Direct Ion Beam Figuring Process and Rotational Measurement Method for Ultra-smooth Aspherical Surfaces of a 46.5 nm Telescope (Postprint)

Authors:

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Full Text

Direct Ion Beam Figuring Process and Rotational Measurement Method for Ultra-Smooth Aspherical Surfaces of a 46.5 nm Telescope

Weichen Gu[12], Jun Yu[12]*, Pengfeng Sheng[12], Qiaoyu Wu[12], Qiushi Huang[12], and Zhanshan Wang[12]

[1] Key Laboratory of Advanced Micro-structured Materials, Ministry of Education, Tongji University, Shanghai 200092, China; yujun_{88831}@tongji.edu.cn

[2] Institute of Precision Optical Engineering, School of Physics Science and Engineering, Tongji University, Shanghai 200092, China

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Keywords: EUV telescope, optical system, ultrasmooth mirror, Sun: UV radiation

1 Introduction

There have been some satellites equipped with extreme ultraviolet (EUV) telescopes—for example, SPICE (SPICE Consortium et al. 2020) and SDO-AIA (Fineschi et al. 2009; Lemen et al. 2011)—to perform various solar observations. However, there is no available equipment for probing the solar high transition region. Now, with the advance of EUV multilayers, it is possible to fabricate a 46.5-nm solar telescope to observe the solar high transition region with a bandwidth of less than 3 nm. A 46.5-nm telescope would be designed as a Ritchey-Chretien configuration with a field of view of 42 arc min and imaging resolution of 6 arc sec. The primary mirror would be a hyperboloidal concave surface, with an aperture of 180 mm, a radius of 1164 mm, a conic coefficient of 1.40454, and a maximum asphericity of approximately 2 µm. Because the optical resolution of the 46.5-nm telescope is influenced mainly by the accuracy of the surface profile of machined reflectors and the optical collection efficiency its limits are set mainly by the surface reflectivity, which, in turn, can be seriously degraded by surface roughness. Thus, a hyperboloidal concave mirror with sub-nanometer roughness (Solak et al. 2001) (RMS <0.5 nm) and a nanometer-level surface profile error (RMS <10 nm) is a needed core optical element for an EUV telescope.

Needing a super smooth aspheric characteristic, the hyperboloidal concave mirror cannot be machined by classic optical fabrication methods. The computer controlled optical surfacing (CCOS) technology (Greenleaf 1980) is an optical fabrication method that can efficiently modify the surface profile (Jones et al. 1990), including magnetorheological finishing (MRF) (Jacobs et al. 1995), bonnet polishing (BP) (Lee et al. 2010; Wang et al. 2014), and ion beam figuring (IBF) (Allen & Keim (1989); Drueding et al. (1995)). MRF and BP are contact figuring methods, often used to form aspherical surfaces quickly. However, these contact methods can introduce subsurface damage, and the residual polishing slurry may easily lead to more surface roughness (Du et al. 2021). IBF is a non-contact figuring technology, which can remove substrate material at the atomic level. IBF is performed under a vacuum without polishing contamination, and can achieve both superior surface profile accuracy and very low roughness (Chkhalo et al. 2016, 2017). Thus, IBF is an attractive choice as a final step to finish the super smooth surface figuring for the hyperboloidal concave mirror. For higher machined surface accuracy, surface profile measurements of the hyperboloidal concave mirror should be conducted often during iterative IBF. Aspherical surface interferometry has the advantages of high precision and efficiency, and includes null test and non-null test methods.

Non-null test methods often require some complex correction methods to compensate for system errors, such as partial null test and sub-aperture stitching interferometry (Liang et al. 2022). Null test methods, such as Offner compensation (Offner 1963) and Dall compensation (Malacara et al. 2007), conveniently correct the aspherical aberrations of the optical testing system using a compensation lens. The Dall compensation has only one compensator, and the entire optical path is less than for the others. Thus, the Dall compensation method has the advantages of fewer lenses and shorter optical path, and could be adopted in our measurements. However, this common null test may not fully satisfy the measurement demand with sub-nanometer accuracy due to errors in the reference surface profile, compensator surface profile, and residuals. For higher measurement accuracy, the rotational method (Evans et al. 1996; Freimann et al. 1999) can be used to reduce such error in the interferometry. Combination of the null test and the rotational method is a good solution to balance efficiency and accuracy. In particular, the method of solving for the system errors in the machined surface, as well as the number of rotation times, also needs to be taken into consideration when solving for the machined surface profile by rotational measurement.

In this work, a high precision hyperboloid concave mirror was fabricated by IBF and measured by the null compensation method. In Section 2, the direct figuring process of the hyperboloidal concave mirror from a spherical surface to an aspherical surface by IBF is described. In Section 3, a high-precision aspherical measurement method combining a rotational measurement and null compensation method is described. Also, the residual measurement errors of the two methods are analyzed with the goal of optimizing the fabrication flow. Section 4 deals with the efficient fabrication of the hyperboloid concave mirror using an optimized process and with the proposed subsequent measurement method.

