Tool path generation for grinding a Φ1.45 m off-axis aspherical SiC mirror blank

Zhiyu Zhang (张志宇)

Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, Changchun 130033, China

Corresponding author: zhangzhiyu@ciomp.ac.cn

Received January 8, 2014; accepted March 15, 2014; posted online October 7, 2014

Off-axis aspherical mirrors are growing in popularity in modern space-borne cameras having high resolution and large field of view. Fabrication processes for these mirrors include surface generation by grinding wheel, free-abrasive lapping, and various polishing cycles. Surface generation by grinding wheel is the most efficient process among the whole fabrication processes. Therefore, technologies for accurately and cost efficiently generating the mirror blanks are highly indispensable. We propose, a single-point grinding mode and a four-step tool path generation technology to resolve the over travel problem, for directly machining the off-axis aspherical mirror blank. Technologies for surface geometrical modeling and wheel wear reduction/compensation are established. Using a commercial-available HASS-VF8 machining center, a silicon carbide mirror blank having a 1.45 m aperture is successfully generated. Result indicates that the main error source affecting the obtained grinding accuracy is wheel wear amount, other than the positioning accuracy of machining center. Therefore, error-compensation grinding is indispensable. We provide an alternative economical resolution to efficiently fabricate the large-scale off-axis aspherical surface.

OCIS codes: 220.1920, 220.4610.

doi: 10.3788/COL201412.S22204.

It has been long suggested that silicon carbide (SiC) would be a great ceramic material to apply for the large mirrors of telescopes, particularly the space-borne cameras, because of its several properties that are important for high-performance mirror substrates, such as high stiffness-to-density ratio and low thermal distortion properties[1]. Conventional methods for manufacturing SiC ceramic include pressureless sintering, gas pressure sintering, hot pressing, and reaction-bonding (RB) technology. By several decades' effort, we have successfully developed the reaction-bonded capability for forming space mirror blank up to 4 m scale[2]. Our mirror blank is fabricated by infiltrating silicon (Si) melt into a green compact consisting of carbon (C) and SiC powders. The liquid Si reacts with C particles, forming new SiC particles. In this way, a very dense SiC body is produced without generating micropores. However, the infiltrated Si melt cannot react with C completely, thus the excessive Si remains in the body as a bonding material[3].

On the other hand, RB-SiC is a typical difficult-to-machine material. The current state of the art for machining RB-SiC mirror blank is usually composed of the following steps. Firstly, the surface of the mirror blank is generated using a diamond grinding wheel. Secondly, the shape deviation between the ground surface and the designed off-axis aspherical surface is reduced by a great deal of lapping and polishing cycles. Thirdly, the surface is coated with a layer of several micrometers of amorphous Si. Subsequently, the Si layer is processed to the final accuracy, which is always less than 12 nm in root mean square (RMS).

Machining of large-scale mirror blank is a time-consuming task and therefore improvement of machining efficiency is a research focus. The efficiency and production cycle of the whole manufacturing process will be greatly affected by wheel grinding performance, because diamond wheel grinding is high-efficiency process and its material removal rate is about 20–50 times that of subsequent diamond lapping process. Therefore, effective technology with good productivity and accuracy is of great importance. Martin *et al.* in Arizona University reported diamond milling method to machine the surface to an accuracy of about 10 μm[4]. But the diamond milling cannot be used to cut SiC. Comley *et al.* in Cranfield University developed a three-axis ultra-precision grinding machine having very high dynamic loop stiffness called BoX®[5]. By employing the R-θ grinding mode and toric-shaped resin-bonded diamond cup wheels, a 1.4 m glass mirror blank could be ground to a surface accuracy of about 1 μm in RMS[6]. However, the cost of such ultra-precision grinding machine is extremely high. More importantly, BoX® is unable to fabricate strongly curved off-axis aspherical surface which are most frequently used in space-borne cameras.

