Ultraprecision 5-Axis Control Machining of Fly-Eye Mirror in EUV Lithography*

Yoshinori HASHIMOTO**, Yoshimi TAKEUCHI***, Tomohiko KAWAI****, Kiyoshi SAWADA****, Hideo TAKINO† and Kazushi NOMURA†

The study deals with the manufacture of fly-eye mirrors for EUVL by means of ultraprecision 5-axis control milling. The mirrors consist of many small spherical mirror elements with many steps among them. In the present study, two new methods for manufacturing the mirrors using a single-crystal diamond tool are proposed. One method uses a sphere type tool with a circular arc cutting edge. Though the method is theoretically efficient, it is found that it is not practical due to the difficulty of manufacturing the tool accurately. The other one uses a cylinder type tool with a right-angled cutting edge. The tool enables the manufacturing of spherical surfaces with any radius and supports practical use because the efficiency of this method is independent of tool form accuracy. The fly-eye mirror was machined by the latter method to have an array of four spherical mirror elements with the required steps and without any burrs.

Key Words: Ultraprecision Machining, 5-Axis Control Machining, Diamond Tool, Fly-Eye Mirror

1. Introduction

In the past few years, electric devices equipped with semiconductor chips, such as portable personal computers and cellular phones, have tended to have multiple functions although they are small in size. To further increase their functionality and minimize their size, semiconductor chips require an increase of their degree of integration. One method for achieving this requirement is to minimize the width of the line of the semiconductor circuits. Thus, in a reduction-projection exposure system used for the manufacture of semiconductor chips, a shorter wavelength of the exposure light is used to increase the exposure resolution. At the present time, an ArF laser wavelength of 193 nm allows the creation of lines of approximately 100 nm in width.

As the next-generation exposure system, an extreme ultraviolet lithography (EUVL) system has been proposed, in which an extreme ultraviolet light with a wavelength of approximately 13 nm is used as the exposure light[(1)–(3)]. It is anticipated that this system will create lines with a width of less than 50 nm, which will result in the high integration of the semiconductor chips and the reduction in their size. However, at the present time, no EUVL system has yet been realized worldwide, and research is under way to resolve many important technical issues.

One of the important tasks in the realization of the EUVL system is the improvement of its optical system. To achieve an EUVL system with superior optical characteristics, in recent years a new illumination system has been proposed, in which novel optics, fly-eye mirrors, are installed[(3)]. The fly-eye mirrors have a complex reflective surface. Moreover, the fly-eye mirrors require surfaces with high shape accuracy and smoothness because they must reflect a short wavelength of approximately 13 nm. For these reasons, the fly-eye mirrors are difficult to manufacture[(4)].

In the present study, as the first step in realizing the fly-eye mirrors, we discuss the machining of the shape of their reflective surfaces by means of ultraprecision 5-axis control milling. Furthermore, we propose a new tool and

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** Department of Mechanical and Control Engineering, University of Electro-Communications, 1–5–1 Chofugaoka, Chofu, Tokyo 182–8585, Japan

*** Department of Computer-Controlled Mechanical Systems, Osaka University, 2–1 Yamadaoka, Suita, Osaka 560–0871, Japan. E-mail: takeuchi@mech.eng.osaka-u.ac.jp

**** FANUC Ltd., Oshino, Yamanashi 401–0597, Japan

† Nikon Corp., 1–10–1 Asamizodai, Sagamihara, Kanagawa 228–0828, Japan

a feeding method of the tool for the milling, and demonstrate their effectiveness in manufacturing the mirrors.

2. Fly-Eye Mirrors

Figure 1 shows an optical system for an EUVL system proposed by Komatsuda[3]. In this optical system, diverging EUV rays from the light source are converted to a bundle of parallel rays by the collector mirror group. This bundle of rays is reflected at the fly-eye mirror group and the condenser mirror group. Thus, the mask can be illuminated uniformly. Then, the rays reflected by the mask expose a wafer through a projection camera. The fly-eye mirrors are essential optics for achieving uniform illumination on the mask.

The fly-eye mirror group is composed of two types of fly-eye mirror, as shown in Fig. 2; both fly-eye mirrors consist of many mirror elements. Although the fly-eye mirrors in Fig. 2 are constructed using nine mirror elements, the actual fly-eye mirrors used in the EUVL system are designed so as to have approximately 500 mirror elements. Since the arc-shaped fly-eye mirror has a more complex shape than the rectangular one, it appears to be difficult to machine, and it particularly attracts interest from the viewpoint of manufacturing engineering. Thus, in the present study, we focus on the arc-shaped fly-eye mirror, and discuss the machining of it.

Figure 3 shows a schematic of the mirror element, which has an arc-shaped contour with a width of 1 mm, a radius of 15 mm, and a length of 15 mm. One design of the mirror element has a reflective surface with a radius of 660 mm, in which the reflective surface requires a slope accuracy of less than 120 arc-sec and a root-mean-square (rms) roughness of less than 0.3 nm.

