Grinding strategies for machining the off-axis aspherical reaction-bonded SiC mirror blank

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Demand for large-scale off-axis aspherical mirrors is increasing in next-generation space-borne optical imaging systems. In this paper, a variable-axis single-point grinding strategy is developed for precisely, cost-effectively figuring silicon carbide (SiC) mirror blanks that have high-order high-gradient off-axis aspherical surfaces on a precision five-axis machining center. The grinding strategies also include tool path generation/optimization, feeding direction control and wheel wear reduction/compensation. Applying the developed grinding strategies, by only one grinding cycle, a near-circular Φ372-mm SiC mirror blank is successfully grounded to 7.8 μm in peak to valley, which is comparable to the reported machining accuracy of the BoX® ultraprecision grinding machine. Moreover, the wheel need not have to be dressed during the whole grinding cycle due to the rotary ultrasonic grinding method. Therefore, this paper offers an efficient and economic solution for grinding off-axis aspherical and free from surfaces to micron-level accuracy, thus significantly decreasing the subsequent lapping/polishing production cycle time.

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Advantages of aspherical elements over spherical ones are well recognized for its compactness, high performance and low cost. In recent years, designing of large-scale telescopes has evolved towards systems incorporating off-axis aspherical mirrors, which are the cut-outs of their own parent rotationally-symmetric aspherical mirrors. These mirrors can be used in groups to form a segmented primary mirror for building extremely large ground-based telescope, or utilized to build off-axis three-mirror-anastigmat imaging system in an earth observation satellite[1–3]. However, fabrication of off-axis aspherical mirror is an extremely difficult task due to not only its non-rotational symmetrical feature, but also extremely strict requirements on surface form accuracy.

Fabrication of off-axis aspherical mirrors usually involves two main steps. The first step is a deterministic process, which involves removing large amount of material using diamond-grinding wheels. At this stage, the surface form accuracy obtained is directly dependent on the intrinsic positioning accuracy of the machine tool used. The second step is a non-deterministic process, dealing with the ground surface through computer-controlled iterative lapping and polishing namely the computer controlled optical surfacing (CCOS)[4,5]. At this stage, material removal rate is controlled by relative velocity and pressure between tool and workpiece.

The deterministic grinding is a high-efficiency process, and its material removal rate is about 20–50 times that of non-deterministic lapping and polishing. Therefore, it is expected that by grinding, one can yield surface form as close as the theoretical one.

Traditionally, the best-fitted spherical surface of the off-axis aspherical surface is alternatively grounded. After that, the deviation between the calculated spherical surface and the designed aspherical surface is corrected by subsequent lapping/polishing processes. This method is easy to perform, but inefficient in the fabrication of mirrors having large deviation. For example, when machining the 8.2 m VLT primary mirror in REOSC, the maximum sag difference of the aspherical surface to the best-fitted sphere for figuring is 2.3 mm at the edge, with a mass of glass (Zerodur) to be removed of about 150 kg. The amount removed will be very large and the subsequent lapping/polishing time will be very long[6].

In 2005, Cranfield University developed an ultra-precision grinding machine, BOX®, which provides a rapid and efficient solution for grinding large-scale off-axis aspherical components, e.g., a meter-scale mirror blank made from Zerodur could be grounded to several microns in peak to valley (PV)[7]. However, due to its three-axis machine tool structure, it is very difficult for BoX® to fabricate high-order and high-gradient off-axis asphercial surface, which is used more frequently in space-borne imaging components. More importantly, the cost of this specially-designed grinding machine is extremely high. Thus, it is highly expected to develop the technologies for machining off-axis aspherical surface by using common precision machine tools, which gives comparable form accuracy and also which decreases the CCOS machining time significantly.

On the other hand, silicon carbide (SiC) is a high-performance substrate material for building large-scale mirrors, particularly the space-borne components, because of its high stiffness-to-density ratio and low thermal distortion properties, which facilitate to resist the gravity and temperature changes in space environment[8,9].

However, severe wheel wear occurs during grinding because SiC is harder than most of other materials except diamond, cubic boron nitride and boron carbide[10]. Severe wheel wear becomes the main cause of deterioration of surface accuracy. Therefore, wheel dressing is always required. According to Tonnellier[11], when grinding a hexagonal SiC part of 400 mm across corners using BoX®, the diamond wheel requires to be dressed each 26.5 minutes during finish cut, and even during rough cut, the wheel needs to be dressed every 2 minutes to maintain a grinding power below 10 kW. Frequent dressing work seriously delays production cycle. Therefore, grinding large-scale SiC precisely and efficiently is a challenge task.

