

Basic Study on Ultra-precision Grinding of Optical Glass Lens by CeO₂ Chemical Reaction Assistance

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Abstract. Large aperture lenses which are used for single-lens reflex cameras and astronomical telescopes are manufactured by both ultra-precision grinding to make precise shape and polishing to improve surface quality. However, prolonged polishing deteriorates lens shape accuracy and decreases productivity. In order to reduce polishing amount and obtain finer surface without cracks before polishing, it is required to develop a highly-efficient ductile-mode grinding technology. In this study, a novel ultra-precision grinding method assisted by CeO₂ chemical reaction is proposed and its performance is experimentally evaluated. The results show that crackless surface can be successfully obtained over the entire surface at three times higher tool feed rate, compared with conventional grinding without CeO₂ assistance.

Introduction

Recently, the demand for optical lenses with high surface quality has increased with the improvement of image quality. Generally, small-aperture optical glass lenses used for smartphones and compact cameras are manufactured by molding process. However, the molding process is not the main method of manufacturing large-aperture glass lenses requiring the capability of photographing high quality image such as single lens reflex cameras and astronomical telescopes. This is because it is difficult to manufacture a large mold accurately and the contraction error during the cooling process is large. Therefore, in order to sufficiently satisfy excellent optical characteristics, high processing surface quality, and shape accuracy, manufacturing methods such as grinding and polishing are used to produce large-aperture optical glass lenses. In many cases, in terms of productivity, the optical glass lenses are formed by grinding processing that allows generation of cracks and sufficient polishing that is performed to remove cracks generated by grinding. However, prolonged polishing causes a reduction in shape accuracy and in production efficiency due to an increase in processing time. Therefore, a high efficiency ductile mode grinding process which does not cause cracks, is desired.

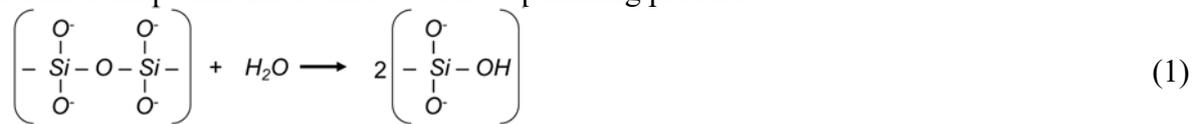
High precision grinding of optical glass lenses has been studied for decades. Gua et al. [1] were subjected to horizontal grinding of optical glass BK7 using a diamond wheel and showed that the influence of wheel feed rate is dominant in brittle-ductile transition and surface roughness. Regarding high efficiency and high accuracy ultra-precision grinding, Sekiguchi et al. [2] proposed a grinding technique controlling the tool feed rate and workpiece velocity simultaneously. These studies focus on ductile-mode grinding technology. On the other hand,

if polishing effect can be integrated into grinding process, total production time including both grinding step and polishing step would become much shorter. Therefore, development of a grinding method taking into account of polishing effect has been recently required. Reddy and Rao et al. [3] conducted studies on the effect of lubricating when abrasive grains were used in rough metal cutting. Yan, Zhang and Kuriyagawa et al. [4] succeeded in reducing tool abrasion and low surface roughness using a complex type of cutting oil material in which metal nanoparticles were mixed in grease of high viscosity and high adhesion in ultra-precision turning processing.

Cerium oxide (CeO₂) is the material most widely used for polishing of optical glass. The reason is that the chemical reaction of CeO₂ strongly acts on the processing of the glass and realizes a satisfactory surface. In this study, ultra-precision grinding of high quality and high efficiency optical glass lens BK7 assisted by CeO₂ chemical reaction was aimed as a final object. Concretely, focusing on the component of the grinding fluid, we have proposed a grinding method using a chemical polishing effect by supplying slurry containing CeO₂ during the grinding process and verified the validity through experimental evaluation.

