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ORIGINAL ARTICLE

On-machine self-calibration method for compensation during precision fabrication of 900-mm-diameter zerodur aspheric mirror

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Abstract An effective on-machine self-calibration compensation grinding method for the fabrication of a 900-mm-diameter zerodur aspheric mirror is presented in this paper. The proposed independent on-machine measuring system consists of a linear motion and a Heidenhain CT60 length gauge. Measurement errors caused by the length gauge's tilt angle and offset would decrease the compensation grinding accuracy. The length gauge tilt angle and offset could be determined by using the workpiece itself, as the ground workpiece has excellent symmetry and small axial runout values. Three points on the workpiece concentric circle are sampled to determine the tilt angle. Multiple points along the *X*-axis are also sampled to determine the offset between the length gauge probe and the workpiece grinding center. Trial measurement experiment of the 180-mm K9 workpiece showed an excellent coherence with the PGI1250 measuring results. Based on the proposed self-calibration method, the raw measured profile error curve is firstly smoothened and then spline fitted to generate the compensated grinding path. The grinding experiment indicated that the profile error could be improved to be less than 5 μm from 40 μm for the 900-mm zerodur mirror after four compensation grinding cycles.

Keywords Precision grinding · Aspheric mirrors · On-machine measurement · Compensation grinding

1 Introduction

Large aspheric mirrors are needed for large optical systems. The mirror material is hard and brittle, such as fused silicon, zerodur as well as SiC, with extremely low thermal expansivity; thus, profile accuracy would be maintained under great temperature changing circumstances [1]. In order to guarantee the mirror profile accuracy and machining efficiency, the fixed diamond abrasive grinding method is traditionally used to generate the specified profile [2]. The grinding machine needs ultraprecise motion control and structure stiffness to guarantee the grinding accuracy and material removal efficiency [3]. The geometric error of the large-scale grinding machine could be compensated using the spatial circular curve ball bar test which would improve the grinding accuracy [4]. However, the grinding wheel wear is inevitable and would decrease the machining accuracy seriously and material removal capability [5, 6]. Different compensation grinding methods with on-machine measurement have been proposed to improve the ground profile accuracy [7–11]. On-machine error compensation grinding could save the second setup and eliminates alignment error. Furthermore, the profile accuracy could be improved. Previous machines provided separate metrology frame including optical straight edge and interferometer, which is much more costly [12]. The digital error compensation grinding could be done using the focus lens on-machine measurement system [13]. The tilt and offset misalignment calibration method was also proposed using the ball method for the 800-mm SiC mirror compensation grinding [14]; the on-machine measuring structure was not stable enough. Meanwhile, the calibration operation is much complicated as the ball needs to be adjusted precisely. The coordinate relationship between the grinding machine and length gauge was also not stable. The probe radius error and the corresponding compensation method were proposed for the micro-mold fabrication [15]. On-machine compensation grinding method for large aspheric mirrors was proposed, which is effective for the off-axis aspheric mirror compensation grinding [16].

In this paper, a Numerical control (NC) grinder with a separate metrology frame is presented, which is able to

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implement the proposed self-calibration compensation grinding. This machine consists of three linear motions (*XYZ*), rotary table (*C*), and grinding spindle. The grinding mode utilized the *XZC* interpolating motions to fabricate the aspheric surface, while the *Y*-axis together with the Haidenhain CT60 builds up the independent metrology frame. The measurement error caused by the length gauge tilt and offset is simulated, and the results indicate that the tilt and offset misalignment error could be adjusted to be less 0.005 rad and 0.002 mm; thus, the measurement error could be less than 2 μm. A Three-point method is proposed to determine the tilt angle between the probe and *Z*-axis. A multiple-point method for the length gauge offset determination is also proposed. The measuring results are filtered and fitted by using the spline interpolation method. The compensation grinding points are generated through combining the fitted profile error curve with the original grinding path. The compensation grinding cycle strategy was adopted to remove the convex features with the chosen grinding depth. The final compensation indicated that the profile error could be improved to be less than 5 μm from 40 μm.

2 Machining and measuring concept

The aspheric mirror could be machined based on the Cartesian or polar coordinates. The polar grinding method is extremely effective for the symmetric mirror fabrication. As the rotary motion means less interpolating motions, the machine developed for the 900-mm zerodur fabrication consists of *XYZ* linear motions, a rotary table, and a wheel spindle as shown in Fig. 1. The polar interpolating grinding mode contains *XZ* linear motions, rotary motion, and the wheel spindle. The diamond abrasive grinding wheel is a 400-mm-diameter disk with 90-mm arc edge, while the wheel thickness is 20 mm.

