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# GRINDING OF ASPHERICAL SiC MIRRORS

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## ABSTRACT

This paper describes the methods using bonded cup wheels for grinding toroidal and cylindrical SiC mirrors with large curvature radii. Since the angle between the cutting direction of bonded abrasives and feed direction of the cup wheel is about 90°, it is possible to obtain a surface with very low surface roughness independent of the direction of measurement.

Toroidal mirrors, circular and elliptic cylinder mirrors made of SiC were successfully obtained by automatic grinding operations with high shape accuracy and very low surface roughness. The time consumed in the processes is very short. The control method and the structure of the grinding system are simple.

## 1. INTRODUCTION

Some mirrors used in synchrotron radiation facilities made of advanced ceramics [1][2] are very difficult to machine and shape because of their extreme hardness and brittleness. They usually are of high precision in shape accuracy and in surface roughness. Traditionally, several complicated manufacturing processes are necessary to machine them. In the finishing process, loose abrasives are usually used and manual operations are carried out by trial and error while repeatedly performing shape inspections. Because the amount removed can be very large and the finish machining difficult to automate, the process time can be very long. The productivity is hence low and even the shape accuracy of the curved surface produced cannot be guaranteed. In particular, it is extremely difficult to automatically manufacture, by means of bonded abrasive wheels, toroidal SiC mirrors with large curvature radii, high shape accuracy and very low surface roughness.

This paper describes the methods using bonded cup wheels for grinding toroidal and cylindrical SiC mirrors with large curvature radii. Also, experimental results are reported. Since the angle between the cutting direction of bonded abrasives and feed direction of the cup wheel is about 90°, it is possible to obtain a surface with very low surface roughness independent of the direction of measurement.

Toroidal mirrors, circular and elliptic cylinder mirrors made of SiC were successfully obtained by automatic grinding operations with high shape accuracy and low surface roughness. The control method and the structure of the grinding system are simple. The surface roughness is very low as $R_{max}$ = 20 nm, $R_a$ = 2 nm. The time consumed in the processes is very short.

## 2. GRINDING METHOD

### 2.1 Toroidal and cylindrical mirrors

In this paper, grinding of toroidal mirrors, circular and elliptic cylinder mirrors is investigated. These mirror surfaces have two planes of symmetry.


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Toroidal SiC mirrors with large curvature radii are often used in synchrotron radiation facilities. Instead of toroidal mirrors, the combination of two circular or elliptic cylinder mirrors with large curvature radii is also used. Apparently, the manufacturing of toroidal mirrors is much more difficult than that of cylindrical mirrors.

The requirements for surface roughness and shape accuracy are extremely strict. In the finishing process, loose abrasives are usually used and manual operations are carried out by trial and error while repeatedly performing shape inspections. If the surface finish and shape accuracy are not good enough before the process, the finishing process time would be very long as the amount removed is large.

There is a great demand to automatically grind the SiC mirrors with high shape accuracy and very low surface roughness. If the mirrors with high shape accuracy and surface roughness of several nanometers can be obtained by means of automatic grinding operation, it may be good enough without polishing. Even if polishing operations are still needed after grinding for some special requirements that need surface roughness of several angstroms, the polishing time will be very short because the amount removed is very small.

Automatic grinding of toroidal mirrors was tried [3]. The principle of the method is to shape a toroid-shaped (barrel-shaped) grinding wheel and control the relative position of the workpiece and the grinding wheel in the grinding process. Two kinds of grinding operations are possible. One is the plunge grinding operation, in which there is no crossfeed. The other is the traverse grinding operation in which crossfeed is given in the direction of the workpiece's width. One of the features of plunge grinding is that grinding streak lines remain on the ground surface. In the case of the traverse grinding operation, to decrease the crossfeed marks, the time expended in the process becomes longer than that for the plunge grinding operation.

In the next two sections, some good grinding methods using bonded cup wheels are described. Theoretically, the methods are approximate methods. However, experiments proved that practically the profiles of the mirrors obtained by using the methods were very smooth and much more accurate as compared to the methods mentioned above. Also, the process time was very short. Most important was the fact that mirror surfaces with very low surface roughness independent of the direction of measurement could be obtained.

## 2.2 Grinding of cylindrical mirrors

The methods using a cup wheel for grinding the mirrors are schematically illustrated in Fig. 1. In Figs. 1(a) and (b), the principles are the same, although the methods of feeding and fixing the tool and workpiece are different.