The prime objective of this report is to develop an economical surface grinding technology, by which the large off-axis aspherical RB-SiC mirror blank could be rapidly and accurately machined using a common commercially -available machining center. The over travel problem of C-axis table was resolved by a computer-aided design (CAD)/ computer-aided manufacturing (CAM) assisted numerical control (NC) programming strategy, generating accurate tool trajectory for directly machining off-axis aspherical surface. Here we also include the development of a wheel wear compensation technology for the improvement of surface grinding accuracy.

For off-axis aspherical machining, one common way is to generate a best fit sphere as a start point or mount the mirror blank off-axis and do an axisymmetric cut. We have developed a method to mount the mirror blank just centered on the rotary table in a different manner, and generate the off-axis aspherical surface directly and accurately. Figure 1 shows the surface grinding procedures.

Using CAD software, we developed an accurate geometrical model to describe the off-axis aspherical surface as shown in Fig. 2. Aspherical surface is always prescribed by means of the following aspherical equation, if taking the Z-axis as the axis of revolution:

$$z(S)=\frac{cS^2}{1+\sqrt{1-(1+k)c^2S^2}}+A_2S^4+A_3S^6+A_4S^8+\ldots,\quad (1)$$

where $S^2 = x^2 + y^2$, $c = 1/R$, R is the radius of curvature, $A_2 - A_4$ are aspherical coefficients, and k is the conic coefficient ($k = -e^2$). The cross-section curve (the generatrix) of aspherical surface can be expressed as follows:

$$z(x)=B_1x^2+B_2x^4+B_3x^6+B_4x^8+B_5x^{10}+B_6x^{12}+\cdots,\quad (2)$$

where $B_1 - B_6$ are curve coefficients. Using Taylor's expansion, we derived the coefficients relationship between the Eqs. (1) and (2). The coefficients were used in modeling of parent aspherical surface as shown in Fig. 2. The off-axis segment of parent aspheric surface can be subsequently generated based on given mirror contour and distance between optical axis and geometrical center of the off-axis aspherical surface.

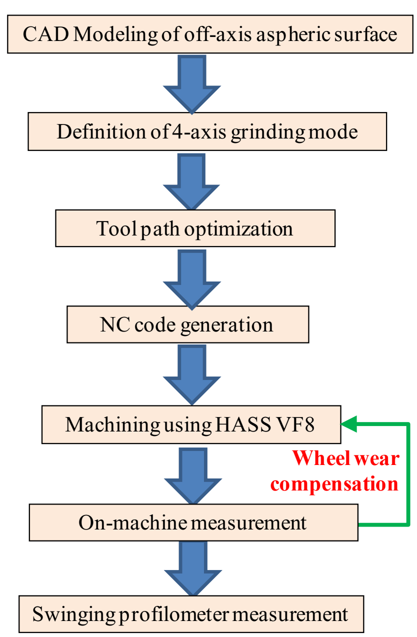


Fig. 1. Surface generation procedures.

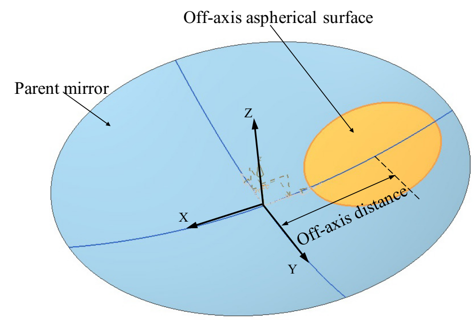


Fig. 2. Off-axis aspherical surface as a segment of the parent aspherical surface.

Generation of an accurate CAD model is the basic work of the proposed four-axis grinding mode as shown in Fig. 3. During machining, X- and C-axes move to provide expected tool path, while Z-axis goes up and down according to surface sag. Meanwhile, B-axis swings back and forth to keep a constant angle between tool spindle and surface normals. The advantage of this strategy is that the contact point of the grinding wheel will keep unchanged and it is easier to compensate the wheel wear.

Thus, it has a very low requirement for the wheel profile accuracy and eliminates the contact point calculation. The surface shape error could be easily compensated in spite of serious wheel wear. Therefore, the proposed grinding mode has sufficient freedom for machining off-axis aspherical/free-form surfaces, and can be used to fabricate the mirrors having increasingly complex shapes in next-generation space cameras that cannot be fabricated by three-axis grinding mode.

