Paper:

Fabrication of Thin-Film Fresnel Optics by Combining Diamond Turning and Photolithographic Processes

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A novel fabrication process is proposed for manufacturing thin-film metal Fresnel lenses for X-ray applications. This process combines diamond turning technology and photolithographic processes. To prevent thin-film lens substrates from deflection during diamond turning, films were prepared on single crystalline silicon wafers by electrolytic plating. After the Fresnel lens structure is generated on the metal thin films by diamond turning, the silicon substrate was then removed selectively by reactive ion etching. Experimental results demonstrated that the proposed hybrid fabrication process achieves submicron form accuracy and nanometer surface roughness.

Keywords: Fresnel lens, photolithography, ultraprecision cutting, diamond turning, optical elements

1. Introduction

Demand is increasing for thin film optics, such as X-ray Fresnel lenses, in advanced optical systems like space observation satellites [1, 2]. This is because conventional reflecting optics has insufficient angular resolution and sensitivity and is difficult to deal with high-energy short wavelength rays. To use thin film Fresnel optics, extremely high angular resolution ($\sim$ 1 μs) is realized that enables dealing with high-energy hard X-rays and γ-rays. For this reason, thin-film Fresnel lenses made of metal materials such as copper which has high permeability and a high refraction index for X-rays are required by the optical industry.

To fabricate thin film optics on soft metal materials by mechanical machining is extremely difficult, however, because thin film substrates are very easily deflected during clamping and machining due to external force. To solve this workpiece deflection problem, we propose fabricating thin film optics by combining diamond turning and photolithographic processes. Key steps in the proposed process are described in detail and preliminary fabrication experiments are done for a miniature model copper Fresnel lens for X-ray applications.

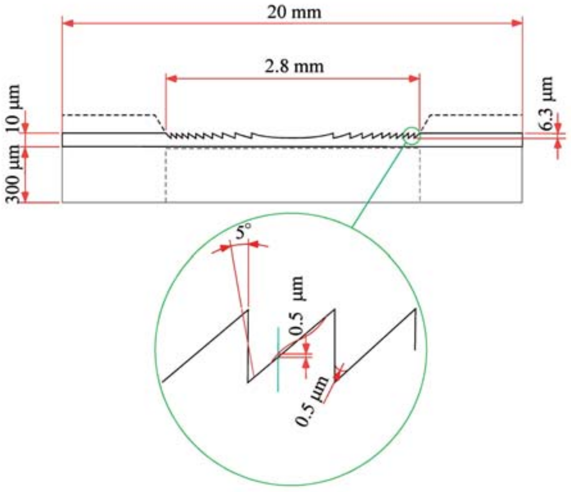


Fig. 1. Schematic diagram of thin film Fresnel lens.

2. Experiments

2.1. Process Steps

For the test piece, a Fresnel lens 10 μm thick was fabricated on a copper substrate. The designed shape of the Fresnel lens is schematically shown in **Fig. 1**. The diameter of the lens substrate is 20 mm and that of the effective Fresnel lens area is 2.8 mm. The designed height of the Fresnel zone step is 6.3 μm. To fabricate the thin film Fresnel lens, a hybrid process was adopted involving diamond turning and photolithography.

A flow chart of the hybrid fabrication process is schematically shown in **Fig. 2**. The process has the following main steps: (a) Spattering thin films of Cr 50 nm thick and Au 100 nm thick on a silicon wafer; these films act as interlayers for electrolytic plating of Cu 30 μm thick. (b) Diamond turning of the Cu layer for the Fresnel lens structure. (c) Spin coating of a photoresist layer on the back of the silicon wafer and using photolithography to remove the center of the photoresist layer that corresponds to the Fresnel lens. (d) Removing exposed silicon substrate by using Reactive Ion Etching (RIE). (e) Re-

