscope image shown in Fig. 12(a), the surface was not glossy even though the translation speed was high. This is because the current density decreases with increasing distance from the edge of the electrode; therefore, on the next tool electrode translation, the adjacent surface that was machined earlier is affected by the low current density of the passing electrode edge, thus deteriorating the surface quality. When the pick feed was 2.7 mm, the ridge formed for the 3 mm pick feed could be removed, and an almost flat surface was obtained. The area roughness $S_a$ with the 2.7 mm pick feed was 2.0 $\mu$m, smaller than those with 3 mm ($S_a = 8.7 \mu$m) and 2.4 mm ($S_a = \ldots$)
12.5 μm) pick feeds. However, the area roughness becomes worse than the surface roughness of the groove shown in figure 8 because the small valley was generated on the machined surface due to the material removal around the edge of the tool electrode. The machined surface with a pick feed of 2.7 mm has a glossy surface, as shown in the optical microscope image of Fig. 12(c). Therefore, this appears to be an optimum pick feed for obtaining a better surface quality for high-speed
electrode translation. These results indicate that the current density distribution in the direction perpendicular to the translation direction must be considered for obtaining a better surface finish, and there exists an optimal pick feed that can obtain both a flat surface and good surface quality when the tool electrode is translated.

6. CONCLUSIONS

By translating the tool electrode at high speeds, it is expected that the surface finish can be improved with electrochemical milling. Therefore, electrochemical milling was performed using a delta-type parallel mechanism to realize a fast translation of the tool electrode. The influence of the translation speed on the machined surface was investigated. Experimental results show that the surface roughness decreased with increasing translation speed. It was also found that the high-speed translation of the tool electrode prevented damage to both the tool electrode and the workpiece caused by an electrical discharge. A flat bottom of the groove was obtained when the workpiece was submerged in the electrolyte. The results of large-area machining also showed that a higher translation speed of the electrode was effective in improving the surface finish. The machined profile was a good match of the calculated profile, which was the obtained superimposing profile. Experimental results indicate that there is an optimal pick feed for obtaining both a flat surface and good surface quality when the electrode is translated.

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