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# Ultraprecision error compensation turning for high-gradient aspheric surface based on B-axis platform

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**Abstract:** High-gradient aspheric elements need to meet the requirements of both high-gradient aspheric characteristics and a streamlined shape in aerodynamics. The shape characteristics of high-gradient aspheric surfaces bring great challenges to machining. Aiming at hard machinability of single-point diamond turning high-gradient optical opponents, an ultraprecision *XZB* axes single-point diamond turning technique was presented based on rotation *B*-axis platform. Through analysing the traditional *XZ* axes turning method, the new *XZB* axes turning process was proposed to fabricate a high-gradient aspheric surface. The influences of setting errors and cutting edge of arc lathe tool in *Y*-direction and *X*-direction on profile accuracy were analysed for correcting the new tool position. The compensation turning method of axisymmetric surface was presented. An error compensation turning experiment of copper was proposed and carried out to obtain a high-gradient aspheric surface. After three time cycles, the profile accuracy was improved from *PV* 590 nm to *PV* 103 nm.

**Keywords:** ultraprecision turning; rotation B-axis; error compensation; high-gradient aspheric.

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## 1 Introduction

With the high-speed development of technologies applied in optical engineering, aerospace, photoelectric weapon systems and other fields, aspheric components play an increasingly important role (Chen et al., 2010). Surface quality is an essential requisite in the precision manufacturing filed (Ancio et al., 2018). As the performance of aspheric surface systems was gradually enhanced, the requirements for aspheric shape, machining accuracy and surface quality become higher and higher (Li et al., 2022). High-gradient optical guidance elements in special fields such as missile systems need to meet not only optical functions but also aerodynamic shape requirements, to improve and optimise the overall performance of the entire weapon optical system. Generally used in infrared optical systems, it can obtain higher energy, better dynamic performance, and less resistance in the air.

The high-gradient aspheric surface brings great challenges to machining. Ultraprecision grinding technology is an effective method for manufacturing aspheric components or moulds made of highly hard and brittle materials. A multi-scale grinding model could predict surface uniformity and profile accuracy of aspherical-cylindrical microstruction array mould by three tool path planning methods (Yu et al., 2022). The formation mechanism of aspheric surface roughness was studied for revealing the influence of machining parameters on surface roughness (Yang et al., 2022). A profile error of 0.21 μm and a surface roughness of 10.5 nm could be achieved by using a hybrid approach of compensation grinding and machining silicon infrared optics in large volumes (Sharma et al., 2019). A variable-axis single point grinding method was proposed for figuring SiC surfaces with high-gradient off-axis aspheric (Zhang and Zheng, 2014).

To further improve the surface roughness and profile accuracy, the ultraprecision polishing of aspheric elements has become the most important process. A self-adaption polishing tool was designed to machine full frequency range error of high-gradient aspheric surface based on silly putty (Bao et al., 2019). A lot of theoretical analyses and experiments could predict the tool influence function to wrap a small rigid ball. The peak-to-valley value was decreased to 0.083 μm (Zhu et al., 2022). An optimised Archimedes spiral polishing path could improve the uniform depth of material removal of aspheric surfaces, considering the effect of the surface curvature variations on material removal (Qu et al., 2022).