A concave surface with a large curvature radius in the direction of the workpiece's width is generated by fixing the rotational axis of a cup wheel with an angle ß against the direction $z_c$ and feeding the cup wheel parallel to the direction $z_c$, as shown in Fig. 1(a). Also, the same surface can be obtained by fixing the rotational axis of the cup wheel perpendicular to the machine's table and moving the cup wheel along the direction $z_c$ shown in Fig. 1(b), where the angle between $z_c$ and the rotational axis of the wheel is ß. To grind a convex surface, allow only the inner part of the cup wheel to contact the workpiece, as shown in Fig. 1(c).

Thus, we can easily machine a circular or elliptic cylinder surface with extremely large curvature radius by using a rotating tool such as a cup wheel with a small curvature radius. Since the angle between the cutting direction of bonded abrasives and feed direction of the cup wheel is about 90°, it is possible to obtain a surface with very low surface roughness independent of the direction of measurement.

From the results of theoretical analysis, if the curvature radius required is very large, when ß is given by Eq. (1) or (2), the surface obtained by means of the methods can be practically regarded as part of a perfect circular or elliptic cylinder surface.

$$\beta = \cos^{-1} \frac{\sqrt{R^2 - (\frac{B}{2})^2} - R}{\sqrt{r^2 - (\frac{B}{2})^2} - r} \tag{1}$$

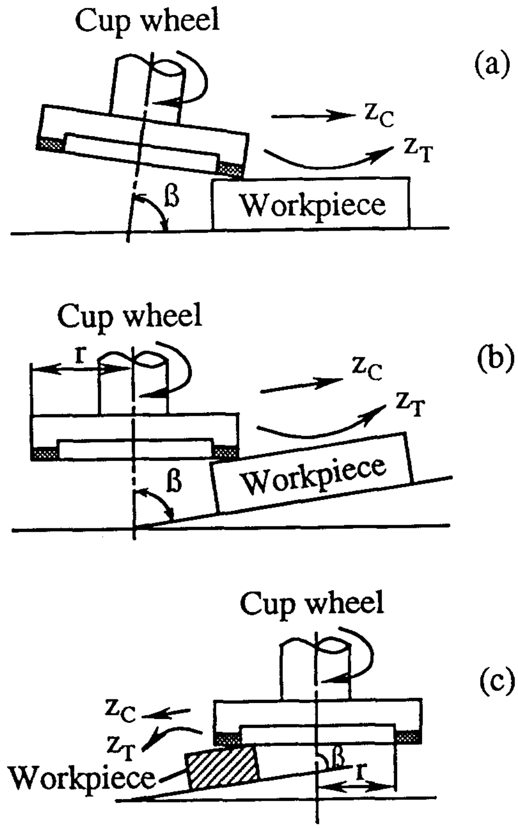


Fig. 1. Grinding methods using a cup wheel.

$$\beta = \cos^{-1} \frac{b\left(\sqrt{a^2 - (\frac{B}{2})^2} - a\right)}{a\left(\sqrt{r^2 - (\frac{B}{2})^2} - r\right)} \quad (2)$$

Here, r is the radius of outer or inner part of the grinding tool, and B the width of the mirror. The directrix of the circular cylinder is the circle $x^2+y^2=R^2$ while the directrix of the elliptic cylinder is the ellipse $x^2/a^2+y^2/b^2=1$.

### 2.3 Grinding of toroidal mirrors

A concave or convex surface with another curvature radius in the direction of the workpiece's length can be generated by fixing the rotational axis of the cup wheel with an angle ß against the direction $z_C$, and changing the relative position of the wheel and workpiece while feeding the cup wheel as indicated by the trajectory notation $z_T$ in Fig. 1. That is, a toroidal surface can be generated by using a cup wheel. However, if the angle ß is fixed as a constant, the curvature radius in the direction of the ground mirror's width will change depending on the measurement position, and the errors generated will be large.

A toroidal mirror with high shape accuracy can be obtained by changing the angle ß precisely while feeding the cup wheel so that the machining error is minimum. In other words, as shown in Fig. 2, the generated curved surface F is a function of x, y, z, r, $R_1$, ß as

$$F(x, y, z, r, R_1, \beta) = 0 . \quad (3)$$

The generating error E compared with the target toroidal surface is given by

$$E = f(x, y, z, r, R_1, R_2, \beta) \tag{4}$$

where $R_1$ and $R_2$ are the radii in the directions of the length and width of the mirror respectively. It is possible to minimize $e$ to a very small value by controlling z and ß in the grinding process, where $e = \max\{E \mid -L/2 \le x \le L/2, -B/2 \le y \le B/2\}$ and L is the length of the mirror.