In this paper, we developed a variable-axis single-point grinding mode for figuring SiC mirror blanks that have high-order and high-gradient off-axis aspherical surfaces. Moreover, a variable-axis rotary ultrasonic grinding method has been introduced to realize a non-dressing grinding process, which means that the wheel dies not need to be dressed during the whole grinding cycle. Feeding direction control and tool path optimization were also performed to obtain a constant surface speed as well as a uniform surface quality via the CAD/CAM method. It is expected that obtained surface accuracy in this work could be in a similar level with the reported results of the ultraprecision BoX® grinding machine.

Figure 1(a) is a schematic representation of the cross-axis grinding mode. The grinding wheel is driven along the wheel axial direction, which is perpendicular to the wheel cutting direction. When this grinding mode is used, the scratches on the ground surface along the wheel cutting direction could be eliminated. However, the wheel–workpiece contact zone is actually a straight line because of the axis-direction thickness of the wheel. Since straight line and curve can never coincide, the line-contact feature make it cannot precisely machine the curved surfaces.

In order to resolve this problem, an inclined-axis grinding mode, as shown in Fig. 1(b), is often adopted[12,13], such as the BoX® grinding machine. However, due to the three-axis configuration of BoX®, grinding point varies on the toric-shaped wheel surface. Therefore, high-accuracy profile of the wheel and complicated calculation of changing contact point are required. It should be noted that wheel–workpiece interference cannot be avoided when machining a strongly-curved off-axis aspherical surface.

In terms of the inclined-axis grinding mode, the wheel should be moved in such a way that the wheel axis is adjusted in the process of keeping a fixed-point contact between the wheel and workpiece. As for machining the off-axis aspherical surface as shown in Fig. 1(c), an additional Y-axis motion needs to adjust the wheel-axis angle according to the random variation of surface normal vector. Moreover, an angular C-axis rotation is also needed because of the non-rotational symmetric characteristics of the off-axis aspherical surface. Therefore, we proposed a five-axis (XYZBC), single-point grinding mode as shown in Fig. 1(c).

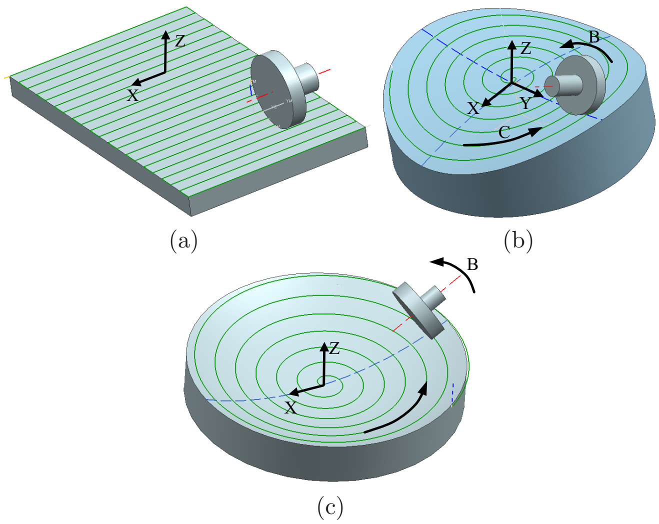


Fig. 1. Schematic representation of (a) the cross-axis grinding mode, (b) the inclined-axis grinding mode, and (c) variable-axis inclined-axis single-point grinding mode.

There are three beneficial points to use this grinding mode. It has sufficient freedom for machining high-order and high-gradient off-axis aspherical surfaces. It has a very low requirement for the wheel profile accuracy and eliminates the contact point calculation. In spite of serious wheel wear, surface form error could be reduced by a compensating grinding. Therefore, the proposed grinding mode is very efficient in fabricating the mirrors having increasingly complicated surfaces in the next-generation space-borne telescopes/cameras that cannot be fabricated by the above-mentioned three-axis grinding mode.

Rotary ultrasonic machining is regarded as one of the high-efficient and cost-effective methods for grinding hard-brittle ceramics[14,15]. However, no study reports the machining effects of inclined-axis rotary ultrasonic grinding combined with the single-point grinding mode. Figure 2 is a schematic diagram of the inclined-axis rotary ultrasonic machining, in which the wheel is ultrasonically vibrated along the wheel axis during the grinding process.