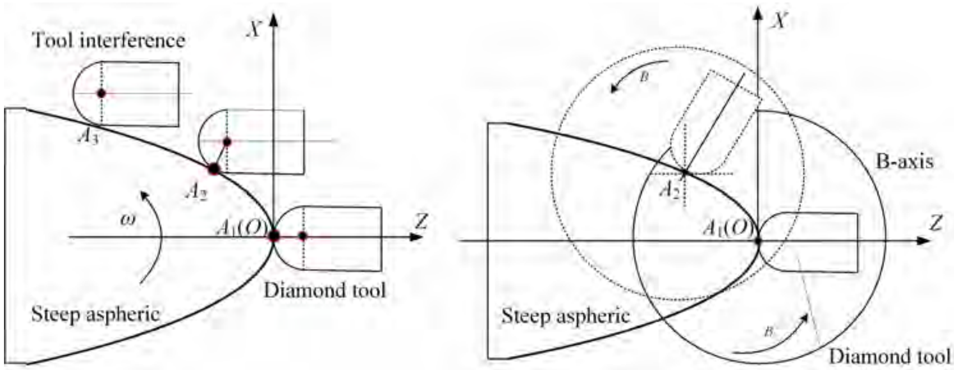
The high-gradient aspheric elements are mostly formed by direct machining, while the single-point diamond turning technology is increasingly widely used in the processing of monocrystalline silicon germanium, red copper, electroplated nickel, infrared glass and other materials. Grzesik and Żak (2016) analysed the different micro-topographical surfaces by comparing precision hard-turning and precision grinding. In the turning process, the inclination and rake angles of the tool will influence the surface roughness because of the tool-workpiece contact geometry (Sung et al., 2018). Goel et al. (2012) studied the influences of turning temperature and crystal orientation on tool wear when turning monocrystalline silicon materials. Chang et al. (2022) performed a lot of simulations and experiments for improving the machining accuracy of non-axisymmetric aspheric surfaces by using various controllers. Li et al. (2020) proposed a geometric error model for turning aspheric surfaces by using a fast tool servo system. Ji et al. (2016) studied kinematic analyses of two linear axes during turning off-axis parabolic surfaces. Sun et al. (2017) turned an optical mandrel with a high-gradient aspheric surface using an arc-edged diamond tool in XZ axes machine tool. Dai et al. (2021) studied the influences of tool deviation on the profile accuracy and the cutting force in processing turning a convex spherical surface. A chromatic confocal measurement probe (Zou et al., 2017) was used in an ultraprecision turning machine to conduct the non-contact on-machine measurement of a high-gradient freeform surface (Wang et al., 2021). Zhou et al. (2022) combined precision glass moulding and single-point turning technology to fabricate aspheric lenses on Chalcogenide glass. Zhu et al. (2017) proposed an optimal algorithm for planning toolpath to avoid the inherent defects in F-/STS turning of micro-lens arrays.

For a high-gradient aspheric surface, the turning method and the edge error of the diamond tool have great influences on the surface shape. How to accurately turn and compensate aspheric surfaces with high-gradient needs further research. In this paper, the purpose is to establish a single-point diamond turning and compensation method based on a rotating B-axis, which can effectively solve the key problems of turning quality and accuracy of high-gradient aspheric parts.

## 2 Ultraprecision turning with XZB axes

The traditional single-point diamond turning adopts the XZ two-axis motion to control the tangency between each cutting point and the machining surface. The principle is shown in Figure 1(a). The axisymmetric part rotates around the workpiece axis at an angular speed $\omega$, and the arc turning tool moves along the meridian of the axisymmetric part through the XZ axis, and always keeps the turning tool arc tangent to the meridian. For example, when the diamond tool moves from turning point $A_1$ to turning point $A_2$, the tool always keeps point contact with the workpiece. Because the circular cutting edge of the diamond tool has certain waviness and shape error, if the turning point of the cutting edge changes constantly in turning, the tool shape error will affect the quality and accuracy of the machined surface. In particular, if a certain area of the cutting edge of the lathe tool is worn, normal machining cannot be carried out. In addition, for the high-gradient aspheric surface, because the length-diameter ratio is large, the general arc turning tool cannot be processed to the base of the aspheric surface. For example, if the turning point is to $A_3$, there will generate problems of undercutting or machining interference in Figure 1(a).

**Figure 1** Single-point diamond turning modes in (a) XZ two-axis and (b) XZB three-axis turning (see online version for colours)




(a) (b)

Because of the above problems in the two-axis diamond turning, an XZB axes single-point diamond ultraprecision turning method was proposed for high-gradient aspheric surfaces. The principle is shown in Figure 1(b). High-gradient aspheric surface wraps around the workpiece spindle at an angular speed $\omega$. The fixed turning edge (vertex $O$) of the diamond tool moves along the meridian path of the axisymmetric workpiece, while the turning tool rotates around the centre of the rotation table of B-axis. The normal at the machining point on the workpiece surface is always tangent to the fixed turning edge. For example, when the turning point is from $A_1$ to $A_2$, moving X and Z axes make the point $A_2$ of the workpiece contact the turning tool arc, and meanwhile, the turning tool rotates a certain angle around the B-axis. By controlling the X, Z and B axes, the high-gradient aspheric surface can be effectively machined. Since the turning point is always kept in the fixed area of the tool edge, this method can accurately control the cutting path, eliminate the influence of the shape error of the tool cutting edge, improve the turning accuracy, and make the subsequent error compensation simpler.

