Study of Deposition Machining Using Electrical Discharge with Reciprocating Rotation in Air Gap

Atsutoshi Hirao 1*, Takayuki Tani 2**, Hiromitsu Gotoh 2***, Shoju Aoshima 3***, Naotake Mohri 4****
(Received Jan. 1, 2015)

* Faculty of Education, Niigata University, Niigata 950, Japan
** Department of Industrial Information, Tsukuba University of Technology, Tsukuba 305, Japan
*** Technocoat Co., Ltd., Shizuoka, Fujieda 426, Japan
**** National Institution for Academic Degrees and University Evaluation, Tokyo 187, Japan

Abstract
This paper describes surface modification and surface deposition using a high-peak current discharge in an air gap and describes the relation between capacitance, which determines the peak current, and the deposition rate. The process is controlled manually using a rotating tool. The discharge circuit is a resistor-capacitor (RC) circuit, and switching is executed by means of a thyristor. The deposition of nickel onto a steel surface was performed using a nickel-based alloy for the electrode. The electrode was controlled with reciprocating rotation. The influence of the capacitance of the capacitor and the diameter of the electrode on the deposition rate was investigated. Using the proposed method, excellent surface deposition was achieved.

Key words: Deposition machining, EDM, Surface modification, Reciprocating rotation

1. INTRODUCTION
A variety of surface modification methods have been proposed to improve the surface functionality of tools and molds (1,2). Surface modification using an electrical discharge in a liquid provides an extremely high peeling strength for the modified layer and the base metal (3). Recently, this method has been applied to turbine blades of jet engines (4,5). However, the machine required to control the narrow gap between the electrode and the workpiece is expensive, and there are limitations with respect to the liquid used.

There is a surface modification and surface deposition method that uses electrical discharge in the air, using a resistor-capacitor (RC) circuit to establish an electric arc (6). The electrode is rotated using a hand grinder, and surface modification is performed manually. This method requires considerable skill. Surface modification and surface deposition methods are classified according to the type of electrode material used. Surface modification has been studied by electrical discharge machining (EDM) using composite structured electrodes. A composite structured electrode is made of a green compact product or sintered product (7). Deposition machining can be performed using a nickel-based alloy for the electrode. When a metal mold is repaired using deposition machining, the device can be moved close to the mold because the device is small. It is difficult to control the surface deposition speed and surface roughness at the same time using this method, because the surface roughness depends on the current value and the pulse duration. As a result, a high surface deposition speed may result in unacceptable surface roughness.

This paper proposes a method for controlling the electrode with reciprocating rotation. The clockwise (CW) and counterclockwise (CCW) rotation angles were controlled individually. The difference between the CW and CCW rotation angles was calculated. The electrode was rotated slowly in one direction by maintaining the differences in the CW and CCW rotation angles. In this study, the influences that the capacitance and the diameter of the electrode have on the deposition were investigated for one-way rotation and reciprocating rotation.

2. DEPOSITION MACHINING
2.1 Experimental setup
Figure 1 (a) shows an overview of the experimental apparatus. The electrode, which is fitted into the chuck of a hand grinder, is called an applicator. In operation, an electrical discharge onto the workpiece is generated, and argon gas is supplied around the electrode as a shielding gas. Figure 1 (b) shows the discharge circuit, which is an RC circuit that is switched by means of a thyristor. A charge is stored in the capacitor for the electrical discharge, and an electric arc is established by switching the thyristor.

Table 1 summarizes the experimental conditions. In this study, a nickel-based alloy was used for the electrode. Table 2 shows the composition of the nickel-based alloy. Nickel-based alloys are often used to repair molds because of their high corrosion resistance and high abrasion resistance.

Figure 2 illustrates the deposition machining experiment. The rotating electrode was scanned...
over a 10 mm × 10 mm area manually. Deposition machining was performed under the conditions summarized in Table 1, and the amount of deposition under various machining conditions was evaluated.

2.2 Characteristics of deposition machining

Figure 3 shows the relation between the peak current and the electrical discharge duration for three levels of capacitance. The peak current value and the electrical discharge duration were found to increase with increasing condenser capacitance.

Figure 4 shows the measurement results for deposition machining speed using three electrode diameters (φ1.6 mm, φ2.4 mm, φ3.2 mm) at three different capacitance levels. The differences in the electrode diameters had no effect on the deposition machining speed for capacitances of 10 μF and 40 μF. However, the electrode diameter did affect the deposition machining speed for the 100 μF capacitor. In the machining process, the deposition rate is not high in initial machining stage. However, the electrode heats up to a red heat as machining continues, and the deposition rate increases during this red-heat state. When the diameter of the electrode is small, the thermal capacity of the electrode is small. Therefore, it is thought that the deposition rate, which increases when the electrode reaches the red-heat state, is achieved more easily when the diameter of the electrode is small.

