euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
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Highly efficient texturing of electroless Ni-P plate for optical mold surface by ultrasonic vibration assisted indentation

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Abstract
Texturing technology is increasingly required to apply to many advanced optical devices. This study proposed and developed the fabrication technology of a textured surface by ultrasonic vibration-assisted indentation to decrease the processing time of the structured mold, decrease the cutting cost, and increase the processing efficiency. The indentation process of the molds using a sharp indenter can machine the textured surface, and ultrasonic vibration-assisted motion was added to increase the precision and efficiency of the structured mold. In the experiments, the electroless Ni-P plated copper substrates were indented using single crystalline diamond indenters, which were fabricated using a laser scanning process. In the indentation tests, the effects of the plated electroless Ni-P thickness on the indentation characteristics such as an indentation load, burr height, form accuracy were measured and evaluated.

Keywords: ultrasonic vibration assisted indentation, highly efficient texturing, optical mold, electroless Ni-P plate, micro array mold

1. Introduction

Texturing technology is increasingly being applied to many advanced devices. Textured flat panel of micro lens array having many minute dimples are used in flat panel display devices such as light guide plates, for smartphones, and heads up displays (HUD) for automobile installations. These dimples help to reduce reflections so that the brightness of the display panels can be increased, thus increasing the market of these panels. The production of hundreds of millions of display panels is required, and the molds of micro lens array having many minute dimples are mass-produced by the injection molding of the resin. Therefore, the precision machining of the structured or textured mold becomes very important. In conventional machining process, electroless Ni-P plating of amorphous material on a stainless-steel substrate is mirror-finished by the ultraprecision cutting using a diamond tool. However, in the conventional process of cutting with a sharp cutting tool of single crystalline diamond, there were many problems. The cutting time required to decrease the surface roughness was too high and the tool wear was too large because the tool size was so small compared with the workpiece size. In addition, burrs of the cut materials appeared, and the workpiece surface finish was limited. In this study, an ultrasonic vibration-assisted indentation system was developed to overcome the problems of the conventional cutting process.

1.1 Effects of ultrasonic vibration assisted indentation

The indentation process of the molds that uses a sharp indenter can machine the textured surface, and ultrasonic vibration-assisted motion was added to increase the precision and efficiency of the structured molds as shown in Figure 1. In the experiments, the single crystalline diamond indenter was fabricated by the laser fabrication process. In the proposed method, the high frequency motion of the indenter improves the precision and efficiency of the processing performance.

In the case of ultrasonic vibration-assisted indentation, the displacement Z of the indentation tool is given by:

$$Z = \lambda \cdot \sin(2\pi \cdot v \cdot t) \quad (1)$$

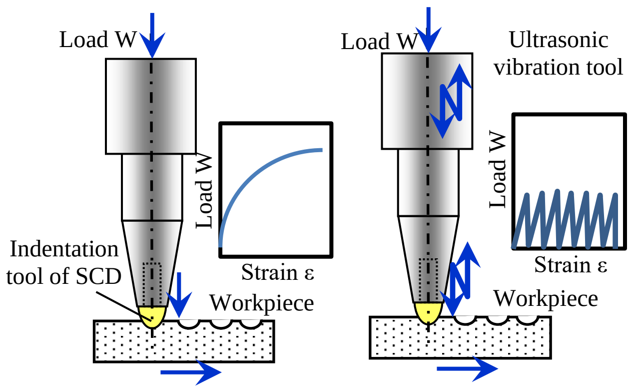
where λ and v are the amplitude and frequency of ultrasonic vibration, respectively, and t is the time.
Tool velocity is given by:

$$V = dZ/dt = 2\pi \cdot v \cdot \lambda \cdot \cos(2\pi \cdot v \cdot t) \quad (2)$$

Then, the tool acceleration is given by:

$$a = dV/dt = -4\pi^2 \cdot v^2 \cdot \lambda \cdot m \cdot \sin(2\pi \cdot v \cdot t) \quad (3)$$

Force is given by



(a) Conventional indentation method (b) Proposed ultrasonic vibration assisted indentation

Figure 1. Fabrication of textured surface by ultrasonic vibration-assisted indentation

$$F = m \cdot a = -4\pi^2 \cdot v^2 \lambda \cdot m \cdot \sin(2\pi \cdot v \cdot t) \qquad (4)$$

From Eq. (4), the force, *F* will increase considerably as the frequency of vibration increases when the ultrasonic vibration is applied [5, 6]. This reciprocating movement of the indentation tool at high speed and high load is expected to form the micro mold using hard metals, such as electroless Ni-P, with high accuracy and efficiency.

