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Micro grooving on single-crystal germanium for infrared Fresnel lenses

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Abstract

Single-crystal germanium is an excellent optical material in the infrared wavelength range. The development of germanium Fresnel lenses not only improves the optical imaging quality but also enables the miniaturization of optical systems. In the present work, we developed a ductile-mode micro grooving process for fabricating Fresnel lenses on germanium. We used a sharply pointed diamond tool to generate the micro Fresnel structures under three-axis ultraprecision numerical control. By adopting a small angle between the cutting edge and the tangent of the objective surface, this method enables the uniform thinning of the undeformed chip thickness to the nanometric range, and thus provides complete ductile regime machining of brittle materials. Under the present conditions, a Fresnel lens which has a form error of 0.5 μm and surface roughness of 20–50 nm R_y (peak-to-valley) was fabricated successfully during a single tool pass.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Single-crystal germanium is an important infrared optical material, which has very high permeability and high refractive index in the wavelength range of 2–14 μm. Thus, it is an excellent substrate material for infrared lenses with extensive applications in thermal imaging systems, dark-field optical instruments, astronomical telescopes and so on [1, 2]. Recently, the demands for complex-shaped infrared optical elements such as aspherical lenses, Fresnel lenses and diffraction grating lenses [3, 4] are increasing remarkably. A Fresnel lens is a plano-convex or plano-concave lens that is cut into concentric narrow rings, namely Fresnel zones, and flattened. It retains the optical characteristics of a plano-convex or plano-concave lens but is much smaller in thickness, and therefore has less absorption losses. There are numerous optical designs that can benefit from the application of Fresnel lenses. If the Fresnel zones are sufficiently narrow, the surface of each zone can be approximately made conical (with straight cross section) and not spherical (with arc cross section) for the ease of production. However, for recent high-precision optical systems, Fresnel lenses with spherical zones with arc cross sections are necessary.

Photolithography and diamond turning are two major machining methods used for fabricating micro Fresnel structures. Lithography technology is usually used to produce two-dimensional microstructures on flat substrates. By using a varying dose during the illumination, it is also possible to fabricate three-dimensional microstructures such as Fresnel and blazed diffractive optical elements by recent lithography technology. However, the depth of structures is limited by using lithography techniques. Especially for Fresnel structures with large depth, the low material removal efficiency of lithography becomes a problem. For these applications, diamond turning will be preferable. The fabrication of the Fresnel structure by diamond turning on ductile metals such

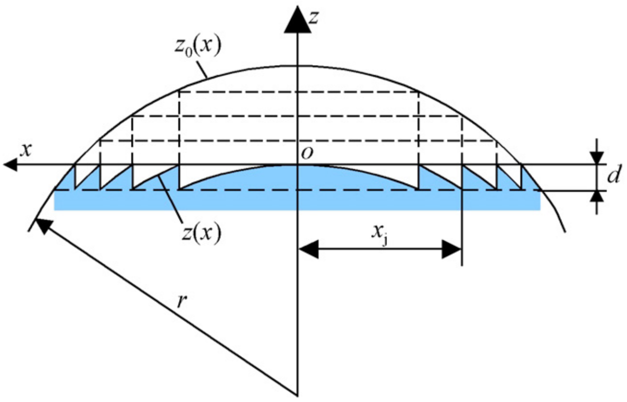


Figure 1. Schematic of the geometry of a Fresnel lens.

as oxygen-free copper and electroless-plated nickel has been reported in previous studies [5]. However, no literature can be found on the fabrication of the Fresnel structure on brittle crystalline materials such as germanium. Germanium is nominally a hard brittle material. At room temperature, it responds in an extremely brittle manner; thus it is very difficult to machine. Micro grinding has also been reported as a fabrication method of Fresnel structures on hard brittle materials, such as tungsten carbide [6], but the groove profile distortions resulting from the roundness of the grinding wheel remain a critical problem.