## 3 Error compensation in ultraprecision turning

There are many factors affecting the machining quality and accuracy in diamond turning. The influence of entering errors must be considered. In addition, the tool shape and size also affect the profile errors of the workpiece. The error needs to be corrected step by step to obtain the required shape and quality.

### *3.1 Eccentric error and compensation in Y-direction*

An eccentric error of diamond tool in Y-direction will lead to an undercutting area in the workpiece centre, enlarging the machining range. In the actual turning process, the eccentric error in Y-direction is generally observed under the high-power microscope after the top area is pre-machined, and then calculated and eliminated. Due to the shape structure characteristics of the turning tool in Figure 2(a), if the turning tool has a deviation $d$ in the positive Y-direction, there will be a conical boss in the workpiece centre. As shown in Figure 2(b), if the deviation $d$ is in the negative Y-direction, there will be a cylindrical boss in the workpiece centre. Through observing the shape type of cone or cylindrical boss under a high-resolution microscope, the boss diameter was measured, and the turning tool moved up or down again with deviation *d* to eliminate the eccentric error in Y-direction.

**Figure 2** Eccentric error in Y-direction for single-point diamond turning, (a) positive deviation (b) negative deviation (see online version for colours)

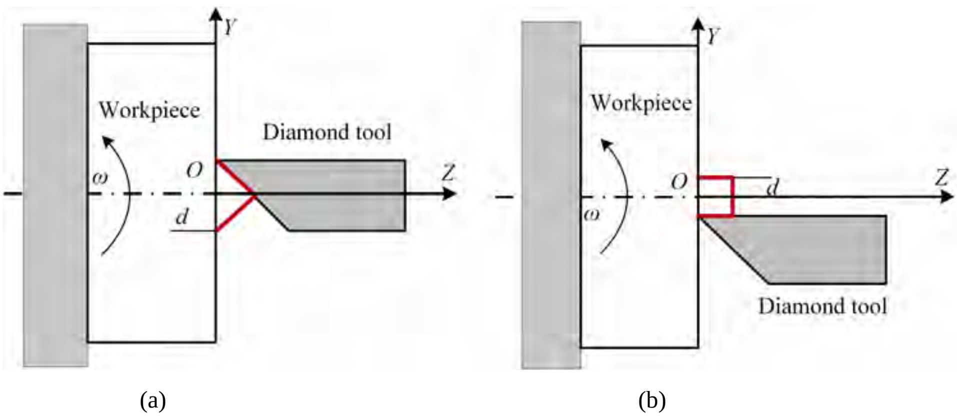
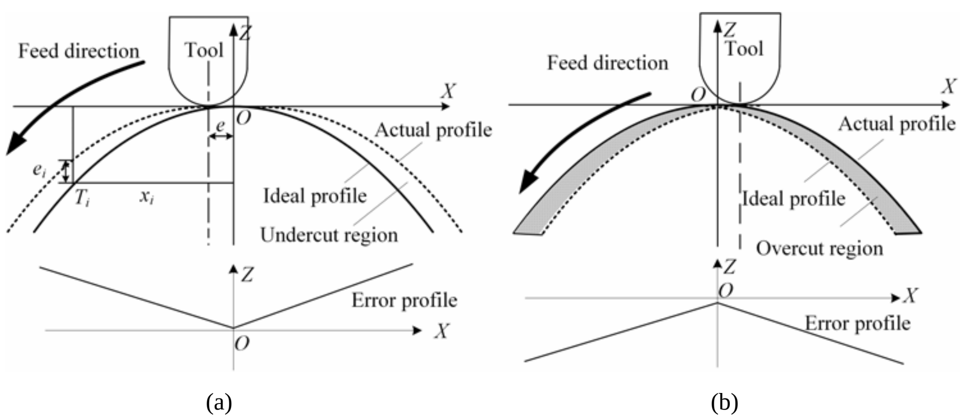



**Figure 3** Eccentricity error in X-direction for turning convex surface, (a) inner eccentricity and (b) outer eccentricity of the convex surface




## 3.2 *Eccentric error and compensation in X-direction*

The eccentric error of turning tool in X-direction has a great influence on the shape accuracy. Figure 3 shows the shape of the profile error caused by the eccentric error of the turning tool in the X-direction when turning convex surfaces. The shapes are approximate ‘V’ and ‘Λ’. As shown in Figure 3(a), if there is an internal eccentric error when turning convex workpieces from the centre to the outside, and there will be undercut areas at the vertex and outside of the work-piece, the profile error is shown as a ‘V’ shape. Similarly, when the external eccentricity exists in Figure 3(b), the workpiece vertex and the external overcut area generate, and then the profile error is in the shape of

'Λ'. Therefore, the type of eccentric error of the turning tool in X-direction can be distinguished by measuring the shape of the profile error.

