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Ultra-Precision Machining of Off-Axis Asymmetric Large-area Reflecting Mirror Using ELID Grinding Process

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ELID 연삭을 이용한 비축 비구면 렌즈의 초정밀 가공

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ABSTRACT

This study focused on the application of ELID mirror-surface grinding technology to the manufacture of off-axis asymmetric large-area reflecting mirrors made of BK7 glass. The size of the parts, such as asymmetric large-area mirrors or lens, made form-accuracy or roughness especially hard to measure after machining because of the measuring range limit of measurement devices. In this study, the ELID grinding system has been set up for mirror-surface machining experiments manufacturing off-axis asymmetric lenses. A measuring method using a reference workpiece has been suggested to measure the form-accuracy and roughness. According to the experimental results, even when using only a reference workpiece, it is confirmed that the surface roughness was 8 nmRa and form-accuracy was 80 nmRMS, with a best fit asymmetric radius when using a grinding wheel of #8,000. It is found that the accuracy of large-area parts could be estimated by the proposed process.

Key Words : ELID Grinding(ELID 연삭), BK7 Glass(광학유리), Form Accuracy(형상정밀도), Surface Roughness(표면거칠기), Off-Axis(비축)

1. Introduction

A variety of uses and applications of thermal imaging recognition technology have been made in high-tech sensors for military, medical, environmental, and other analysis technology. This technology has been classified as strategically protected technology due to fierce competition among nations, and the technical limit is high. Thermal imaging recognition technology is based on the infrared band, which is not perceived by humans. Infrared has the smallest absorption rate in the atmosphere, resulting in enabling not both short- and long-range detection. Thermal imaging cameras for image recognition require inspection, evaluation, and correction of infrared image sensors and

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cameras for application to various fields. In general, an 8-inch collimator optical system has been widely used to correct image cameras. Radiation energy in the infrared region that is emitted from a black body continuously is passed through the target and reaches the thermal imaging camera. The 8-inch collimator optical system, which is the most widely type, converts the radiation energy reaching the thermal imaging camera, and radiation energy is emitted directly from the black body into visible light images and the images are compared. As shown in Fig. 1, the 8-inch collimator optical system has an off-axis optical system consisting of a parabolic optical system. The off-axis optical system has no loss of light due to the primary mirror shielding in the on-axis optical system, and no diffraction or contrast degradation occurs in the secondary mirror and its support. It has also no restriction of the primary mirror shielding, so that a wide-field optical system can be designed using unifocal multi-mirrors. However, an off-axis system has difficulties in asymmetric lens machining since it employs off-axis reflectors, in contrast with existing on-axis optical systems. In addition, although optical glass materials such as germanium or BK7, which are excellent in refractive index, transmittance, and aberration, are used as materials of reflectors, they make machining difficult due to their brittleness and rigidity[1-3].

It is essential to have micro-machining methods such as grinding or polishing to obtain high-precision workpieces of nanometer level, such as ultra-precision aspherical surface and free-formed surface, and machining in consideration of brittleness of workpieces is needed[4]. In grinding, it is preferable to apply fine abrasive grinding wheels efficiently. Grinding should be done in the ductile mode to minimize cracks and layer deformation in the material surface due to machining. The electrolytic in-process dressing, ELID grinding technique can prevent the wheel loading phenomenon and facilitate the use of high grit size of grinding wheels. It is also useful to perform mirror finishing due to the low processing resistance through the minimization of depth of cut[5-7].

In this study, ultra-precision machining experiments were conducted to fabricate a large-area off-axis aspheric reflector mounted in the 8-inch collimator optical system. This study proposed a method to evaluate the surface roughness and surface profile precision of the completed large-area reflector by applying ELID grinding to the cylindrical BK7 glass material using an ultra-precision rotary grinder and measuring the reference workpiece.