In the past decade, a few studies have revealed that plastic deformation occurs in germanium during micro indentation, scratching and machining tests without brittle fracture, and that the plastic deformation is facilitated by the high-pressure phase transformations [7–10]. These findings provided insights into the fundamental physics governing the micro deformation mechanism and contributed significantly to the ductile regime machining technology of germanium. In a previous paper [11], the present authors have investigated the ductile machinability of germanium with various crystal orientations, namely (1 0 0), (1 1 0) and (1 1 1), and found that the critical undeformed chip thickness for generating a completely ductile-cut surface on these substrates was almost the same, approximately 60 nm.

In this work, we propose a micro grooving method for fabricating infrared Fresnel lenses on germanium by ductile-mode diamond turning. It is expected that the proposed method will provide new feasibilities for producing various types of micro Fresnel structures on hard brittle materials at high efficiency.

2. Geometrical definition and machining model of a Fresnel lens

Figure 1 shows a schematic of the geometry of a Fresnel lens. The shape of the Fresnel structure, $z(x)$, can be described by the modulus function (MOD) of the equivalent plano-concave or plano-convex lens shape $z_0(x)$ and the zone depth d as

$$z(x) = \mathrm{MOD}[z_0(x), d], \tag{1}$$

where the MOD function is a function that returns the remainder when one number is divided by another. For example, MOD (4, 3) = 1.

The surface function of a spherical lens shape $z_0(x)$ can be simplified from that of an aspherical surface. In optical

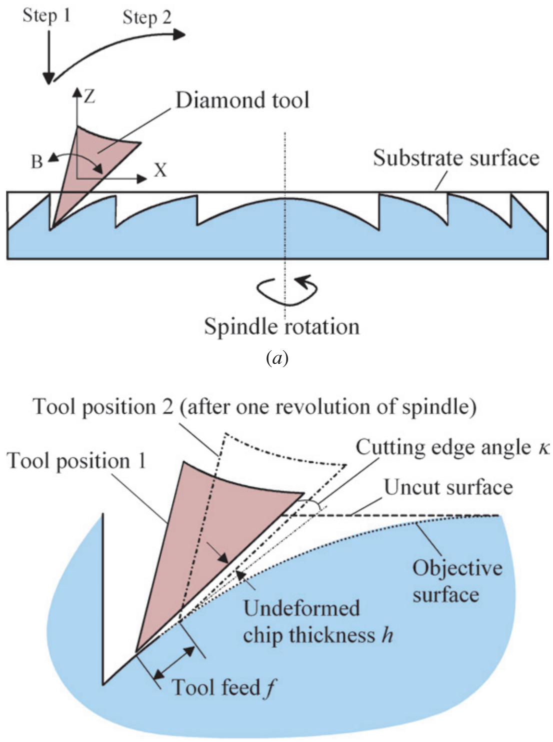


Figure 2. Machining models for the Fresnel structures: (*a*) process steps, (*b*) ductile machining model of a single microgroove.

design and manufacturing, the topology of an axis-symmetric aspherical surface is usually expressed as

$$z_0(x) = \frac{Cx^2}{1+\sqrt{1-(k+1)C^2x^2}} + \sum_{i=1}^{m} a_i x^i. \tag{2}$$

Here $C = 1/r$, where r is the radius of curvature of the sphere, x is the distance from the optic axis z and k is the conic constant representing the eccentricity of the conic surface [12]. For even i, a_i are aspherical deformation constants, and for odd i, a_i are aspherical coefficients used to define other polynomial curves by setting $C = 0$. Therefore, for a spherical shape, we can just set $k = 0$ and $a_i = 0$ in equation (2). Thus, the function of a spherical lens surface can be described as

$$z_0(x) = \frac{Cx^2}{1+\sqrt{1-C^2x^2}}. \tag{3}$$

This equivalent lens surface is cut into concentric rings by cylindrical surfaces at the zone steps. The radial coordinate of each zone step can be calculated by

$$x_j = \sqrt{j\cdot d\left(\frac{2}{C} - j\cdot d\right)}, \tag{4}$$

where j is the sequential number of the Fresnel zone counted from the optical axis z, and d is the zone depth, as in equation (1).

