Abstract

The tribological characteristics of sliding parts can be controlled by creating a microstructure on their surface. However, the effect of microstructures on the surface of a small hole of an inner sliding part or a hardened part has not been investigated. Thus, an efficient method, electrical discharge texturing (EDT) was previously developed to create a microstructure using a single discharge. In this study, whirling electrical discharge texturing (whirling EDT: WEDT) was developed as a method of creating microstructures on the inner surface of small holes and mechanical parts made of high-hardness materials. It was examined whether the WEDT equipment can be used to texture the inner surface of small holes and high-hardness materials. In addition, the fundamental characteristics of WEDT were studied. It was verified that, it is possible to create microstructures via the whirling phenomenon and single discharge of WEDT. The shape and texture-area ratio can also be controlled by WEDT, where the texture-area ratio is controlled by varying the feed speed.

Key words: Whirling Phenomenon, Single Discharge, Whirling Electrical Discharge Texturing, Microstructure, Crater Diameter, Texture-Area Ratio

1. Introduction

In recent years, global warming and energy problems have become an international concern since the world’s fossil fuel reserves are limited. Since, a lot of time is required to popularize new energy sources, energy problems can be mitigated by improving energy efficiency. In general, tribological characteristics can be controlled by creating microstructures on surfaces to decrease the friction coefficient and maintain a good lubrication condition [3-11]. Therefore, the creation of microstructures on the sliding parts of transport machinery has been studied [1, 4-5, 8]. The reduction of friction of tribological components is considered to reduce energy use and environmental impact [1-2, 4, 5, 9]. Textured surfaces have been studied in an attempt to reduce the friction of components [4-7]. It is expected that textured surfaces and textured patterns can act as reservoirs for engender persistent lubrication by increasing the quantity of lubricating oil during sliding while also keeping the lubricant oil at the desired location as shown in Fig.1. [4]
Microstructures are conventionally processed by cutting or laser beam machining. However, it is difficult to apply cutting to process high-hardness materials and laser beam machining cannot easily be used to process the inner surface of a cylinder with a small diameter. Since many bearings made of high-hardness materials having small diameters are used in transport machinery, an effective method of processing such parts is required. Electrical discharge machining (EDM) can process high-hardness materials and small-diameter parts. Therefore, it is used to create microstructures to decrease friction. However, EDM is a processing method that transcribes the electrode; thus, the machining time of EDM is long. In previous study, electrical discharge texturing (EDT) was developed as a method of creating microstructures by a single discharge [9] to reduce the machining time. However, a process with an even shorter machining time is required in manufacturing industries. Consequently, whirling electrical discharge texturing (WEDT) was developed as a method of creating microstructures on the inner surface of a cylinder by a single discharge.

In general, the design of textured surfaces is an important part of surface engineering to enhance the hydrodynamic lubrication effect and improve the tribological performance to reduce friction in automobile parts. The design of textured surfaces is a complicated problem involving many factors, such as the geometry of the texture as well as the depth, size, density, pattern, imperfections, surface finish, lubricant and operation conditions. Each factor may affect the contact and lubrication performance under certain conditions [3]. The density of a microstructure on a textured surface was previously studied in an attempt to reduce the friction coefficient [1, 4-5, 7]. In this study, the texture-area ratio on a cylindrical inner surface and the diameter of craters processed by WEDT were studied. In the WEDT process, a tool electrode rotates with a high speed and a gap voltage with a high frequency is applied to create craters with high efficiency. In addition, the whirling phenomenon is applied to rotate the shaft of the tool electrode along the inside of the cylinder to process it with high efficiency. The purpose of this study is to develop equipment for WEDT and to verify the fundamental characteristics of WEDT. Craters were generated on a small-diameter cylinder made of a high-hardness material, where the shape and number of craters were controlled.

2. Concept of texturing on surface

The concept of texturing on a surface by EDT is shown in Fig. 2. First, a voltage is applied to the tool electrode causing its shaft to rotate with a constant rotational speed while maintaining a constant optimal gap width, which is the distance between the tool electrode and the workpiece, as a result of which, a crater is generated. The interval between craters can be controlled by varying the timing and the feed speed applied to the tool electrode. The interval between craters depends on the pulse frequency and feed speed. Figure 3 shows microphotographs of craters on a surface obtained by EDT.
3. Principle of whirling electrical discharge texturing