2. Experiment and measurement methods

2.1 Experimental device and method

To perform the experiments, two workpieces (⌀ 211.5 mm) of a real large-area reflector and one reference workpiece (⌀ 50 mm) were fabricated. They were fixed in the same jig, and off-axis aspheric machining was conducted using an ELID grinding machining. The devices used in the experiment are presented in Table 1 and Fig. 2. For grinding wheels, cast iron-bonded grit size #140, #600, and #2,000 diamond wheels were used, and for finished machining, grit size #8,000 copper-resin bonded diamond wheels were used. All diameters and widths of the used wheels were set to the same dimensions, of 200 mm and 5 mm, respectively. The ultra-precision rotary grinder (RG-800, Nagase), with 10nm positioning resolution, was an ultra-precision machining device that employed a non-contact hydrostatic bearing in the spindle and rotary table. Electrodes were installed at the side of the wheel for the ELID grinding experiments so that the metal-bonded wheels can perform dressing continuously during machining. To fix the workpiece, a 600mm-diameter aluminum jig was fabricated. The fabricated reflector was a large-area reflector (⌀ 211.5 mm), and two specimens were positioned in the same distance from the center of the rotary table because of the machining of an off-axis aspheric shape. The tool path of the grinding wheel was set using the aspheric data[8]. Since the center of the rotary table is the rotation center of the off-axis lens, the reference workpiece was fixed at the center of the rotary table.

To prevent the precision degradation due to the imbalance of the center of gravity as the jig and rotary table were rotated during grinding machining, the specimens were arranged to face each other in the same distance from the rotation center, as shown in Fig. 3. After fixing the workpiece in the jig, the diameter of the wheel was measured, and truing and tool path were created to generate the machining program. Once the machining start and end locations were designated, rough and fine grinding, and finishing machining were conducted sequentially using low-grit to high-grit wheels[9]. The aspheric surface R and surface accuracy of the completed specimen were measured by separating the BK7 glass reference workpiece (⌀ 50 mm). For pre-machining preparations, the aluminum jig was installed on the rotary table, and the surface of the aluminum jig was self-cut evenly and the workpiece was fixed at the jig. During truing, the ELID voltage and current were inputted to 90V and 20A, respectively, when using #140, #600, and #2,000 wheels, and 60V and 10A when using the #8,000 wheel. After truing was complete, diameters of BK7 specimen and wheel were measured to create the numerical control (NC) data code, and a total of 10 measurements were obtained to calculate a mean for the dimension reliability. The experimental conditions are summarized in Table 2. All wheels had the same rotation speed, 1000 rpm, and the rotation speed of the rotary table was set to 40 rpm when using #140, #600, and #2,000 wheels, and 240 rpm when using the #8,000 wheel during machining. Eq. (1) presents the aspheric surface equation of the aspheric reflector. Here, R is -4,000 and K is -1.0.

$$z = \frac{y^2}{R(1+\sqrt{1-(1+K)y^2/R^2})} \quad \text{--------} \quad (1)$$

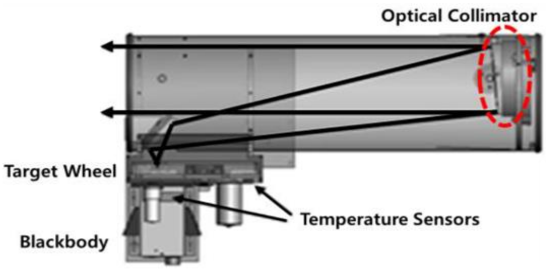

Fig. 1 Schematic diagram of generic infrared target projector

Table 1 Specification of experimental equipment

Machine		NAGASE RG-800
Grinding wheel	Mesh no.	#140,#600,#2000,#8000
	Abrasive	Diamond
	Bonding material	Metal / Copper resin
Power supply		ED-910
Grinding fluid		CG-7
Material		BK7
Diameter	workpiece	Ø211.5
	reference	Ø50

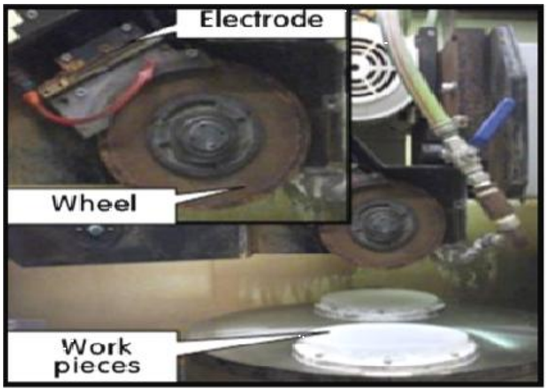

Fig. 2 Schematic diagram for profile machining of reflecting mirror using reference workpiece

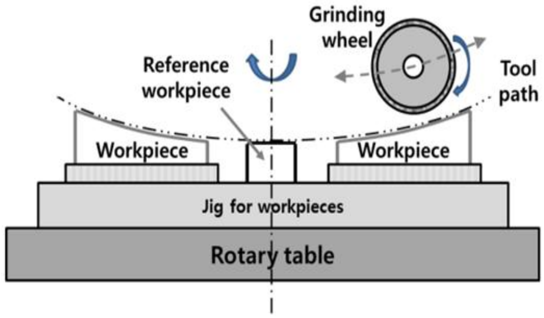

Fig. 3 Schematic diagram for profile machining of reflecting mirror using reference workpiece