Figure 3(a) shows the contour offset when there is an internal deviation in the X-direction of the convex workpiece. The relationship between the eccentric value $e$ and the contour error value $e_i$ at the machining point $T_i$ can be expressed as:

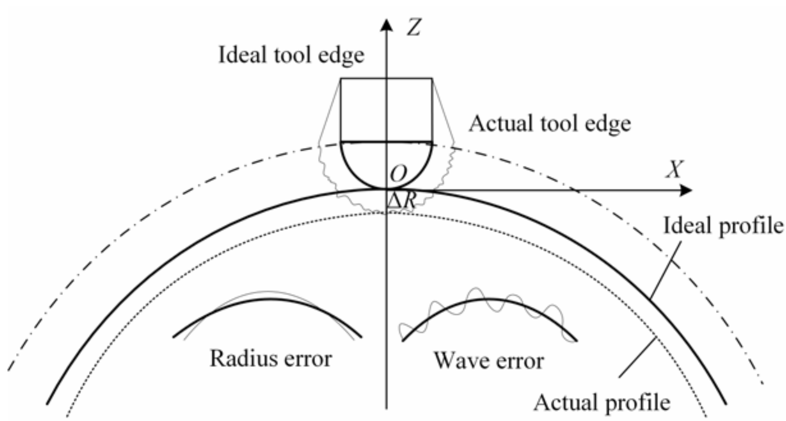
$$f(x_i - e) + e_i = f(x_i) \tag{1}$$

where $f(x)$ is the curve equation of the ideal axisymmetric surface contour. The formula can be obtained by the multiple iteration method. Meanwhile, the calculation method is also applicable to other surface types and eccentric situations.

## *3.3 Tool edge error and compensation*

The diamond tool after being used several times and recycled will have edge error. The dotted line in Figure 4 is the actual machining surface, while the solid line is the ideal machining surface. There are two kinds of edge errors. One is the waviness error of the tool arc edge. With the gradual wear of the tool edge, the waviness error gradually increases, and the workpiece surface quality also increases. The waviness error can be minimised by regularly grinding the cutting edge or changing the position of the arc cutting edge. The other is the radius error of the cutter edge. If the arc radius of the tool cannot be accurately determined during machining, the workpiece will have obvious shape errors. Especially for turning high-gradient aspheric surfaces, the edge error of diamond tools has a great influence on the final surface shape. The larger the relative aperture of the aspheric surface, the larger the argument angle between the tool edge and the circular arc of the workpiece surface, and the greater the influence of the tool edge error on the surface shape error of the workpiece. The compensation method of tool edge error is generally to measure the turned surface and feedback on the measurement results for compensation turning. In particular, if the B-axis rotation mode is adopted, the radius error and waviness error of the tool can be effectively solved.

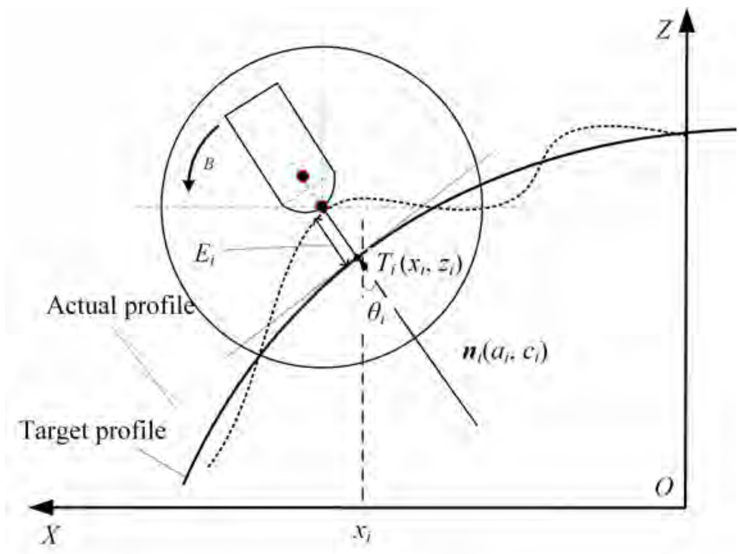
**Figure 4** Edge errors of the circular turning tool



### 3.4 Profile error compensation based on B-axis

When single-point turning based on a rotating B-axis, the fixed cutting edge of the arc tool always removes materials along the normal direction of the machined surface, so that the tool edge error can be effectively avoided from being reflected on the workpiece. It is convenient to turn the high-gradient aspheric surface, which is more consistent with the normal compensation law. The profile error compensation procedure is shown in Figure 5.