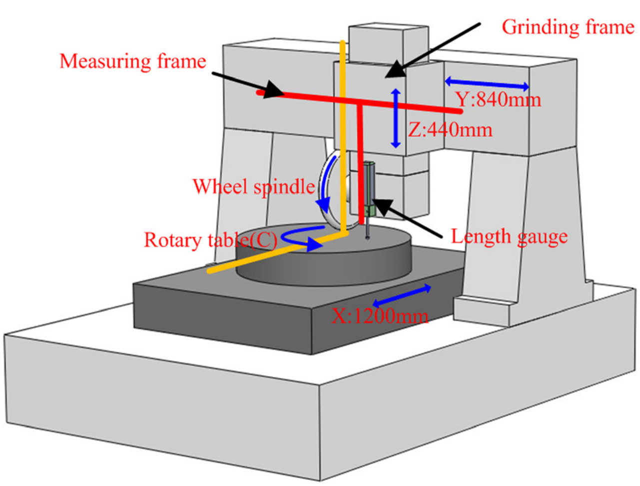


Fig. 1 Configuration of the grinding and measuring frame

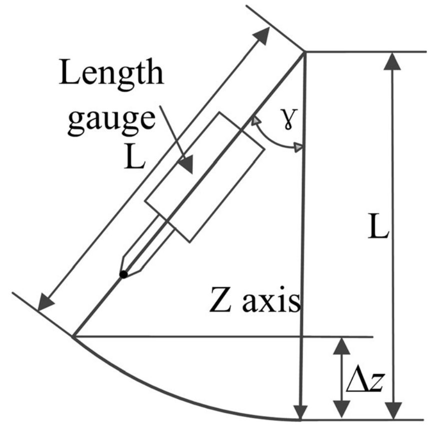


Fig. 2 Illustration of tilt measuring error

The ground profile error is the compound results of the geometric error, kinematic error of the interpolation motions, the wheel form error as well as the wheel alignment error. Different measures could be used to avoid and attenuate these errors. Effective fabrication of large aspheric mirror needs integration of powerful machining capability and accurate on-machine compensation function. On-machine compensation grinding is critically important for large mirror fabrication through the elimination of complicated setup and alignment operations. On-machine measuring frame should be separated with the machining frame physically; thus, an additional linear axis is designed to implement the on-machine measurement, as shown in Fig. 1. The measuring frame motion range is 840 mm in the *Y* direction. Measurement range of the length gauge is 60 mm, which would be sufficient for most large aspheric mirrors. Length gauge is commanded by the NC system as the *Y* motion. Measuring line space is recorded by the *Y*-axis grating sensor while length gauge displacement is gained through Heidenhain ND287. Measuring results would be obtained by using a 17-pin connector to PC from ND287. The filtering and fitting of the measured profile and the generation of the compensation grinding path are carried out in a PC.

3 Self-calibration for the length gauge tilt and offset determination

The ideal measuring status is that the length gauge is parallel to the *Z*-axis and passes the rotary table center. However, there is always tilt and offset caused by the imperfect part and assembly which would cause measuring error. The tilt error could be eliminated by using the informational compensation while the offset error may be eliminated by using the *XY* motions. As the fine ground aspheric surface is symmetric, it could be used to determine the length gauge offset to the rotary table center as the self-calibration datum. After fine

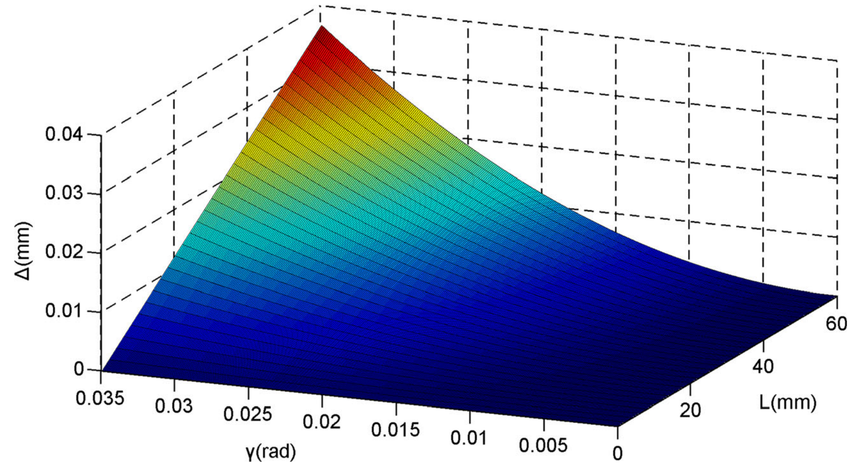


Fig. 3 Measuring error simulation of tilt angle (c=0.0004, k=−0.1355)

grinding, the axial runout of the workpiece in the concentric circle is in micrometer-order accuracy which is flat enough to be used as the calibration datum.

