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A Study on the Mirror Grinding for Mold of a Small Aspherical Lens

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ABSTRACT

This paper deals with mirror grinding of a small-sized aspherical lens by a resin bonded diamond spherical wheel. Up to now, a spherical lens has been used for the lens of the optical communication optical part. However, recently, aspherical optical parts are mainly used in order to attempt the improvement in image quality and miniaturization of the optical device. It is possible to manufacture the aspherical lens which is presently being used in optical instrument through ultra-precision machining technology. Also, to realize compactness, efforts are being made to produce a micro aspherical lens, for which the development of a high-precision, micro molding die is inevitable. Therefore, extensive research is being done on methods of producing a micro aspherical surface by high-precision grinding. In this paper, the spherical wheel was trued by cup-shaped truer and tool path was calculated by the radius of curvature of the wheel after truing and dressing. Then in the aspherical grinding experiment, WC material which is used as a molding die for the small-sized aspherical lens was ground. The results showed that a form accuracy of 0.1918 ㎛ P-V and a surface roughness of 0.064 ㎛ Rmax could be achieved.

Key Words : Mirror grinding, Aspherical lens, Spherical wheel, Cup-shaped truer, Truing, Dressing, Form accuracy

Nomenclatures

Ds = Diameter of cup-type wheel
θ s = Tilt angle between spherical lens and cup-type wheel
Rs = Generated radius of spherical lens
R = Generated radius of spherical wheel
D = Diameter of cup-type truer
θ = Tilt angle between truer and spherical wheel
$Z_2(i)$ = Corrected aspherical form coordinate
$Z_1(i)$ = Ground aspherical form coordinate
EC(i) = Aspherical form error

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1. Introduction

Because of present day industrial developments, video camcorders and digital cameras are becoming more and more widespread and customers are becoming increasingly interested in the enhanced performance of such devices. Therefore, higher precision, high-tech functions and smaller size and weight are a necessity, and enhancing the performance of the lens is one of the most important factors in meeting such customer demands. Today's optical field is experiencing a shift from a spherical lens-oriented optical field to an aspheric lens-oriented optical field.[1,2] Because the spherical lens by principle includes aberrations, spherical lens performance had to be enhanced by increasing the assembly number and applying multi-coating layers to remove such aberrations. However, the aspheric lens optical field has many advantages, as spherical lens aberrations are eliminated through enhanced spot condensing ability, complicated lens assembly is not required, and higher transmission rates are produced. Therefore, the use of an aspheric lens is necessary in order to make smaller, lighter, and better performing optical devices. Such advantages of aspheric lenses have long been known, but because of difficulties in the planning and manufacturing of aspheric lenses, spherical lenses with approximate solutions obtained through empirical data have been used. However, with the development of aspheric processes using cutting and grinding as well as high precision aspheric grinding devices, it has now become possible to manufacture aspheric lenses through mechanical procedures.[3,4]

To date, many lens manufacturing methods have been developed, but the most common methods are the injection molding process where the lens is shaped and a mold is manufactured using a cemented carbide steel, high strength steel or non-electrolytic nickel, a method of press-shaping the lens in a ceramic or cemented carbide steel mold with a high thermal endurance after the lens material is heated to the softening temperature, and a method of directly manufacturing the plastic or glass lens through cutting and grinding. Table 1 shows the trends and manufacturing methods of general aspheric optical parts. Until now studies on aspheric optical parts were mostly limited to relatively large lenses of over 10mm in diameter.[5]

Table 1 The general trend of aspherical optical parts

Optical Component	Material	Form Accuracy (μm P-V)	Surface Accuracy (nm Rmax)	Machining Method
CD, Camera Lens	Plastic	0.1 ~ 1	10 ~ 30	Injection molding
Laser Mirror	Cu, Al	1 ~ 5	30 ~ 100	Cutting
Infrared Lens	Si, Ge, ZnS	0.3 ~ 1	20 ~ 30	Cutting, Grinding
CD,Camera Lens	Glass	0.1 ~ 1	10 ~ 30	Grass pressing
Telescope Mirror	Glass	5 ~ 50	10 ~ 30	Grinding, Polishing
Lithography Lens	Glass	0.1 ~ 0.2	5 ~ 10	Grinding → Polishing

However, with the miniaturization of the optical parts, the importance of research and development into micro-aspheric lenses is increasing. Despite such increasing importance, there are still insufficient studies on the development of a grinding wheel suitable for the grinding of micro-aspheric lenses, and a lack of research on developing improved truing and dressing technology to achieve superior surface roughness and form accuracy of the aspheric lens through grinding processes.