Figure 2 schematically shows the proposed machining models for fabricating a Fresnel lens. The Fresnel structure is generated on a flat substrate using a diamond tool which has a sharply pointed V-shaped tip. The machining operation for one microgroove consists of two steps, as shown in figure 2(*a*). First, the tool moves along the Z-axis, namely the vertical axis,

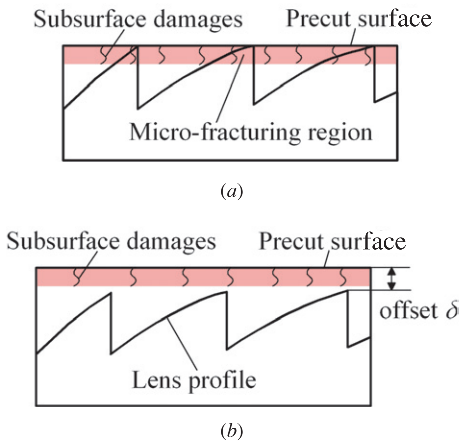


Figure 3. The depth-offsetting method to avoid the influences of precut-induced damaged layer.

to generate the cylindrical surface at the zone step. Next, the tool moves and at the same time rotates under *X*-*Z*-*B* three-axis simultaneous control to generate the spherical surface. The detailed schematic model of step 2 is shown in figure 2(*b*). In the figure, the thickness of the material removed during one revolution of the workpiece, namely the undeformed chip thickness *h*, is determined by

$$h = f \cdot \sin\kappa, \tag{5}$$

where κ is the angle between the cutting edge and the tangent of the objective curved surface, namely cutting edge angle, and *f* is the tool feed.

From equation (5), one can see that by using a small cutting edge angle κ, the undeformed chip thickness *h* can be decreased without reducing the tool feed *f*. Therefore, if *h* is thinned to be smaller than the critical undeformed chip thickness, a ductile-cut surface can be obtained. This method enables ductile machining of brittle materials under a high tool feed; thus the tool wear, and in turn, the production cost, can be reduced. The significance of using a straight edge tool to ductile machining has also been demonstrated in the fabrication of silicon wafers and infrared aspherical lenses of silicon [13, 14].

When fabricating a Fresnel lens, it is important to prevent the edges of the zone steps from microfracturing. One of the possible reasons for microfracturing is the subsurface damage caused by precuts. Usually, precuts are required to make the lens substrates flat and smooth before micro grooving. However, the precutting process may cause subsurface damage such as potential microcracks and dislocations [15]. If the lens apices are located within the damage layer, as shown in figure 3(*a*), microfractures can easily occur to the zone steps. In order to solve this problem, we used a depth-offsetting method, as shown in figure 3(*b*). That is, by off-setting the lens apices a few microns lower than the substrate surface, the precut-induced damage layer will be removed during the finishing cut, without damaging the micro Fresnel structures.

3. Experimental procedures

The machining experiments were carried out on a three-axis numerically controlled ultraprecision lathe, NACHI-ASP15.

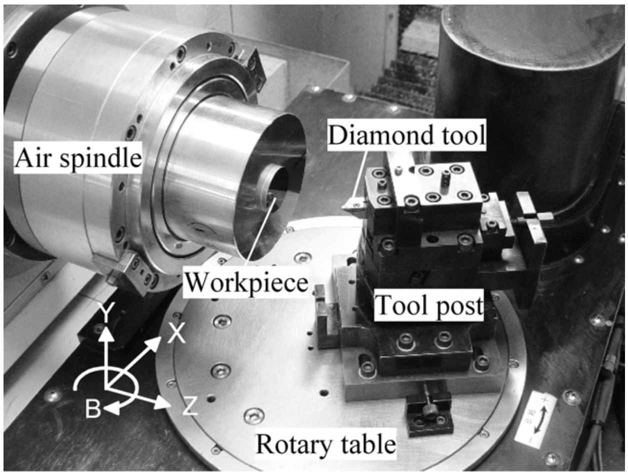
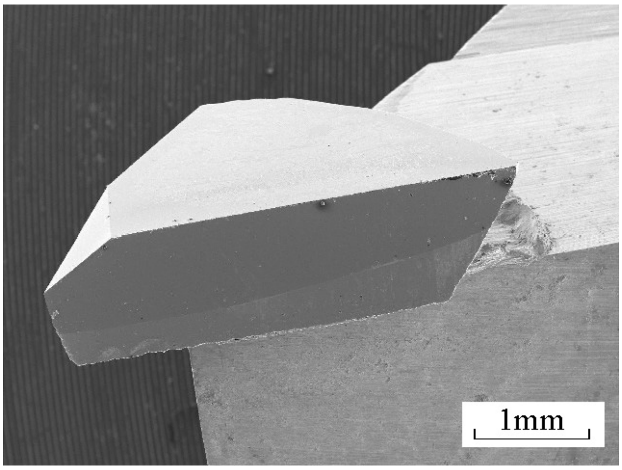