2. Fabrication of textured surface by ultrasonic vibration assisted indentation

In the indentation tests, micro indentation tools made of single crystalline diamond (SCD) were fabricated using a laser fabrication process, as shown in Figure 2. The SCD chip was bonded with a silver alloy onto a cemented carbide shank by a high frequency heating system and then, the outer surface of the SCD chip was machined to a cylindrical shape by a laser beam. Finally, the spherical surface was fabricated by laser scanning [4].

Figure 3 shows micro-image of the developed micro SCD indentation tools. The top radius of the tool were 0.1 mm and 0.5 mm.

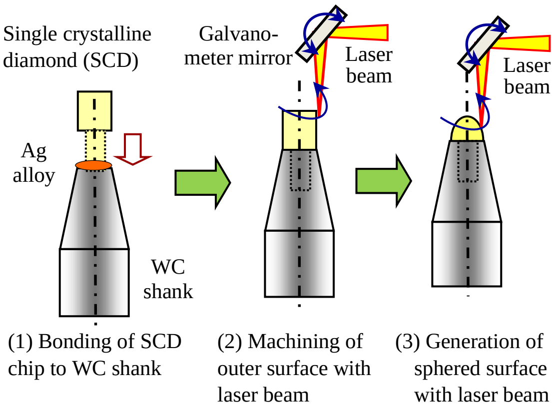
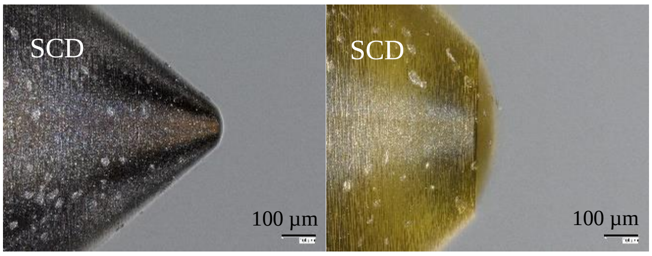


Figure 2. Laser fabrication process of SCD indentation



(a) Indenter of R0.1 (b) Indenter of R0.5

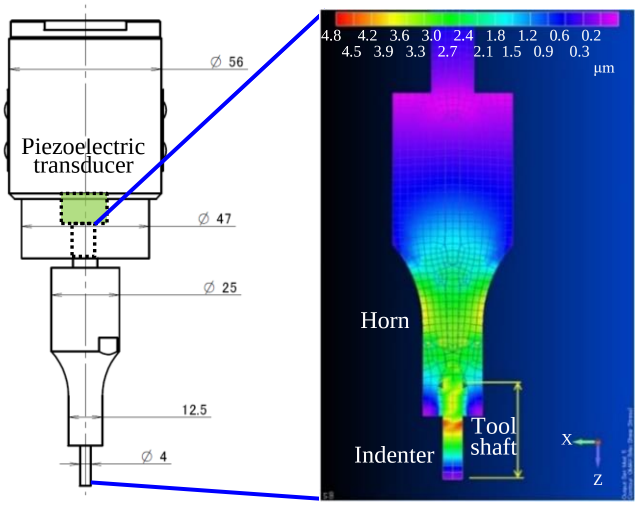
Figure 3. Micro images of micro SCD indentation tool fabricated by laser fabrication process

3. Experimental set-up and method

The developed ultrasonic-assisted vibration transducer is shown in Figure 4. A piezoelectric transducer was installed in the upper device and the vibration amplitude was amplified by the horn [7]. The single crystalline diamond indentation tool was chucked on the tip of the horn. An analyzed vibration amplitude is shown in Figure 4 (b). The vibration amplitude of the piezoelectric transducer was decreased in the center and it became maximum at the top of the indentation tool.

A view of the ultrasonic vibration-assisted indentation set-up was shown in Figure 5. The developed ultrasonic vibration-assisted device was installed on a 3-axes controlled precision machine driven by the ball screws. The table (X,Y,Z) axes were controlled by the linear scale feedback system. The positioning resolutions were 0.01 0.03 µm and the positioning accuracies of the tables were 0.03 µm. The workpiece was set on the dynamometer and the indentation force was measured. The indentation experiments were carried out in the lubricant coolant mist of white kerosene.

The indentation conditions are shown in Table 1. The frequency and amplitude of the ultrasonic vibration were 39 kHz and 0 - 6.2 µm, respectively. Indentation depth was 50 µm. The movements of the tool and the indentation time were controlled by the NC system of the ultraprecision machine.



