Metal Mold Manufacturing of Fresnel Lens by Use of Micro Grooving Technology*

Nuttaphong SORNSUWIT**, Yoshimi TAKEUCHI**

Kiyoshi SAWADA*** and Toshio SATA****

The study deals with cutting of metal mold for a tiny Fresnel lens which is composed of circular micro grooves. Conventional methods such as photolithography and cutting by a lathe often lead to the burr generation due to a reduction of cutting speed, especially at the center of lens, and to low surface quality such as step-like cross-section of groove by photolithography. The employment of a rotational diamond cutting tool is expected to eliminate the above problems. Thus, a workpiece of Fresnel Lens is set on the main spindle of a lathe-type ultraprecision milling machine, which has the positioning accuracy of 1 nm. The diamond cutting tool is rotated by a high speed air turbine spindle. According to the cutting experiment, no burr was found at the edge of grooves, and the surface roughness of a slope in the groove was 80 nm ($R_{\max}$). The cross section of lens groove is slightly curved due to the unique way of cutting, which made a profile of lens get closer to the ideal one.

Key Words: Ultraprecision Machining, Surface Roughness, Micro Fresnel Lens, Rotational Tool, Burr

1. Introduction

In recent years, a wide range of technologies including electronic, electric and mechanical ones have substantially improved to achieve higher efficiency, higher accuracy and smaller size for electronic products, medical equipments and so on. In such a situation, high integration and size reduction of parts are thus required. Especially, the demand on parts which are composed of micro grooves are rising. Thus, the study focuses attention on the high precision metal mold manufacture of tiny Fresnel lens which is composed of circular micro grooves.

Fresnel lens, as shown in Fig. 1, consists of a lot of

small rings arranged in a concentric circle and serves as a corresponding concave or convex lens. Each circular groove of the Fresnel lens is a small piece of the lens surface translated toward the plano-side of lens so as to keep the height constant, and also has the same lens center point. Among conventional methods of micro groove manufacturing, there are cutting by a lathe⁽¹⁾ and photolithography which is applied to semiconductor manufacturing. Photolithography is generally used for the minute part manufacturing, however, 3-dimensional shape is a pile of layer since the shape-

Fig. 1 Cross section of Fresnel lens

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** Department of Mechanical and Control Engineering, The University of Electro-Communications, 1-5-1 Chufugaoka, Chofu, Tokyo 182-8585, Japan. E-mail: nuttap-s@takeuchi.mce.uec.ac.jp

*** Basic Research Laboratory, FANUC Ltd., 3580 Oshinogusa, Oshino, Yamanashi 401-0597, Japan

**** Toyota Technological Institute, 2-12-1 Hisakata, Tenpaku-ku, Nagoya 468-8511, Japan

forming is done by the exposure of light. As a result, the cross-sectional profile of grooves appears to be a step-like one. On the other hand, in the case of manufacture by a conventional lathe, the tool is at standstill while cutting workpieces. Therefore, the cutting speed is approximately zero at the center of a rotating workpiece, and then leads to the burr generation and surface roughness deterioration.

In the study, we employed another way of cutting, where a rotational diamond cutting tool is used to solve the problems. The micro grooving technology by a rotational diamond tool has the advantage of allowing a constant cutting speed and high degree of freedom on the work material selection to manufacture 3-dimensional structures. To evaluate the practical effects of the micro grooving technology, we carried out our experiments of manufacturing a high precision micro Fresnel lens.

2. Ultraprecision Machine Tool and Diamond Cutting Tool

An ultraprecision machine tool used in the study is a lathe-type milling machine, ROBOnano Ui of Fanuc Ltd.⁽²⁾ The machine tool has two rotational axes (B and C), two straight feed axes (X and Z) for its fundamental composition. All axes in the machine tool are provided with static air bearing to get rid of frictions which cause a positioning error. The positioning accuracy of X and Z axes is 1 nm, and that of B and C axis 0.0001°. To exert this level of accuracy, the machine tool is set in a specially designed vibration-proof room, and the temperature is kept at $20 \pm 0.1^\circ\text{C}$. In case of Fresnel lens cutting, as shown in Fig. 2, B axis is used for the determination of groove's slope angle, C axis for the rotation of workpiece, and X axis for the control of pitch between grooves, while the depth of cut is determined by Z axis. As shown in Fig. 3, a cutting tool is

Fig. 2 Arrangement of positioning axes in an ultraprecision machining center

composed of a single crystal diamond with cutting angle of 70° at the top of shank of 6 mm in diameter, and is mounted on the air turbine spindle which rotates at high speed while cutting lens grooves.