3.1 Length gauge tilt self-calibration

The length gauge should be perpendicular to the rotary table surface. Due to its assembly error, there is generally a tilt angle γ which would cause the measurement error Δz as shown in Fig. 2. The tilt angle between the length gauge and the Z-axis could be measured by using the workpiece itself. Measuring profile error caused by the length gauge tilt is simulated as shown in Fig. 3, which indicates that the measuring error increases with the increases of tilt angle and the measuring length. The fine ground workpiece possesses micrometer-order axial runout on the concentric circles. The axial runout values were measured on six concentric circles of a 150-mm K9 fine ground aspheric surface by using an inductance micrometer, and the radii of the circles above are from 10 to 60 mm as shown in Fig. 4, where c and k are the curvature and second-order conic parameters, respectively. The axial runout values are less than 2 μm, which means that the tilt angle of the circle datum plane to the rotary table is within 2 μrad.

As shown in Fig. 5, in order to calibrate the tilt angle γ, three points on a concentric circle are selected to form a datum plane. Once the datum circle is selected, the X and Y coordinates could also be determined. Coordinates of these three points are expressed as $P_1(x_1, y_1, z_1)'$, $P_2(x_2, y_2, z_2)'$, and $P_3(x_3, y_3, z_3)'$. The Z coordinates of the sampling points are the indication of the length gauge, while the X and Y coordinates are defined by the machine coordinate system. The tilt angle γ could be expressed as Eq. (1)

$$n = \frac{n_1 \times n_2}{|n_1||n_2|} = \begin{pmatrix} \cos\alpha \\ \cos\beta \\ \cos\gamma \end{pmatrix} (n_1 = P_1 - P_2, n_2 = P_3 - P_2) \qquad (1)$$

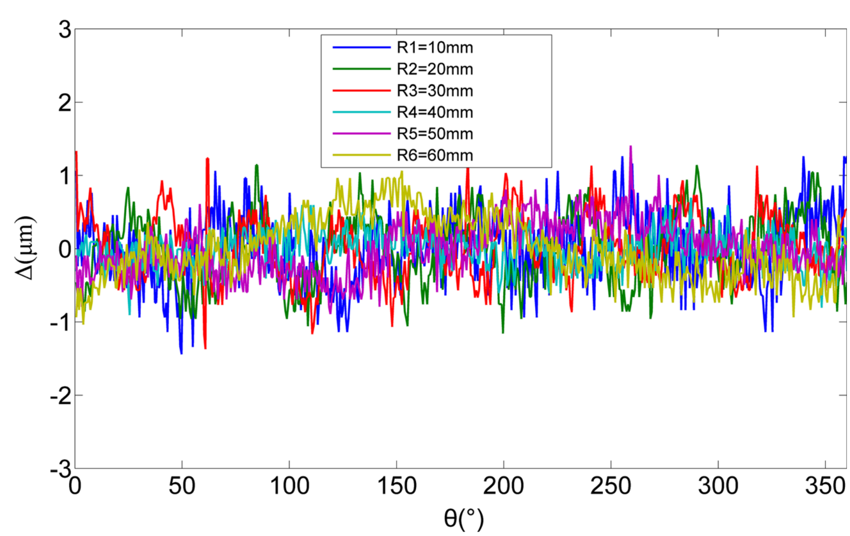


Fig. 4 The measured concentric axial runout values of K9 mirror with a diameter of 150 mm

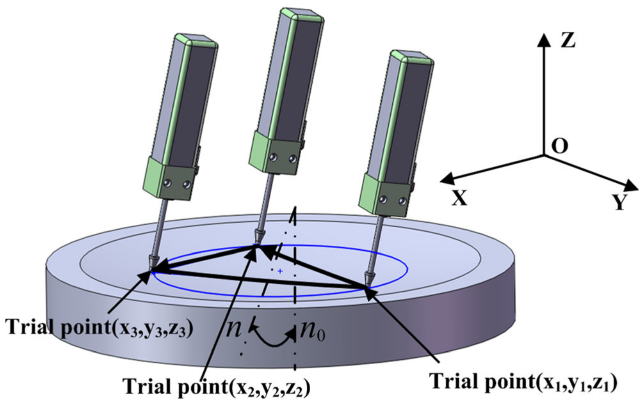


Fig. 5 Three-point method for tilt angle determination

If the length gauge indication is L during measuring stage, the tilt angle error could be expressed as Eq. (2).