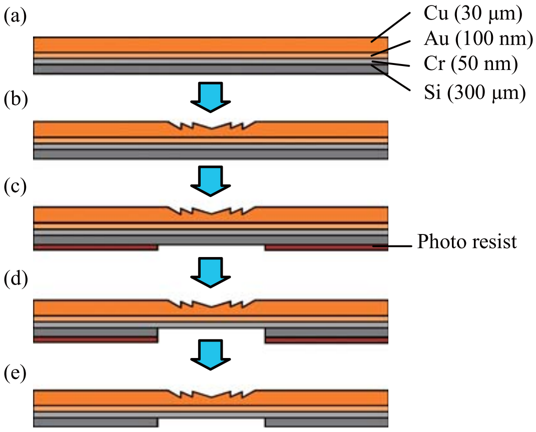


Fig. 2. Flow chart of the hybrid fabrication process.

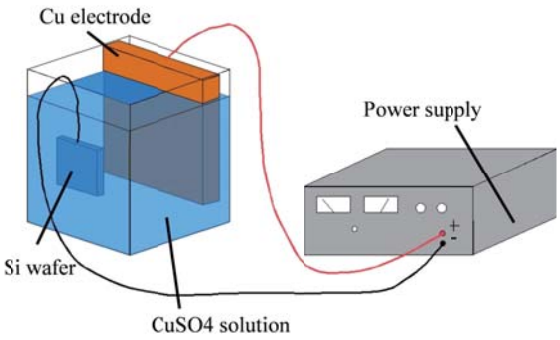


Fig. 3. Schematic diagram of electrolytic plating setup.

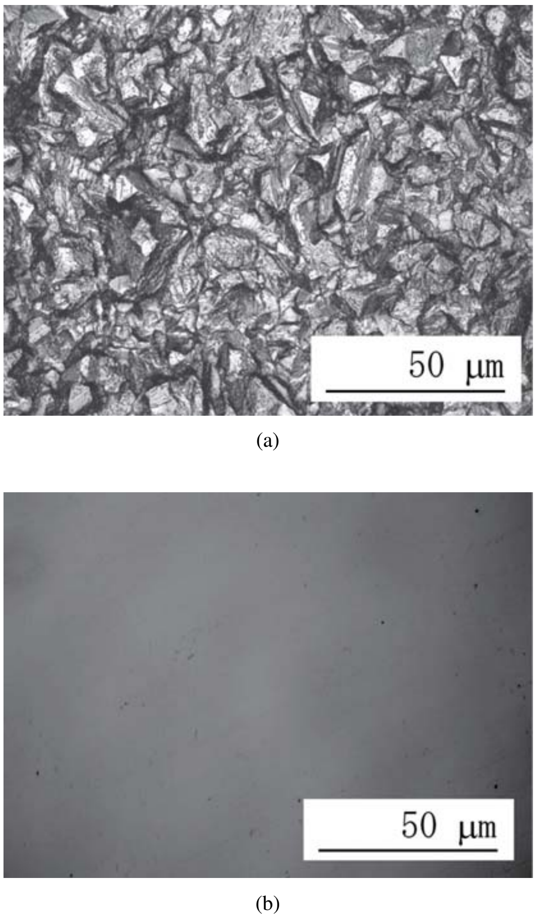


Fig. 4. SEM micrographs of (a) plated Cu surface and (b) face turned surface.

moving the residual photoresist layer by using chemical etching to obtain a thin film Fresnel lens on Cu.

In step (a), sputtering of Cr and Au thin films was performed by high frequency multi-sputtering equipment (JEOL JEC-SP360R). RF power was 300 W and the pressure used was 3×10^{-3} Pa. Note that Cr and Au interlayers were not removed after the lens was fabricated because they do not adversely affect the optical performance of the copper Fresnel lens.