**Figure 5** Profile error compensation of single-point diamond turning based on B-axis




The original measurement error value contains high-frequency interference signals, which must be filtered. The normal error $E_i$ is calculated by analysing the normal distance between the ideal curve and the actual turning contour curve. During compensation processing, the top edge of the turning tool moves the corresponding error value $E_i$ along the normal direction of the target contour curve. $n_i$ is the normal vector of $T_i(x_i, z_i)$ on the target curve. $\theta_i$ is the angle between the normal vector $n_i$ and the Z-axis, that is, the rotation angle of B-axis. The path of the new turning point ($X_i$, $Z_i$, $B_i$) after compensation can be expressed as:

$$\begin{aligned} X_i &= x_i + E_i \sin\theta_i \\ Z_i &= z_i - E_i \cos\theta_i \\ B_i &= \theta_i \end{aligned} \quad (2)$$

where $B_i$ is the rotation angle of the rotary table. The machining surface is processed in a 'machining-measurement-compensation' cycle many times, and the shape error is gradually corrected to finally obtain the required quality.

# 4 Turning compensation of high-gradient aspheric surface

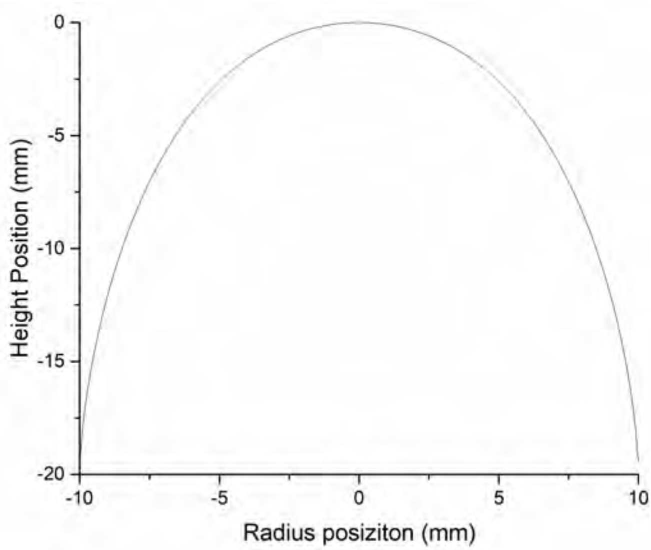
## *4.1 Aspheric surface expression*

The mathematical expression of the convex aspheric surface with a high gradient is

$$z = \frac{cx^2}{1+\sqrt{1-(k+1)c^2x^2}} + \sum_{i=2}^{n} A_i x^{2i} \tag{3}$$

where $c$ is the paraxial curvature and $c = 1/R_0$, $R_0$ is the base radius of curvature, which is 5.5 mm. $k$ is the eccentricity of the quadric surface, $k = -0.7$. $A_2$ is 0.000284, and the effective diameter is 20 mm. The shape of high-gradient aspheric surface is shown in Figure 6.

**Figure 6** Convex aspheric surface with high-gradient




## *4.2 Single-point diamond rough turning*

Red copper materials are used for experimental testing to verify the ultraprecision turning and compensation method for high-gradient aspheric surfaces. The data points of the aspherical curve are given according to Figure 6. Straight line fitting is performed with an interval of 0.001 mm. Rough turning is performed from the work blank. The diameter of workpeice is 20 mm. The rhombic blade with a tip angle of 80 degrees is used. The back angle is 0, the blade thickness is 4.76, and the tip arc is 0.8. Rough turning conditions include a revolving speed of 400 r/min, the back-cutting amount of 1 mm, and a feed rate of 0.15 mm/r, as shown in Figure 7(a). Then fine turning conditions include a revolving speed of 800 r/min, back-cutting amount of 0.25 mm, and feed rate of 0.05 mm/r, as shown in Figure 7(b). The processed workpiece is shown in Figure 7(c).