The fly-eye mirror is constructed such that four types of the mirror elements are arranged in order. The reflective surface of each mirror element is a part of a sphere, which is shifted from the center of the sphere as shown in Fig. 4. The four types of the mirror elements differ in terms of their shift values as shown in Fig. 4, with the result that the directions of the reflective surfaces of the four types are different. Thus, when the radius of the sphere is 660 mm, the boundaries of the mirror elements have steps of a maximum value of approximately 100 μm. These steps are the cause of the difficulty of the fabrication of the fly-eye mir-

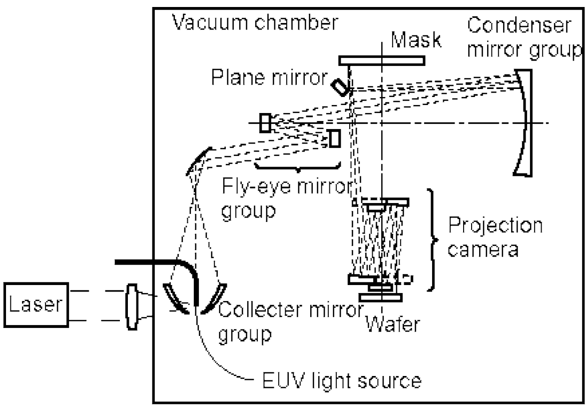
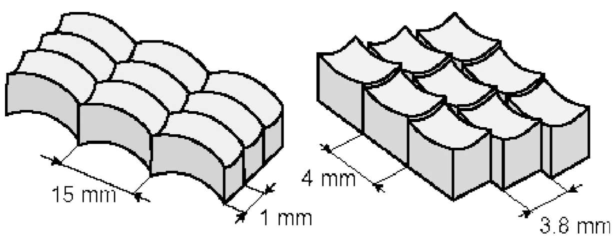


Fig. 1 Optical system of extreme ultraviolet lithography (EUVL) system



(a) Arc-shaped fly-eye mirror (b) Rectangular fly-eye mirror

Fig. 2 Fly-eye mirror group

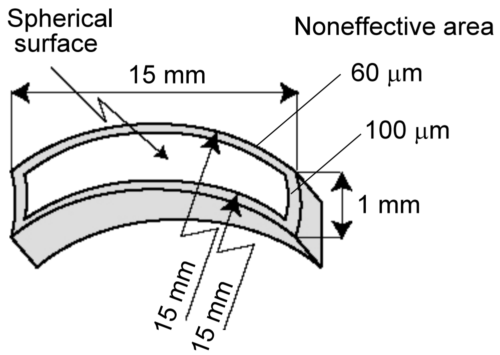
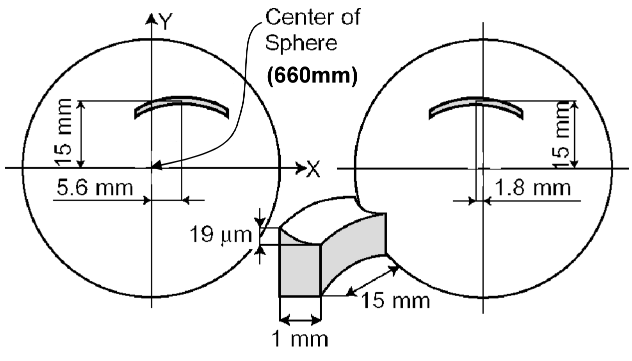


Fig. 3 Configuration of an arc-shaped mirror element



(a) First element (b) Second element

(c) Third element (d) Fourth element

Fig. 4 Four kinds of arc-shaped mirror elements

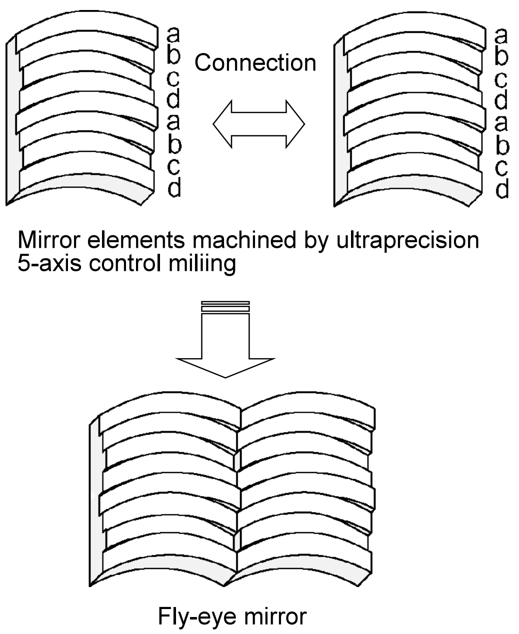
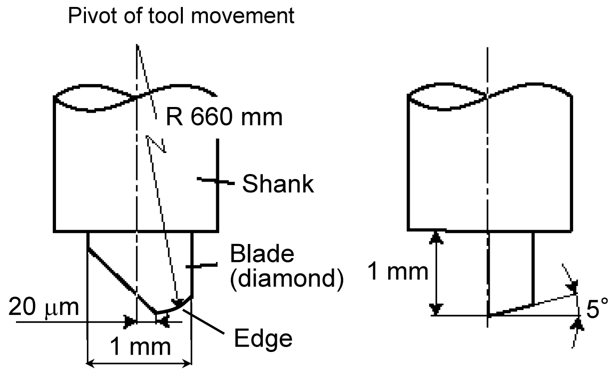


Fig. 5 Manufacturing of a fly-eye mirror



(a) Front view (b) Side view

Fig. 6 Configuration of a sphere type tool

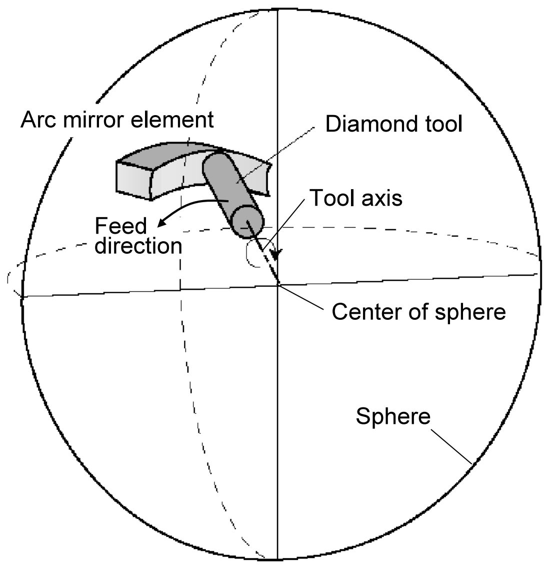


Fig. 7 Method for feeding a sphere type tool for machining an arc mirror element

ror by conventional milling.