Figure 4. Photograph of the main section of the ultraprecision lathe.

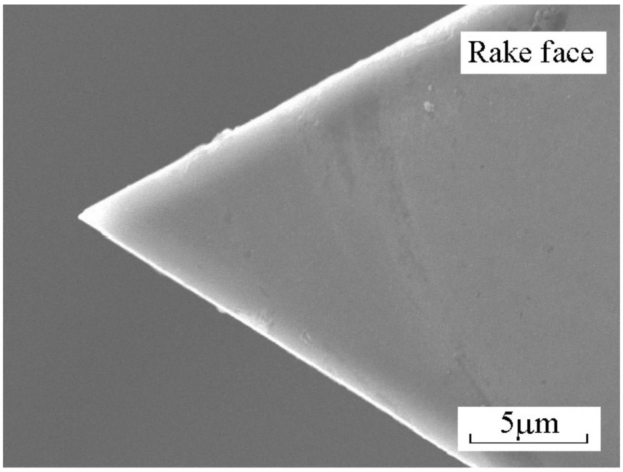
Figure 4 is a photograph of the main section of the lathe. The lathe has an ultraprecision air-bearing spindle, two perpendicular linear tables (*X*- and *Z*-axes) and a rotary table (*B*-axis). The linear tables are supported by high-stiffness hydrostatic bearings and are driven by servomotors via hydrostatic screws, allowing smooth nanometric movement with negligible mechanical friction. The rotary table is also supported by hydrostatic bearings and driven by a friction drive in order to prevent backlash movements. Laser hologram scales are used to accurately position all these tables. Under precise numerical control, the linear tables can be moved at 10 nm per step and the rotary table can be rotated with an angular resolution of 0.001°. To isolate the lathe from environmental vibration, the main section of the machine was fixed to a granite bed, which is supported by a set of air mounts.

Figure 5 shows the scanning electron microscope (SEM) photographs of the cutting tool. The tool is made from single-crystal diamond and has a 60° included angle, a –30° rake angle and a 6° relief angle. As known from previous studies, the nose radius of the diamond cutting tool causes roundness to the relief profiles of the Fresnel optics, and in turn, leads to a significant refraction efficiency loss [16]. The cutting tool in figure 5 has an extremely sharpened V-shaped tip which theoretically has no nose radius. The roundness of the tool tip was estimated to be smaller than 1 μm by SEM observation. During machining, the cutting edge angle κ of the tool was adjusted and controlled using the *B*-axis rotary table of the lathe.