Cu was electrolytic plated using the electrolytic plating setup as shown in **Fig. 3**. Plating was performed in a $CuSO_4$ solution having a pH of 1.8. Electrical current was 40 mA and plating time was 6 h. This condition yields a plating thickness of $\sim 30\ \mu$m. The plated surface was quite rough, so face turning was performed before machining the Fresnel structure.

Figure 4 shows SEM micrographs of the plated surface and the face-turned surface. Step (b), namely, diamond turning of the Fresnel lens structure, is described in detail in the next section.

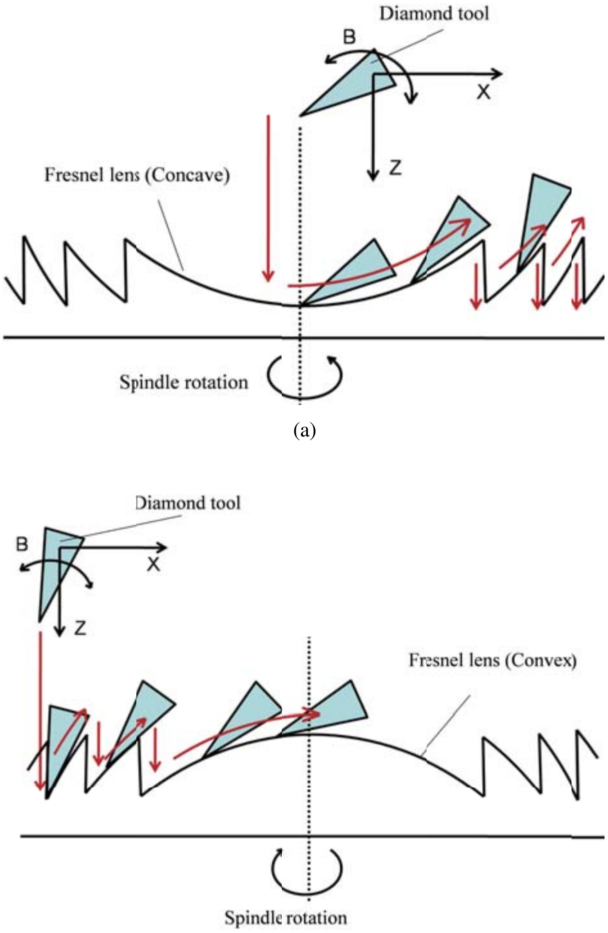
In step (c), mask aligner MA6 (SUSS Microtech) was used for photolithography. Photoresists OAP and PMER were spin-coated at 500 rpm for 5 s and 2000 rpm for 20 s. Prebaking was done for 5 min at 90°C and at 110°C. The developer was P-7G and developing was done for 6 min.

In step (d), an inductive coupled plasma RIE (ICP-RIE) system was used to remove silicon on the back of the Fresnel lens. The silicon layer must be removed because it is not transparent to X-Rays.

In step (e), acetone was used to remove residual photoresist.

2.2. Diamond Turning

To generate the Fresnel structure on the Cu layer, diamond turning tests were performed in step (b) as shown in **Fig. 2**. An extremely sharp single-crystalline diamond tool is used under simultaneous three-axis (XZB) numerical control [3]. The schematic model of the Fresnel structure machining is shown in **Fig. 5**. When a concave Fresnel lens is produced, as shown in **Fig. 5(a)**, the diamond tool is fed from the workpiece center to the outer region. The workpiece is rotated by an air spindle. The machining operation for the Fresnel zone consists of two steps: First, the tool moves along the Z axis, namely the vertical axis, to generate the cylindrical surface of the zone step. Second, the tool moves and at the same time rotates under XZB three-axis control to generate the curved surface. When a convex Fresnel lens is machined, as shown in **Fig. 5(b)**, the diamond tool is fed from the outer region to the center of the workpiece while the air spindle



(a)

(b)

Fig. 5. Schematic model for Fresnel structure cutting.

rotates. This tool feed direction arrangement is to prevent burrs from forming on the edges of grooves.