3. Manufacture of Fresnel Lens Mold and Dies by Using Rotational Cutting Tool

It is the surface roughness of the lens groove, the existence of burr, and the shape accuracy of lens that significantly affect optical efficiency of Fresnel lens. It is confirmed that micro grooves could be effectively manufactured by using a rotation diamond cutting tool, where the surface is less than $0.1 \mu\text{m}$ which is the standard of the mirror finished surface, no burr takes place and high precision of lens shape is realized⁽³⁾. Therefore, we applied the technology for the manufacture of mold and dies for Fresnel lens.

3.1 Consideration of cutting tool shape

The locus of tool cutting edge forms a circle, whose radius is the distance from the tool center axis to the tool cutting edge. In case of manufacturing curved or circular grooves such as grooves in Fresnel lens, an interference may take place between cutting tool edge and the groove edge. However, the interference depends on the relationship between the cutting edge radius and the groove curvature. The tool used in the study has a shank of 6 mm in diameter due to the spindle chuck's diameter. Therefore, the manufacture

(a) Configuration of cutting tool

(b) Enlarged tool edge

Fig. 3 Single crystal diamond tool

Table 1 Possibility of cutting Fresnel lens by two types of tool

	Concave Fresnel lens	Convex Fresnel lens
$R < r_n$: able $R \geq r_n$: collision avoidance is required	$R < r_n$: able $R \geq r_n$: unable

of Fresnel lens of a few millimeters in diameter is much more difficult to produce, compared with a larger lens. As another type of cutting tool, so called "pencil bite" which makes the circular locus of cutting edge extremely small, is applicable for any radius of lens groove curvature. However, the tool manufacturing technology at present could not make the top of cutting edge absolutely coincident with the tool center axis. As a result, it may cause an undesired plane in the bottom of grooves and deteriorate the optical efficiency of Fresnel lens.

The condition of interference is different according to concave and convex lens, as shown in Table 1. In case of convex Fresnel lens, the groove cutting is possible only when the radius of circular locus of cutting edge is smaller than the radius of lens groove. On the other hand, in case of concave Fresnel lens, the groove cutting becomes possible even when the radius of circular locus cutting edge gets larger than that of lens groove by changing the tool attitude calculated on the basis of several parameters such as depth of cut, pitch of lens groove and tool shape. If the ordinary convex and concave lens has the inverse shape each another, then concave and convex Fresnel lens can be duplicated from the shape of each other as well. Thus, convex Fresnel lens, whose lens groove radius is larger than the radius of circular locus of cutting edge, can be produced by using the inverse concave Fresnel lens shape as its mold.

3.2 Determination of tool attitude

There are some unique characteristics in manufacturing Fresnel lens by a rotational cutting tool. The material removal is done by only the top of cutting tool edge which is the circumference of circular locus of cutting tool. The slope of lens groove is not directly transferred from the inclination of tool cutting edge, but is gentler than the inclination of

Fig. 4 Determination of cutting tool attitude

cutting edge. The inclination of cutting edge has to be calculated from the radius of lens groove and circular locus of cutting edge so as to avoid the interference between cutting tool and the edge of lens groove and to achieve the required depth of cut, pitch and angle of lens groove.

Let us define the parameters as below ;

R : Radius of cutting tool edge

r_n, r_{n-1} : Radius of neighboring lens groove

d : Depth of lens groove

ϕ : Inclination of cutting tool edge.

Then, the following relations are obtained from Fig. 4,

Fig. 5 Relationship between workpiece and cutting

$$\begin{aligned} a^2 &= a'^2 + d^2 \\ R^2 &= c^2 + (R-a)^2 \\ r_n^2 &= c^2 + (r_{n-1} + a')^2 \end{aligned} \quad (1)$$

The above relations yield the following equation,

$$\begin{aligned} (4R^2 - 4r_{n-1}^2)a'^2 + 4r_{n-1}(r_n^2 - r_{n-1}^2 + d^2)a \\ + 4R^2d^2 - (r_n^2 - r_{n-1}^2 + d^2)^2 = 0 \end{aligned} \quad (2)$$