(a) Illustration of ultrasonic vibration tool (b) Amplitude analysis of ultrasonic vibration

Figure 4. Ultrasonic vibration-assisted indentation set-up

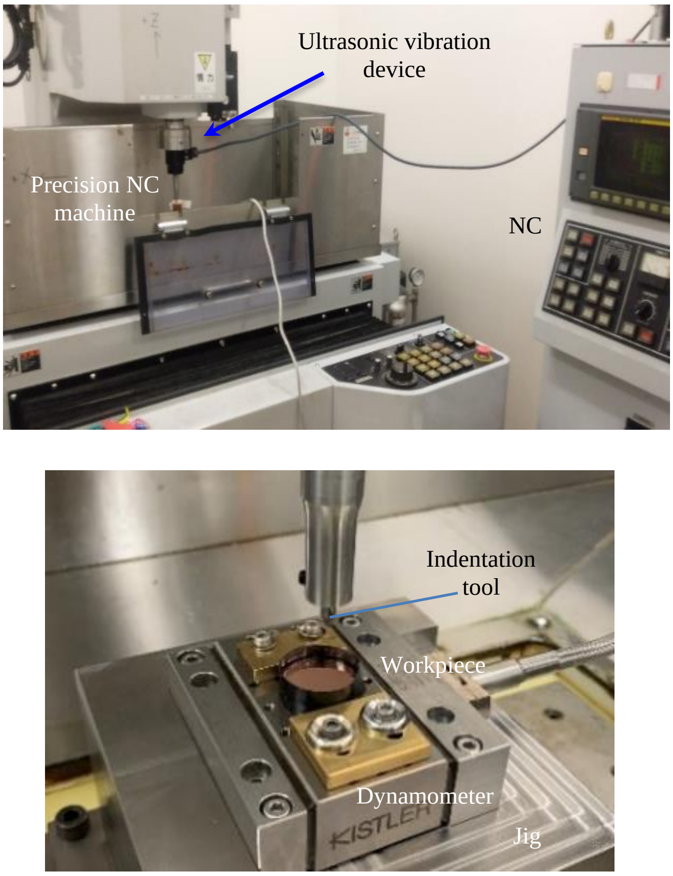


Figure 5. Ultrasonic vibration-assisted indentation set-up on the3-axes controlled precision machine.

Table 1 Conditions of indentation tests

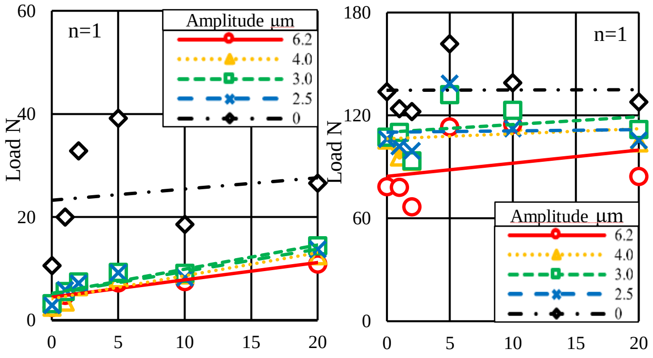
Tool material Top radius	Single crystalline diamond (SCD) R0.1, R0.5 mm
Ultrasonic vibration Frequency Amplitude	Piezoelectric 39 kHz 0, 2.5, 3.0, 4.0, 6.2 μm
Workpiece Base material Thickness	Electroless Ni-P (HV 519) Oxygen-free copper (HV 200) 1, 2, 5, 10, 20 μm
Depth of indentation Feed rate	50 μm 10 mm/min
Coolant	White kerosene

4. Experimental results

Indentation test was carried out on the electroless Ni-P plated oxygen-free copper molds. The thickness of the Ni-P plate was changed by controlling plating time and the plate thickness was measured the X-ray fluorescence film thickness meter (Olympus). The apparent set indentation depth was 50 μm by controlling the precision NC machine system, and the amplitude of ultrasonic vibration were varied between 0 - 6.2 μm.

4.1 Indentation load

Figure 6 shows the changes in the indentation load with amplitude and electroless Ni-P film thickness when the indented depth was 50 μm. The indentation load was measured using the dynamometer (Kistler) which was installed on to the machine table. As the amplitude of the ultrasonic vibration increased, the indentation load decreased.