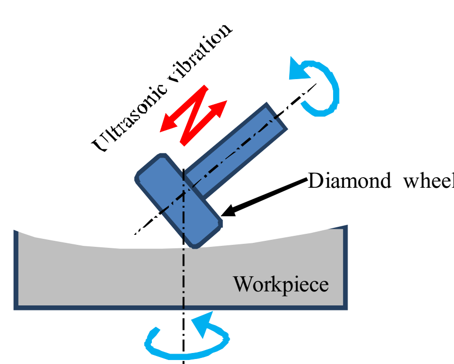


Fig. 2. Schematic representation of the inclined-axis rotary ultrasonic grinding method.

There are two benefits of this machining mode. First is the self-sharpening of the wheel edge owing to micro fragments of the diamond grits on the wheel surface. Thus, an uninterrupted grinding process without intermediate dressing of the wheels could be achieved, which will significantly shorten the whole grinding time. The other benefit is the improved surface quality including better surface finish and minimized subsurface damages.

It needs to be emphasized that when using a cylindrical grinding wheel, the machining efficiency could be improved significantly by feeding direction control. As shown in Fig. 3(a), the grinding direction is perpendicular to the radial feeding direction. Assuming that the wheel axis has an angle of α with the normal surface at the grinding point (generally, consider $\alpha = 30 - 45°$) and f is the feeding pitch, then the theoretical residual height on the ground surface can be expressed as

$$d_p = f \sin\alpha \cos\alpha. \quad (1)$$

As shown in Fig. 3(b), the grinding direction is parallel to the radial feeding direction. Then, the wheel needs to feed along the Y-direction other than X-direction. If the wheel has a radius of R_w (in this paper, $R_w = 100$ mm), the theoretical residual height on the obtained surface can be approximated as

$$d_c = \frac{f^2}{8R_w}. \quad (2)$$

In the grinding process, $R_w >> f$. As for a same value of f, $d_c << d_p$. Therefore, the theoretical surface roughness could be dramatically decreased by setting the grinding direction parallel to the radial feeding direction.

As the main aim of this work was not to improve surface roughness, the f-value was significantly increased to improve the machining efficiency. It is reasonable to assume that the shortened machining time will bring out a lower wheel wear amount and thus significantly improves surface accuracy.

Grinding work was carried out on a five-axis numerically controlled machining center (ULTRASONIC 100-5 SAUER, DMG Corporation, Germany). The photo of the machining center and its configuration are shown in Figs. 4 and 5, respectively. The programming resolution of X, Y, and Z axes is 1 μm, and that of B and C axes is 0.001°. The positioning accuracy of the linear axes is 8 μm in their own travel ranges.

Ultrasonic spindle and ultrasonic tool holder were adopted on this five-axis machining center, which enables rotary ultrasonic machining by vibrating the wheel along wheel-axis direction at a high frequency of 20–50 kHz for improving grinding quality. The ultrasonic vibrations are generated by the ultrasonic wave generator and transmitted to the piezoelectric device inside of the special tool by the electric inductor attached to the end face of the spindle, and ultrasonic vibration with amplitude of 2–3 μm is generated. The ultrasonic vibration along the wheel-axis direction adds to the high-speed rotation of spindle, realizing rotary ultrasonic machining.

As for grinding a rotary symmetrical aspherical surface is considered, the mirror blank rotates slowly on a C-axis rotary table while the wheel moves slowly along a profile z(r) from edge to center, producing a spiral-shaped path on the mirror blank surface. Figure 6 shows the conventional spiral tool path. When using this tool path, one often encounters problems such as the overcut or ground surface being concavely deviated from the theoretical form at spiral center[16]. The concave error dramatically increases the removal amount in subsequent lapping process.

To totally eliminate the residual form error at the center point, we proposed a new tool path as shown in Fig. 7. For this path, the spiral center is set out of the workpiece surface. When using this tool path, no spiral center exists, and therefore, the central residual error does not exist. A uniform surface could be realized and the subsequent lapping time could be significantly reduced.

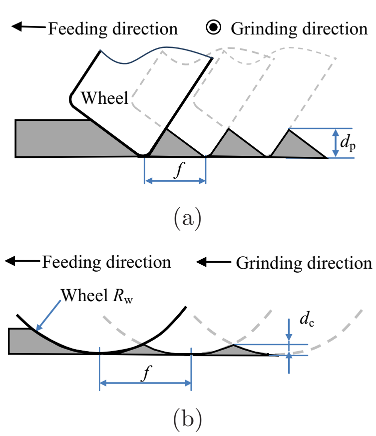


Fig. 3. Residual shape on machined surface and the theoretical roughness: (a) the grinding direction is perpendicular to the radial feeding direction, and (b) the grinding direction is parallel to the radial feeding direction.