The results of observations of a cross section of a workpiece using electrodes of three different diameters (φ1.6 mm, φ2.4 mm, φ3.2 mm) with a 100 μF capacitor are shown in Figs. 5 (a), (b), and (c), respectively. A uniform deposition layer was not formed with the φ1.6mm electrode, under which the deposition machining speed was the highest, and a large asperity surface formed. This suggests that an electrode diameter of 1.6 mm may not be suitable for deposition machining.

![Deposition area and electrode diagram](image)

**Table 1. Experimental conditions.**

| Electro-spark machine | MicroDepo (TechnoCoat Co., Ltd) |
|-----------------------|---------------------------------|
| Electrode             | Ni-based alloy φ1.6, 2.4, 3.2 (polarity: +) |
| Workpiece             | Steel (S45C, S50C) |
| Open circuit voltage, E | 150 V |
| Capacitance, C        | 10 μF, 40 μF, 100 μF |
| Frequency             | 500 Hz |
| Atmosphere            | Ar (0.005 MPa) |

**Table 2. Ni-based alloy composition.**

| Element | Ni | Cr | Fe | Mo | other |
|---------|----|----|----|----|-------|
| wt%     | 48.85 | 21.60 | 18.85 | 8.36 | 2.34 |

![Deposition area diagram](image)
2.3 Process of deposition machining

To investigate the reason for the formation of the asperity surface, its appearance under deposition machining was observed using a high-speed video camera. Figure 6 shows a photograph of the formation process (capacitor: 100 μF, electrode diameter: φ1.6 mm, frame rate: 250 fps). It was confirmed that the electrode material dropped out of the side of the workpiece side from the center of a heated electrode. A similar occurrence was observed for a φ2.4mm electrode. It is thought that the surface asperity was caused by the drop-out of the electrode material.

Next, the growth process of the deposition layer was observed using a laser displacement sensor. The laser displacement sensor head was scanned along the same route after electrical discharge machining of the scanned area, and the deposition process was observed. Figure 7 shows the measurement method. Electrode scanning was repeated periodically, and the growth of the deposition each time was measured using the laser displacement sensor. Figure 8 shows the section profile for 20, 40, 60, and 80sec time intervals. Initially, electrode scanning was repeated every 20 sec, and the growth of the deposition was measured using the laser displacement sensor. This was then repeated for 40, 60, and 80sec time intervals. When a deposit was generated in a specific place, it was confirmed by scanning at the next scanning time interval that a deposit was made in a place that had already received a deposit. An electrical discharge is generated easily in a place where the gap is small. Therefore, it is thought that an electrical discharge is selectively generated at the deposit point and that electrode material is deposited at a projecting part.

A model for the deposition process, shown in Fig. 9, is based on the results shown in Fig. 8. The electrode material is deposited onto the growth of the deposition part by electrode scanning. In subsequent scans, the electrical discharge is selectively generated in this deposited part, and this place receives more deposits. This phenomenon has also been observed under conditions of constant pressure and constant speed.

Fig. 6 Observation of electrode drop-out process by high-speed camera.
Therefore, this deposition machining method is an unstable system, which may cause problems in terms of automation.

3. RECIPROCATING ROTATION
3.1 Mechanistic rationale
Figure 10 shows the superheated electrode surface during surface deposition. Fig. 10 (a) shows a schematic view of the one-way rotation method. Fig. 10 (b) shows a schematic view of the reciprocating rotation method. During one-way rotation of the electrode, the electrode surface becomes hot around its whole circumference. Discharge arcing has a strong tendency to occur in the projection of the workpiece. The high-temperature area of the electrode is sufficient in the vicinity of the discharge point in the case of surface deposition using discharge. An electrical discharge is generated at places where the gap is small.

The reciprocating rotation method is proposed to limit the heating area to the rotation angle of the electrode. Figure 11 illustrates the reciprocating rotation method. The electrode is rotated in steps. The input frequency from the function generator is 10 kHz. This corresponds to a reciprocating rotation speed of 600 rpm. The CW and CCW rotation angles are different. As a result, the electrode rotates slowly, in proportion to the difference between the CW and CCW rotation angles. The electrode appears to stop. The force applied to the electrode is very small. The high-temperature region of the electrode is limited to the range of the rotation angles, as shown Fig. 10 (b). It is easy to control the applicator and aim it at a specific point using this method. In contrast, during one-way rotation, the electrode rotates in one direction at a high speed. As a result, the electrode is repelled in the direction of rotation because of the one-way action force produced, and it is more difficult to control the applicator.
3.2 Reciprocation rotation results
The experimental conditions for reciprocation rotation are summarized in Table 1. Electrode diameters of φ1.6 mm, φ2.4 mm, and φ3.2 mm were used, as with one-way rotation method. Surface modification was performed manually. Table 3 shows the conditions for reciprocating rotation. The CW rotation angle was 36°. The reciprocating rotation speed was 600 rpm. The electrode rotated slowly at 3 rpm.