2 Direct Figuring Process for Ultra-Smooth Aspheric Surfaces

Because the surface roughness of a reflective mirror made of fused silica can be diminished using an ion beam etching process (Chkhalo et al. 2014; He et al. 2021) and because the fused silica has a low thermal expansion coefficient (Xie et al. 2012), the hyperboloidal concave mirror substrate is made of fused silica. Specifically, this aspheric surface can be fabricated from the spherical surface directly based on IBF, and with an experimental etching depth of more than several hundred nanometers, it is possible to obtain an ultra-smooth surface efficiently (Barysheva et al. 2013; Chkhalo et al. 2016).

Based on the null compensation method, this hyperboloidal concave mirror can be measured by a single lens null compensator. The single lens null compensator should therefore be fabricated first. Because the manufacture accuracy of the null compensator can influence the aspherical surface directly, the single lens null compensator should also be machined by IBF. A flow chart of the direct figuring process is shown in Figure 1 [Figure 1: see original paper]. The initial mirror surface is first machined by chemical mechanical polishing (CMP). The main purpose of CMP is to obtain supersmooth surface with subnanometer roughness (initial surface roughness is 0.799 nm RMS). Before the hyperboloidal concave mirror is fabricated, the null compensator is machined with nanometer surface accuracy. Thus, the spherical surface of the null compensator is machined to improve surface figure accuracy by iterative IBF. The null compensator is measured by rotational measurement to modify the machined surface profile. Then, the aspherical figuring is achieved by iterating several cycles to reach the null compensation measurement range. During the aspherical mirror measurement, the rotational measurement method combined with null compensation is applied. After the preliminary and precise iterative stages, the desired aspherical surface can be achieved. The surface roughness of the machined mirror is then scanned by atomic force microscopy (AFM) to compare the roughness before and after the IBF.

3 IBF Figuring and Surface Profile Rotational Measurement

The IBF was conducted using an ion beam device, SCIA trim200, with an RF ion source (Ar), which contains XY axes for controlling the linear movement of the mounted mirror. The RF ion source is mounted on the Z axis, and rotates through angle around the X axis. The ion-beam source parameters can significantly affect the roughness (Chkhalo et al. 2014). The initial ion-beam source working parameters are listed in Table 1 . The etching rate is approximately proportional to the beam voltage. The selected beam voltage is

1500 V, which balances machining efficiency and machined surface roughness.

3.1 IBF Figuring and Calibration

Considering possible large sag deviation of the hyperboloidal concave mirror from the center to the edge, the IBF footprint and the angle etching compensation need to be calibrated accurately. For each measurement, the surface profile is used to produce a simulation result of the removal, where the amount of material removed at each point is determined using the dwell time algorithm. The amount of material removed at a point Z(x, y) in IBF can be expressed as a convolution of the removal function G(x, y) and the dwell time t (x, y):

$$Z(x, y) = G(x, y) \otimes t(x, y)$$

The surface shape profile can be measured before machining, and the dwell time at each point is determined directly by the removal function. To obtain the exact removal function G(x, y), the IBF removal function is obtained by a single-point etching experiment and a Gaussian fit is performed to initialize the etching rate, as shown in Figure 2(a) [Figure 2: see original paper]. The calibration of the IBF rate proceeds as follows:

A. A wedge etching experiment is used to calibrate the etching rate with linear fitting. During the wedge etching stage, the difference between the actual etching rate and the etching rate obtained by single point etching can cause a difference between the actual removal amount and the theoretically removal amount. As shown in Figure 2(b) [Figure 2: see original paper], through a linear fitting of the actual removal amount, the real etching rate can be obtained as the single point etching rate multiplied by the slope.

B. An angle etching experiment is performed to compensate the etching rate error caused by the slope of the surface. A correction matrix can be obtained in this experiment, and can be used to correct the etching rate at different positions on the surface, as shown in Figure 2(c) [Figure 2: see original paper].

3.2 Surface Figure Measurement and Analysis

The Dall null test is an aspherical measurement method requiring a high-precision compensator. The compensator should therefore be machined and measured before the hyperboloidal mirror is fabricated. The Dall null test configuration is shown in Figure 3 [Figure 3: see original paper], where the null test is conducted by a Zygo interferometer. The detailed design parameters of the null test are shown in Table 2 .

In our test optical path, we pre-manufactured the rod of a fixed length to calibrate the position of optical components in the test according to design. We measured the length of rod precisely using calipers, and the error is within 20 microns. The distance deviation can be converted to the errors in radius R and conic coefficient K according to the Figure 4(a) [Figure 4: see original paper], and it is a trivial value (not more than 0.002%). From Figure 4(b) [Figure 4: see original paper] and Figure 4(c) [Figure 4: see original paper], we can know that the wavefront change due to the distance deviation can be offset by optimized radius R and conic coefficient K. The distance deviation can ultimately be translated into an adjustment value for the spacing between the primary and secondary mirrors in the system. It also can be observed from the designed system (Figure 4(d) [Figure 4: see original paper]) to system with optimized coefficients (Figure 4(e) [Figure 4: see original paper]) that the spot diagram has not been significantly affected.