Therefore, as a preliminary stage to developing a grinding technology for micro-aspheric grinding, truing was carried out with a small diamond spherical grinding wheel through the sphere generation method using a cup-shaped truer. Based on the obtained curvature radius of the spherical grinding wheel, the tool path trajectory was measured and ultra-super precision mirror surface grinding was carried out on the small aspheric lens mold in order to evaluate the accuracy of the form and the roughness of the surface.

2. Aspheric lens grinding system

2.1. General equation of the aspheric lens

The basic design of the aspheric lens is based on the principle of tracking the light path considering the index of refraction and angle of incidence of the lens according to each radius location of the lens, finding the solution for the coordinates (X,Z) when the optimal imaging is obtained, and approaching the aspheric polynomial expression through the least squared method. The axis-symmetric aspheric lens form, which is generally used, can be expressed by the following equation:

$$Z(X) = \frac{C_V \cdot X^2}{1+\sqrt{1-(k+1)C_V^2 \cdot X^2}} + \sum_{i=1}^{m} C_i \cdot X^i \qquad (1)$$

where X is the horizontal distance from the aspheric axis and Z is the location of the aspheric axis direction. The 1st term on the right hand side of Eq.(1) is the spherical term and the 2nd term is the compensation of the spherical term or the aspheric term. Also, k is the cone constant and C_v is the coefficient expressing the index curvature radius of the aspheric surface. $C_i(i=1\sim m)$ is the aspheric coefficient of the aspheric term which is obtained through light path tracking in order to obtain the optimal form.

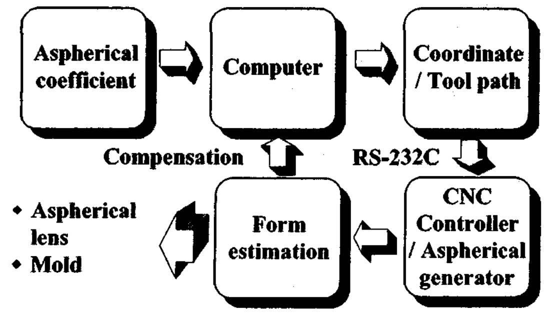

Fig. 1 Mirror grinding process of aspherical lens

2.2 Grinding System

Aspheric lens grinding processes can be divided largely into tool coordinate generation, aspheric processing and compensation grinding. First, coordinates (X, Z) of the aspheric lens form is obtained through Eq. (1) and the tool path is obtained according to the curvature radius of the grinding wheel. The obtained tool path is encoded into NC code and the NC data is transmitted to the CNC controller through RS-232C transmission. Grinding is carried out on the aspheric grinder through CNC control and the aspheric lens is evaluated by observing the form accuracy and surface roughness through a form tester. In order to obtain the desired form accuracy of the aspheric lens, compensation grinding is carried out a number of times. Fig. 1 shows an outline of the ultra-super precision grinding process of the aspheric lens.

2.3 Truing of the spherical grinding wheel and the tool path

In this study, the tool trajectory of the spherical grinding wheel was determined through the relationship between the aspheric form and the central coordinates of the grinding wheel. Aspheric grinding is carried out through a grinding wheel trajectory, which has a constant radius R. In the case of a concave lens, the curvature radius of the grinding wheel must be smaller than the minimum curvature radius of the aspheric surface. Therefore, the radius of the grinding wheel is determined through the aspheric form and the form accuracy is an important factor. In this experiment, the grinding wheel radius was generated through the CG truing method, which is based on the CG(curve generator) grinding principle, using a cup-shaped truer. The CG grinding method uses a cup-shaped grinding wheel to generate the spherical lens. The generation principle of the CG grinding method is shown in Fig. 2(a). The radius of the spherical lens can be determined through the relationship between the radius of the grinding wheel and the inclination angle of the workpiece. D_s is the radius of the cup-shaped grinding wheel, θ_s is the gradient of the grinding wheel to the lens, and R_s is the radius of the generated spherical lens. Using this principle, truing was carried out on the spherical grinding wheel using a cup-shaped truer. The schematic of the CG truing method is shown in Fig. 2(b).