## 3. EXPERIMENTAL EQUIPMENT AND CONDITIONS

Many types of machines can be used to grind a cylindrical mirror using the methods shown in Fig. 1. For instance, a machine with a linear movement facility and an inclinable spindle can do the work shown in Fig. 1(a). Also, it is possible to use the line compensation function of a numerically controlled machine to realize the method shown in Fig. 1(b). To grind a toroidal mirror with large curvature radii and high shape accuracy, a CNC machine with high-resolution servomechanisms is needed. This machine must have the capacity to change the angle ß precisely in the grinding process. There are such good machines for ultra-precision machining available in the market. However, these machines are usually expensive.

The experiments reported in this paper were carried out by the use of an inexpensive machining center. The machine was not specially made for the purpose of ultra-precision grinding. A micro-displacement table developed by the authors [4] was attached to the machining center to grind toroidal mirrors.

The scheme of the grinding system is shown by Fig. 3 and its specifications are shown in Table 1.

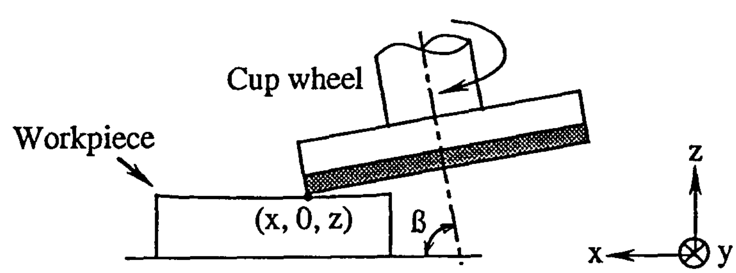


Fig. 2. Grinding method of toroidal mirror.

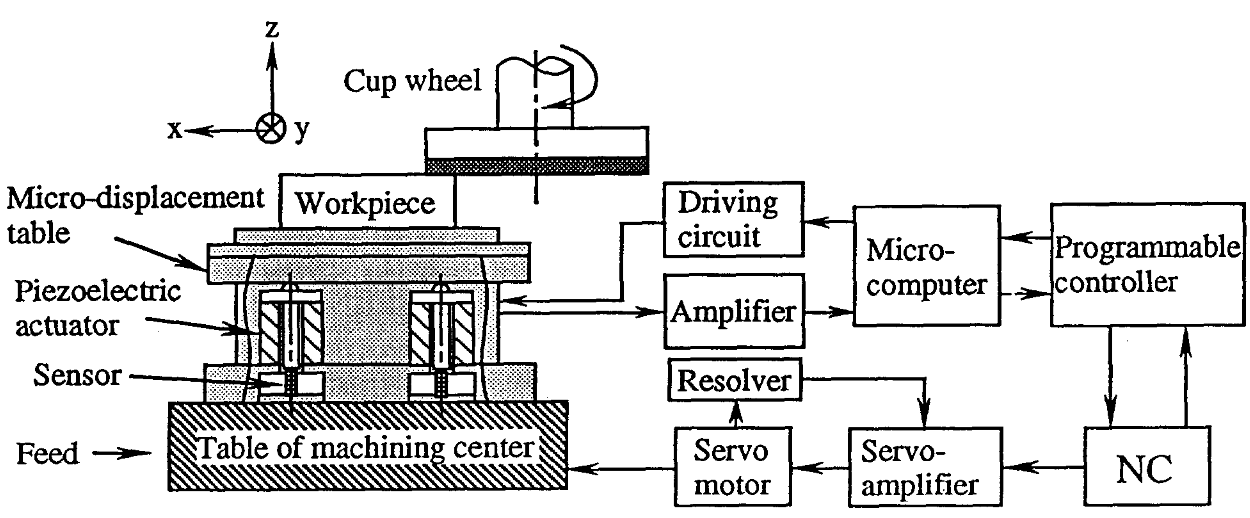


Fig. 3. Grinding system.