Whirling Electrical Discharge Texturing (WEDT) equipment is a prototype machine comprises the fundamental technique of Electrical Discharge Texturing (EDT) and whirling phenomenon for creating microstructures on the inner surface of small hole. Texturing experiments were conducted to evaluate the performance of WEDT for the formation of craters on the inner surface of a small hole. The aim of this experiment is to show that the shape and number of craters can be controlled by the WEDT method and this highly efficient process can also be controlled through the whirling phenomenon. A schematic diagram of the WEDT process is shown in Fig. 4. As shown in the cross-sectional of small hole in Fig. 4, as a voltage is applied to the tool electrode, the tool electrode shaft rotates with a high speed until the whirling phenomenon occurs, during which the gap width is kept at the optimum value, as a result of which, a crater is generated. As shown in the figure, the crater pitch, which is the interval between craters, can be controlled by varying the pulse frequency and the feed speed applied to the tool electrode. The feed speed in the horizontal direction (Vr) depends on the number of rotations and the diameter of the workpiece, as can be seen from Eq. (1). The horizontal pitch (Lr) depends on the horizontal feed speed and the pulse frequency Eq. (2) and the vertical pitch (Lz) depends on the vertical feed speed and the pulse frequency Eq. (3).
Fig. 4 Schematic diagram of WEDT process.

\[ V_r = n\pi D \]  \hspace{1cm} (1)

\[ L_r = V_r T \]  \hspace{1cm} (2)

\[ L_z = V_z T \]  \hspace{1cm} (3)

\[ V_r : \text{ Feed speed in horizontal direction} \]
\[ V_s : \text{ Feed speed in vertical directions} \]
\[ n : \text{ Number of rotations} \]
\[ D : \text{ Diameter of workpiece} \]
\[ L_r : \text{ Horizontal pitch} \]
\[ L_z : \text{ Vertical pitch} \]
\[ T : \text{ Pulse frequency} \]

Next, Fig. 5 (a) – (b) show expected crater pattern of textured surface of cylindrical part by WEDT with a motor rotational speed of 4000 min\(^{-1}\). Cylindrical part has 6 mm in diameter and 10 mm height which can be expanded to be rectangular part with 18.8 mm width and 10 mm height as described in Fig. 5 (b). From Fig. 5 (a), numbers 1 to 12 indicate the direction and order of crater generation during texturing by WEDT. In the whirling phenomenon, the tool electrode whirls efficiently with a high speed along the inside of the cylinder to generate craters on the inner surface. In the whirling phenomenon, the tool electrode whirls efficiently with a high speed along the inside of the cylinder to generate craters on the inner surface. The tip of the tool electrode is located at the end of the whirling shaft, and the horizontal displacement of the rotating shaft is obtained using the cantilever model shown in Fig. 6. The displacement in terms of number of revolutions, degree of eccentricity and natural frequency, is given by Eq. (4), and the natural frequency of the rotation system is obtained from Eq. (5).
Fig. 5 Expected crater pattern of textured surface on the cylindrical part

(a) Example calculation of crater pattern  (b) Schematic of cylindrical part

Fig. 6 Cantilever model.

\[ r = \frac{\varepsilon}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\zeta \omega)^2}} \]  \hspace{1cm} (4)

\[ \omega_0 = \frac{3\pi d^4 E}{64l^3(m + 0.23m_e)} \cdot \frac{60}{2\pi} \] \hspace{1cm} (5)
Figure 7 shows a schematic diagram of the prototype WEDT equipment. The equipment consists of a power supply, tool electrode shaft, rotating device, work tank, workpiece and Z table. The whirling system consists of a motor, coupling, bearing and whirling shaft. The feed mechanism of the WEDT equipment is implemented via the Z-table. Figure 8 shows the procedure of WEDT. First the voltage is applied from the power supply to rotate the tool electrode shaft at a high constant rotational speed while maintaining a gap width. Then the discharge occurs and a crater is generated. Figure 9 shows the tool electrode and workpiece. A long thin beryllium copper shaft was used as the tool electrode shaft to maximize the displacement of its tip for a given motor rotational speed. The length of the shaft from the end face of the collet to the center of gravity is 70 mm and the shaft has a diameter of 1 mm. In addition, the tip of the tool electrode is made of copper tungsten and has a mass of 0.536 g. Craters are generated by the electrical discharge between the tool electrode and workpiece. Part of the tool electrode has a conical shape. The chamfering angle is 60°, which is the sum of the tilt angle of the tool electrode and the cone apex angle. The workpiece, in which craters were formed, had a 6 mm diameter and was made of carbon steel. The gap width was adjusted by controlling the rotational speed of the whirling shaft. Since the deflection of the whirling shaft is proportional to its rotational speed, the tool electrode shaft can be controlled at a high rotational speed via the whirling phenomenon.
Next, Table 1 shows the experimental conditions for texturing by WEDT when the effect of the feed speed was investigated. Microphotographs of the results obtained at two feed speeds are shown in Fig. 10. After texturing by WEDT, a small hole was cut in a workpiece using a cutting machine (MC-120, Maruto Instrument Co., Ltd), which was then cut into two parts, referred to as workpiece 1 and workpiece 2. From Fig. 10, it appears that the number of craters when the feed speed was 0.1 mm/s was larger than that when the feed speed was 1 mm/s. Figs. 11 shows high-magnification microphotographs of workpiece 2. From Fig. 11, it was shown crater and debris that occur from discharge process and 3D image of a crater with its cross-sectional profile observed using a digital microscope (KH-1300, Hirox). One of the craters was examined; its diameter was 48 μm and its depth was 3.7 μm.