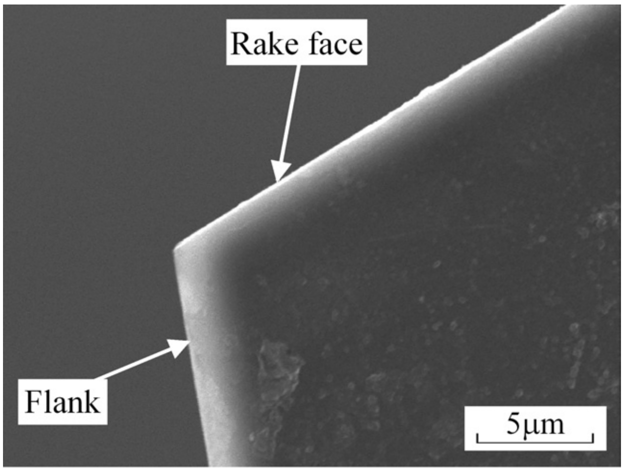
As a test piece, a Fresnel lens which has a curvature radius of 100 mm was fabricated. Thus, in equation (3), $C = 0.01$. For practical applications, the zone depth *d* in equation (3) should be decided according to the design wavelength, the refractive index of substrate material and the focus length. In this work, we set the zone depth *d* to 50 μm to avoid particularity. A single-crystal germanium (1 1 0) substrate was used as a workpiece. It is optical-grade pure germanium with no doping. The workpiece was 30 mm in diameter, 5 mm in thickness and was obtained with ground finish. To remove the damaged layer due to grinding, precuts were performed with other cutting tools, namely straight-nosed diamond tools [13], providing a mirror-like flat surface. The position of the



(*a*)



(*b*)



(*c*)

Figure 5. Scanning electron micrographs of the diamond cutting tool: (*a*) general view, (*b*) top view and (*c*) side view.

Fresnel lens apex was offset to 2 μm lower than the precut surface.

The machining conditions are summarized in table 1. For step 1 in figure 2(*a*), i.e., when generating the zone steps, the tool feed rate f_1 was 0.05 μm rev^{-1}; and during step 2, the feed rate f_2 was set to 15 μm rev^{-1}. The cutting edge angle κ in figure 2(*b*) was set to 0.2°. Under these conditions, the undeformed chip thickness h was approximately 50 nm, which is smaller than the critical undeformed chip thickness for ductile machining at all crystal orientations [11]. The rotation rate of the machine spindle was fixed to 1000 rpm. Kerosene mist was used as coolant.

Table 1. Machining conditions.

Workpiece	Single-crystal Ge (1 1 0) ϕ30 mm
Lens curvature radius (r)	100 mm
Zone depth (d)	50 μm
Tool included angle	60°
Tool rake angle	−30°
Tool relief angle	6°
Cutting edge angle (κ)	0.2°
Feed rate (f_1)	0.05 μm rev^{-1}
Feed rate (f_2)	15 μm rev^{-1}
Undeformed chip thickness (h)	50 nm
Spindle rotational rate	1000 rpm
Cutting fluid	Kerosene mist