$$\Delta z = L - L\cos\gamma \tag{2}$$

3.2 Length gauge offset self-calibration

The length gauge measuring path needs to pass the workpiece center which means that length gauge probe should be aligned to the workpiece center in the XY directions. The Y direction alignment guarantees the comparison between the ideal aspheric curve and the measured curve, while the X direction alignment ensures the coherence of the actual measuring profile to the grinding curve profile. The aspheric curve is generally expressed as Eq. (3).

$$z(x,y) = -c\left(x^2+y^2\right)/\left(1+\sqrt{1-(1+k)c^2(x^2+y^2)}\right) \tag{3}$$

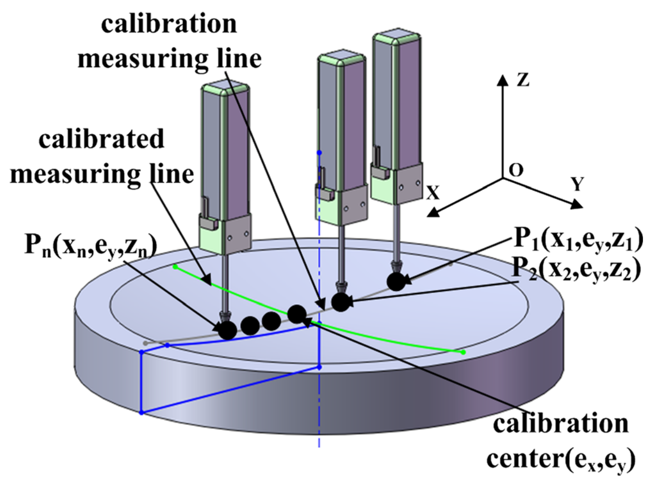


Fig. 7 Multiple-point method for offset determination

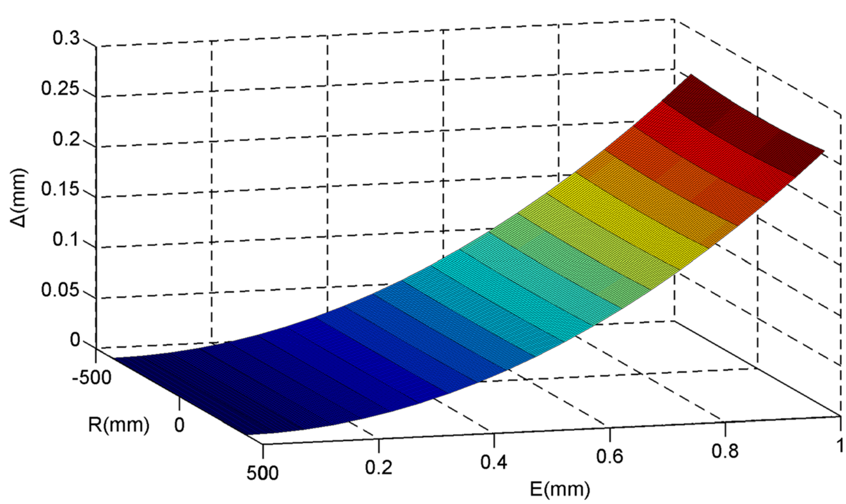
Where c and k are the curvature and second-order conic parameters, respectively. The ideal measuring curve could be expressed as Eq. (4).

$$z(x,0) = -c\left(x^2+0^2\right)/\left(1+\sqrt{1-(1+k)c^2\left(x^2+0^2\right)}\right) \tag{4}$$

However, an offset between the mirror center and gauge probe in X direction exists and causes measuring error. The actual curve with offset e_x in X direction could be expressed as Eq. (5).

$$z(y,e_x) = -c\left(y^2+{e_x}^2\right)/\left(1+\sqrt{1-(1+k)c^2(y^2+{e_x}^2)}\right) \tag{5}$$

Fig. 6 Measuring error simulation caused by the length gauge offset (c=0.0004, k=−0.1355)



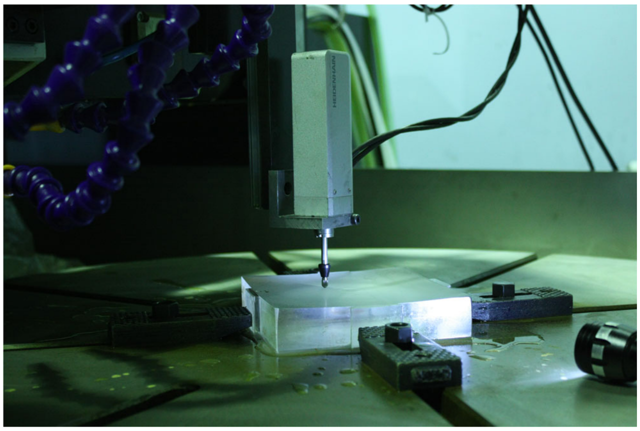


Fig. 8 Photograph of measurement of a trial mirror

The measuring error caused by the offset could be expressed as Eq. (6).

