Development of Aspherical Gradient Index (GRIN) Lens Fabrication System based on VCAD Concept and ELID Grinding

Yutaka Watanabe¹, Hitoshi Ohmori², Weimin Lin³, Yoshihiro Uehara⁴, Toru Suzuki⁵, Shin-ya Morita⁶, Nobuhide Mitsuishi⁷, and Akitake Makinouchi⁸

1 V-CAD Fabrication Team, Integrated Volume-CAD System Program, Center for Intellectual Property Strategies (CIPS), RIKEN, 2-1 Hirosawa Wako-shi Saitama 351-0198, Japan, E-mail: watanabe@nano.gr.jp
2 Materials Fabrication Laboratory, Discovery Research Institute (DRI), RIKEN, 2-1 Hirosawa Wako-shi Saitama 351-0198, Japan, E-mail: ohmori@mfl.ne.jp
3 V-CAD Fabrication Team, Integrated Volume-CAD System Program, Center for Intellectual Property Strategies (CIPS), RIKEN, 2-1 Hirosawa Wako-shi Saitama 351-0198, Japan, E-mail: lin@nano.gr.jp
4 V-CAD Fabrication Team, Integrated Volume-CAD System Program, Center for Intellectual Property Strategies (CIPS), RIKEN, 1-7-13 Kaga, Itabashi-ku, Tokyo, Japan, 173-0003, uehara@micro.ne.jp
5 V-CAD Fabrication Team, Integrated Volume-CAD System Program, Center for Intellectual Property Strategies (CIPS), RIKEN, 2-1 Hirosawa, Wako-shi, Saitama, 351-0198, Japan, suzuki@micro.ne.jp
6 V-CAD Fabrication Team, Integrated Volume-CAD System Program, Center for Intellectual Property Strategies (CIPS), RIKEN, 2-1 Hirosawa Wako-shi Saitama 351-0198, Japan, E-mail: morita@neutron.ne.jp
7 The Nexsys Corporation, 1-7-13 Kaga, Itabashi-ku, Tokyo 173-0003, Japan, mitsuishi@nexsys.ne.jp
8 V-CAD Fabrication Team, Integrated Volume-CAD System Program, Center for Intellectual Property Strategies (CIPS), RIKEN, 2-1 Hirosawa Wako-shi Saitama 351-0198, Japan, E-mail: akitake@riken.jp

Summary

ELID (Electrolytic In-process Dressing) grinding method is possible to achieve ultraprecision smooth surface of hard and brittle materials. To obtain ultra smooth surface required such as micro lens and its metal mold, final polish process which required long time after conventional grinding process was necessary. ELID grinding method using an ultraprecision grinding machine tool will be very effective in reducing the time required for final polishing process. In this paper, a fabrication experiment using this ELID grinding process was studied for Gradient Index (GRIN) lens. Especially, as a nano-precision micro-ELID grinding machining for GRIN lens, we studies on conditions of ELID grinding using a desk-top type 4 axes machine for development of GRIN aspherical lens with paraboloidal form, and GRIN prism.

Keywords: ELID grinding, desk-top machine, micro mechanical fabrication, GRIN aspherical lens, GRIN prism

1. Introduction

With the progress of the electronics industry, electronic/optical parts, and related molds are required higher quality, higher precision, and lower costs. Many of these parts are small, have microscopic shapes, and are made of special materials. Integrated production systems are therefore indispensable for the product design to manufacturing/production of these parts. Given these needs, the authors are currently conducting the R&D of intellectual manufacturing technology applying IT called Volume-CAD (VCAD) system. The VCAD system differs from existing surface CAD and solid CAD in that it is able to express the internal structure of objects and internal physical attributes directly, it allows CAD software and simulation software to read and write in the same data format, and it can be connected to machining systems directly using special CAM (VCAM), nano-level CAM (NCAM) (2), (3) software. The authors are currently using the expression function of the VCAD system and corresponding simulation functions to conduct R&D of applied manufacturing technologies (2). In particular, we are gradually developing three-dimensional manufacturing technologies with nano-level accuracy using elemental technologies such as the existing ELID grinding technology (3) and ultra-precision cutting technology, as well as the development of manufacturing simulation, desktop measurement and feedback technology.