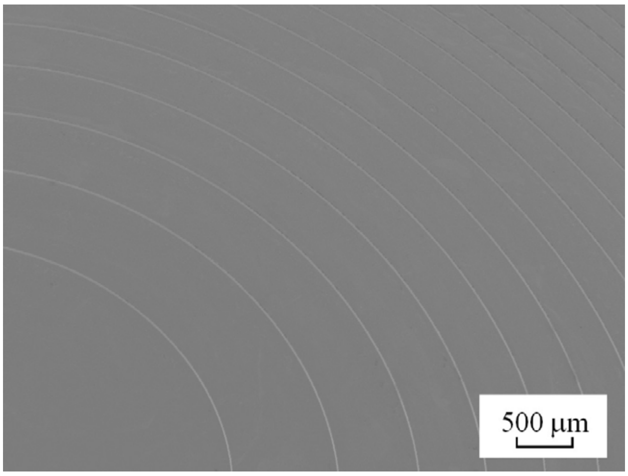
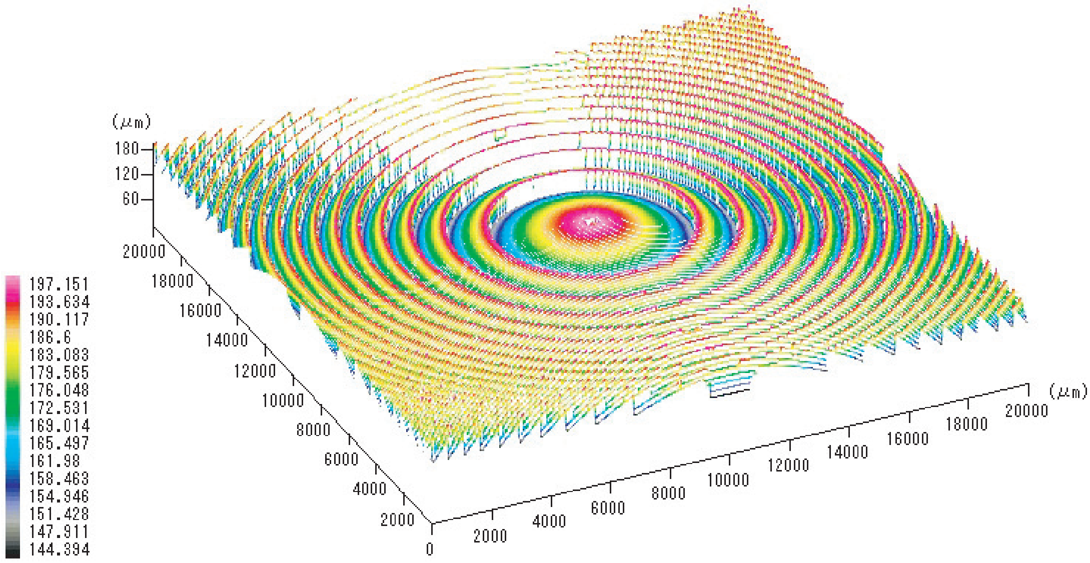


Figure 6. Scanning electron micrograph of the fabricated Fresnel lens.

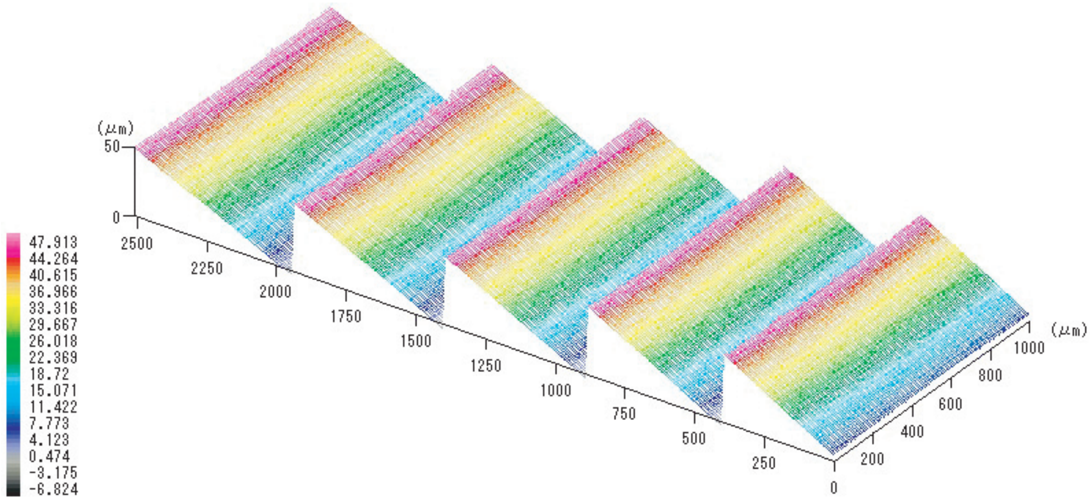
4. Results

Figure 6 is a SEM photograph of the fabricated Fresnel lens. It can be seen that the lens surface is very smooth, without any appearances of brittle fractures. The zone steps can be identified clearly as concentric rings, indicating that the microgrooves have been ductile-cut. The Fresnel lens was finished by a single tool pass, and the total time for machining was approximately 30 min, demonstrating a high machining efficiency.