Principle of grinding process assisted by CeO₂ chemical reaction

The chemical reaction of CeO₂ is described in this chapter. When polishing the glass, electrons formed by oxidation of Ce³⁺ ionized at the surface of CeO₂ will transfer to anti-bonding orbital of Si-O [5]. The charged electrons in the orbitals extend Si-O bonding distance and weaken the bonds. This chemical reaction is shown in Eq.1. It is assumed that the fixed diamond abrasive grains in the wheel accurately remove the softened glass workpiece and the supplied free CeO₂ abrasive grains take an important role in not only the above chemical reaction but also polishing process. The CeO₂ assisted grinding has a feasibility to achieve both accurate shape and finer surface without polishing process.



Set up

Grinding tests were conducted using a resin bonded diamond wheel. An optical glass lens BK7 with a diameter of 30 mm (radius of curvature is 60.225 mm) is used as a workpiece. The workpiece is attached to the jig using solid wax and the jig is attached to the aspherical grinding machine (ULG-100E (HYC), Toshiba Machine Ltd.) as shown in Fig.1. As a grinding method, cross grinding is adopted where a tangential workpiece velocity is perpendicular to the tangential wheel feed rate. The diamond wheel moves along the curved surface from the outside of the workpiece toward the center. A grinding fluid mixed with CeO₂ is supplied using the apparatus as shown in Fig.2. In the tank, distilled water, CeO₂, and a water-based grinding coolant diluted at a ratio of 1: 100 as a lubricant are stirred, which is used as a grinding fluid. The grinding fluid is supplied to the grinding point through the damper under discharge pressure of the pump at 0.4 MPa. The supply rate of grinding fluid is adjusted to 570 mL /min by installing a pressure gauge in front of the nozzle. The grinding condition is listed in Table 1. The wheel feed rate V_r is varied in the range of 0.5 mm/min to 3.0 mm/min. The wheel velocity V_s , the workpiece velocity V_w and the depth of cut a_p are kept constant. After the experiment, the surface quality is evaluated by using a digital microscope (VHX - 5000, Keyence). The arithmetic surface roughness Sa is measured by a scanning white interferometer (New View™ 6200, Zygo).

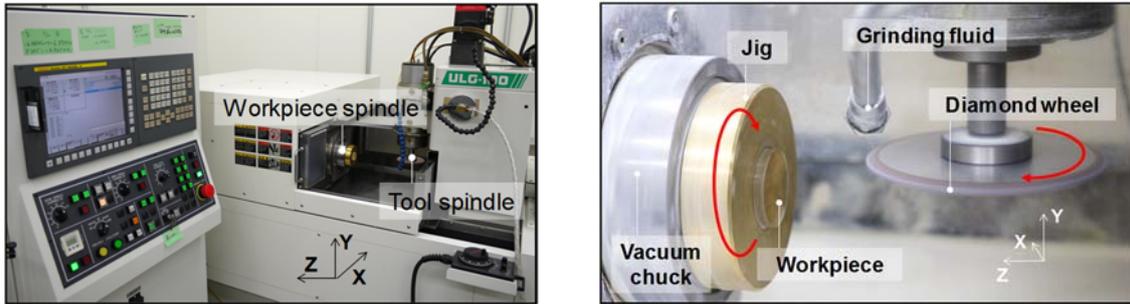


Fig.1 Experimental setup for ultra-precision grinding

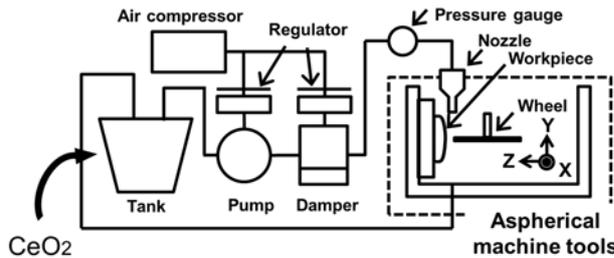


Fig.2 Schematic diagram of the slurry supply system

Table 1 The grinding conditions

Wheel velocity V_s	36.7 m/s
Workpiece velocity V_w	0.016 m/s
Wheel feed rate V_r	0.50, 1.0, 3.0 mm/min
Depth of cut a_p	0.5 μm

