ELID Grinding Characterization of Large Schmidt Lens for Large Telescope

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Summary

This paper introduces a schmidt lens manufacturing process, focusing on its axis-aymmetric aspherical surface manufacturing by synthesizing ELID grinding and arc-enveloped grinding method. For test experiment, an off-axis spherical surface was ground to obtain suitable grinding and ELID conditions. Then, the large axis-aymmetric aspherical concave and convex were ground on the developed grinding system using #325, #1200 diamond cast-iron bond wheels. Grinding characteristics such as attainable form accuracy, surface roughness were investigated.

Keywords: ELID grinding, Large axis-aymmetric aspherical surface, Arc-enveloped grinding method, Form accuracy.

1. Introduction

To explore various scientific frontiers from nearby substellar objects to large scale structure of the high redshift universe, a Fibre Multi-Object Spectrograph (FMOS) is being developed under an international collaboration team between the Japanese National Astronomical Observatory (NAOJ), the Anglo Australian Observatory (AAO), and a consortium of UK groups [1]. FMOS is expected to employ as a second generation near-infrared measuring instrument for the prime focus of 8.2m Subaru telescope.

In order to improve the image quality and to reduce the volume of the FMOS, the new large special Schmidt plate was designed by Maihara team in Kyoto University [1] as shown in Figure 1. The special Schmidt plate consists of a concave plate and a convex plate. One side of plate was designed as off-axis axis-aymmetric aspherical surface, the curvature radius of approximate sphere is 1500mm. Size is L315×W251mm. A material was designed as fused silica. To obtain the required optical performance, form accuracy of the large surface under 5μm p-v and surface roughness under rms 50nm are essential.

In this paper, for realizing ultraprecision fabrication of the large special Schmidt plate, we considered to adopt the following process: 1) Conventional (rough) grinding, 2) ELID arc-enveloped grinding, and 3) Polishing. Conventional (rough) grinding aimed to remove a lot of materials to generate approximate sphere, ELID arc-enveloped grinding was used to obtain higher form accuracy and desired surface roughness so that polishing period could be shorten; polishing aimed to obtain better surface roughness and less damaged layer.

ELID arc enveloped grinding experiments were carried out using #325, #1200 diamond cast-iron bond (CIB) wheels, and grinding characteristics such as attainable form accuracy, surface roughness were investigated. Furthermore, some measures to improve form accuracy were discussed and verified.

2. Grinding test for off-axis spherical surface

Before grinding the designed large special Schmidt plate for FMOS, we performed some basic experiments to test the attainable accuracy of ELID grinding process [2] - [4]. Two miniature fused silica glass blank (one for concave and the other for convex) were used to carry out test grinding. Desired surface was set as off-axis sphere with a curvature radius of 400mm.

A schematic diagram of three-dimensional controlled ELID arc-enveloping grinding is shown in Figure 2. The workpiece surface is divided into many small squares, a disk type of round shape CIB diamond wheel

was controlled to move in XZ or YZ plane. These series motions are employed to generate a desired surface. The feature of the grinding mode is: 1) a grinding point on the wheel changes with the changes of the gradient angle of grinding points, 2) relatively slow wheel wear, 3) good effect of form error compensation.

Truing and grinding were conducted on an ultra-precision 4-axes grinding machine with a maximum resolution of 1nm for 3-axis linear feeding. The wheel profile (tip radius, wheel radius) was at first measured to prepare an NC program that decided motion of the wheel center points. Grinding conditions are shown in Table 1.

Figure 3 shows the ground samples, and the results of their profile maps recorded by an Zygo interferometer. For the concave lens, the rms micro-roughness and P-V form deviation were resulted in 56nm and 0.58 μm , respectively. While for the convex lens, p-v form deviation was resulted in 0.68 μm , the rms micro-roughness was resulted in 160 nm. From those results, we considered that the grinding method was possible to obtain desired surface for the special Schmidt plate in a high efficiency.