As shown in Fig. 5, we plan to manufacture the fly-eye mirror such that the mirror elements are machined in line on a surface of a blank, and then are connected to each other side by side to assemble the fly-eye mirror. Therefore, in order to confirm the feasibility of our plan, in the present study, as a preliminary experiment, we performed machining experiments on the four types of mirror elements which are in line on a blank, and then evaluated the machined surfaces.

3. Machining Using a Sphere Type Tool

3.1 Principle of machining

To efficiently machine the complex shape of the fly-eye mirror surfaces with high accuracy by ultraprecision 5-axis control milling, we discuss a tool and its operation. First of all, we performed fabrication experiments using the tool shown in Fig. 6; the tool is referred to as a sphere type tool. This tool has a blade made of diamond. The edge of the blade is an arc shape, the center of which is on the pivot of the tool movement. The tool is used by rotating it during machining so that the tool acts as an end-mill. In this experiment, a desired reflective surface of the mirror element has a width of 1 mm and a radius of 660 mm. To machine such reflective surfaces, we use a tool with a diameter of 1 mm which is the same as the width of the mirror element. The radius of the edge of the blade is 660 mm, which is the same as that of the reflective surface. In this tool configuration, the tool rotation causes its edge to describe a sphere with a radius of 660 mm and a diameter of 1 mm.

The sphere type tool is operated as follows. During the process, the tool is moved by 5-axis motion control so that its pivot is always at the center of the sphere of the reflective surface to be machined as shown in Fig. 7, and the sphere described by the edge of the blade remains in contact with the spherical reflective surface. Moreover, the tool is fed along the arc of the contour of the reflective surface. This movement of the tool allows the machining of the spherical surface having the contour of an arc. In this method, the tool cuts in to the workpiece so that the axis of the tool is perpendicular to the reflective surface, as shown in Fig. 8. Moreover, the surface is machined without a pick feeding motion of the tool because the diameter of the tool is equal to the width of the reflective surface. This results in surfaces which are smooth with no cusps, and a shortened process time.

3.2 Checking of interferences

We analyzed the interference by the tool and the mirror elements that are the neighbors of the targeted mirror element by means of a three-dimensional computer-aided design (3D-CAD) system. The result of the anal-

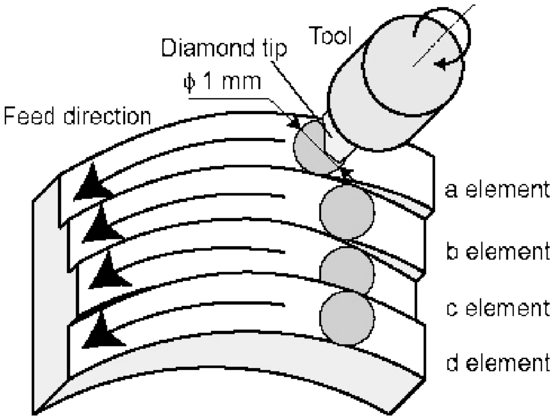


Fig. 8 Machining method for a fly-eye mirror using a sphere type tool

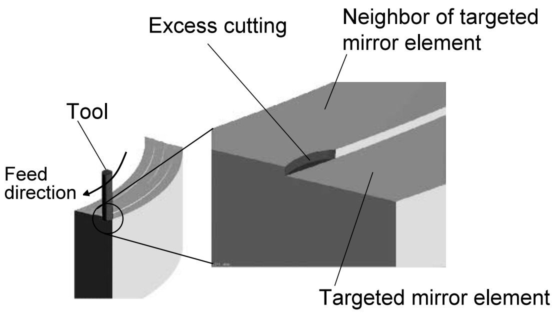


Fig. 9 Interference check using 3D-CAD

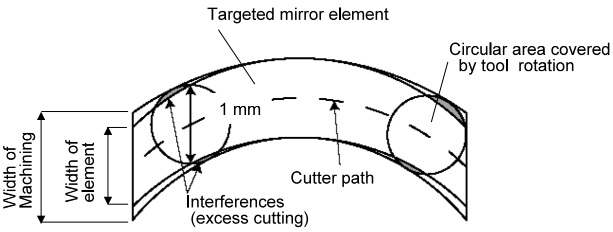


Fig. 10 Schematic of 3D-CAD result. The top view of the targeted mirror element is shown.