In experiments, an ultraprecision diamond turning machine, the NACHI-ASP15, was used. The machine has an ultraprecision air-bearing spindle, two perpendicular linear tables (X- and Z-axes) and a rotary table (B-axis). Linear tables are supported by high-stiffness hydrostatic bearings and are driven by servomotors via hydrostatic screws with negligible mechanical friction. The rotary table is also supported by hydrostatic bearings and driven by a friction drive in order to prevent backlash. Laser hologram scales are used to position all of these tables accurately. After renovation of the numerical feedback control system of the machine, linear tables are moved at 1 nm per step and the rotary table is rotated at an angular resolution of 0.00001°. To isolate the lathe from environmental vibration, the main section of the machine was fixed to a granite bed that is supported by a set of air mounts.

Two single-crystalline diamond tools were used. The one used for face turning was a round-nosed tool having a nose radius of 2 mm, a rake angle of 0° and a relief angle of 6°. The depth of cut in face turning was 10 μm and the feed rate was 5 μm /rev at a spindle speed of 1000 rpm.

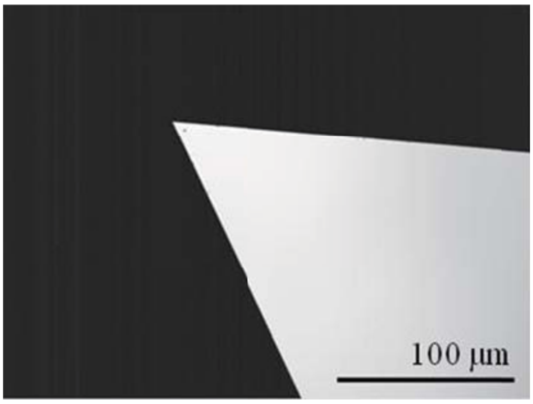


Fig. 6. SEM micrograph of diamond tool tip.

Table 1. Diamond turning conditions.

Workpiece	Cu plating (thickness 30 μm)
Lens diameter	20 mm (Fresnel area 2.8 mm)
Zone depth	6.3 μm
Tool included angle	60°
Tool rake angle	0°
Tool relief angle	10°
Feed rate	0.05 μm/rev
Spindle rotational rate	2000 rpm
Cutting fluid	Kerosene mist

A V-shaped tool was used for generating the Fresnel structure. This tool has an included angle of 60°. The edge radius was estimated to be a few tens of nanometers. A SEM micrograph of the tool tip is shown in **Fig. 6**. The cutting edge angle of the tool was adjusted and controlled using the B-axis rotary table of the lathe. Experiment conditions are listed in **Table 1**.

A three-dimensional noncontact surface profilometer, the Mitaka NH-3SP, was used to measure lens accuracy. A Scanning Electron Microscope (SEM) was used to observe the machined surface and cutting chips collected during diamond turning.