Figure 1 Large special Schmidt plate

Figure 2 Principle of ELID arc-enveloped grinding

Figure 3 Test samples after grinding and its form deviation profile map

Table 1 Grinding conditions

Grinding machine	Ultraprecision mirror surface 4-axes grinding system with 1nm resolution
Grinding wheel	CIFB diamond wheel, $\phi 40\text{mm} \times W10 \text{ mm}$, #325, #1200, Tip radius 5.0mm, Concentration: 50
Grinding conditions	Wheel rotational speed: 10000min^{-1} , Table feed-rate: 200~500mm/min, Depth of cut: 25 μm /pass for #325; 5 μm /pass for #1200; Pick feed pitch: 1mm for #325, 0.1~0.5mm for #1200; Feed pitch: 0.2-1mm
ELID conditions	Open circuit voltage (E_o): 60V, Peak current (I_p): 5A, On/off-time (τ_{on}/τ_{off}): 2/2~10 μs , Pulse wave: square
Workpiece	Material: Fused silica glass; Size: 60mm $\times$ 60mm
Grinding fluid	Chemical-solution-fluid (2% dilution of water)

3. Grinding experiments for large axis-aymmetric aspherical surface of the large special Schmidt plate
Before ELID grinding, the approximate spherical surface with a curvature radius of 1500mm was generated by conventional grinding. Accordingly, removal depth distribution (depth of cut) in ELID grinding process was calculated as Figure 4, the maximum removal depth was about 4.5mm.

Figure 4 Removal depth distribution in ELID grinding process

Figure 5 External view of grinding system

Figure 6 Plasma electric discharge truing

Table 2 Truing and dressing conditions

Equipment	Ultraprecision mirror surface 3-axes grinding system with 10nm resolution
Truing instrument	Micro electrical discharge truing instrument
Truing wheel	Bronze bonded diamond wheel, $\phi 150 \times W10$ mm straight, #325, Concentration: 75.
ED truing	Grinding wheel rotation: 600min^{-1} , Rotary electrode rotational speed: 200min^{-1} , Feed rate: 30mm/min , Depth of cut: $1\mu\text{m/pass}$
Electrical conditions	Open circuit voltage (E_o): 120V, Peak current (I_p): 30A, On/off-time (τ_{on}/τ_{off}): $2/2\mu\text{s}$, Pulse wave: Square
Mechanical truing	Grinding wheel rotation: 600min^{-1} , Rotary truing wheel rotation: 200min^{-1} , Feed rate: 20mm/min , Depth of cut: 0.5, $1\mu\text{m/pass}$
ELID conditions	Open circuit voltage (E_o): 90V, Peak current (I_p): 20A, On/off-time (τ_{on}/τ_{off}): $2/2\mu\text{s}$, Pulse wave: Square

3.1 Precision truing and dressing

Wheel preparation includes precision truing and dressing. In the precision-truing process, plasma electric discharged truing and ELID assisted mechanical truing were conducted. The former is aiming to obtain higher truing efficiency, the latter is to obtain high-precision topography of the wheel. To obtain desired cross-section arc profile, the grinding wheel was controlled by NC program to move continuously along arc direction. After the desired topography of the wheel was obtained, initial electrolytic dressing was exerted to remove metal matrix of the wheel to form oxide layer to let the abrasive protrude from the wheel surface.

The truing and grinding process were accomplished on a developed large ultraprecision mirror surface 3-axes grinding machine with the minimum resolution of 10nm for 3-axis linear feeding under full closed feedback. Figure 5 shows external view of grinding system. Plasma electric discharge truing and mechanical truing conditions are shown in Table 2, respectively. Figure 6 shows external view of plasma electric discharge truing. The cross-section of #1200 CIB diamond wheel was trued to an arc shape with a tip radius of 10mm by using a rotary truer thereafter was used to grind a carbon block. Then, we measured the arc shape of the machined surface on the carbon block regarding approximately it as arc shape of the grinding wheel. The cross-section of the grinding wheel after truing was measured by use of a laser three-dimensional shape measuring instrument NH-3, and the approximate curvature radius of the arc was calculated. Figure 7 shows the cross-section profile of the grinding wheel and the data fitted to the arc radius calculated by the least mean squares method. The radius became 9.96 mm after fitting, which is somewhat less than the designed tool radius. Moreover, it shows the form error from the arc after fitting. The form error after filtering is within $\pm 1.2\mu\text{m}$, indicating that the precision truing was realized successfully.