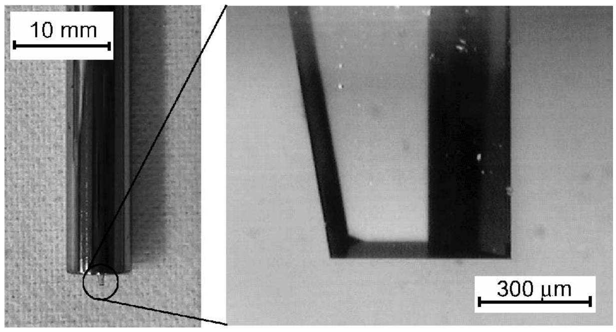
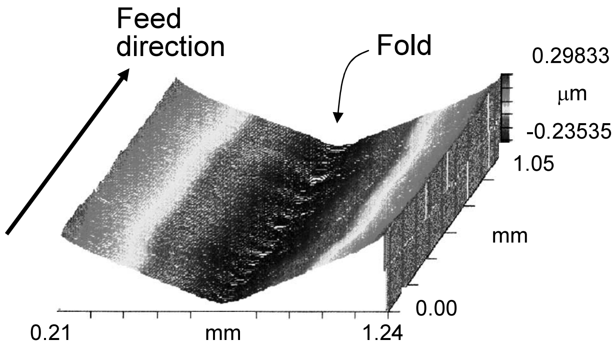
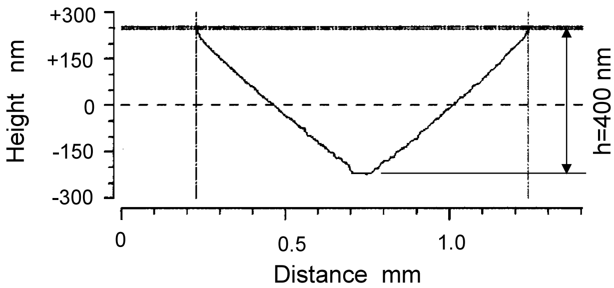


Fig. 11 View of a sphere type diamond tool



(a) Bird's-eye view



(b) Cross section

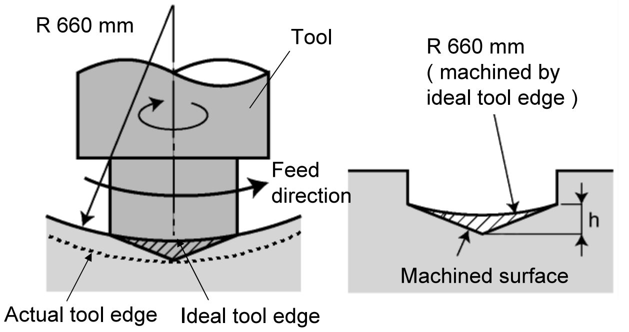
Fig. 12 Profiles of surface machined by a sphere type tool

ysis is shown in Fig. 9, proving that the neighbor mirror is slightly cut in while the targeted mirror element is machined. Figure 10 shows the schematic of the top view of the analysis, revealing that the neighbor mirror is cut in excessively because the tool removes a circular area with a diameter of 1 mm. However, we confirmed that this excessive cut value is within the permissible range of error for the specifications of the mirror element.

3.3 Machining experiments

We performed machining experiments on the fly-eye mirror having four types of mirror elements, using a sphere type tool. Figure 11 shows a photograph of the sphere type tool used. The tool was installed with an ultraprecision milling machine, ROBOnano Ui of FANUC LTD.[5],[6] This milling machine permits the 5-axis motion control of the tool with the resolutions of the translation and rotational axes of 1 nm and 0.000 01 degree, respectively. For the material of the fly-eye mirror, various materials, such as glass, silicon, and metal can be used because the machined surfaces of any material can have a multicoating applied to obtain a high reflectivity of EUV light for actual usage. Therefore, we used brass as a mirror material because brass is easily cut. Consequently, the reflective surfaces of the fly-eye mirror, however, cannot be accurately machined. To clarify the reasons for this disappointing result, the basic machining characteristics of the sphere type tool were experimentally investigated as follows.

In this experiment, flat plates were used as workpieces. The tool cuts in the direction perpendicular to the flat plate, and then was fed parallel to the plate in one direction. Figure 12 shows the resultant profile. Since the tool used in this machining has a spherical edge with a radius of 660 mm, the removal profile should be cylindrical. However, the resultant profile is not cylindrical, as it



(a) Front view (b) Side view (Cross section)

Fig. 13 Surface machined by the tool with a tilted tip

has a fold at the center of the profile as shown in Fig. 11. The depth of the center of the removal profile is 400 nm, which is larger than that calculated based on the radius of 660 mm of the tool tip. The reason why the surface was not machined to a cylindrical profile is interpreted as follows. The tool was fabricated such that the tip was polished to a desired profile, and this in turn was soldered to a tool shank. Therefore, it is considered that the tip is difficult to accurately solder to the shank, since it tends to be tilted against the shank. This causes the shape error on the mirror surface as shown by hatching in Fig. 13.

The method for machining a spherical reflective surface described in this section requires a tool the edge of which draws a perfect sphere by rotation. However, we found that this method is difficult to apply in practice because of the difficulty of fabricating such a tool, although it is theoretically useful for machining the reflective surfaces of the fly-eye mirror.

4. Machining by a Cylinder Type Tool

4.1 Principle of machining

The method described in the section 3 has a problem of the manufacturing of the tool. To realize the fly-eye mirror with high shape accuracy, a method in which the tool configuration does not affect the shape accuracy of the machined surface is required. Thus, in this section, we propose a new method.

The new method uses a tool shown in Fig. 14 which is referred to as a cylinder type tool. This tool has a blade made of diamond. The angle of the edge of the blade is 90° or less. The tool is applied by rotating during machining so that it acts as an end-mill. This rotation causes the edge of the tool to describe a circle with a diameter of 1 mm. The diameter described by the tool is the same as the width of the mirror element. Since the tool edge has an angle of 90° or less, the removal is effected only by the tool edge.