Performance evaluation of a novel ultra-precision grinding method assisted by CeO_2 chemical reaction

At first, the influence of the grinding wheel feed rate on the workpiece surface quality is investigated in the CeO_2 assisted grinding. Fig.3 shows the observation results of ground surface at 1, 7 and 15 mm from the center of the workpiece. At the feed rate of 0.5 and 1.0 mm/min, excellent surface quality without cracks was obtained on the entire surface of the workpiece. In particular, no grinding marks were left on the surface. In contrast, at the wheel feed rate of 3.0 mm/min, brittle fractures were partially and slightly observed outside 7 mm from the center of the workpiece. These figures show the possibility that the grinding process using CeO_2 does not require polishing. Fig.4 shows the relationship between the surface roughness S_a and the distance from the center of the workpiece according to the wheel feed rate. The error bars show the minimum and maximum surface roughness. The surface roughness S_a less than 5 nm is achieved at the wheel feed rate of 0.5 and 1.0 mm/min. When the wheel feed rate is lower, the depth of cut per one abrasive grain becomes smaller theoretically, which causes decrease of the grinding load. As the result, lower surface roughness can be obtained.

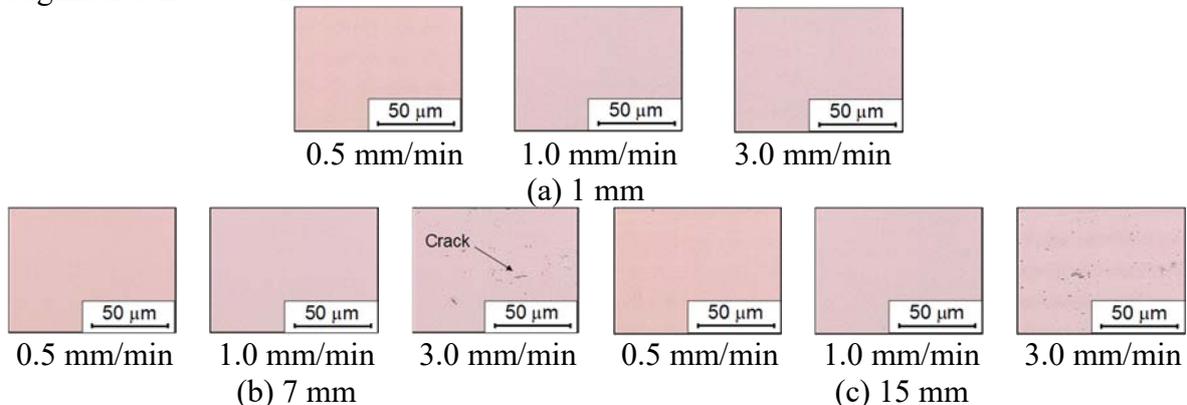


Fig.3 Micrographs of the ground surface at each region from the center of the workpiece by CeO_2 assisted grinding : (a) 1 mm, (b) 7 mm and (c) 15mm