A noncontact three-directional measuring machine, Mitaka NH-3SP, was used to measure and evaluate the lens geometry. This measuring instrument uses a semiconductor laser probe (wavelength 635 nm) to scan the lens surface; thus the contact damage due to the conventional stylus profiling instrument can be avoided. The resolution of this measuring instrument is 1 nm. The laser beam has an extremely small spot size, approximately 1 μm, so that



(*a*)



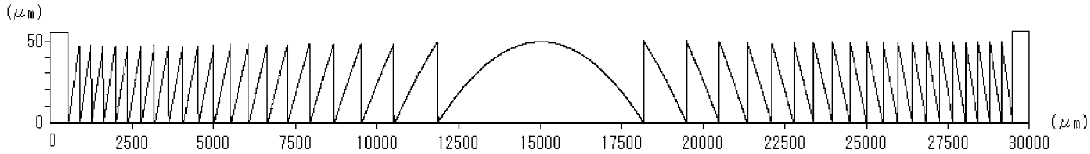
(*b*)

Figure 7. Three-dimensional topographies of the lens: (*a*) central region, (*b*) outer region.

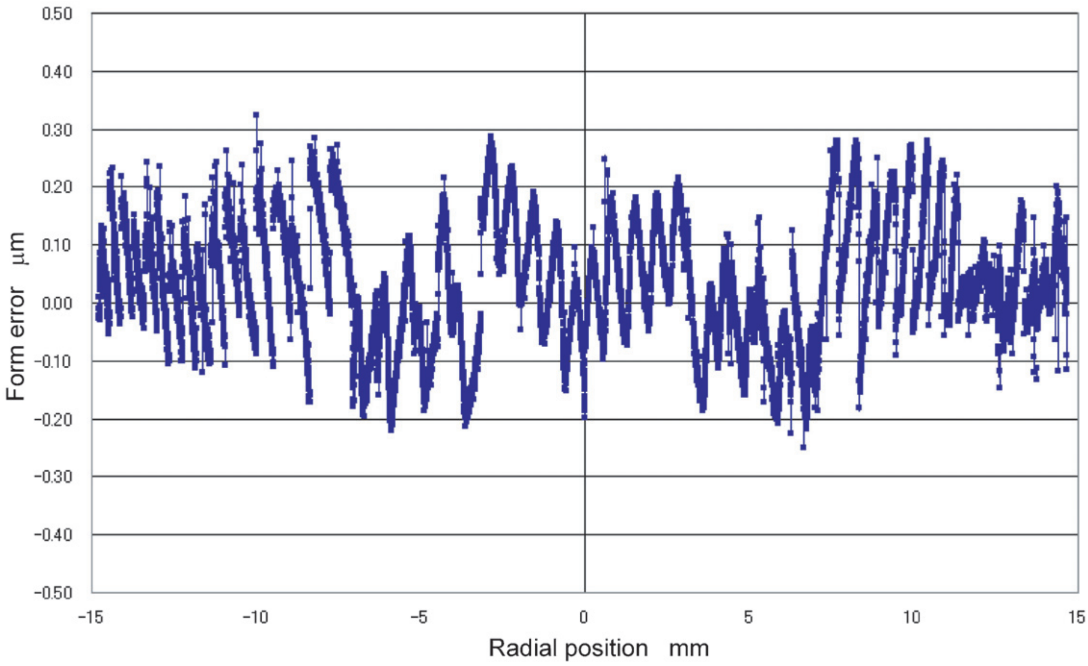
the narrow microgroove corner can be precisely measured without the edge-rounding effect occurring in traditional stylus-profiling methods. Although sometimes the large incident angle may cause errors at steep rims of microgrooves, the problem can be solved to some extent by selecting suitable measuring conditions and by processing the measured data using software techniques. Figure 7 shows the three-dimensional topographies of the lens center and a part of the outer region. It can be seen that the Fresnel structures have been precisely fabricated both at the workpiece center and at the outer regions, without any visible defects.