As VCAD data is able to express the internal structure of workpieces and internal physical attributes directly, it enables the expression of voxel temperature, pressure, and distortion during nano-precision manufacturing of irregular materials and different materials, various types of simulation evaluation of manufacturing distortion are possible. This report introduces the measurement and optical path simulation in the development of optical parts currently developed by the authors using GRIN optical material with irregular material properties as a model (5).

2. Development of nano-precision mechanical fabrication system based on IT

The information technology (IT) is changing the framework of the manufacturing industry in product design and manufacturing design as well as research and development of new technologies. In order to help such activities, Volume CAD (VCAD) system has recently been developed. Unlike the surface CAD and the solid CAD,
which are used widely now, VCAD can express the internal structure and the physical attribute of the internal part of a 3D-object directly.

We are promoting R&D activities on VCAD applied fabrication technologies. VCAD applied fabrication technologies are based on VCAD, VCAM (Volume-CAM) and many simulations core technologies, as shown in Figure 1 and Figure 2. We currently have three subjects. The first is development of 3-dimensional nano-precision fabrication systems, which are combined with simulation techniques, new machining processes such as ELID-grinding, ultraprecision cutting, molding, and forming, and new measuring methods, utilizing volume data generated from VCAD system. The second is research and development on VCAD fabrication processes based on VCAD/VCAM core technologies. The third is research and development on new micro-fabrication processes such as fs laser fabrication, supporting VCAD fabrication system and process.

3. Types of GRIN Lens

The R&D of GRIN lens has been conducted for more than ten years now, and currently, a large number are being put to practical application as information equipment devices. As GRIN lens can be designed freely unlike regular lens, such advantages as reduction of the number of lenses and improved optical performance are looked forward to. Generally, GRIN lenses have axial and radial shapes as shown in Figure 3 (5). Axial GRIN lens has diffraction distribution refractive index profile along the optical axis of the lens. Diffraction distribution \( n_a(x) \) can be expressed by the following equation;
\[ n_z(z) = N_{00} + N_{01}z + N_{02}z^2 + \cdots \]  

(1)

where \( z \) is the distance in the optical axis direction, and \( N_{0j} \) is the diffraction distribution coefficient. On the other hand, radial GRIN lens has diffraction distribution refractive index profile in the direction perpendicular to the optical axis. The diffraction distribution \( n_r(r) \) can be expressed by the following equation;

\[ n_r(r) = N_{00} + N_{01}r^2 + N_{02}r^4 + \cdots \]  

(2)

where \( r \) is the distance in the vertical direction from the optical axis, and \( N_{0j} \) is the diffraction distribution coefficient ratio of refractive index profile. The following equation is another way of expressing the diffraction distribution refractive index profile \( n_r(r) \) of the radial GRIN lens;

\[ n^2(r) = n_0^2[1 - g(r)^2 + h_1(r)^4 + h_2(r)^6 + \cdots] \]  

(3)

where \( n_0 \) is the optical axis diffraction rate coefficient and \( g \) and \( h_i \) are diffraction distribution coefficients.

In the study described, ultra-precision aspherical shape grinding were conducted using this radial GRIN lens.

Figure 3  Kinds of GRIN lens and shape of ELID ground GRIN optical elements

Table 1  Conditions of ELID grinding

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>Radial type GRIN lens (Φ 4mm) [Nippon Sheet Glass Co., Ltd.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding Machine</td>
<td>Desk-top Type 4 Axes Precision Machine with Nozzle type ELID Fermion [The NXSYS Corp.]</td>
</tr>
<tr>
<td>Wheels</td>
<td>Cast iron fiber bonded diamond grinding wheel SD#2,000, SD#4,000 (Φ 60mm×15mm) [The NXSYS Corp.]</td>
</tr>
<tr>
<td>ELID power supply</td>
<td>Open Voltage: 90V, Pulse Timing: ( T_{on}/T_{off} = 2/2 \mu \text{sec} ) [The NXSYS Corp.]</td>
</tr>
<tr>
<td>Grinding Conditions</td>
<td>Wheel Rotation: 4,000rpm, Workpiece Rotation Speed: 2000rpm, Feeding Rate: 50mm/min, Depth of Cut: 60µm (2µm/pass), Pitch of X axis: 5µm</td>
</tr>
</tbody>
</table>