Figure 15 shows a schematic of the feeding of the cylinder type tool for machining the mirror element. In this method, the tool is moved by 5-axis motion control so that the pivot of the tool is on the center of the sphere

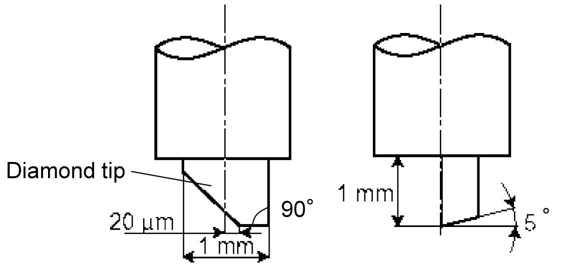


Fig. 14 Configuration of a cylinder type diamond tool

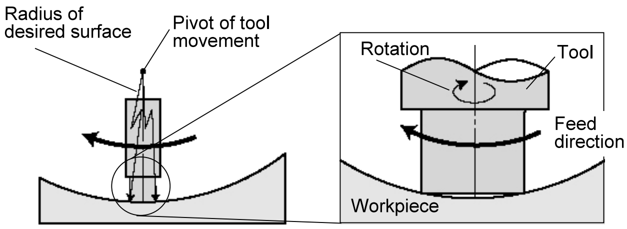


Fig. 15 Method for feeding a cylinder type tool for machining a mirror element

of the reflective surface to be machined. By feeding the tool along the arc, the spherical reflective surface with the contour of an arc-shape is machined.

Here, we show how this tool machines the desired radius of the reflective surface. It can be understood easily that the cross section of the surface machined by this method is a circle in the feed direction because the tool is fed by fixing its pivot at the center of the sphere as indicated by an arrow in Fig. 15. Next, we show in detail that the cross section of the surface is also a circle in the direction perpendicular to the feed direction. As shown in Fig. 16 (a), once the tool starts cutting on the line of X – X, that is an imaginary line perpendicular to the feed direction on the surface, the point indicated by the position of the dot is machined by a tool edge. The tool edge is located at a position at a distance where the pivot of the tool is equal to the desired radius of the sphere. Then, by feeding the tool as shown in Fig. 16 (b) – (d), the points indicated by the positions of the dots are continually machined by the tool edge. In this manner, since all points on the line X – X are machined to a constant distance from the pivot of the tool, the mirror has a spherical surface in the direction perpendicular to the feed direction.

In addition, the 3D-CAD analysis shows that the neighbor mirror is cut in excessively by machining the targeted mirror, but the amount of the excess is within the permissible range of error of the specifications.

4.2 Machining experiments

To demonstrate the effectiveness of the cylinder type tool proposed, the fly-eye mirror having four elements was machined. The desired radius of their reflective surfaces to be machined was 295 mm. Brass was used as the material of workpieces. The same milling machine as described in section 3 was used. The cutting conditions are summa-

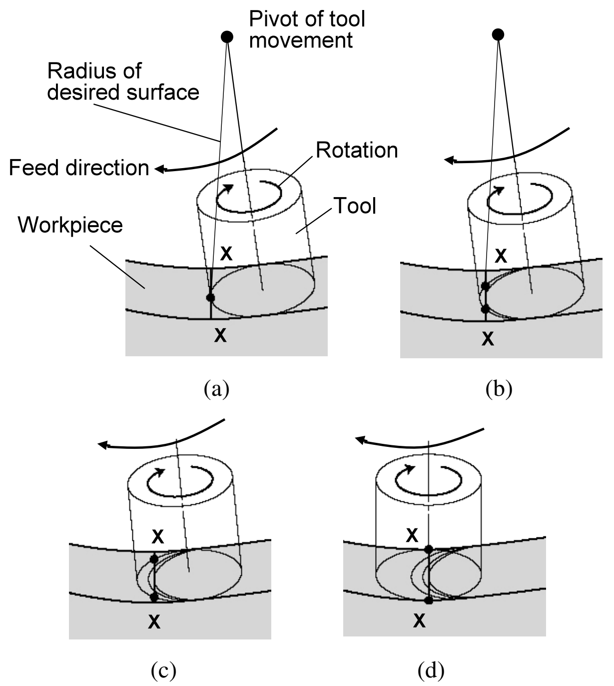


Fig. 16 Principle of sphere surface creation by a cylinder type tool

Table 1 Cutting conditions

Spindle rotation (min^{-1})	40000
Depth of cut (μm)	Rough : 50 , Finish : 1
Feed rate (mm/min)	1
Workpiece	Brass

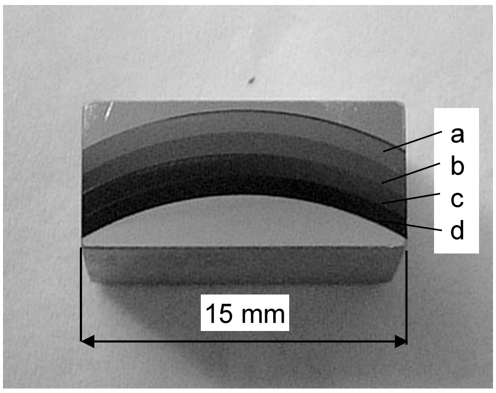


Fig. 17 Photograph of the machined fly-eye mirror with four mirror elements

rized in Table 1.