![Tool electrode and workpiece](image)

**Table 1 Experimental conditions for texturing by WEDT.**

|                |          |
|----------------|----------|
| Gap voltage [V]| 100      |
| Discharge current [A]| 4.4      |
| Pulse frequency [Hz]| 1000     |
| Pulse duration [μs]| 200      |
| Rotational speed [min⁻¹]| 4010     |
| Feed speed [mm/s]| 0.1, 1   |

Fig. 9 Tool electrode and workpiece.

Fig. 10 Microphotographs of workpieces at feed speeds of (A) 0.1 and (B) 1 mm/s.

![Microphotographs of workpieces](image)
Next, a pattern of craters was examined. Table 2 shows the experimental conditions of WEDT used to generate the examined crater pattern. Figure 12 shows a high magnification microphotograph of the crater pattern after texturing. Crater diameter was 80 μm, average from three craters.

Table 2 Experimental conditions used to generate examined crater pattern.

| Gap voltage [V] | 100   |
|----------------|-------|
| Discharge current [A] | 4.4   |
| Pulse frequency [Hz] | 99.78 |
| Pulse duration [μs] | 200   |
| Rotational speed [min⁻¹] | 4010 |
| Feed speed [mm/s] | 1     |

Fig. 11 High magnification microphotograph of workpiece 2 and 3D image of crater.

Fig. 12 High magnification microphotograph of the crater pattern after texturing.
4. Development of WEDT equipment

It is necessary to examine whether texturing can be performed using the WEDT equipment. In EDM, the shape of the crater can be controlled by varying the gap voltage, discharge current and pulse duration. In addition, the number of craters can be controlled via the feed speed and pulse frequency. The prototype WEDT equipment was used in texturing experiments. The prototype WEDT equipment maintains a constant discharge current while the gap voltage and pulse frequency are changed and the whirling mechanism rotates the tool electrode along the inside surface of a small hole. Next, the developed WEDT equipment is described. A photograph of the WEDT equipment is shown in Fig. 13. The tool electrode was made of tungsten wire of 0.3 mm diameter, which was inserted in the screw part at the end of the shaft and fixed with a nut. The workpiece used was a cylinder part made of carbon steel with a small hole of 7 mm internal diameter. The gap width is adjusted by controlling the rotational speed of the whirling shaft. Since the deflection of the whirling shaft is proportional to its rotational speed, the tool electrode shaft can be controlled to obtain highly efficient machining from the whirling phenomenon. Figure 14 shows the relationship between the rotational speed and the displacement of the whirling shaft. The dots show the displacement obtained from the experiment and the line shows the displacement obtained by calculation. As shown in Fig. 14, the natural frequencies obtained from the experiment and calculation was different because of the unbalance of the tool electrode and the level of accuracy of the spindle. The natural frequency, which was analyzed using the cantilever model shown in Fig. 6, was used to obtain the maximum displacement. The displacement of the whirling shaft increases with its rotational speed. When the rotational speed approaches the natural frequency, the displacement of the tool electrode reaches its peak value. In addition, the displacement increases gradually with increasing rotational speed from 1000 min\(^{-1}\) to 2000 min\(^{-1}\); thus, the displacement can be flexibly adjusted by varying the rotational speed within this range. Therefore, it has been clarified that the whirling mechanism of the WEDT equipment is necessary for the texturing.

![Fig. 13 Photograph of WEDT equipment.](image)
5. Experiments on texturing inner surface of small hole

Experiments were conducted using the WEDT equipment to confirm that it can texture the inner surface of a small hole by employing the whirling phenomenon. First, experiments on controlling the shape and number of craters were conducted. Table 3 shows the basic experimental conditions used for texturing when the discharge current was changed. The craters were observed using a digital microscope (KH-1300, Hirox). Figure 15 shows microphotographs of the craters formed at discharge currents of (a) 1.5 A, and (b) 15 A.

| Table 3 Basic experimental conditions used for texturing. |
|---------------------------------|----------------|
| Discharge current [A]           | 1.5, 15        |
| Pulse duration [µs]             | 100            |
| Feed speed [mm/s]               | 1              |

![Image of microphotographs](a) 1.5A  (b) 15A

Fig. 15 Microphotographs of craters formed at different discharge currents.