4. Micro-ELID grinding of GRIN lens

A fabrication experiment of GRIN lens using micro-ELID grinding process was studied for development of new optical components. We investigated on conditions of ELID grinding using a desk-top type 4 axes machine (Figure 4) for machining of paraboloidal GRIN lens and oblique form. In this study, the newly developed nozzle-type ELID grinding method of which system does not use a minus electrode for wheel, was applied for micro-ELID grinding. Main conditions of micro-ELID grinding are shown in Table 1, and ELID ground Radial type GRIN lens and prism are shown in Figure 5.

Figure 6 shows the results of surface characteristics using NewView [zygo]. In case of paraboloidal form (No.1), the P-V (Peak to Value) of 1.8 µm, surface roughness (Ra) of 0.28 µm at the center of GRIN lens, and the P-V of 0.36 µm, Ra of 0.08 µm at the edge of GRIN lens was obtained. Figure 7 shows the results of form accuracy using UA3P [Panasonic]. The P-V of 1.89 µm and surface roughness (rms) of 0.399 µm at the global of
GRIN lens was obtained. Figure 8 shows ELID ground paraboloidal form (No.2) and prism type GRIN lens. Figure 9 shows the results of surface characteristics using NewView [zygo] of prism type GRIN lens.

Simple spot evaluation was carried out on the GRIN lens ELID-ground using non-contact measurement device [NH3] as shown in Figure 10. In the future, spot evaluation using the knife-edge method shown in Figure 11 shall be carried out to evaluate the quantitative optical characteristics. The authors also have plans to construct optical characteristics evaluation systems such as aberration and feedback to the manufacturing process through VCAM (NCAM) or VCAD data.

![Figure 4: Desk-top type 4 axes machine with nozzle type ELID grinding method](image)

![Figure 5: ELID ground GRIN lens and prism](image)

![Figure 6: Surface characteristics of ELID ground paraboloidal form](image)
Figure 7  Form accuracy using UA3P

Figure 8  ELID ground paraboloidal form (No.2) and prism type GRIN lens

Figure 9  Surface properties of prism type GRIN lens using zygo NewView

Figure 10  Simple Spot Evaluation

Figure 11  Spot Evaluation Systems (Knife-Edge Method)
5. Development of optical path simulation software (V-OPT)

In this study, GRIN lens was taken up as a representative material with inhomogeneous medium. In the case of the development of optical parts fully applying VCAD data, the development of optical path simulation technology based on VCAD data is important. In particular, integration with fabrication technology of GRIN lens with aspherical shape or complicated shapes is expected to enable development of elements with totally new optical functions. For this reason, the authors have developed optical path simulation software (V-OPT) for predicting optical functions according to the material and shape of GRIN lens developed. Figure 12 shows an example of analysis results when parallel optical path is irradiated parallel to the optical axis for GRIN lens with plane surfaces on both sides. This optical path simulation process consists mainly of (1) reading of VCAD data, (2) setting of simulation analysis conditions, and (3) simulation analysis. In the future, these results will be applied to feedback to VCAD data and VCAM (NCAM) for optical shape design and tool path regeneration. Verification studies will also be carried out by comparing with the results of optical characteristics evaluation of actual manufacturing parts described earlier.

6. Conclusion

The authors are involved in the R&D of intellectual manufacturing process applying IT by making use of the characteristics of VCAD system which can express internal information of materials. This paper introduced measurement and optical path simulation in the development of optical parts taking GRIN optical material with irregular material properties as a model. Higher precision is aimed at in future studies for the practical application of the technology discussed.

7. Reference