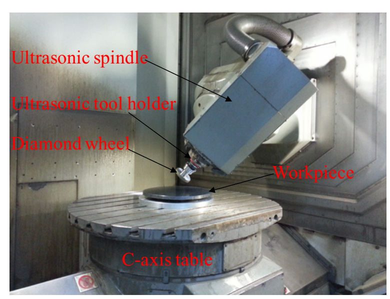


Fig. 4. SiC mirror blank under grinding.

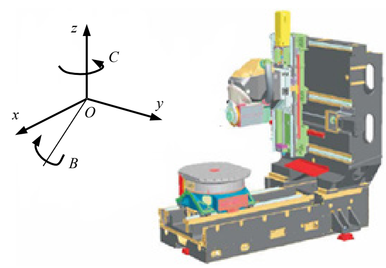


Fig. 5. Axis configuration of the used machining center.

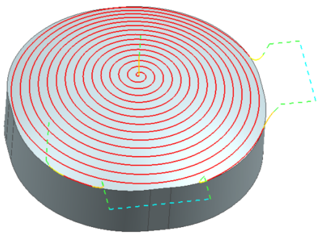


Fig. 6. Spiral-shaped tool path.

Moreover, when using the conventional spiral path, the surface error obtained is always shown as a power deviation due to the gradual wheel wear. By using the proposed tool path, surface form error could be changed to nearly a tilt deviation, which could be easily removed by position adjustment at mirror assembling stage. Therefore, wheel wear influence on surface form accuracy could be completely eliminated.

Furthermore, we created a standard cutting location source file (*.cls) based on the resultant grinding model. As the B-axis nutating head of the used machining center is different from the standard machine tool configuration, a special postprocessor file has to be firstly developed according to the configuration of used machining center. After that, NC code was generated by the developed postprocessor. Finally, the generated NC code was verified using VERICUT® software and some corrections would be performed if errors occurred.

Optical images of the diamond wheel surface before and after machining are examined. As shown in Figs. 8(a) and (b), no visible difference is found between the new wheel surface and the used one. That is to say, the wheel is still sharp enough for use. This is different from the common wheel wear phenomenon, which shows the worn of surface grits. It is the ultrasonic effect that the diamond grits expose above the wheel surface. Therefore, no intermediate dressing work is needed in the whole grinding process. Diamond grit pullout can also be clearly observed in Fig. 7(b). The grit pullout affects the sharpness of wheel, but at the same time, some grits appear underneath, and act as new grits, so that the wheel turns to be sharp again. It is shown that self-sharpness of wheel was also promoted by the ultrasonic-vibration.

As shown in Fig. 9, the surface roughness values are respectively expressed in term of an arithmetic average (Ra), root mean squared (RMS), and peak to valley (PV). It is obvious that the surface finish with ultrasonicvibration is significantly better than that without ultrasonic vibration.

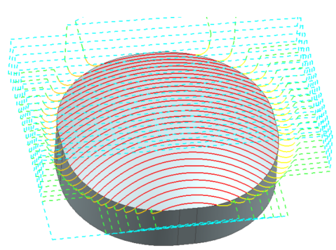
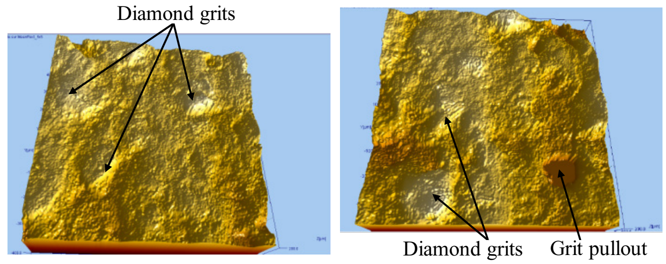


Fig. 7. Improved spiral path without spiral center on surface.



(a) (b)

Fig. 8. Optical images showing the surface topography of the diamond wheel: (a) the brand new and (b) after grinding.

Until now, by using the above-mentioned grinding strategy, we have successfully manufactured more than 10 pieces of mirror blanks. Here, one typical case is introduced. The machining conditions are listed in Table 1.

To reduce the subsurface damage layer, resin-bonded diamond wheels are used in grinding. The grinding wheel has a 100 mm outer diameter and grit size of 126 μm. No truing and dressing were performed before grinding because SiC workpiece could act as the dresser and the truer under the ultrasonic vibration of the wheel. The workpiece is a convex secondary mirror blank having a near-circular shape, whose diameter is 372 mm. The as-received surface was rough casting sphere with radius of about 2600 mm. The initial surface form error was about 0.4 mm. The workpiece was mounted on the center of C-axis rotary table and fastened using A-B glue.