Figure 8(*a*) shows a cross-sectional profile of the Fresnel lens. It can be seen that the depths of all the microgrooves are uniform, without roundness or microfractures at the groove profiles. Figure 8(*b*) shows the form error distribution which is calculated by comparing the measured cross-sectional profile with the designed profile. The form error distribution is almost uniform, with minor random variations. The peak-to-valley amplitude of the form error is approximately 0.5 μm. The surface roughness of the microgrooves was measured along two directions, namely the circumferential direction (cutting direction) and the radial direction (feed direction). The average surface roughness along the cutting direction was 20 nm R_y and that along the feed direction was 50 nm R_y, respectively, where R_y is the peak-to-valley, or maximum height, of the surface. Since the radial surface roughness is determined by the tool-work transcription principle, a much smoother surface can be obtained by using a smaller tool feed and/or a smaller cutting edge angle.

Figure 9(*a*) is a SEM photograph of the cutting chips collected during the machining process, and figure 9(*b*) is a detailed view of the chip surface. The chips are long and generally continuous, showing the plastic deformation appearance. These chips indicate that as a nominally brittle material, single-crystal germanium has been subjected to significant plastic deformation and machined in a complete ductile mode.

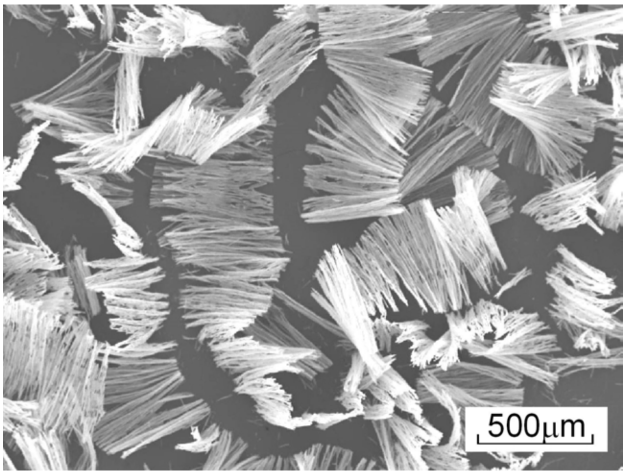


(*a*)

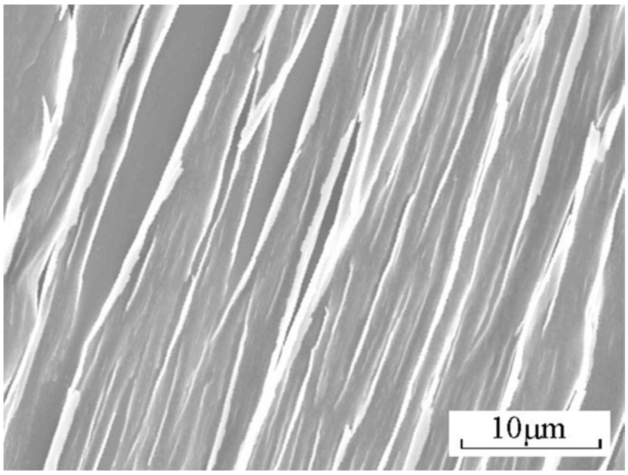


(*b*)

Figure 8. Two-dimensional measurement results of the lens geometry: (*a*) cross-sectional profile, (*b*) form error distribution.



(*a*)



(*b*)

Figure 9. Scanning electron micrographs of the cutting chips: (*a*) general view, (*b*) detailed view.

5. Conclusions

We developed a ductile-regime micro grooving process for fabricating Fresnel lenses with curved cross-sectional profiles on single-crystal germanium. The microgrooves were generated with an extremely sharpened V-type diamond tool under three-axis numerical control, and the angle between the cutting edge and the tangent of the objective surface was controlled to be very small. Under these conditions, the proposed method enables the thinning of the undeformed chip thickness to the nanometric range, providing the ductile regime machining of microgrooves. As preliminary experimental results, a Fresnel lens which has a form accuracy of 0.5 μm, surface roughness of 20–50 nm R_y and precise cross-sectional profiles was fabricated by a single tool pass.

The future work is along two directions: one is to explore the machinability of micron-level Fresnel structures, and the other is to investigate the wear characteristics of diamond tools and improve the tool lifetime by optimizing the geometry and crystal orientation of the tools.

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