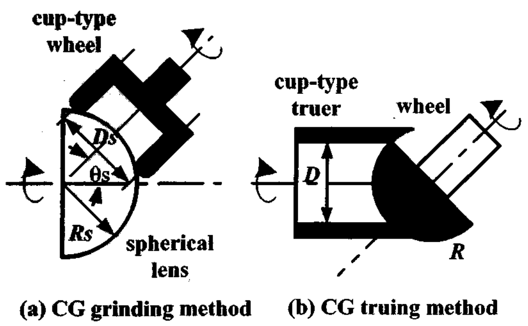

Fig. 2 A schematic diagram of CG grinding method and CG truing method

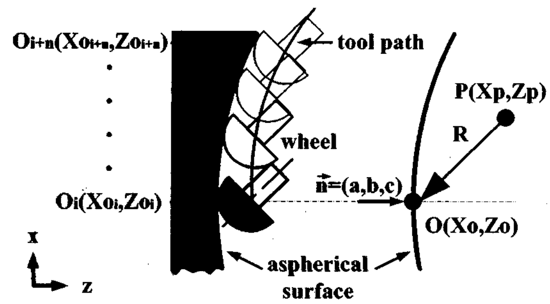

Fig. 3 A schematic diagram of wheel movement and tool path in the aspherical grinding

The relationship between the cup-shaped truer and the radius of the generated spherical grinding wheel is shown in by the following equation:.

$$R = \frac{D}{2\sin\theta} \tag{2}$$

where R is the radius of the generated spherical grinding wheel, D is the diameter of the cup-shaped truer, and θ is the inclination between the truer and the grinding wheel. Fig. 3 shows the path of the spherical grinding wheel during aspheric form grinding and the calculation process of the tool path. From the initial grinding point $O_i(X_{oi}, Z_{oi})$ to the final grinding point $O_{i+n}(X_{oi+n}, Z_{oi+n})$, the spherical grinding wheel follows the calculated grinding path through 2-axis NC control of X and Z. The aspheric form function of the axis symmetry is expressed as $Z=f(X)$ and the normal vector at the grinding point $O(X_o, Z_o)$ can be expressed as follows:

$$\vec{n}(a,b,c) = \left(-\frac{\partial f}{\partial X}, -\frac{\partial f}{\partial Y}, 1 \right) \tag{3}$$

Therefore, if the distance between the grinding point and the center of the grinding wheel, which is the radius of the spherical grinding wheel, is determined as R, the coordinates of the arc center $P(X_p, Z_p)$ of the spherical grinding wheel can be expressed as follows:

$$\begin{cases} X_p = X_o + \dfrac{a}{\sqrt{a^2+b^2+c^2}} \cdot R \\ Z_p = Z_o + \dfrac{c}{\sqrt{a^2+b^2+c^2}} \cdot R \end{cases} \tag{4}$$

3. Experiment and Results

3.1 Experiment devices and methodology

Fig. 4 is a photograph of the ultra-super precision aspheric grinder used in this study(ULG-100A(T), Toshiba Co., Ltd). The aspheric grinder is a hydrostatic bearing type which controls both the grinding wheel axis(X) and the workpiece axis(Z) at the same time and has a location determination precision of 0.01nm. The calculated tool trajectory is encoded into NC code, which is inputted into the CNC controller through RS-232C in order to carry out aspheric grinding. Fig. 4(a) is an enlarged photograph of the grinding part. The workpiece attached to the air chuck is shown on the left, while the grinding wheel is shown on the right.

The ground aspheric form was evaluated using a laser interference-type form tester(Form-Talysurf 402L, TaylorHobson Co., Ltd) with a stylus radius of 2nm and a noncontact 3D-tester(NH-3T, Mitaka Co., Ltd) with a measurement resolution of 0.005nm.