Figure 17 shows a photograph of the machined fly-eye mirror, revealing that the four mirror elements have been successfully machined. The machined surfaces were measured with an interferometoric surface profiler. The measurement results show that the surfaces are machined with radii of 290 mm and 277 mm in the feed direction and in the direction perpendicular to the feed direction, respectively. This proves that the reflective surface with

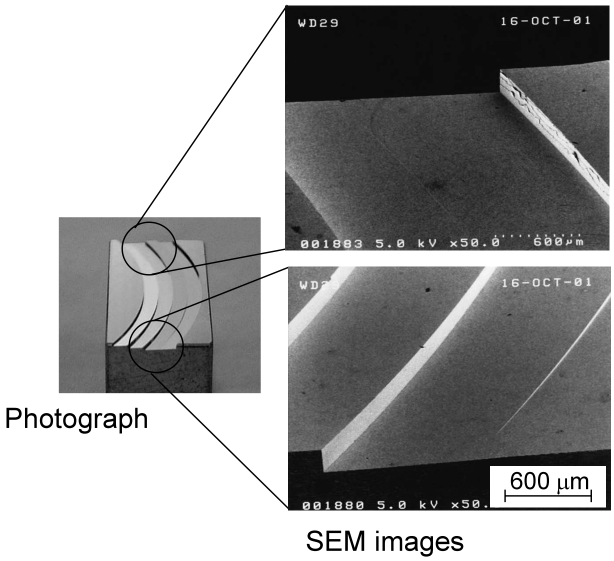


Fig. 18 Enlarged view of steps among the mirror elements

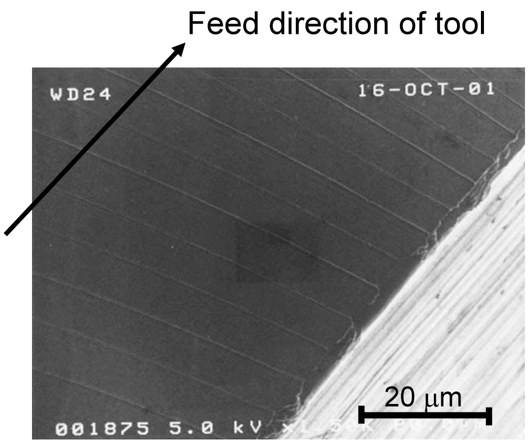


Fig. 19 SEM image of the machined mirror surface

the desired radius was almost achieved.

Figure 18 shows SEM images of the machined surface. It is clear that the edges and corners of the mirror elements are machined sharply. Next, as shown in Fig. 19, we observed the surface by means of SEM with a higher magnification than that used for Fig. 18, revealing that unwanted periodic stripes are yielded on the surface. The measurement shows that the distance between the stripes is 10 μm. For this machining, numerical control data, whose intervals are 10 μm in the feed direction, were used for the tool motion. During machining the tool was moved along the path by connecting the numerical control data with straight lines. Therefore, it is possible that the stripes result from the numerical control data. This indicates that the stripes may be reduced by decreasing the distance between the data points and slightly trimming the edge of the tool to make it smooth.

Figure 20 shows the surface roughness measured by an interferometoric surface profiler. The rms surface roughness is 16 nm although the desired value is 0.3 nm.

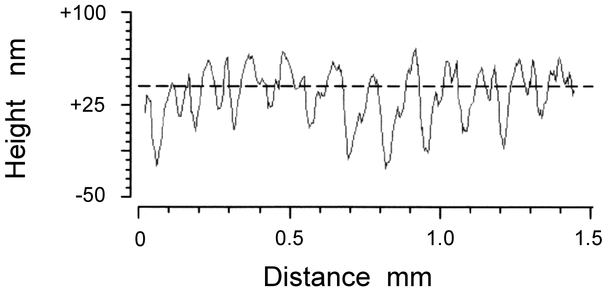


Fig. 20 Roughness profile of the machined surface of the mirror element

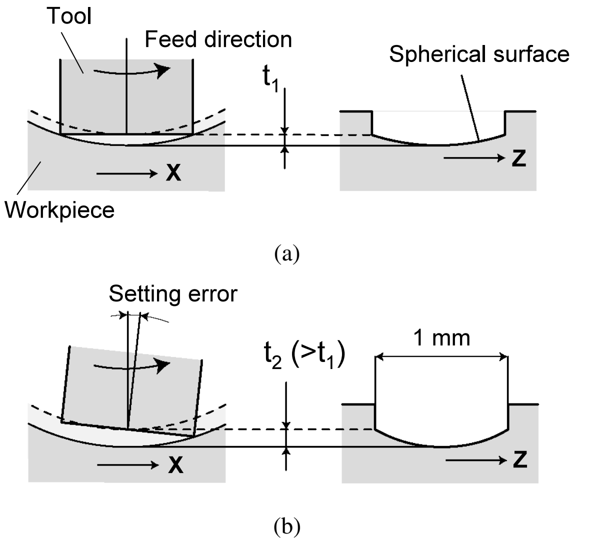


Fig. 21 Schematic of the tool and workpiece during machining process. Tool is set (a) without tilting error and (b) with tilting error.

Hence, the surface roughness must be improved in the future. A preliminary experiment performed before the present study shows that when the brass plate was machined to be flat using the cylinder type tool, the resulting rms surface roughness was approximately 1 nm. Therefore, it is expected that the surface roughness for the spherical reflective surface will be improved by optimizing the cutting conditions.

4.3 Discussion about the tilting of a tool

The cylinder type tool should be installed in the milling machine without tilting to obtain highly accurate surfaces. In this subsection, we discuss the effect of the tilting of the tool on the slope accuracy of machined surfaces. Figure 21 shows schematics of the cylinder type tool and workpiece during the machining process: Fig. 21 (a) and (b) show the tool set without tilting and with tilting, respectively. As shown in Fig. 21 (b), the machined depth t_2 by the tool with tilting is larger than that by the tool without tilting. Thus, the tilting of the tool produces the slope error of the reflective surface.