$$\Delta = \max\{z(y,0) - z(y,e_x)\} y \in (0,R) \quad (6)$$

According to Eq. (6), the measurement error caused by the misalignment of the measuring probe to the workpiece center is increased with offset's increase, as shown in Fig. 6. Simulation results show that the corresponding measurement error caused by a 0.05-mm offset misalignment is 0.025 mm, the XY motion positioning accuracy is better than 1 μm, which may satisfy the offset adjustment and make the offset less than 2 μm. The measuring coordinate system should be confirmed to the grinding coordinate system in XYZ directions, while the compensation grinding path is generated by using the Y coordinates and length gauge. The misalignment in the XY direction is expressed as e_x and e_y. Multiple calibration points P_1, P_2……P_n along the X direction are sampled to determine e_x and e_y as shown in Fig. 7, which is based on the fact that the ground

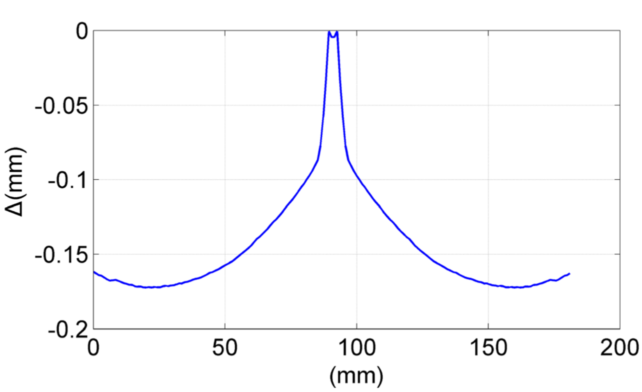


Fig. 9 Measured profile error curve before offset calibration

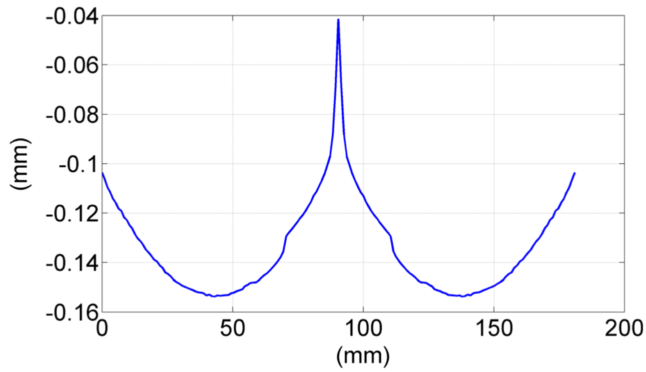


Fig. 10 Measured profile error curve after offset calibration

workpiece is symmetric. The trial measuring line could be expressed as Eq. (7).

$$z(x,e_x,e_y) = -c\left((x+e_x)^2 + {e_y}^2\right) \Big/ \left(1 + \sqrt{1-(1+k)c^2\left((x+e_x)^2 + {e_y}^2\right)}\right) \quad (7)$$

Based on the multiple calibration points (x_1, e_y, z_1), (x_2, e_y, z_2),……, (x_n, e_y, z_n) sampled along the X-axis, Eq. (8) could be obtained. X and Z values are recorded by the NC system and length gauge, respectively.

$$\begin{cases} z_1 = -c\left((x_1+e_x)^2 + {e_y}^2\right) \Big/ \left(1 + \sqrt{1-(1+k)c^2\left((x_1+e_x)^2 + {e_y}^2\right)}\right) \\ z_2 = -c\left((x_2+e_x)^2 + {e_y}^2\right) \Big/ \left(1 + \sqrt{1-(1+k)c^2\left((x_2+e_x)^2 + {e_y}^2\right)}\right) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ z_n = -c\left((x_n+e_x)^2 + {e_y}^2\right) \Big/ \left(1 + \sqrt{1-(1+k)c^2\left((x_n+e_x)^2 + {e_y}^2\right)}\right) \end{cases} \quad (8)$$

In Eq. (8), the meaning of c and k are seen in Eq. (3). It is actually the nonlinear least square problem to determine the offset. The direction of e_y could not be determined from Eq. (8), it was determined by the initial offset value (e_{xo}, e_{yo}). Firstly, initial values (e_{xo}, e_{yo}) were given by the nominal size whose directions were defined by the NC system. Since offset (e_x, e_y) is determined, the length gauge would be moved to the origin measuring point by ($-e_x$, $-e_y$), the ideal and actual measuring aspheric line could be the same one. The actual measuring line along the Y-axis is independent from the grinding loop.