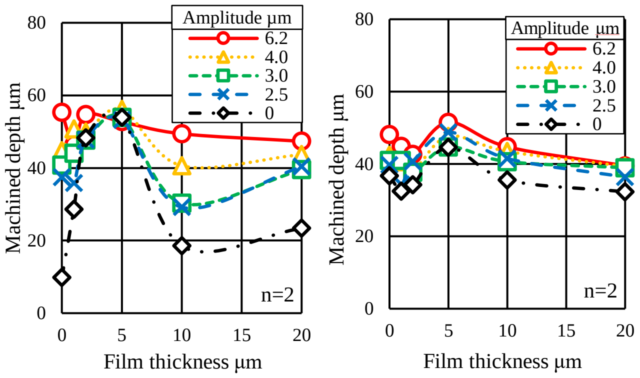


(a) Indenter of R0.1 (b) Indenter of R0.5

Figure 6. Change in the indentation load

4.2 Machined depth

Figure 7 shows the changes in the machined depth with amplitude of ultrasonic vibration and electroless Ni-P film thickness. The set indented depth was 50 μm by using the precision NC machine. In the experiments, the indenters of R0.1 and R0.5 were used. The machined depth was measured using the laser probe scanning profiles measuring system (Mitaka Co. Ltd.). In both cases in, as the amplitude of ultrasonic vibration increased, the machined depth increased. The machined depth using the indenter of R0.1 varied more than that of the indenter of R0.5. In both cases in the experiments using the indenters of R0.1 and R0.5, machined depth was close to 50 μm with an electroless Ni-P film thickness of 5 μm. The decrease in the machined depth with increase in electroless Ni-P film thickness seems due to the increase in the hardness of electroless Ni-P plating.

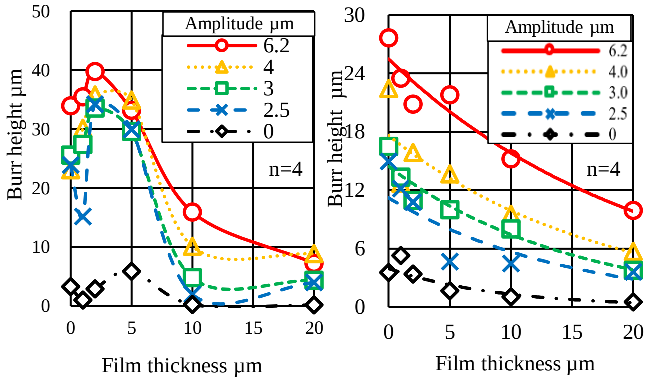


(a) Indenter of R0.1 (b) Indenter of R0.5

Figure 7. Change in the machined depth

4.3 Burr height

Figure 8 shows the changes in the burr height with the amplitude of ultrasonic vibration and electroless Ni-P film thickness. In both cases in the using the indenters of R0.1 and R0.5, as the amplitude of ultrasonic vibration increased, the burr height increased. The machined depth was measured using the laser probe scanning profiles measuring system. In both cases in the using R0.1 and R0.5 indenter, as the Ni-P film thickness increased, burr height decreased. The burr height using the indenter of R0.1 was larger than that using the indenter of R0.5.

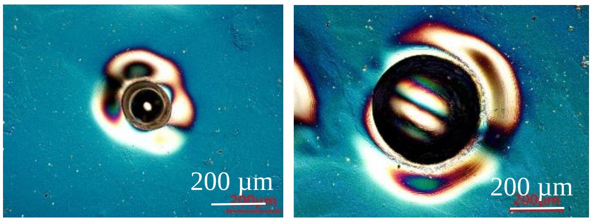


(a) Indenter of R0.1 (b) Indenter of R0.5

Figure 8. Change in the burr height

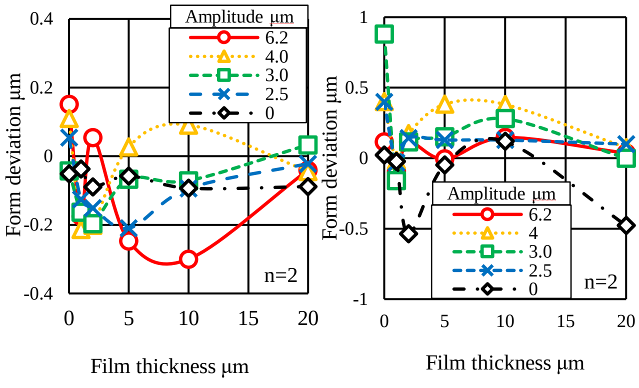
4.4 Form deviation

Figure 9 shows micro images of the surface imprint on electroless Ni-P. Figure 10 shows the changes in the form deviation with amplitude of ultrasonic vibration and electroless Ni-P film thickness. When Ni-P film thickness was 0 – 10 μm, the form deviation was not stable at any amplitude. This seems due to the springback of the base material, oxygen-free copper. However, both the indenters of R0.1 and R0.5 had a form deviation of less than 1 μm, and good transferability was obtained. In particular, for electroless Ni-P thickness of 20 μm, high transferability was obtained for both the indenters of R0.1 and R0.5.