We calculated the slope errors produced by tilting the tool and the necessary setting accuracy of the tool for

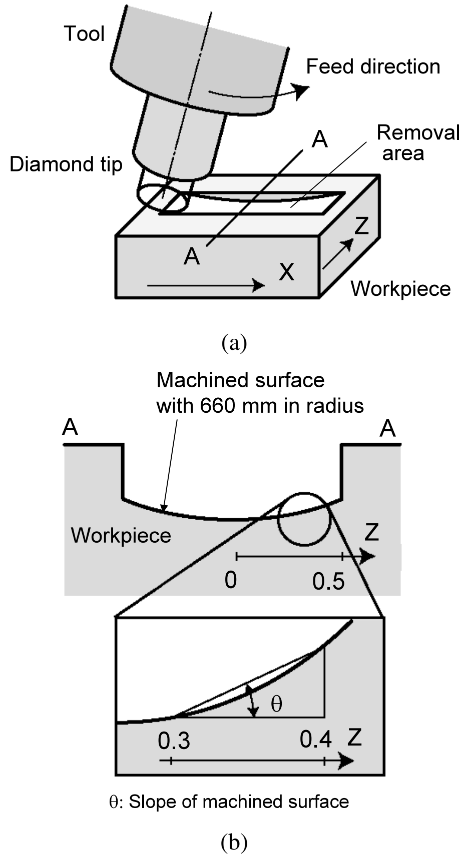


Fig. 22 Calculation of the slope errors produced by tilting the tool, (a) Model for calculation, (b) Cross-sectional view on A – A section

Table 2 Calculated surface errors

Position mm	0~0.1	0.1~0.2	0.2~0.3	0.3~0.4	0.4~0.5
Setting error of 2'	27"	1'24"	2'27"	3'49"	8'20"
Ideal surface	15"	46"	1'18"	1'49"	2'20"
Difference	12"	38"	1'09"	2'00"	6'00"

obtaining the desired slope accuracy, using a 3D-CAD system. The calculations were conducted, as shown in Fig. 22 (a), for the case that the rectangular area is removed by the cylinder type tool. Then, the slope errors were calculated at the interval of 0.1 mm as shown in Fig. 22 (b).

The calculation results prove that as the desired radius of the reflective surface to be machined increases, the slope error is increased by the effect of the tilting of the tool. Table 2 shows an example of the calculations, in which the calculation was conducted such that the desired radius of the surface is 660 mm and the tool is tilted in the feed direction by 2 minutes. As shown in Table 2, the slope error in the position from 0.4 mm to 0.5 mm is 6 minutes. This slope error exceeds the desired value of 2 minutes. The calculations indicate that the tool should be set within the tilting error of 40 seconds to obtain the surface having a radius of 660 mm with the desired slope accuracy.

5. Machining of Various Spherical Surfaces with a Cylinder Type Tool

The cylinder type tool theoretically allows the machining of the spherical surfaces with various radii without changing the configuration of the tool shape. In order to confirm this experimentally, we machined various spherical surfaces using the cylinder type tool. In this experiment, as shown in Fig. 23, the milling machine was operated such that surfaces having the contour of a rectangular area with desired radii of 100, 295, 660, and 1 300 mm were machined.

Figure 23 shows examples of the contour maps of machined surfaces measured by an interferometric surface profiler. The surfaces with an area of $1.0 \times 1.4\,\mu$m are shown. In Fig. 23 (a) and (b), the desired radii are 660 mm and 1 300 mm, respectively. In Fig. 23, since the contour lines are not circles, the machined surfaces are not spheres. This finding indicates that the tool tilted in this machining.

Next, we corrected the tilting of the tool based on the measurement results shown in Fig. 23. After the correction, the machining was performed again. Figure 24 shows the measurement results of the machining after the correction. Since the contour lines are circles in Fig. 24, it was clear that spherical surfaces were successfully machined following the correction.

Figure 25 shows the relationships between the desired radius and the machined radius, in which the machined radii before and after the corrections are shown. From this figure, it is found that as the desired radius increases, the difference between the desired radius and the machined radius increases, before the correction. This experimental result agrees with the result of the calculation described in

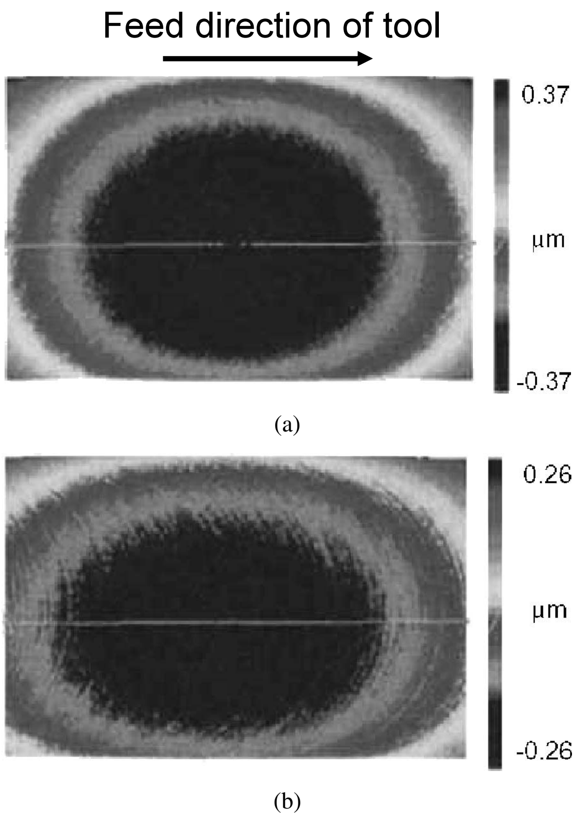


Fig. 23 Surface profiles before the correction of the tilting of the tool. Radii of the desired surface are (a) 660 mm and (b) 1 300 mm.