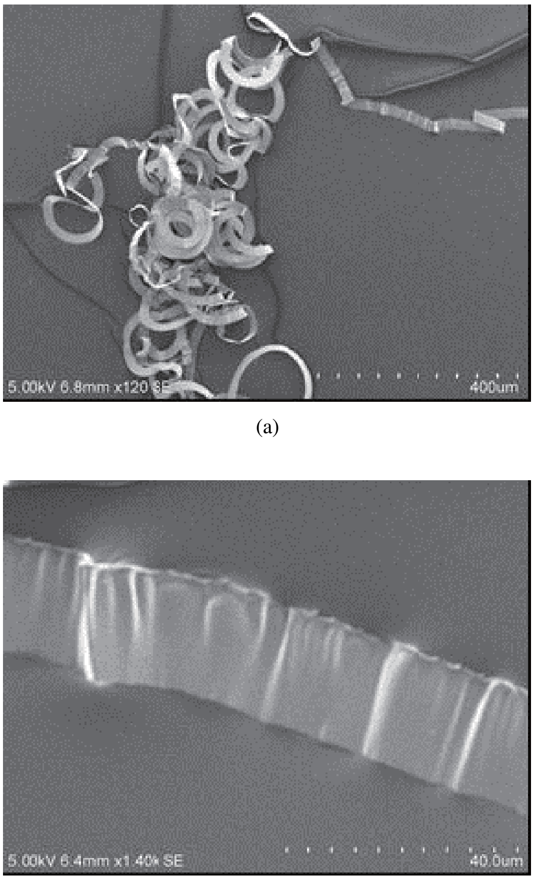
3. Results and Discussion

3.1. Chip Formation

Figure 7 shows SEM micrographs of cutting chips collected during diamond turning of the Fresnel structure. The chips form slightly curled ribbons. The width and thickness of the ribbons are very uniform, indicating that the cutting process was stable.

3.2. Lens Surface

Figure 8 shows SEM micrographs of the machined lens surface. **Figs. 8(a)** and **(b)** show that concentric Fresnel zones are clearly generated and that the lens surface is extremely smooth. **Fig. 8(c)** shows that the zone step



(a)

(b)

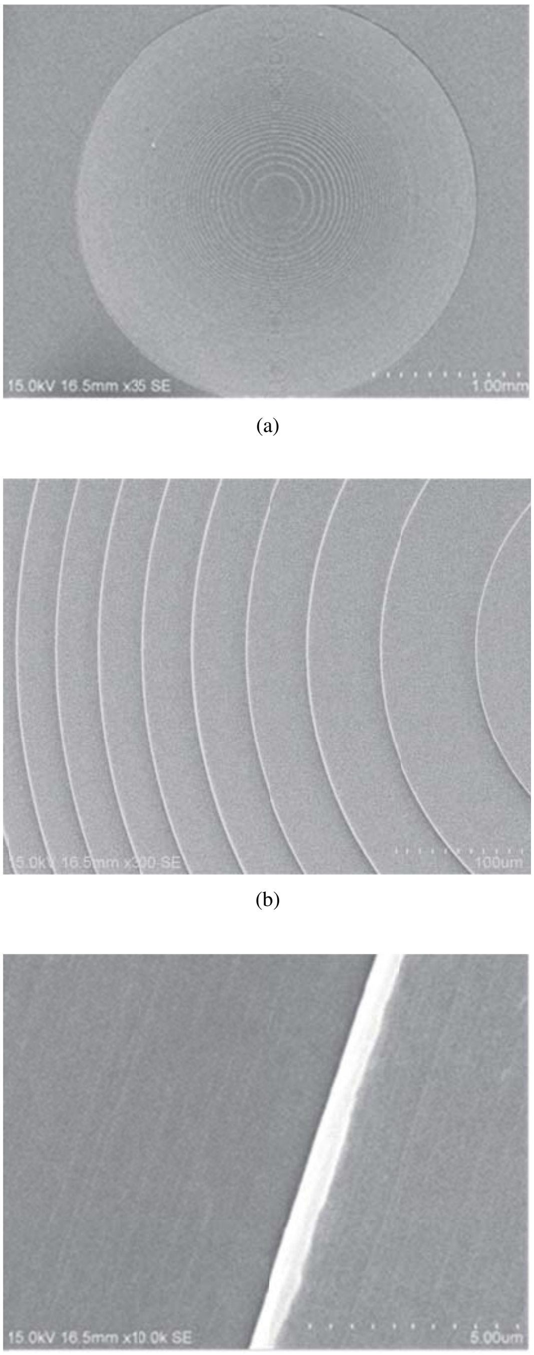
Fig. 7. SEM micrographs of cutting chips: (a) low magnification view and (b) high magnification view.

(height $\sim$ 6.3 μm) is very straight and flat, with no burr formation. This result indicates that the diamond turning conditions used in experiments were suitable. The surface roughness of the Fresnel lens measured by the three-dimensional noncontact surface profilometer, the Mitaka NH-3SP, is 2 nm Ra (15 nmRy).