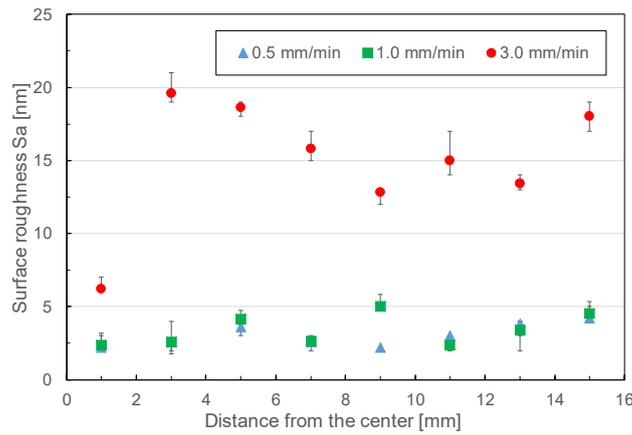


Fig.4 Influence of the feed rate on surface roughness Sa

In CeO₂ assisted grinding, adhesion of CeO₂ was confirmed on the wheel surface after grinding. Fig.5 and Fig.6 show the observation results of the wheel surface after normal grinding and CeO₂ assisted grinding. As shown in these figures, a large amount of CeO₂ were adhered to the wheel surface after CeO₂ assisted grinding. Fig.7 shows the observation images of CeO₂ before grinding and CeO₂ adhered to the wheel surface. The abrasive particle size of CeO₂ used was 1.0 μm on average. However, the particles which adhered to the wheel were smaller than 0.1 μm. It is well-known that the CeO₂ abrasive grains are broken into pieces during polishing process and grain size becomes small [6]. It is suggested that these crushed CeO₂ abrasives easily adhere to the grinding wheel due to moderate grinding pressure between the wheel and workpiece. Therefore, the chemical reaction of CeO₂ to BK7 could be promoted at the grinding point under higher pressure and higher temperature, resulting in extremely fine surface quality.



Fig.5 Normal grinding

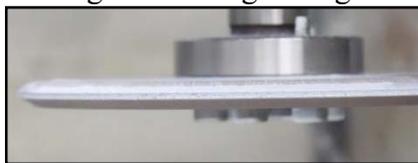
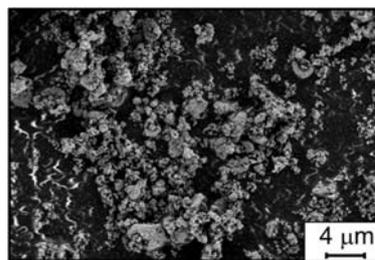
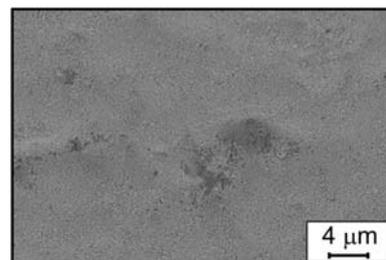


Fig.6 CeO₂ assisted Grinding



(a) CeO₂ grains before grinding



(b) CeO₂ grains adhering to the wheel

Fig.7 Microscopic images of CeO₂ grains

Discussion for high efficiency grinding process

According to the results above, extremely fine surface of BK7 can be obtained by CeO₂ assisted grinding. However, under the wheel feed rate of 3.0mm/min, the surface roughness Sa was large. This is because of the undulation generated on the surface of the workpiece as shown in Fig.8. This undulation is caused by the uncut part of the workpiece owing to the increase in the wheel feed rate per workpiece rotation. During the cross grinding process, the pitch spiral corresponds to the wheel feed per workpiece rotation f mm/rev as shown in Eq.2. V_f is the wheel feed rate mm/min and N_w is the workpiece rotation speed min⁻¹.

$$V_f/N_w = f \quad (2)$$

Sekiguchi et al. [2] has shown that the critical wheel feed per workpiece rotation is about 0.15 mm/rev. In order to set the experimental condition as the critical wheel feed per workpiece rotation to 0.10 mm/rev, the workpiece rotation speed was set to 30 min^{-1} at the wheel feed rate of 3.0 mm/min. Fig.9 and Fig.10 compares the conventional grinding with the CeO₂ assisted grinding at the same grinding conditions. A ductile grinding mode surface was obtained by the CeO₂ assisted grinding. Also, The surface roughness Sa decreases by 97% compared to the conventional grinding. Fig.11 shows that the surface without undulation and cracks were achieved in the CeO₂ assisted grinding. Not only the high surface quality without cracks and grinding marks was obtained but also the grinding efficiency became three times higher than that of the conventional grinding.