It needs to be emphasized that when using a cylindrical grinding wheel, tool path optimization is highly critical for cutting accurately and efficiently. Moreover, in another case, we also used "arc-raster" instead of spiral tool path to avoid "Λ" or "V" marks at the center of the workpiece[7]. After that, we utilized the ICAM-POST® software to generate the corresponding NC machine code.

Subsequently, the 1.45 m scale mirror blank was mounted on the center of rotary table as shown in Fig. 4, and the machining experiment was performed.

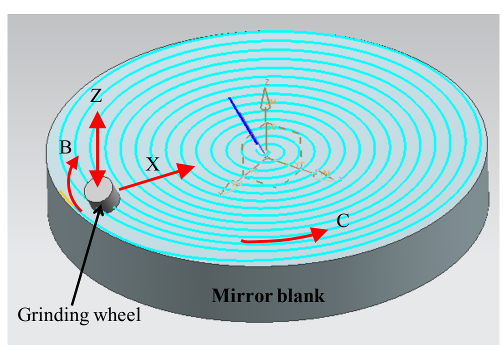


Fig. 3. Schematic of four-axis single-point grinding mode.

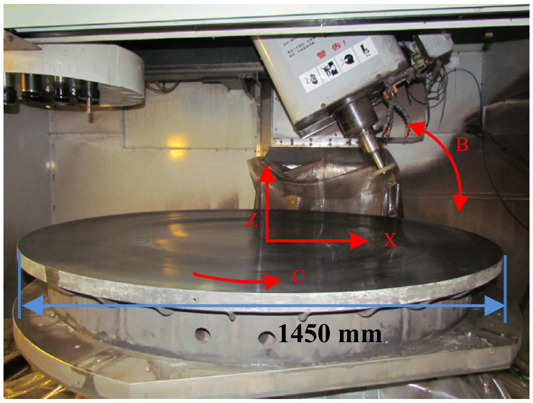


Fig. 4. RB-SiC mirror blank under grinding.

After grinding, surface error distribution was tested by a swinging-arm optical profilometer, which has a profilometer probe with an interferometric sensor for the high-accuracy distance measurement[8,9].

Surface grinding experiments were carried out on a five-axis (*XYZBC*) numerically controlled vertical machining center (HASS VF8). The main section of the experimental setup is shown in Fig. 4. The traverse ranges of *X*-, *Y*-, and *Z*-axes were 1626, 1016, and 762 mm, respectively. The repetitive accuracy of the linear axis was low and was only about 10 μm in the whole traverse range. Moreover, the range of rotary for the *B*-axis was only $\pm$ 94360° which was decided by the built-in angular counter. The *B*-axis had a rotary ability of $\pm$ 32° owing to the machine tool structure.

It can be seen that the workpiece is a convex primary mirror blank having a circular shape, whose diameter was 1450 mm. The as-received surface was a rough casting sphere with a radius of about 7000 mm. The form error of casting surface before machining was measured and was larger than 2000 μm in peak to valley (PV). Moreover, the off-axis distance was close to 1300 mm, making the surface generation a very difficult task.

Disc-like resin-bonded diamond wheels were used in grinding. Each grinding wheel had an outer diameter of 100 mm and a thickness of 10 mm. The abrasive layer width was 5 mm, with a grit size of 76 μm. No truing and dressing of grinding wheel were performed before and during machining because it was known from our former research that the SiC grains on workpiece surface functioned as a dressing tool to slowly scratch the resin-matrix of the diamond wheel[7]. The coolant used was 2% aqueous solution of Chemsearch Dowel.

The diameter of the mirror blank (1450 mm) exceeded the maximum travel range of *Y*-axis (1016 mm). When grinding such a large mirror, the spiral tool path as shown in Fig. 3 was always used. During machining, the *C*-axis rotary table must keep rotating until the whole surface is machined. Regretfully, known from our previous grinding test, the *C*-axis had no enough range of rotary for large-scale mirror blank, and stopped before the whole surface was machined.