3.3. Form Accuracy

The cross-section profiles of the fabricated Fresnel lenses were evaluated by the surface profilometer Mitaka NH-3SP. Results typical for concave and convex lenses are shown in **Figs. 9(a)** and **(b)**, respectively. **Fig. 9(a)** shows that when the concave lens is cut, the lens surface becomes lower at the lens edge than at the center. When the convex lens is cut, however, the surface becomes lower at the lens center than at the edge, as shown in **Fig. 9(b)**. These results show a common phenomenon, namely, the surface height decreases with the cutting time, i.e., tool feeding. This phenomenon may possibly be caused by the thermal expansion of the tool shank. If coolant is not sufficient, cutting heat accumulates in the tool, which causes an extension of the tool shank.

To solve this problem, we improved the cooling method and the quantity of coolant to reduce the heat flux from the tool tip to the tool shank. First, the direction of the coolant jet was changed from the rake face of the tool alone to both the rake face and the flank face. Second, we increased the coolant applied per hour from 5 to 40 cc/h. **Fig. 9(c)** shows a cross-section profile of a concave lens cut under improved cooling conditions. It is clear that the form error became distinctly lower than that in **Fig. 9(a)**, and the lens profile tends to be flat. Lens form accuracy is at the submicron level, which meets the designed requirements of the Fresnel lens. In **Fig. 9(c)**, the slight drift of surface height within a distance of 1000 – 1400 μm could

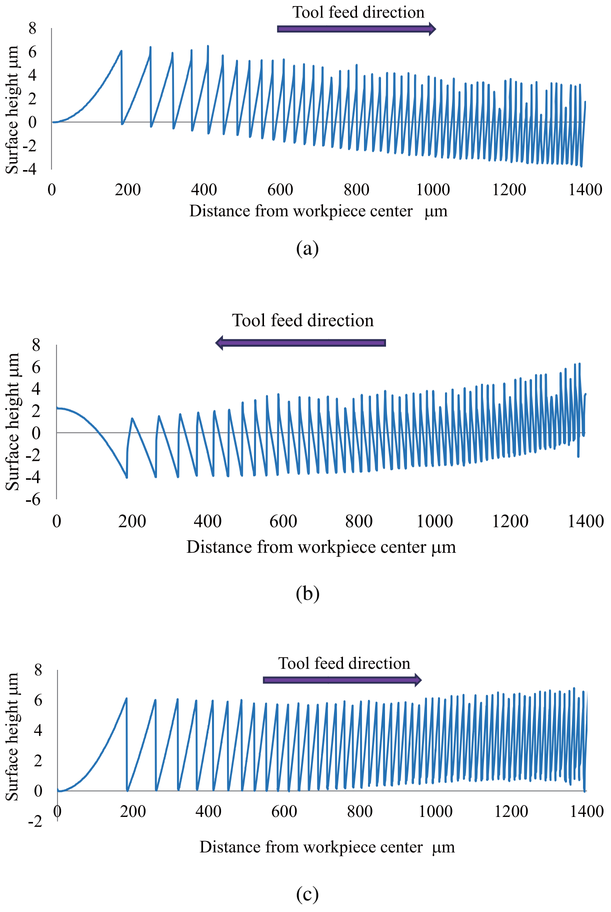


(a)

(b)

(c)

Fig. 8. SEM micrographs of machined lens surface: (a) overall view, (b) Fresnel zones, and (c) a zone step.