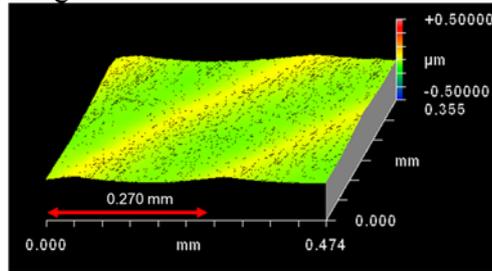


Fig.8 Topography image of the surface after conventional grinding

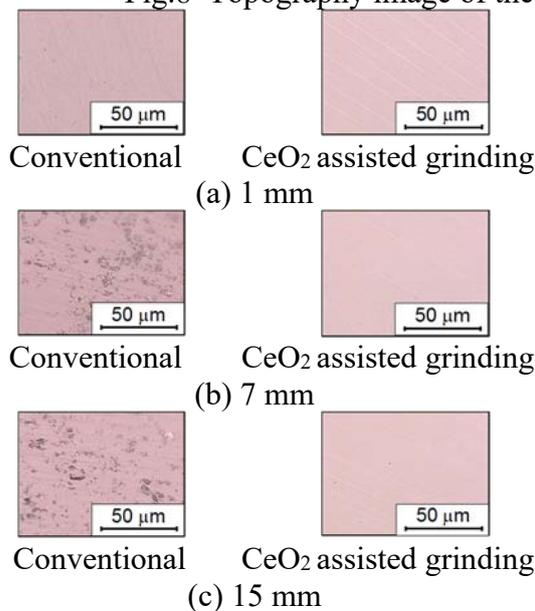


Fig.9 Ground surface at each position from the center of the workpiece : (a) 1 mm, (b) 7 mm and (c) 15 mm

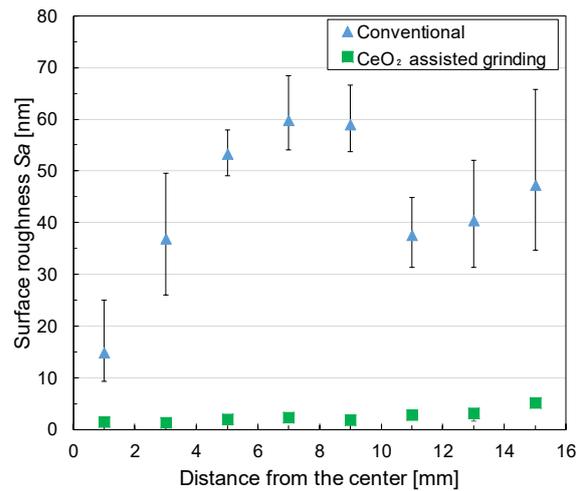


Fig.10 Relationship between distance from the center of the workpiece and surface roughness Sa

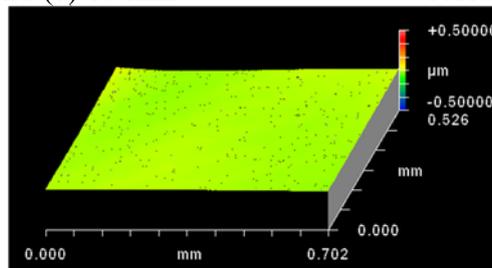


Fig.11 Topography image of the surface after CeO₂ assisted grinding

Conclusion

In this study, ultra-precision grinding assisted by CeO₂ chemical reaction is proposed for optical glass lenses, and the grinding performance is experimentally investigated. As a result, a high surface quality without cracks and grinding marks were successfully obtained after the CeO₂ assisted grinding. It is assumed that chemical reaction of CeO₂ contributes to the enhancement of grinding ability. The high surface quality can be maintained even if the wheel feed rate and the workpiece rotation speed are increased. Consequently, compared to the conventional grinding, the surface roughness decreased by 97%, and three times higher grinding efficiency was achieved.

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