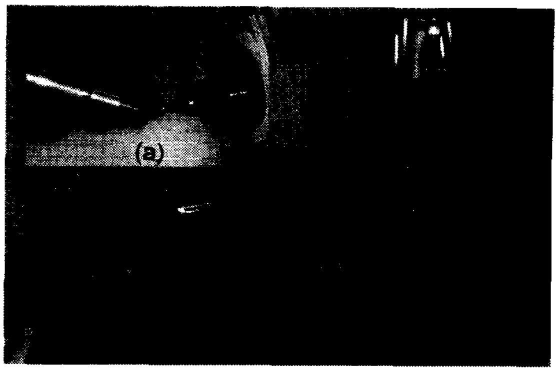

Fig. 4 Photograph of ultra-precision aspherical surface generator

In the aspheric grinding method used in this study, the form accuracy and the curvature radius of the grinding wheel have a direct influence on the accuracy of the aspheric form. Therefore, truing and dressing of the spherical grinding wheel is very important. In this study, truing of the spherical grinding wheel was carried out through the GC truing method using the cup-shaped truer as proposed in section 2.3. The cup-shaped truer is attached to the workpiece axis and the spherical grinding wheel is attached to the grinding wheel axis. The truing process is carried out after moving the grinding wheel axis to the initial truing point following the path of the X, Z axis. Without any variation in the feed rate at the ending coordinates of the truing process, GC slurry with a granularity of #2000 is injected between the truer and spherical grinding wheel. Dressing is carried out on the trued spherical grinding wheel through the generated wrapping effect. Because of the interference of the GC slurry, the grinding wheel rotates without any electric power. The truing and dressing conditions are shown in Table 2. The spherical grinding wheel, which has been trued and dressed, is projected onto the carbon plate and the radius and form accuracy are evaluated using the form tester. In this experiment, a spherical grinding wheel with a radius of 1.41mm and a form accuracy of 3.4136nm was generated and used in the calculation of the tool trajectory.

The material used in aspheric processing was cemented carbide steel for pick-up lens mold. The material was attached to the workpiece axis and contacted to the spherical grinding wheel. The contact point is the index grinding point and grinding was carried out under the conditions shown in Table 3. A resinoid bond diamond spherical wheel manufactured by Noritake with a granularity of #3000 was used as the grinding wheel. Table 4 shows the aspheric coefficient of the pick-up lens, the *X*, *Z* coordinates of the aspheric surface, and the normal angle from each grinding point.

Table 2 Truing and dressing conditions

truing	truer	SD325B
	truer diameter	2 mm
	truer rotaional rate	500 rpm
	wheel rotational rate	5000 rpm
	feed rate	0.01 mm/min
dressing	method	GC #2000 slurry
	time	7 min
	rotational rate	500 rpm

Table 3 Grinding conditions

wheel	SD3000P150BM1
size	5(D)16(T)2.5(W)
wheel rotation rate	30000 rpm
feed rate	1 mm/min
depth of cut	0.001 mm/pass
work rotation rate	500 rpm
coolant	Soluble type

Table 4 Coefficient of aspherical lens and coordinates

Coefficient of aspherical lens		X-axis coordinate (mm)	Z-axis coordinate (mm)	Normal angle (Deg.)
R	1.99418	0.000	0.000000	0.000
K	-2.5	0.200	0.010033	5.731
C_2	0.00000E-00	0.400	0.040178	11.376
C_4	2.59920E-02	0.600	0.090580	16.858
C_6	-4.08240E-04	0.800	0.161489	22.115
C_8	7.52520E-04	1.000	0.253248	27.092
C_{10}	-1.25120E-04	1.200	0.366213	31.726

3.2 Experiment Results

After aspheric grinding, the accuracy of the form and the roughness of the surface was evaluated using the laser interference type form-tester(Form Talysurf-120L) and a noncontact 3D-tester.

As displayed in Fig. 5, the grinding results show that the form accuracy of the aspheric surface was P-V 0.2477μm. A grinding error is generated at the center of the lens, which is caused by an error in the location determination of the grinding wheel and the workpiece before grinding, and an error in the grinding wheel radius caused by abrasion in the spherical grinding wheel after grinding. Therefore, it is necessary to carry out compensation measurements by comparing the ground form data obtained through the form tester with the initial aspheric form data. Then, compensation grinding based on the compensated data obtained through the process should be carried out. The compensation process was carried out by eliminating the form error of the Z axis direction from the aspheric form coordinates. The algorithm is shown in Eq. (5).[6]

$$Z_2(i) = Z_1(i) - EC(i) \tag{5}$$

where, Z_2(i) is the coordinate of the compensated form, Z_1(i) is the coordinate of the ground form, and *EC*(i) is the form error.