Ultrasonic vibration frequency was set at about 30 kHz by testing the largest amplitude of the wheel vibration. After grinding, surface form error was tested

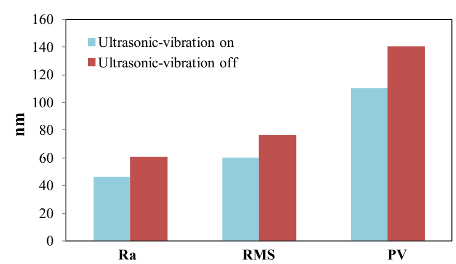


Fig. 9. Surface roughness (Ra, RMS and PV) obtained with ultrasonic vibration and without ultrasonic vibration.

Table 1. Grinding conditions

Machine tool	ULTRASONIC 100-5 SAUER
Grinding wheel	Resin-bonded diamond wheel
Workpiece	Reaction-bonded SiC
Wheel rotation (rpm)	4000–6000
Table feed (mm/min)	80–1500
Depth of cut (mm)	0.05–0.5
Radial feed (mm/rpm)	0.1–2
Grinding fluid	Blaser swisslube

by a coordinate measurement machine (Zeiss Prismo Navigator), which has a 0.6-μm measuring accuracy and a repeatability of 0.3 μm. The ground surface was also examined using a white-light interferometer (ZYGO NewView 7200).

As shown in Fig. 10, surface form error after one grinding cycle was reduced to 7.8 μm in PV and 1.8 μm in RMS. This result is very close to the machining accuracy of BoX® grinding machine, which is 5 μm in PV over 380 mm for SiC[11]. It can be observed that the high-altitude region form error is mainly distributed at the edge. Theoretically, the form error could be further removed by a second grinding cycle, but the machining time will be doubled. Surface roughness ranges from 100 to 120 nm Ra. As shown in Fig. 11, grinding marks can be clearly observed. Figure 12 shows a photo of the mirror blank after grinding.

As for grinding a large-scale SiC mirror blank, the form error of the ground surface directly relies on the wheel wear amount other than the positioning accuracy of machine tool. In this paper, the machine apparatus used is not an ultraprecision machine tool, but commercially-available high-precision machining center. Applying variable-axis single-point grinding mode, an efficient and flexible fabrication of high-order high-gradient surfaces could be realized. By ultrasonic vibration, grinding wheel need not have to be intermediately dressed during the whole grinding cycle, which brings out a high-efficiency uninterrupted grinding process. By tool path optimization, the wheel wear influence on the ground surface could be eliminated. As a result, machining accuracy similar to the positioning accuracy of the used machining center could be achieved. In addition, it can be assumed that roughness of the ground surface could be further improved by using the grinding wheels having smaller grit size, e.g., 25 μm, as used in the BoX® ultraprecision grinding machine.

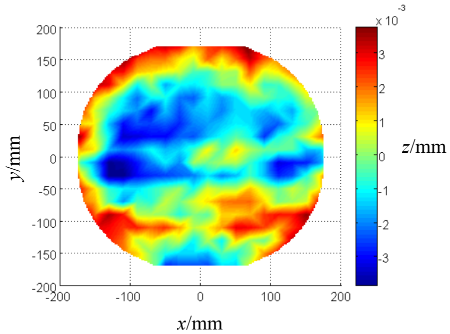


Fig. 10. Form error distribution of the ground SiC surface.

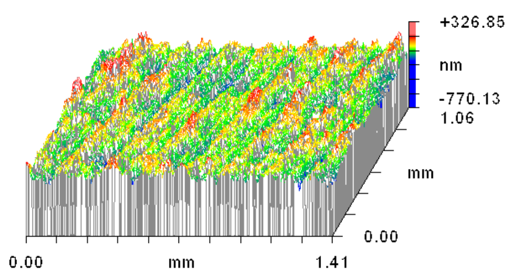


Fig. 11. Surface microstructures of the ground SiC mirror blank.

Fig. 12. Photo of the ground SiC mirror blank.

Grinding of large-scale mirror blanks having complicated off-axis aspherical surfaces is extremely important for building next-generation space-borne optical imaging systems. We are developing a rotary ultrasonic vibration-assisted variable-axis single-point grinding technology. Using the proposed grinding strategy, off-axis aspherical mirror blanks made from SiC could be grounded to micron-level accuracy by only one grinding cycle. Moreover, the wheel need not have to be dressed during the whole grinding cycle. Therefore, this work presents an alternative method for using BoX® grinding machine to fabricate SiC mirror blanks required in space-borne optics. Production cycle time in the subsequent lapping and polishing processes are dramatically reduced.

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