In order to resolve the above-mentioned over travel problem, we developed a four-step grinding method along the radius direction. As shown in Fig. 5, in step 1, the tool fed along the left direction from the mirror edge to a fourth position. After that, the tool retreated a 4 mm distance, and then fed along the left direction in step 2. The whole surface could be machined after the four steps were finished. In other words, we divided the whole surface into one circular region in center side and three annular ones in outer side. Each region had a 4 mm overlap with their neighbor regions to eliminate stitching marks. Thus, the whole surface of mirror blank was successfully machined.

For example, Fig. 6 shows schematic model of an annular region. Based on this model, the tool path was generated and the NC code was obtained. After that, the corresponding region of the mirror surface was machined.

It needs to be emphasized that when using a cylindrical grinding wheel, the machining efficiency can be improved significantly by feeding direction adjustment. There are two kinds of layout for the wheel grinding. In Fig. 7(a), the grinding direction of wheel is parallel to the radial feeding direction, whereas in Fig. 7(b) the grinding direction is perpendicular to the radial feeding direction. The residual feeding marks on the ground surface using feeding direction as shown in Fig. 7(a) is significantly smaller than that in Fig. 7(b). Therefore, the machining efficiency could be dramatically increased by setting the grinding direction parallel to the radial feeding direction. However, we could only use feeding

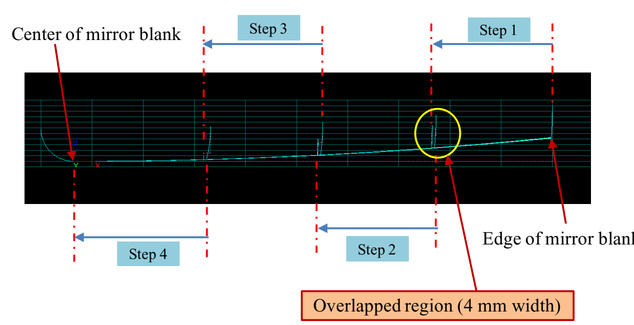


Fig. 5. Four-step grinding method shown in NC Viewer software.

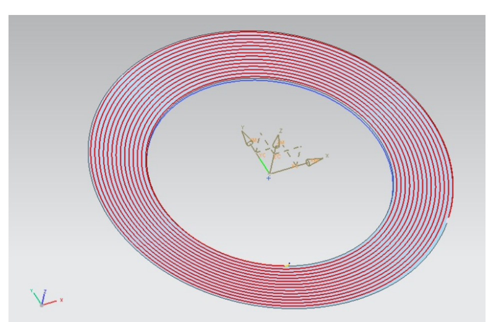
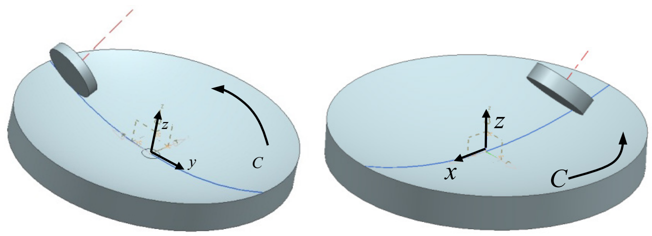


Fig. 6. Schematic model of tool path on an annular region.



(a) (b)

Fig. 7. (a) The grinding direction is parallel to the radial feeding direction and (b) the grinding direction is perpendicular to the radial feeding direction.

direction in Fig. 7(b), due to the insufficient travel range of Y-axis in this case.

Edge profiles of the diamond wheel before and after surface generation are examined. Figure 8 shows the photographs of the grinding wheel and Fig. 9 shows the schematic diagram of edge retreat on the grinding wheel. It can be seen that the edges of both sides of the wheel turns to be extremely worn. Indeed, wheel edge retreat was the main reason of surface error when grinding a large-diameter SiC material. It is also indicated that the self-sharpening of the wheel keeps the wheel sharp enough during the machining.