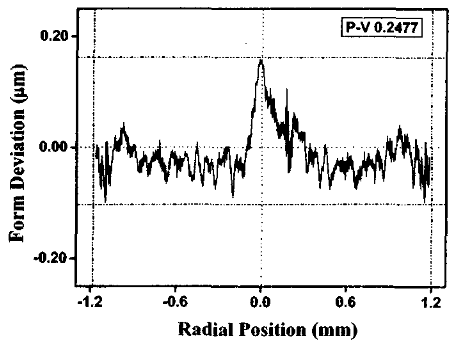

Fig. 5 Form deviation profile of spherical surface after primary grinding

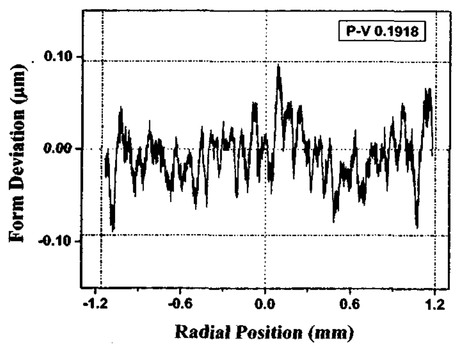

Fig. 6 Form deviation profile of spherical surface after compensation grinding

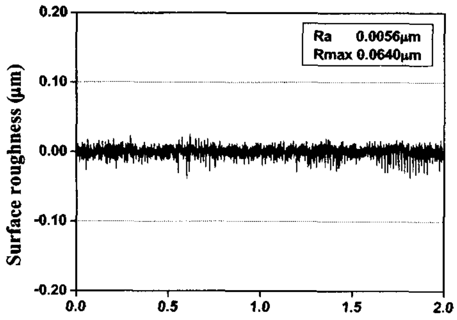

Fig. 7 Surface roughness profile of spherical surface after mirror grinding

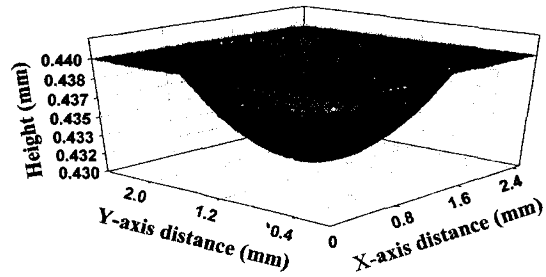

Fig. 8 3D form of the small-sized aspherical lens mold measured by noncontact tester (NH-3T)

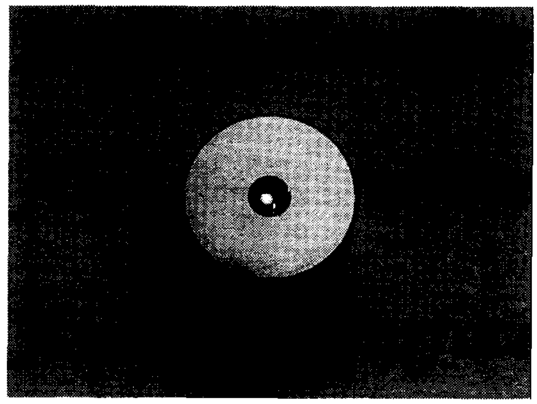

Fig. 9 Photograph of a small-sized aspherical lens mold

Fig. 6 shows the form accuracy of the final aspheric lens mold form which was obtained by measuring the form data error (Fig. 5) obtained after the 1st aspheric grinding and compensation grinding. The form accuracy was measured at P-V 0.1918μm. As shown in Fig. 7, the surface roughness of the aspheric lens mold was Rmax 0.064μm, which falls into the range of mirror grinding. Fig. 8 shows a 3D form of the small aspherical lens mold measured using a 3D noncontact tester, while Fig. 9 shows a photograph of a small ground aspheric lens mold with a diameter of 2.4mm.

4. Conclusion

In this study, a small spherical grinding wheel was used to carry out studies on the mold grinding of small pick-up aspheric lenses.

1. As a research stage to meet the challenge of miniaturization of aspheric lenses caused by the enhancement of mechanical systems and improvements in the accuracy of optical devices as well as the development of smaller systems, grinding was carried out on a small aspheric lens mold with a diameter of 2.4mm.

2. The small spherical grinding wheel was trued through the CG truing method using a cup-shaped truer. The grinding wheel trajectory was measured through the curvature radius of the attached aspheric grinding wheel and the aspheric form coordinates, and ultra-super precision grinding was carried out.

3. By grinding the aspheric surface and carrying out error compensation grinding, a form accuracy of P-V 0.1918μm was obtained and mirror surface grinding was achieved with a surface roughness of Rmax 0.064μm.

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