![Image of 2D and 3D images](Fig. 16 2D and 3D images of textured surface obtained using scanning white light interferometers (NewView7300, Zygo).)
From Fig. 15, it was clarified that crater diameter depended on machining condition which is discharge current. When the discharge current increase from 1.5 A to 15 A, the crater diameter increases. Fig. 16 shows 2D and 3D image of textured surface, which was measured using a scanning white light interferometer (NewView7300, Zygo). From this method, crater shape which is crater diameter and crater depth can be measured. Figure 17 shows the cross-sectional profile of a crater that contained a large amount of debris and a hollow part. From Fig. 17, the crater has a depth around 3 μm. To obtain high-efficiency EDT, the gap width should be controlled. Since it was thought that if the gap width becomes an optimum value the discharge occurs and the crater is generated. However, it is difficult to control the gap width in the WEDT process since discharge does not occur under open circuit and short circuit conditions.

Next, a texturing experiment was conducted to determine the relationship between the crater diameter, discharge current and discharge duration. Table 4 shows the experimental conditions. Figure 18 shows the relationship between discharge current and crater diameter. From the graph, it was clarified that for constant discharge duration, the crater diameter increased with increasing discharge current, and for a constant discharge current, the crater diameter increased with increasing discharge duration.

Table 4: Experimental conditions used to investigate crater diameter in terms of discharge current and discharge duration.

| Gap voltage [V] | 100 |
|----------------|-----|
| Discharge current [A] | 1.5, 4, 9, 15 |
| Pulse duration [μs] | 10, 100, 1000 |

Fig. 17 Example of cross-sectional profile of crater that obtained from scanning white light interferometer (NewView7300, Zygo).

Fig. 18 Relationship between discharge current and crater diameter.
Considering these results, it was clarified that the WEDT method can be used to control the crater diameter via the discharge current and discharge duration. In EDM, it was confirmed that the feed speed affected the number of craters. To confirm these findings for the WEDT equipment, a texturing experiment in which the feed speed was varied was conducted. Table 5 shows the experimental conditions. Figure 19 shows microphotographs of craters formed at feed speeds of (a) 1 mm/s, (b) 0.5 mm/s, (c) 0.25 mm/s, (d) 0.125 mm/s and (e) 0.00167 mm/s. From Fig. 19, it was clarified that the number of craters increased with decreasing feed speed. However, because it was difficult to count the number of craters, a scanning white light interferometer (NewView7300, Zygo) was used to determine the texture-area ratio, which is the total crater area divided by total measurement area as described in Fig. 20. Figure 21 shows the relationship between feed speed and texture-area ratio. It was clarified that the texture-area ratio slightly increased with decreasing feed speed. In addition, it was expected that the texture-area ratio would be doubled when the feed speed was reduced by half. However, when the feed speed was less than 0.125 mm/s, the texture-area ratio was larger than expected. Craters were easily formed when the feed speed was less than 0.125 mm/s. It is considered that as the distance between the tool electrode and the protrusions originating from previous craters decreased, the discharge occurred more easily.

Table 5: Experimental conditions used to investigate relationship between crater number and feed speed.

| Power supply [V] | 100 |
|------------------|-----|
| Discharge current [A] | 4 |
| Pulse frequency [Hz] | 1000 |
| Pulse duration [μs] | 100 |
| Rotational speed [min⁻¹] | 2000 |
| Feed speed [mm/s] | 0.0167, 0.125, 0.25, 0.5, 1 |

Fig. 19 Microphotographs of textured surface for different feed speeds.
Fig. 20 2D and 3D of textured surface observed by scanning white light interferometer (NewView7300, Zygo) to determine texture-area ratio.

(a) Total crater area

(b) Total measurement area

Fig. 21 Relationship between feed speed and texture-area ratio.
6. Conclusions
The following conclusions were obtained from the experiments on texturing a cylinder by the WEDT method.

(1) Whirling Electrical Discharge Texturing (WEDT) was developed in accordance with the principle of EDT.

(2) The microstructures can be generated and controlled on inner surface of small hole with high-hardness material using WEDT.

(3) The surface characteristics of textured surface which are crater diameter and texture-area ratio can be controlled by discharge current and feed speed, respectively.

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