Figure 12 shows the measurement results for the deposition machining speed obtained using the reciprocating rotation method, including the results from Fig. 4 (a) (for an electrode diameter of φ1.6 mm). The deposition machining speed was low for the 10 μF capacitance, as was the case with the one-way rotation method. For capacitance levels of 40 μF and 100 μF, the difference in capacitance had no effect on the deposition machining speed. Furthermore, the electrode diameter did not affect the deposition rate in the cases of 40 μF and 100 μF capacitance.

Figure 13 shows a cross section of a workpiece produced using an electrode diameter of φ1.6 mm and a 100 μF capacitance (indicated by (a)’ in Fig. 12). The cross section indicates that the deposition layer was thin. Figure 14 shows the modified surfaces observed using optical photomicrography. The images show that the surface obtained using the reciprocating rotation method is better than that obtained using the one-way rotation method.

### Table 3 Reciprocating rotation conditions.

| Rotating angle | CW | CCW |
|----------------|----|-----|
| Angular difference | CW-CCW | 0.36° |
| Reciprocating rotation | 600 min⁻¹ |
| Rotation of electrode | 3 min⁻¹ |

3.3 Observation within the workpiece
Figure 15 shows scanning electron microscope (SEM) images of inner surfaces of the workpiece. These surfaces are machined by mirror polishing 20 μm from the deposited layer, formed with a φ1.6 mm diameter electrode at 100 μF capacitance.

A large number of blowholes on the deposited surface formed using the one-way rotation method can be seen in Fig. 15 (a). In contrast, the deposited surface formed using the reciprocating rotation method had few defects such as blowholes, as shown in Fig. 15 (b). These results indicate that reciprocating rotation produces a better surface than one-way rotation.

Figure 16 shows SEM images and EDS (energy dispersive X-ray spectroscopy) results for a cross section of a deposited layer. The boundary between the base material and the deposited layer is not
clearly seen in the SEM image. The thickness of the deposited nickel layer was determined from EDS analysis to be approximately 30 μm. The deposition layer of the boundary between the Ni and Fe was not clearly observed. The adhesion of the deposited layer was high.

4. CONCLUSIONS
The deposition machining characteristics of electrical discharge machining in an air gap were investigated. The results obtained can be summarized as follows:

(1) The deposition machining characteristics depend on the capacitance of the capacitor and the diameter of the electrode. The amount of deposition increases when the capacitance is large and the diameter of the electrode is small.

(2) When the electrode element is deposited in a specific part, further deposits in the area are made more readily. As a result, the heights of projections on the surface become larger in this area.

(3) The deposited surface obtained using the proposed reciprocating rotation method had few defects such as blowholes. This method is considered to produce excellent surface properties.

(4) Observation of the cross section indicate that the deposited layer formed using this method has high adhesion.

5. REFERENCES
(1) T. Moro, N. Mohri, H. Otsubo, A. Goto, N. Saito: Study on the Surface Modification System with Electrical Discharge Machine in the Practical Usage, Journal of Materials Processing Technology 149, (2004) 65-70.
(2) K. Matsukawa, K. Sato, A. Goto, N. Saito, N. Mohri: Wear Properties of Surface Modified Hard Layers Using Electrical Discharge Machine, Journal of Advanced Mechanical Design, Systems and Manufacturing, JSME, Vol. 2, No. 4, (2008) 629-639.
(3) A. Goto, T. Moro, K. Matsukawa, M. Akiyoshi, N. Saito, N. Mohri,: Development of Electrical Discharge Coating Method, Proceedings of the 13th International Symposium for Electromachining, (2001), 581-588.
(4) M. Okane, K. Nakamura, A. Goto, H. Teramoto, M. Akiyoshi, H. Ochiai, M. Watanabe: Development of Coating Technology by Electrical Discharge, The Japan Society of Mechanical Engineers, Vol. 2004 No. 5, (2004) 281-282.
(5) M. Watanabe, H. Ochiai, H. Yoshizawa: Innovation in Coating Technology, Journal of the Japan Society of Grinding Engineers, Vol. 55, No. 8, (2011) 449-452.
(6) T. Tani, H. Gotoh, Y. Kuwabara, S. Aoshima, A. Hirao, N. Mohri: Surface Modification Using Electrical Discharge in Air Gap, Proceedings of the 16th International Symposium for Electromachining, (2010) 159-162.
(7) N. Mohri, N. Satio, Y. Tsunekawa, H. Momiyama, A. Miyagawa: Surface Modification by Electrical Discharge Machining -Composite Electrode Method-, The Japan Society for Precision Engineering, Vol. 59, No. 4, (1993) 625-630.