Table 1. Specifications of grinding system

| | |
|---|---|
| Grinding machine | Machining center: VQC-15/40 (YAMAZAKI MAZAK) |
| Grinding wheel | Cast iron fiber bonded diamond wheel<br>Diameter: 150mm, Width: 10mm,<br>Mesh number: #8000 |
| Mirror material | SiC |
| Microcomputer | PC-9801NS (80386SX, 12MHz) |
| Amplifier | PC-1001 (Photonics) |
| Driving circuit | Originally developed, Three channels |
| Micro-Displacement table | Originally developed.<br>Actuators: Three stacked piezoelectric ceramic actuators (NEC)<br>Rated Displacement: 16μm/150V<br>Sensors: Three non-contract capacitive displacement transducers (Photonics)<br>Range: 50μm Resolution: 50nm |

### 3.1 Micro-displacement table

A micro-displacement table was developed using three stacked piezoelectric ceramic actuators. Since piezoelectric actuators are very weak against shear force and humidity, the table was designed so that it has enough stiffness against not only compressive force but also transverse force, and is waterproof. The table is easily attachable to machine tools horizontally or vertically by means of a simple attachment.

The micro-displacement table must withstand severe conditions in the grinding process. Even the grinding force changes substantially in the grinding process, the output of the system must always track the reference input. Consequently, it is necessary to perform a feedback control dynamically and precisely, detecting the output of the system in the machining process.

Three noncontact capacitive displacement transducers are used as sensors. The three stacked piezoelectric ceramic actuators are controlled independently by three dynamical compensators designed based on the $H_\infty$ control theory that is prominent in robust control. The displacement signals detected by noncontact capacitive displacement transducers are input to the CPU of a microcomputer through an A/D converter. The dynamic compensators were realized as soft servos by assembly and C programs. The controlling inputs are output to the driving circuit through a D/A converter. The controlled output of the system is shown on the display so that it can be monitored in the machining process. The ground surface can be held horizontally and inclined with a very slight angle in the designated direction, by controlling each of the piezoelectric actuators independently. The system has a positioning accuracy equal to the resolution of the sensors used.

### 3.2 Grinding machine

A vertical machining center (Yamazaki Mazak VQC-15/40, controlled axes : 3 axes, least input increment : 1 μm) was used as a grinding machine. When a toroidal mirror was ground, the micro-displacement table was attached to the machining center, and the workpiece was fixed on the micro-displacement table. When a circular or elliptic cylinder mirror was machined, the workpiece was directly fixed on the table of the machining center. The inclined feed was given by using the line compensation function of the machining center.

### 3.3 Bonded grinding wheel

Cast-iron fiber-bonded diamond wheels whose mesh number is #8000 were used as finish grinding wheels. For rough grinding, #325 and #1200 cast-iron fiber-bonded diamond wheels were used.

3.4 Dressing and grinding conditions

A silicon carbide wheel mounted on a brake-controlled truing device was used for truing and dressing of grinding wheels. The truing and dressing conditions were peripheral velocity of grinding wheel = 140 m/min, crossfeed velocity = 100 mm/min, and depth increment after each traverse = 1 μm. The finish grinding conditions were peripheral velocity of grinding wheel = 1200 m/min, table speed = 100 mm/min, and depth of cut = 1 μm.

## 4. EXPERIMENTAL RESULTS

Toroidal mirrors, circular and elliptic cylinder mirrors made of SiC were successfully obtained with high shape accuracy and low surface roughness, by using bonded abrasive wheels. The time consumed in the processes is very short.

4.1 Surface roughness of ground mirrors

Figure 4 shows an example of surface roughness of the ground mirrors. The surface roughness is $R_{max}$ = 20 nm, $R_a$ = 2 nm. The roughness is not dependent on the direction of measurement.

4.2 Results of profile and shape inspections

Figure 5 shows two profiles of a ground toroidal mirror with curvature radii of 40 m and 10 m in the directions of the length and width of the mirror. Figure 6 shows the measured shape of the mirror. The dimensions of the mirror made of SiC, were 61X31X20 mm.

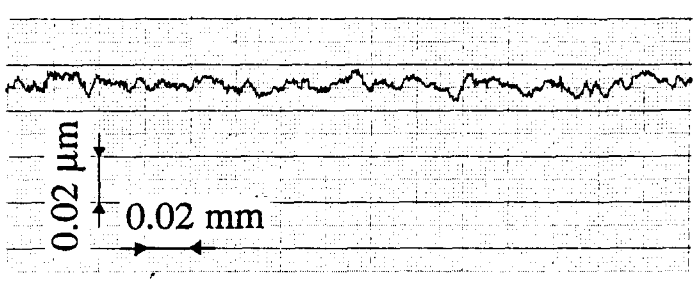


Fig. 4. Surface roughness.