Table 2 ELID grinding condition

Mesh no.		#140	#600	#2000	#8000
Feedrate [m/min]		5.0	1.0	2.0	1.0
Depth of cut [μm]		1			
Total depth of cut [μm]		560	17	59	30
Grinding time [Hr]		36	9	18	20
ELID Condition	IP [A]	10			
	Voltage[V]	120			

Fig. 4 Measurement devices, NewView5032(Zygo) and UA3P(Panasonic)

2.2 Measurement device and method

To determine the surface roughness and machining status of the material after machining, the machining surface of the reference workpiece was measured after machining by grit size of the grinding wheels since a three-dimensional (3D) surface shape measurement device (NewView5032, Zygo) was employed, as shown in Fig. 4. The enlarged photo of the machining surface was shot using a contactless 3D measurement device (NH3), and grinding traces were analyzed and compared to verify the machining characteristics of the workpiece. Since the diameter of the large-area reflector as a workpiece was more than 200 mm, a large 3D shape measurement device was needed to measure the aspheric surface profile precision. Since the size of the workpiece that was fabricated in this experiment exceeded the measurement range of the UA3P device, the shape precision of the reference workpiece was measured to predict the precision of the large-area workpiece. The shape precision of the workpiece was predicted after machining with #2,000 and #8,000 wheels and measuring the reference workpiece in the 3D shape measurement device (UA3P, Panasonic).

3. Experiment results and discussion

3.1 Analysis of machining surface

The surface roughness was measured using a 3D surface shape measurement device (NewView5032, Zygo), with four measurement locations, including the center, in the clockwise direction as shown in Fig. 5. The reference workpieces (Ø50 and 27.11 mm of height) was machined at different grit sizes, and each surface roughness was measured. In #140 wheel machining, 36 hours were taken, and full machining started when reaching 550 passes. The total depth of cut was 560 μm. When measuring at the center and three locations in the circumferential direction after machining with the #140 wheel, the surface roughnesses were 0.37, 0.81, 0.69, and 0.83 μmRa, which showed the best result in the center. In the case of the #600 wheel, the machining time took 9 hours, and the full machining started when reaching 13 passes. The total depth of cut was 17μm. The surface roughness was measured using the same method, and the results were 0.21, 0.43, 0.47, and 0.32 μmRa, which were improved. The center location was also the best result. In the #2,000 wheel machining, which corresponded to fine grinding, full machining started when reaching at 2 passes, and the surface roughnesses were 0.07, 0.05, 0.05, and 0.04 μmRa. There was no significant difference in surface roughness between the center and surrounding areas in the #2000 wheel machining. In the case of the #8,000 wheel for finished machining, the total depth of cut was 30 μm, and the measured surface roughnesses were 0.008, 0.011, 0.016, and 0.012 μmRa, which exhibited excellent finished machining surfaces (around 10 nmRa). Fig. 6 shows the photo of the machining surface using the #8,000 wheel measured with a contactless 3D measurement device (NH3). The measured areas were divided into the center and surrounding areas with 10x and 50x magnifications. In the measurement surface with 10x magnification, grinding traces were found in the rotation direction of the workpiece in the center, and grinding traces were found in the surrounding areas in the straight-line direction.