The length gauge is placed at the bottom of Z-axis ram, next to the grinding spindle, and fixed with a linear guide rail, is moved to the measuring position by the air

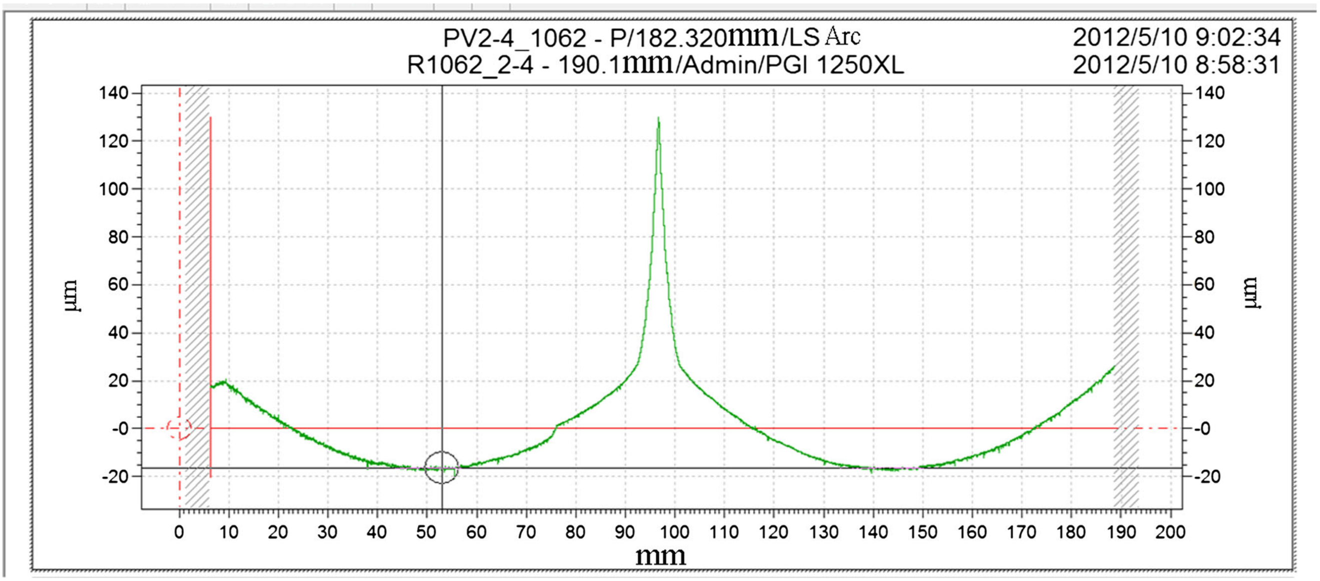


Fig. 11 Measured profile error curve by using the PGI1250XL

cylinder, and fastened manually to prevent the air cylinder interference as shown in Fig. 8. The length gauge would be moved back to avoid collision during the grinding process. In Fig. 9, the measured offset of the trial 180-mm K9 mirror is 0.170 mm with offset. Based on the multiple-point offset determination method, the measured offset values e_x and e_y are 0.080 and 0.075 mm, respectively. After offset calibration, the profile error of the mirror measured again is 0.145 mm. As shown in Fig. 10, the mirror was measured again by using the Taylor Hobson PGI1250XL, as shown in Fig. 11. It may be seen from Figs. 10 and 11 that two profile error curves are exactly coherent which proves the proposed calibration method to be feasible. Figure 9 Measured profile error curve before offset calibration