**Figure 7** Single-point diamond (a) rough turning and (b) fine turning for (c) turned sample (see online version for colours)

(a) (b) (c)

## *4.3 Ultraprecision turning and compensation*

The four-axis ultraprecision machining platform is used for the single-point diamond turning experiment in Figure 8(a). The equipment platform is Nanoform 250, and the guide rail travel is 220 mm; the maximum feed is 4000 mm/min; the rotary volume is 220 mm; the maximum load is 60 Kg; the maximum spindle speed is 7000 RPM; the straightness of XZ axis is 0.2 μm, and the perpendicularity of XZ axes is 0.375 μm.

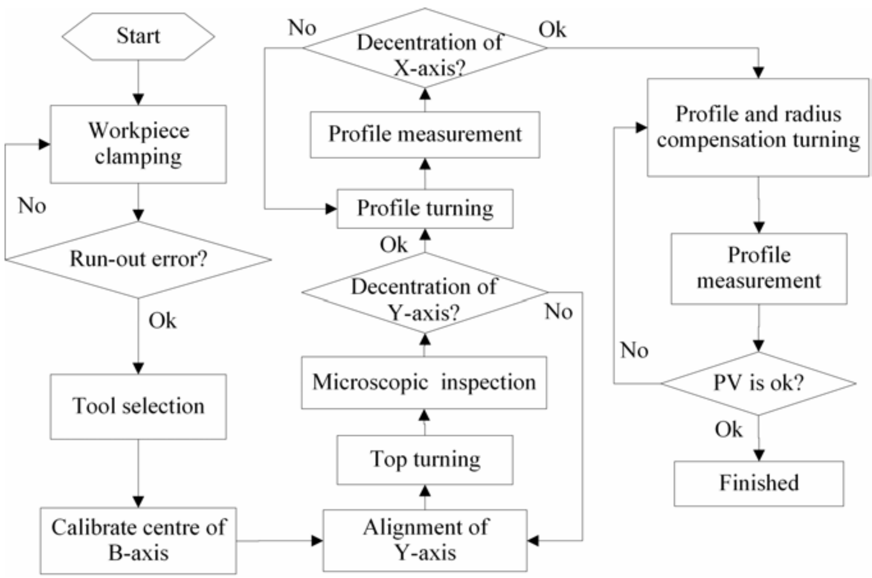
**Figure 8** (a) Schematic diagram of single-point diamond turning device and process based on B-axis platform (b) Vertex turning (c) Turning process (see online version for colours)


(a) (b) (c)

The diamond tool holder is installed on the rotary table that can move forward and backwards with the X-axis platform. The workpiece is installed on the workpiece spindle that can move along the Y-axis and Z-axis. The machining condition includes the workpiece speed of 300 r/min, the feed speed of 2 mm/min, and the cutting depth of 1 μm. A natural diamond turning tool with an arc radius of 0.5 mm is used. During the cutting process, oil mist is used for cooling, and the turning direction is from the centre to the outside. Figure 8(b) shows the process of machining aspheric vertex, and Figure 8(c) shows the process of turning aspheric surfaces.

The process flow of single-point diamond turning and compensation is shown in Figure 9. The clamped workpiece was checked and calibrated to ensure that the installation runout is within the required range. A suitable turning tool was selected to be clamped on the tool holder. The rotation centre of the B-axis was corrected and determined so that the turning tool tip can rotate fixedly around the centre of the B-axis. Through observing the movement of X and Y axes by using a CCD microscope, the tool position was set in XY directions. After turning on the top of the workpiece, analysing the Y-axis eccentricity through the CCD microscope, and the offset error of the turning tool was adjusted and compensated in Y-direction; According to the aspheric surface data, the workpiece was turned, and the deviation curve after machining is measured. The turned workpiece was uninstalled from the ultraprecision machine and installed on the ultraprecision measurement system, which is Form Talysurf PGI 1240. It is an aspheric optical measuring instrument with unique properties suitable for small to medium size. The error profile was measured the deviation curve is measured, and the PV value is also obtained. The eccentric error in X-axis is automatically calculated and compensated according to the error curve for the X-direction. Finally, profile error compensation and tool wear error compensation are carried out until the PV value meets the requirements.