(a) Indenter of R0.1 (b) Indenter of R0.5

Figure 9. Micro images of the surface imprint on electroless Ni-P (Amplitude λ =6.2 μm, Film thickness:20 μm)



(a) Indenter of R0.1 (b) Indenter of R0.5

Figure 10. Change in the form deviation

4.5 Machining test of micro lens array mold of electroless Ni-P plate.

A structured surface with concave dimples was machined by the developed ultrasonic vibration-assisted indentation. Figure 11 shows a Nomarski micrograph of the indented mold surface. The indenter shown in Fig. 3(b) was used. Depth of indentation was 10 μm, feed rate was 100 mm/min and indentation time was 0.1 s. The pitch in the x-direction and y-direction was 150 μm. Figure 12 shows changes in surface roughness of the dimple profiles measured with a non-contact-type laser probe instrument. The shapes of the created concave dimples were very sharp and smooth for applying the light-guiding plate mold. In this proposed ultrasonic vibration-assisted indentation method, the transcribing deviations between the indenter and the indented pattern occurs due to the spring-back of the workpiece. In the actual manufacturing process, this problem would be easily solved by the compensation process of the transcribing deviations or the compensation of the indenter shape.

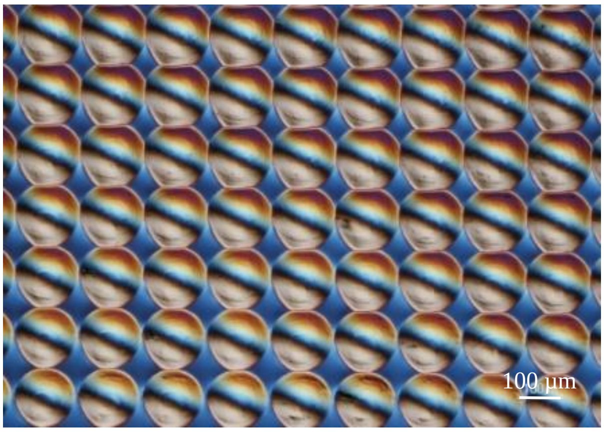


Figure 11. Nomarski micrograph of micro lens array mold fabricated by ultrasonic vibration-assisted indentation (Electroless Ni-P plated mold, 13x13array).

5. Conclusions

Texturing technology is increasingly being applied in the fields of many advanced devices. In this study, a new fabrication method and system using ultrasonic vibration-assisted indentation was proposed and developed for generation of a textured surface. The indentation process of the mold with a sharp indenter can machine the textured surface by laser fabrication and diamond lapping, and ultrasonic vibration-assisted motion was added to increase the precision and efficiency of the structured mold. In the indentation experiments, the single crystalline diamond indenter was machined by the laser scanning process. And the effect of amplitude of ultrasonic vibration and electroless Ni-P film thickness on processing were investigated. In the proposed method, the high frequency motion of the indenter seems to greatly improve precision and efficiency of the processing performance.

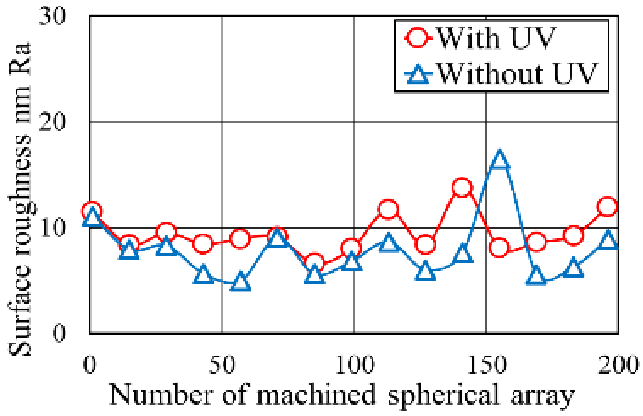


Figure 12. Changes in surface roughness of machined micro lens array mold of electroless Ni-P.

Acknowledgements

This study was supported by the Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research 20H02486, The Amada Foundation (AF-2018032), and The Osawa Foundation.

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