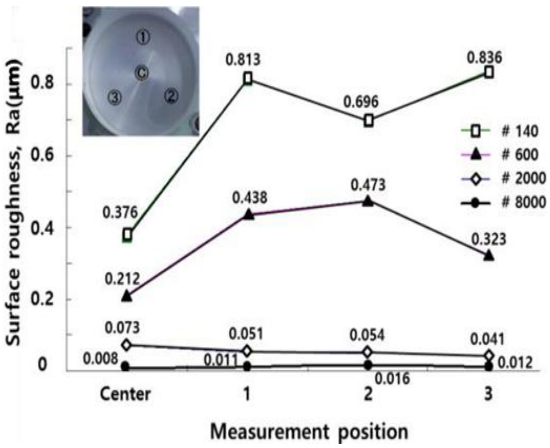

Fig. 5 Measurement results of surface roughness

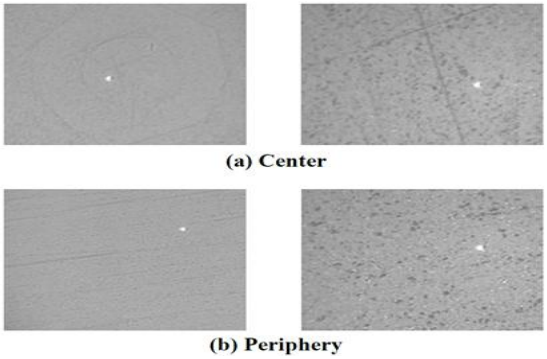

Fig. 6 10 times and 50 times magnified photographs of ground surface by using grinding wheel, #8000

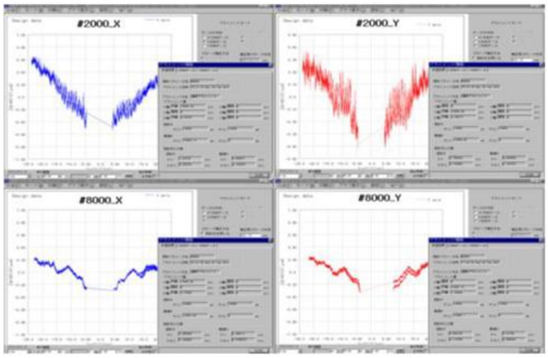

Fig. 7 Measurement results of form accuracy on ground surfaces by grinding wheels, #2000 and #8000

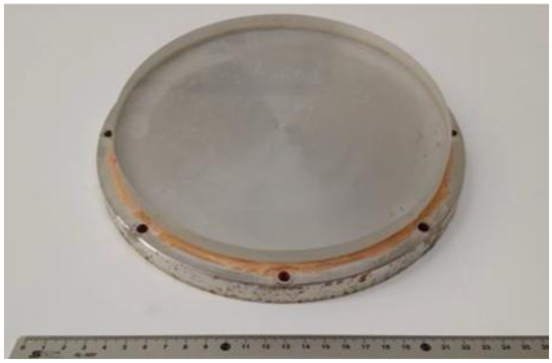

Fig. 8 Photograph of off-axis asymmetric reflecting mirror finished by #8000 grinding wheel

3.2 Shape precision

Fig. 7 shows the reference workpieces machined with #2,000 and #8,000 wheels using the 3D shape measurement device (UA3P) in the X and Y directions. When using the #2,000 wheel, the root mean square (RMS) of the aspheric surface R in the X direction was 0.23 μm, and the RMS of the optimum R was 0.16 μm. The RMS of the aspheric surface R in the Y direction was 0.14 μm and the RMS of the optimum R was 0.10 μm. When using the #8,000 wheel, the RMSs of the aspheric surface R and optimum R in the X direction were 0.10 μm and 0.08μm, respectively, and those in the Y direction were 0.11 μm and 0.08 μm, respectively. The shape precision of the machining surface using the #8,000 wheel was significantly improved compared to that using the #2,000 wheel. Fig. 8 shows the photo of the completed off-axis aspheric reflector after ELID grinding using the grit-size #8000 wheel.

4. Conclusions

This study proposed a method to predict large-area reflector precision by measuring surface roughness and profile accuracy through the reference workpiece after machining a BK7 glass workpiece with an ultra-precision rotary grinder to fabricate a large-area off-axis aspheric reflector. The ELID grinding machining results using 10 nm resolution of ultra-precision rotary grinder by applying grit sizes of #140, #600, #2,000, and #8,000 sequentially revealed the following conclusions.

1. The measurement results on surface roughness of the reference workpiece after machining by grit size of wheels showed that the surface roughness in the center was better than that in the surrounding areas when using a low grit size wheel (#140 and #600). No significant difference in surface roughness was found between the center and surrounding areas when using a large grit size wheel (#2000, #8000). In addition, the surface roughness in the surrounding areas was even better when using the #2,000 wheel.
2. The surface roughness in the surface machined using the #8,000 wheel in the finished machining was 0.008 μmRa in the center and up to 0.016 μmRa in the surrounding areas.
3. The shape precision of the reference workpiece was measured after machining the workpiece with #2,000 and #8,000 wheels. The results showed that the RMSs of the optimum R in the X and Y directions in the surface machined using the #2,000 wheel were 0.16 μm and 0.10 μm, respectively, while those in the surface machined using the #8,000 wheel were improved, at 0.08 μm and 0.08 μm, respectively.

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