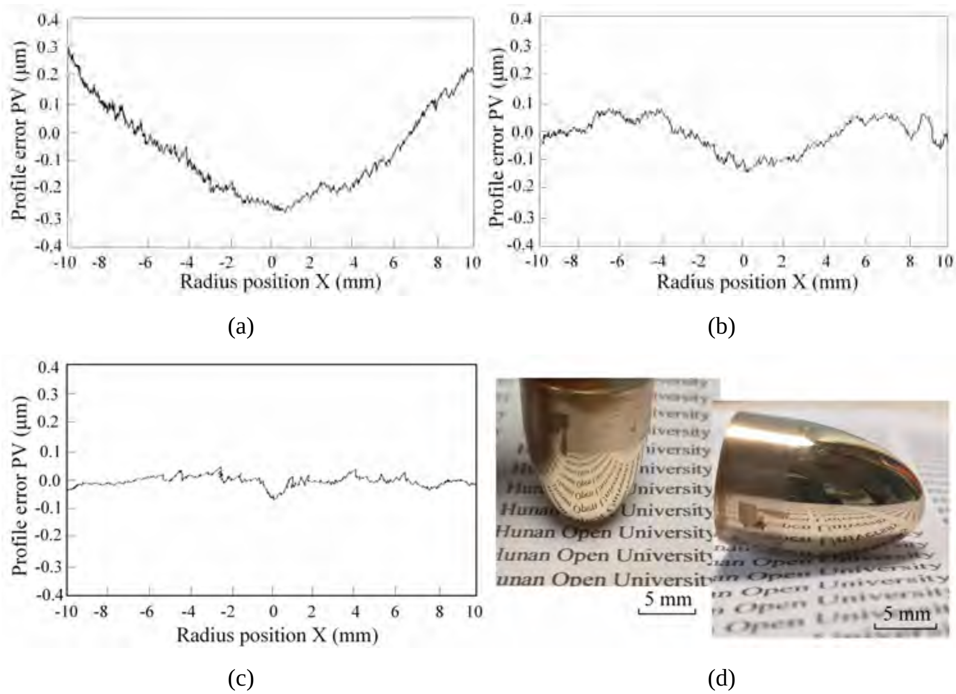
**Figure 9** Single-point diamond turning compensation process




## *4.4 Results and analysis of ultraprecision turning compensation*

After single-point diamond turning according to the processing parameters, the profile error curve shown in Figure 10(a) is obtained, and the PV value is 590 nm. The changing trend in error curve is obvious, with concave in the middle and protruding on both sides. It can be determined that there is an internal deviation in the X-direction. The tool setting error in the X-direction is compensated by adjusting the centring position of the turning tool in the X-direction, and recalling in the CNC program again for the new processing. After turning, the measurement is carried out to obtain the shape error curve as shown in Figure 10(b), and the PV value is improved to 261 nm. The shape error curve changes slightly, showing a wavy type, and the eccentric error in X-direction is eliminated. The normal error between the ideal and the actual contour curve is calculated, and the error value is transferred into the processing program to compensate for the form error. After ultraprecision turning, the measurement is carried out to obtain the profile error curve as shown in Figure 10(c), and the PV value is improved to 103 nm. Figure 10(d) shows the sample after ultraprecision turning. Through software compensation, the shape accuracy of the high-gradient aspheric workpiece has been significantly improved.

**Figure 10** Single-point diamond turning and compensation, (a) PV 590 nm after fine turning (b) PV 261 nm after eccentric compensation in X-direction (c) PV 103 nm after profile error compensation (d) sample after ultraprecision turning (see online version for colours)




## 5 Conclusions

In this paper, a single-point diamond turning based on XZB-axes mode was studied to improve the machining accuracy of high-gradient aspheric surfaces through error analyses and experimental methods. The main results are summarised as follows,

1 A single-point diamond turning method and compensation process for high-gradient aspheric surfaces with XZB-axes are proposed, and good machining stability and accuracy are obtained.

2 The influence of eccentric error (X and Y directions) and edge error of single-point diamond turning tool on the shape accuracy is analysed. The normal error compensation method of rotating B-axis single-point diamond turning is adopted, which is conducive to the error compensation in the actual processing process, and further improves the processing accuracy and surface quality.

3 The aspheric turning and error compensation experiment of high-gradient were carried out on a four-axis ultraprecision platform. After three turning cycles, the shape accuracy of the workpiece is improved from PV 590 nm to PV 103 nm, and a high-precision surface is obtained.

4 This method can also be applied to other types of ultraprecision turning, ultraprecision grinding and ultraprecision polishing technologies for aspheric surfaces and concave surfaces.

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