The inclination of cutting tool edge ϕ is calculated as follows;

$$\begin{aligned} \phi &= \tan^{-1} \frac{d}{a'} \\ &= \tan^{-1} \frac{2d(R^2 - r_{n-1}^2)}{-r_{n-1}M \pm \sqrt{r_{n-1}^2M^2 - R^2 - r_{n-1}^2(4R^2d^2 - M^2)}}, \end{aligned} \quad (3)$$

where

$$M = (r_n^2 - r_{n-1}^2 + d^2)$$

3.3 Analysis of manufactured lens groove profile

When the circular groove is manufactured by a rotational tool, the cross-section of lens groove will have a slight curve. As shown in Fig. 5, when the circular locus of cutting edge rotates around the rotational center of workpiece to manufacture lens groove, the profile of lens groove is characterized by the gap between s_1 , the distance from the rotational center of workpiece A to the point B on the line which gets through the center of the circular locus of cutting edge, and s_2 , the distance from the rotational center of workpiece A to the point C on the locus of cutting edge. In other words, because s_2 is longer than s_1 , the cutting of lens groove is conducted only by the edge of tool, and the area within the locus of cutting edge has nothing to do with the workpiece removal. As a result, the relationship between the slope and the cutting tool is shown in Fig. 6. The cross-section of lens groove is slightly curved and the angle of lens groove is gentler than the inclination of tool cutting

Fig. 6 Actual cross-sectional profile of Fresnel lens

Fig. 7 Calculated cross-sectional profile of Fresnel lens

edge. The distance Δ depends on s_1 and s_2 at an arbitrary position in N direction and can be calculated by using the following equation, Eq. (4), including the various conditions with regard to the tool attitude when s is a distance from the rotational center of workpiece to the point O standing for the center of the circular locus of cutting edge;

$$\begin{aligned} \Delta &= \sqrt{(s - (R-x)\cos\phi)^2 + (R^2 - (R-x)^2)} \\ &\quad - (s - (R-x)\cos\phi) \end{aligned} \quad (4)$$

The computed result of the cross-sectional lens groove is shown in Fig. 7.

4. Experimental Results of Fresnel Lens Mold Cutting

The Fresnel lens which has 15 lens grooves with a pitch of 125 μm and a depth of 5 μm was created on an oxygen-free copper workpiece of 6 mm in diameter.

Fig. 8 Actual cutting of micro Fresnel lens

Fig. 9 Shape of machined lens groove

The depth of cut is $1\text{ }\mu\text{m}$. By repetition of cutting 5 times, the outermost lens ring has the deepest groove of $5\text{ }\mu\text{m}$. Because the pitch of lens groove and the inclination of tool are constant, the inner grooves are shallower than the outer. The rotation of cutting tool is 30 000 rpm, while the workpiece rotates at the speed of 30 deg/min. The actual machining of Fresnel Lens is shown in Fig. 8.

About 3 hours was spent to finish the cutting. A 3-dimensional surface structure analysis microscope (ZYGO NEW VIEW 100) was used to evaluate the shape of Fresnel lens and the surface roughness. The measured lens shape is shown in Fig. 9. It was found that the manufactured mold and dies of Fresnel lens had a good shape of groove, as seen in the figure. The cross-section of groove is slightly curved, as shown in Fig. 10. In general, a slight curve is more desirable for the Fresnel lens groove than a straight cross-sectional profile in terms of the optical efficiency. Such a result is another advantage of the manufacturing method, where a rotational diamond cutting tool is employed.

There is also another characteristic on the lens groove surface, as shown in SEM image in Fig. 11. Straight lines are observed, which are considered to be the tracks of cutting edge. As mentioned before,

Fig. 10 Cross-sectional profile of lens groove

Fig. 11 SEM image of lens groove

Radial direction: Peak to valley = $0.078\text{ }\mu\text{m}$ Circumferential direction: Peak to valley = $0.084\text{ }\mu\text{m}$

Fig. 12 Surface roughness of lens groove

the lines are probably formed since the lens groove surface is machined only by the top of cutting edge of a rotational tool.

The surface roughness of lens groove surface in the circumferential direction and in the radial direction was 78 nm (R_{max}) and 84 nm (R_{max}) by Form

Talysurf respectively. The problem of burr generation on the edge of lens groove was also solved.

5. Conclusion

In order to eliminate the problems of the burr and to improve the surface roughness of micro Fresnel lens groove which used to be manufactured by conventional turning and photolithography, the new manufacturing method was developed to use a rotational diamond cutting tool and the cutting experiment was conducted. The micro grooving technology in the study led to the following conclusions;

(1) Only concave Fresnel lens can be manufactured when the lens groove radius is smaller than the radius of the locus of tool cutting edge. In this case, the interference between the cutting tool and the lens groove could be avoided by changing the inclination of cutting tool.

(2) The cross-sectional profile of lens groove is slightly curved due to the unique way of cutting.

(3) Lens grooves have good shape, and no burr is found at the edge of lens grooves.

(4) The surface roughness of lens groove is 78 nm ($R_{\max}$) and 84 nm ($R_{\max}$) in the radial and circumferential directions respectively.

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