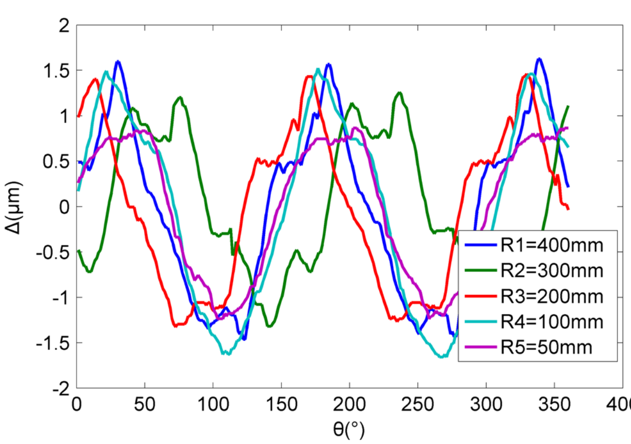


Fig. 12 Axial runout of the concentric circles

4 Experiments

4.1 Self-calibration measurement

During the compensation grinding stage, the tilt and offset of the length gauge need calibrating. The concentric circle axial runout values are measured at a series of circles with radii from 50 to 400 mm to validate the calibration datum, as shown in Fig. 12. The maximum of the runout values above is below 3.5 μm, which means that the tilt angle of datum plane is less than 3 μrad. The measured results of the five concentric circle axial runout values in Fig. 12 do not show a scaled-up tendency with the diameter's increase, the reason of which is that the grinding velocity on the larger-diameter circle is higher. Three points measured on the circle with a diameter of 100 mm are shown in Table 1, where α, β, and γ are the tilt angle of the length gauge in X, Y, and Z direction, respectively, and their first point is set to be an origin one. The tilt angle 0.0059 rad would also be used during the offset calibration.

To determine the alignment offset error, 21 points were sampled along the X direction in the range of −100 to 100 mm as shown in Table 2. The initial

Table 1 Three points for tilt determination

	X (mm)	Y (mm)	Z (mm)
P_1	0	0	0
P_2	−100.005	0	−0.02
P_3	−50.01	−50.01	0.040

α=1.5705 rad, β=1.5649 rad, γ=0.0059 rad

Table 2 *X* and *Z* coordinates for offset determination

Number	*X* (mm)	*Z* (mm)
1	−100	−2.4843
2	−90	−2.01156
3	−80	−1.58677
4	−70	−1.21544
5	−60	−0.89117
6	−50	−0.61235
7	−40	−0.39591
8	−30	−0.21442
9	−20	−0.08987
10	−10	−0.01692
11	0	0.000441
12	10	−0.02187
13	20	−0.09339
14	30	−0.22012
15	40	−0.40031
16	50	−0.62048
17	60	−0.89748
18	70	−1.23178
19	80	−1.59908
20	90	−2.03127
21	100	−2.50613

E_{x0}=0.200 mm, E_{y0}=0.100 mm, E_{xf}=0.254 mm, E_{yf}=0.143 mm

solution of E_{x0} and E_{y0} value is the nominal size. MATLAB nonlinear least-squares solution function lsqnonlin is used to obtain the final calibration offset E_{xf} and E_{yf}.

4.2 Compensation grinding

As the tilt and offset values for calibration are determined, length gauge is moved to the origin measuring position by $-E_{xf}$ and $-E_{yf}$. After the measurement of profile error, each error data Δ_i would be calibrated as Δ_i *cosγ.

Table 3 Compensation grinding conditions and aspheric mirror parameters

Compensation grinding conditions	
Wheel speed	1800 RPM
Rotary speed	10 RPM
V_{feed}	8 mm/min
Cutting depth (C_{depth})	8 µm
Aspheric mirror parameters	
1/*C*	2500 mm
K	−0.135592
Sagger	51.09 mm
Diameter	900 mm

The higher profile accuracy should be obtained as far as possible in the grinding process in order to reduce the thereafter polishing time for large aspheric mirrors. The raw measuring profile contains many high-frequency signals after fine grinding which includes the information of scrap, roughness, and vibration. These virtual profile features would be firstly filtered and fitted by using the spline numerical method to obtain the compensation grinding error. Final compensation grinding path is the combination of the original grinding path and the calibration profile data. It is known that the "convex" features may be removed through the compensation process. The compensation strategy is that the compensation path is generated against the raw profile while the cutting depth is constant on the premise that the cutting depth is smaller than the profile error. Much deeper cutting depth would cause larger profile error, while much less cutting depth would cause low compensation efficiency. The compensation grinding cycle times *N* is equal to $P-V/C_{depth}$, where *P*,