(a)

(b)

(c)

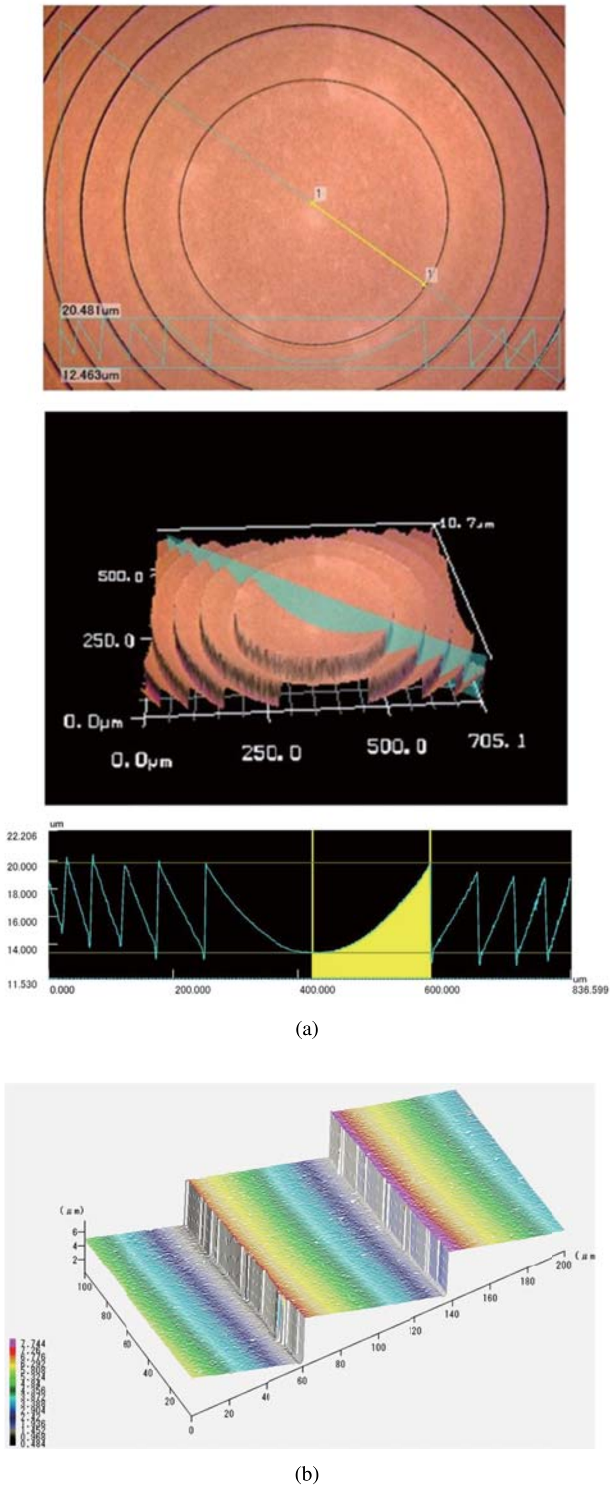
Fig. 9. Cross-sectional profiles of (a) a concave lens and (b) a convex lens, showing dependence of form error on tool feed direction. (c) is a cross-sectional profile of a concave lens machined under improved coolant providing conditions, showing decrease of form error.

be caused by the instability of the coolant flow.

Figure 10 shows the three-dimensional surface topographies of the center and the edge region of the Fresnel lens measured by a digital microscope, the Keyence VHX-1100. From these results, we clearly confirmed that the lens has been precisely fabricated with a smooth surface and sharp zone steps. There is neither protrusion due to tool decentering at the lens center nor burr formation due to workpiece material side flow at the edge of the zone step.

4. Conclusions

A miniature model of a thin film metal Fresnel lens for hard X-ray applications has been fabricated by combining diamond turning and photolithographic processes involving sputtering, electrolytic plating, reactive ion etching, and photolithography. The proposed method has solved the problem of deflection in thin film lens substrates effectively. Preliminary results have shown that submicron-level form accuracy and nanometer-level surface roughness have been achieved by using the proposed hybrid fabrication process.



(a)

(b)

Fig. 10. Three-dimensional topographies of a concave Fresnel lens: (a) center region, (b) outer section.

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