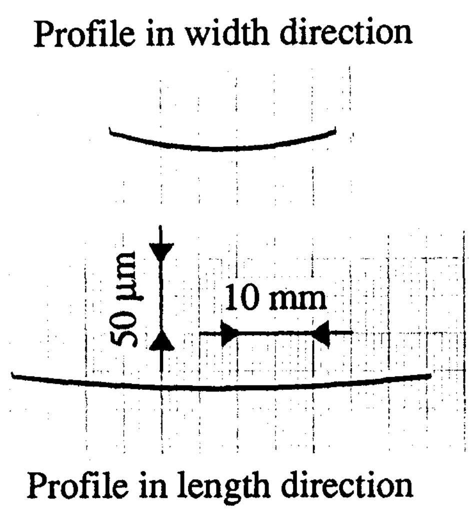


Fig. 5. Profiles of ground toroidal mirror.

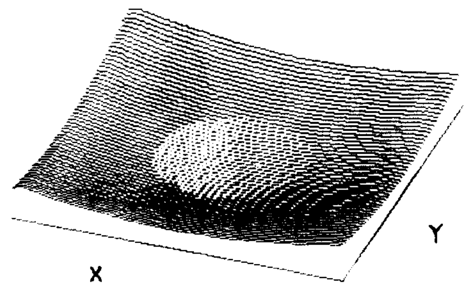


Fig. 6. Shape of ground toroidal mirror.

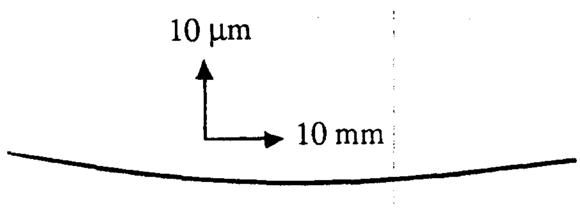


Fig. 7. Profile of ground elliptic cylinder concave mirror.

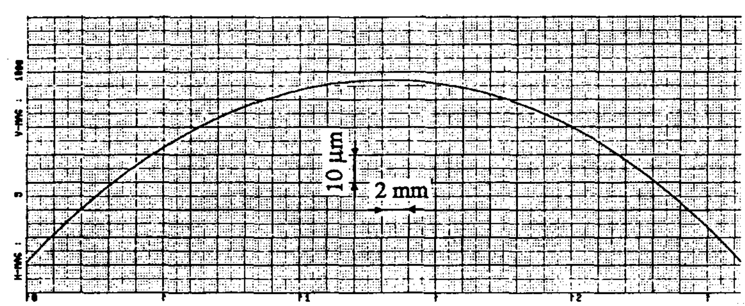


Fig. 8. Profile of ground circular cylinder convex mirror.

Figure 7 shows an example of the profiles of ground elliptic cylinder concave mirrors with a = 150 m, b = 100 m and B = 80 mm. The dimensions of the mirrors, which were made of SiC, were 180X80X20 mm.

Circular cylinder convex mirrors with R = 5 m and B = 55 mm, were also ground. The dimensions of the mirrors made of SiC, were 55X15X15 mm. An example of the profiles of machined circular cylinder convex mirrors is shown in Fig. 8.

As shown by Figs. 6 ~ 8, very smooth convex or concave mirror surfaces were obtained by automatic grinding operations.

## 5. CONCLUSIONS

Grinding methods for SiC mirrors with large curvature radii were proposed, and grinding experiments were carried out. Toroidal mirrors, elliptic and circular cylinder mirrors made of SiC with large curvature radii were precisely and automatically obtained with high shape accuracy and low surface roughness by using bonded abrasive wheels.

Traditionally, grinding streak lines or cross-feed marks remained on the ground surface, and surface roughness depended on the grinding direction. These problems have been solved so that perfect mirror surfaces can be obtained by using the methods of this paper. The roughness is not dependent on the direction of measurement.

The time consumed in the manufacturing processes is greatly shortened. The machine used for the experiments was inexpensive and was not specially designed for the purpose of ultra-precision grinding.

## 6. ACKNOWLEDGMENTS

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