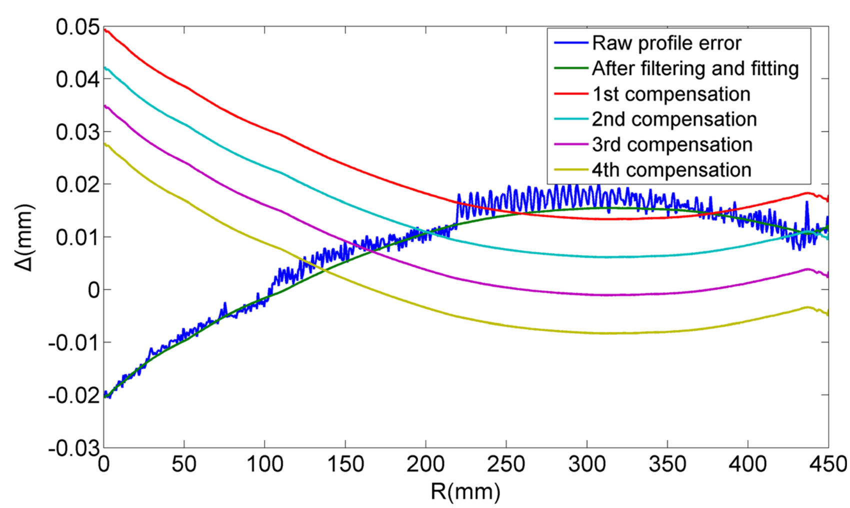


Fig. 13 Calibration measuring data and compensation grinding data

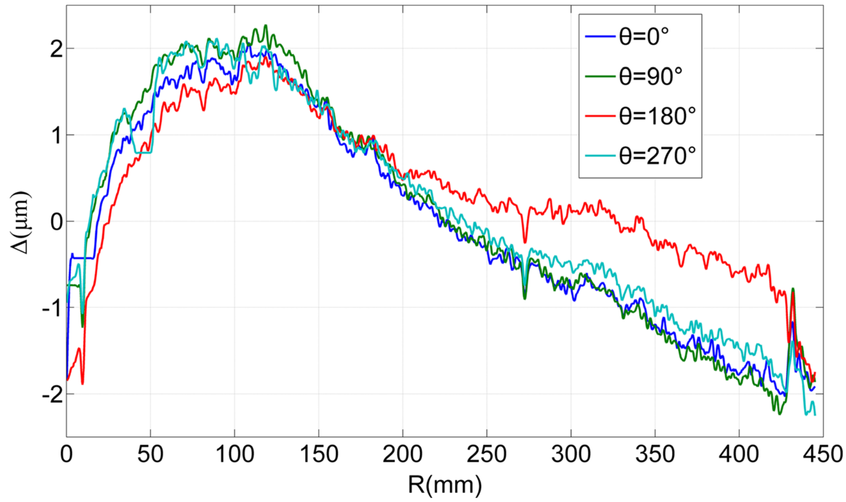


Fig. 14 Profile error after compensation

V, and C_{depth} are peak and valley values of the profile error curve and the cutting depth, respectively.

A 900-mm-diameter zerodur mirror with a thickness of 100 mm was ground after finish grinding; the profile error is 40 μm, as shown in Fig. 13. Cutting depth in the fine grinding stage is 10 μm. Compensation grinding depth is smaller than the normal finish grinding depth, and this compensation cutting depth is 8 μm. The grinding parameters are shown in Table 3. Under the grinding condition above, the grinding wheel's wear would be less obvious and the error induced by the grinding wheel's wear is much smaller. As shown in Fig. 13, the compensation path is generated against the measuring profile, and four cycles of the compensation were implemented. The final ground surface profile error after compensation and the 900-mm-diameter zerodur mirror are shown in Figs. 14 and 15, respectively. The grinding profile error is less than 5 μm after four compensation cycles, which is exactly consistent with the compensation grinding path.

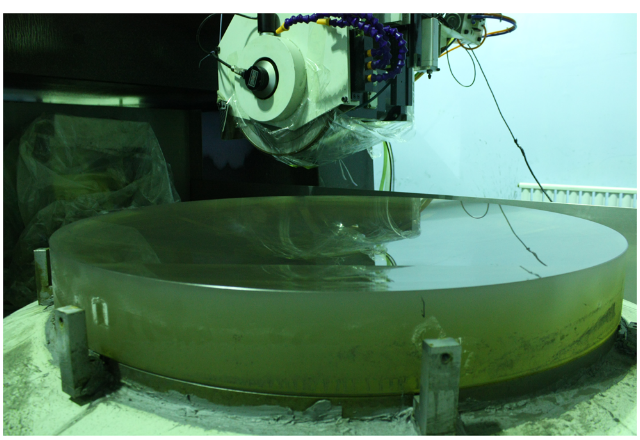


Fig. 15 Picture of a 900-mm-diameter mirror after compensation grinding

5 Conclusions

The on-machine self-calibration compensation method is proposed based on the fact that the grinding aspheric mirror is rotationally symmetric and the axial runout values on the concentric circles are in micrometer order. Three points on the concentric circle were sampled to determine the tilt angle between the length gauge and the Z-axis. Multiple points along the X direction were sampled to form an equation for the offset e_x and e_y. The trial measuring results of 180-mm workpiece showed an excellent coherence with the commercial PGI 1250XL measuring results. The measuring profile error curve with length gauge tilt and offset calibration is filtered and fitted to generate the compensation grinding path. Average compensation method is used to remove the convex features of the profile errors. The 900-mm zerodur aspheric mirror profile errors could be improved to be less than 5 μm from 40 μm after four compensation cycles.

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