3.2 Grinding experiments and form error compensation

Grinding conditions are shown in Table 3, and two CIB diamond wheels of #325 and #1200 were used. The ground surface by #1200 wheel was measured with on-machine measurement system as shown in Figure 8. Form deviation profile from the designed curved surface after fitting is shown in Figure 9. Form accuracy

in X-direction was about $1.2\mu\text{m}/270\text{mm}$ P-V. Form accuracy in Y-direction was about $2.8\mu\text{m}/180\text{mm}$ P-V. Unavoidably, owing to wheel wear of a long time, the Y-section error was larger than the X-section error. For mitigating the Y-section error, a viable alternative is conducting form error compensation.

Tool path compensation, initial tool diameter and tip radius compensation were conducted. Initial ground surface was measured for calculating the distribution of the form deviation profiles. With these deviation profiles, the NC data was compensated. As shown in Figure 10, form accuracy in X-section was not improved remarkably, however, in Y-section it was improved $1.5\mu\text{m}/180\text{mm}$ p-v. In 3-dimensional evaluation, the profile error was improved to $2.5\mu\text{m}$ for area of $300\text{mm}\times 200\text{mm}$.

Measuring of surface roughness for large part is usually a problem owing to restrict of allowable measured size and weight of workpiece in most measuring instruments. In this study, a mobile AFM was used to measure surface topography and surface roughness. The AFM probe head can be mounted directly on the workpiece or on the machine stage to conduct on-machine measuring. Figure 11 shows surface topography after grinding by #1200 wheel. Surface roughness was resulted in rms $120\text{nm}\sim 180\text{nm}$. Schmidt plate samples after polishing were shown in Figure 12. Form accuracy under $2.5\mu\text{m}$ p-v and surface roughness under rms 40nm were achieved successfully.

Table 3 Grinding conditions

Grinding machine	Ultraprecision mirror surface 3-axes grinding system with 10nm resolution
Grinding wheel	CIFB diamond wheel, $\phi 305\times W10\text{ mm}$, #325, #1200, Tip radius 10 mm, Concentration: 75
Grinding conditions	Wheel rotational speed: 1200min^{-1} , Table feed-rate: $500\sim 1000\text{mm/min}$, Depth of cut: $25\sim 50\mu\text{m/pass}$ for #325; $1\sim 5\mu\text{m/pass}$ for #1200; Feed pitch: $0.2\sim 1\text{mm}$; Feed pitch: $0.2\sim 1\text{mm}$
ELID conditions	Open circuit voltage (E_o): 60V, peak current (I_p): 5A, On/off-time (τ_{on}/τ_{off}): $2/10\mu\text{s}$, Pulse wave: Square
Workpiece	Material: Fused silica glass; Size: $315\text{mm}\times 251\text{mm}$
Grinding fluid	Chemical-solution-fluid (2% dilution of water)

Figure 7 Cross-section profile and form error of grinding wheel after mechanical truing

Figure 8 On machine measuring system

Figure 9 Form deviation profile before compensating form error

Figure 10 Form deviation profile after compensating form error

Figure 11 Measured surface topography by Mobile AFM

Figure 12 Fabricated large special Schmidt plates

4. Discussions

Generally speaking, it is well known that the grit size of abrasive on the grinding wheel has profound effects on the attainable surface roughness. In order to obtain the better surface finish and the less damaged layer, needless to say, ultra-fine abrasives wheel is necessary to be used. However, in conventional grinding without ELID, fine abrasives wheel may be easily loaded, especially, when grinding brittle material such as fused silica glass. Therefore, traditional grinding using a grinding wheel with small diamond grains, less $5\mu\text{m}$ in size is not practical. In the ELID grinding process, however, effective dressing is possible even if the diamond grains on the wheel surface are less $5\mu\text{m}$ in size. During electrolysis, the bond material on the wheel surface does not simply be dissolved into the grinding solution but is converted into non-conductive films liable to wear without affecting the bonded diamond grains mechanically, so the diamond grains can continue to protrude beyond the bond material. The worn wheel surface may be to the previous state. The ELID grinding technique offers an effective way of in-process dressing for grinding wheels, which enables the wheel of ultra-fine abrasives to be used. Because the in-process automatical dressing may maintain stable grinding in a long time, it is suitable to be applied to large elements. Grinding large glass optical elements using ELID technique is an alternative.