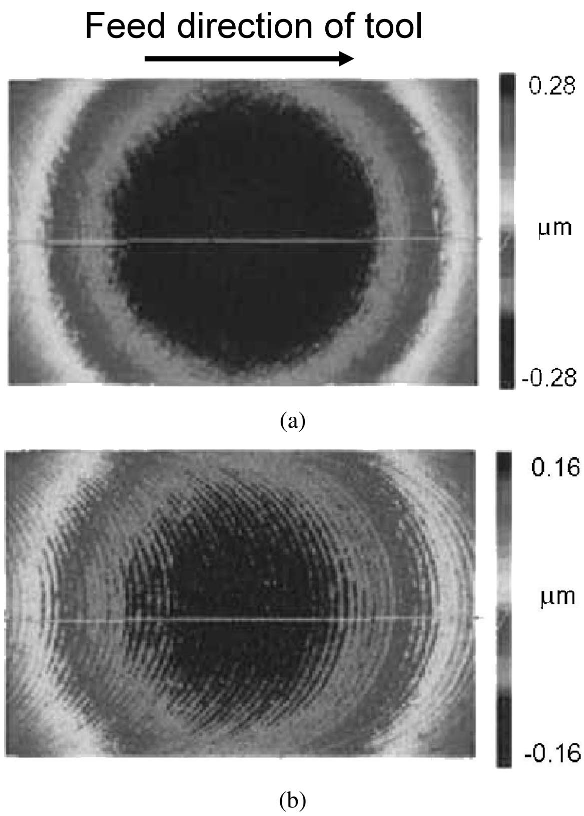


Fig. 24 Surface profiles after the correction of the tilting of the tool. Radii of the desired surface are (a) 660 mm and (b) 1 300 mm.

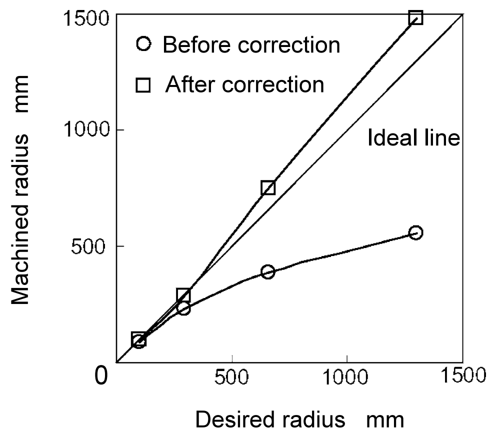


Fig. 25 Relationship between the desired radius and machined radius

subsection 4.3. The correction has the effect of bringing the machined radii close to the desired radii. As examples, for the desired radius of 660 mm, the machined radius is improved from 390 mm to 750 mm through the correction, and for the desired radius of 1 300 mm, the machined radius is improved from 557 mm to 1 481 mm. Thus, we can confirm the effectiveness of the correction of the tool tilting as well as the usefulness of the cylinder type tool for machining various radii.

6. Conclusions

We discussed the machining of a fly-eye mirror using a 5-axis ultraprecision milling machine. The fly-eye mirrors are essential optics for use in an EUVL system that is expected for next-generation lithography systems. Although two kinds of fly-eye mirrors are necessary for the EUVL system, in this paper we focused on one type of fly-eye mirror, the arc-shaped fly-eye mirror. The results of this study can be summarized as follows.

(1) Ultraprecision 5-axis control milling in which a single-crystal diamond tool as an end-mill is applied enables the machining of the complex reflective surface of a fly-eye mirror.

(2) A new cylinder type tool and a method for feeding it were proposed. Reflective surfaces of the fly-eye mirror with 295 mm radius are successfully manufactured by the tool, demonstrating the usefulness of the proposed tool and its feeding method. However, the roughness of the machined surfaces must be reduced for the application of the mirrors in an actual EUVL system.

(3) Spheres with various radii such as 660 mm and 1 300 mm, that have a rectangular contour, can be machined by the cylinder type tool. This indicates that the tool allows the manufacturing of a fly-eye mirror with reflective surfaces having various radii.

References

(1) Setoya, H., Semiconductor Industry and Precision Engineering, J. Jpn. Soc. Prec. Eng., (in Japanese), Vol.67, No.1 (2001), pp.34–37.
(2) Takino, H., Kobayashi, T., Yamamoto, T., Shibata, N., Gomei, Y. and Sugisaki, K., Subnanometer Fabrication of Optics by Plasma Chemical Vaporization Machining, Proc. of 10th ICPE, Yokohama, (2001), pp.67–71.
(3) Komatsuda, H., Novel Illumination System for EUVL, Proc. SPIE, Vol.3991 (2000), pp.765–776.
(4) Takino, H., Kobayashi, T., Shibata, N., Kuki, M. and Komatsuda, H., Fabrication of a Fly-Eye Mirror for an Extreme Ultraviolet Lithography Illumination System, Proc. SPIE, Vol.4343 (2001), pp.576–584.
(5) Sornsuwit, N., Miyagawa, O., Takeuchi, Y., Kawai, T., Sawada, K. and Sata, T., Manufacture of Aspherical Convex Fresnel Lens with Ideal Cross-Sectional Profile, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol.66, No.651 (2000), pp.3754–3759.
(6) Sawada, K. and Takeuchi, Y., Ultraprecision Machining Center and Micromachining, (in Japanese), (1998), NIKKAN KOGYO SHIMBUN, LTD.