Therefore, compensation grinding for wheel wear was definitely indispensable due to the above-mentioned serious edge retreat. Conventionally, the surface error was measured and a new tool path was then generated by off-setting the residual shape error along the normal direction at certain grinding point. Alternatively, tool path was not changed but repeated grinding was performed. The Z-direction value was measured using an on-machine profilometer, and then compared with the theoretical coordinator. During second grinding, depth of cut was shallow and thus wheel edge retreat was small. Generally, two to three grinding cycles are required to achieve surface accuracy of several micrometers.

After machining, surface error distribution of the ground surface was measured using a swinging-arm optical profilometer[9]. Figure 10 shows the surface form error after grinding. The form error was significantly reduced to 824 μm in PV. It can be seen that the high-altitude region is mainly distributed at the middle region of the ground surface. Theoretically, the form error could be further removed if the compensation grinding was performed more number of times. However, we did not have the chance of compensation grinding for wheel wear due to a very tight production schedule. That is the key reason why the form error was not removed. Surface roughness ranged from 400 to 500 nm Ra. In addition, feeding marks, which is the main cause of surface roughness, can be clearly found on the ground surface.

By choosing the four-axis single-point grinding mode, an efficient and flexible fabrication of large-scale off-axis aspherical surface could be realized. It can be seen that the principal factor affecting the PV value is the high-altitude region at the middle of the workpiece. This kind of shape error was generated owing to the diamond wheel wear. This residual region has to be removed by a second cut according to another tool path. If the high-altitude region is fully eliminated, the PV value would turn to be smaller than 20 μm. In another case, we successfully eliminated the high-altitude region by wheel wear compensation grinding[7]. We can say that as for grinding a 1.45 m scale SiC mirror blank in this case, the main error source affecting the obtained surface error distribution of the ground surface is the wheel wear amount, other than the positioning accuracy of machining center. We also found that due to the hardness of SiC grain, diamond grinding wheel need not to be intermediately dressed during the whole grinding cycle, which brings out a high-efficiency uninterrupted grinding process.

Fig. 8. Photos of grinding wheels before and after grinding.

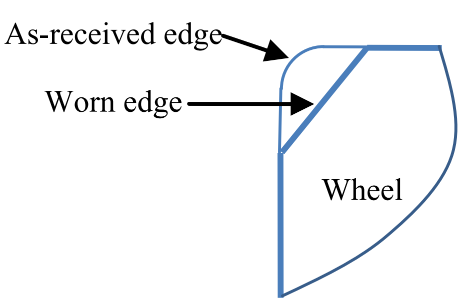


Fig. 9. Schematic diagram of the wear region on wheel edge.

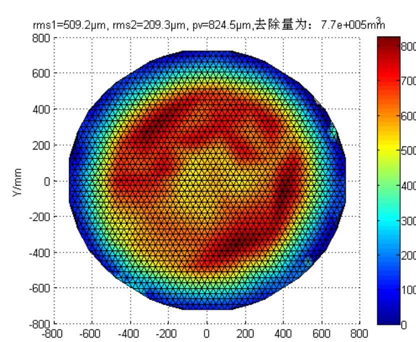


Fig. 10. Surface error distribution after grinding.

By the way, the surface roughness of the ground surface could be further improved by using the grinding wheels having smaller grit size, for example, 25 μm. The next step will be carried out to eliminate high-altitude region and reduce the surface roughness, in order to further reduce subsequent free-abrasive lapping/polishing times.

In conclusion, single-point grinding mode can be realized on a multi-axis machining center for directly machining a 1.45 m off-axis aspherical RB-SiC surface. Results show that in this case the high-altitude region at the middle of the workpiece generated owing to the serious wheel wear is the main reason for surface shape error. The error-compensation grinding is indispensable and a surface accuracy of several micrometers in RMS can be obtained depending on enough grinding cycles. In addition, we also found that self-dressing and self-truing of the diamond wheel occur in the whole grinding period of SiC mirror blank.

This work was supported by the National Natural Science Foundation of China under Grant No. 51305422. I am grateful to Dr. Xiao Luo and Mr. He Huang for equipment support. I also thanks the reviewers for the professional review and valuable suggestions.

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