In the arc-enveloping grinding for large free form surface, tip radius error and tip radius deviation of the wheel directly affected form accuracy of the ground surface. However, the arc radius value and arc form precision may be affected by in-process electrolysis. Wheel wear resulting from electrolysis may not be ignored when grinding large surface. Decreasing electrolysis current, voltage, increasing off time, i.e., adopting weak electrolytic dressing or interval electrolytic dressing is an effective alternative. Therefore, voltage 60V, current 5A, on-off time 2/10 μs were selected in this study. Choosing suitable ELID parameters and grinding conditions to make the grinding wheel to be maintained as the best grinding state is very important. If electrolysis is not enough, the wheel may be easily loaded. Conversely, if electrolysis is

overwork, the oxidized layer and abrasives on the wheel surface may be easily removed, stable grinding may not be carried out.

If ELID parameters are decreased to the lowest value to maintain electrolytic balance, and the residual form error may not be tolerable, another effective method is to conduct form error compensation as verified in this study. The most important feature of ELID-grinding is that very smooth and small damage surface may be obtained as many research have verified. However, the strong electrolytic dressing is harmful to maintain wheel surface topography precision, properly applied or interval electrolytic dressing are to be used to decrease the influence. Form error compensation may be used to improve form accuracy of ground surface.

5. Conclusions

In this study, we developed a new grinding process and system for fabrication of large axis-aymmetric aspherical surface by applying synthetically ELID grinding method and arc enveloped grinding mode, and obtained success to fabricate the large special Schmidt plate for FMOS. In ELID grinding for large axis-aymmetric aspherical surface, truing precisely the grinding wheel, selecting suitable electrolytic and grinding parameters, and compensating form error are some effective measures to improve form precision. By taking these measures, we will be able to obtain higher form precision and better finish surface simultaneously.

As future works, we will continue the research using ultra fine abrasive grinding wheels to obtain simultaneously sub-micron form accuracy and nano-meter order surface roughness for large axis-aymmetric aspherical surface. The results are expected to contribute to fabrication of large axis-aymmetric aspherical optical elements.

7. References

- (1) K. Masahiko, T. Maihara, K. Ohta, F. Iwamuro, S. Eto, M. Lino, D. Mochida, T. Shima, H. Karoji, J. Noumaru, M. Akiyama, J. Brzeski, P.R. Gillingham, A.M. Moore, G. Smith, G.B. Dalton, I.A. Tosh, G.J. Murray, D.J. Robertson, and N. Tamura, Fibre-Multi-Object Spectrograph (FMOS) for Subaru Telescope, Proceeding of SPIE, 4841, (2003) 974-984.
- (2) H. Ohmori and T. Nakagawa, Analysis of mirror surface generation of hard and brittle materials by ELID (Electrolytic In-Process Dressing) grinding with superfine grain metallic bond wheels, Ann. CIRP, 44/1, (1995) 287-290.
- (3) H. Ohmori and T. Nakagawa, Utilization of nonlinear conditions in precision grinding with ELID(Electrolytic In-Process Dressing) for fabrication of hard material components, Ann. CIRP, 46/1, (1997) 261-264.
- (4) H. Ohmori, W. Lin, Y. Yamagata, S. Moriyasu, A. Makinouchi, and S. Morita, Grinding characteristics of large ultraprecision aspheric optics ELID-grinding for integrated and computerized fabrication system, Proceedings of 3rd International Symposium on Advances in Abrasive Technology (Advances in Abrasive Technology 3), (2000) 129-134.
- (5) S. Yin, H. Ohmori, Y. Uehara, T. Shimizu, and W. Lin, A large number of micro V-grooves fabrication of large germanium immersion grating element for mid-infrared spectrograph by ultraprecision micro-grinding technique, International Journal of JSME, (C), Vol. 47, No. 1, (2004) 59-65.
- (6) Y. Watanabe, H. Ohmori, W. Lin, K. Katahira, and Y. Uehara, Ultraprecision on-machine measurement, Proceeding of international workshop on optics and sensors, (International progress on advanced optics and sensors 2003) 99-104.