When the profile error is larger than several hundred nanometers, the preliminary figuring stage can be performed without considering measurement system errors, including mainly reference surface profile error, compensator surface profile error, and residual alignment errors. When the surface profile error is reduced to the nanometer level, the measurement system errors cannot be ignored. The measurement results include the surface profile error and the system errors, which can be analyzed by the reconstructed optical measurement model. The surface profile and position of these optical elements in the model need to be measured accurately. The reference spherical surface on the Zygo interferometry can be calibrated with a standard reflective mirror, and directly subtracted from the subsequent measurement result. Because it is difficult to measure the residual alignment errors of the null compensator during aspheric measurement, the measurement errors on the null compensator cannot be fully eliminated.

When the surface profile reaches nanometer level, rotational measurement methods are performed at a precise iterative stage, as shown in Figure 5(b) [Figure 5: see original paper]. The rotational measurement method can separate the machined surface profile from the measurement wavefront by rotating and averaging these measurement results (Evans & Kestner 1996A). The rotational measurement is a better method for reducing the system errors; it directly simplifies the decomposition of various types of errors. At this stage, the measurement wavefront can be expressed by W = E + M, where E is the sum of the system errors and M is the machined surface profile. For any circular aperture, the wavefront can be expressed by Zernike polynomials:

$$W(r,\theta)=\sum_{k,l}R_k^l(r)(a_k^l\cos k\theta+a_{-k}^l\sin k\theta)$$

Here $R_k^l(r)$ is the radial term, a_k^l is the magnitude of the angular term, r is the normalized radius, θ is the angular coordinate, k is the rotational order, and l is the radial order. After rotation of the angle ϕ, the wavefront can be expressed as:

$$W(r,\theta+\phi)=\sum_{k,l}R_k^l(r)[a_k^l(\cos k\theta\cos k\phi-\sin k\theta\sin k\phi)+a_{-k}^l(\sin k\theta\cos k\phi+\sin k\phi\cos k\theta)]$$

ϕ is the angular interval (equal to $i \times 60^{\circ}$). The sums of these wavefronts are expressed as:

$$\sum_{i=0}^{5} W_i^{kl} = 6E_k^l \cos(ik60^{\circ}) + M_{-k}^l \sin(ik60^{\circ})$$

$$\sum_{i=0}^{5} W_i^{-kl} = 6E_{-k}^l + [M_{-k}^l \cos(ik60^{\circ}) - M_k^l \sin(ik60^{\circ})]$$

Here W_i^{kl} and W_i^{-k} are positive and negative rotational order terms of wavefront polynomial after each rotation, respectively. The summed wavefront contains unrotated part (the sum of the system errors E_{-k}^l) and the rotated terms of machined surface part. For $k = 0$, Equation (4) and Equation (5) can be written as:

$$\sum_{i=0}^{5} W_i^{0l} = 6E_0^l + 6M_0^l$$

which is a summary of rotational symmetric terms. Because of the orthogonality of trigonometric functions, the non-N-order terms $k \neq N$ are eliminated. After averaging the six-angle measurement results, the averaging wavefront from Equation (4), Equation (5) and Equation (6) is:

$$\bar{W}_k^l = E_k^l$$

in which $\bar{W}_k$ is the calculated result of the averaging. The machined surface profile M and the term E can be calculated in contrary ways. The M_0 terms cannot be eliminated by this method. If the rotated component is E, the E_0 terms cannot be eliminated. Equation (7) is changed to Equation (8):

$$\bar{W}_k^l = M_k^l + E_0^l$$

The number of rotations and the calculating methods were researched as follows. As shown in Figure 5(a) [Figure 5: see original paper], at the beginning of the precise iterative stage, the N-angle averaging result by single measurement data is simulated. According to a principle similar to that of Equation (7) and Equation (8), the N-angle averaging result T_{avg-N} can be expressed as:

$$T_{avg-N} = E_0^l \pm N \times j + M_0^l \pm N \times j$$

In machining and rotational measurement, the difference between the calculated machined surface profile and the actual result M contains either the first two terms or the last two terms of Equation (9). The angular order of the term increases with the rotation number in Equation (9). Thus, the remaining accumulation of $N\times$ times angular-order terms can be derived from the comparison between different numbers of rotations (N-angle averaging).

In order to calculate the machined surface profile, there are two different methods, as shown in Figure 5(c) [Figure 5: see original paper]. The first method is to rotate the measurement wavefronts to the same angular position and average them. The second method is to calculate the system errors by averaging the wavefront directly and then subtracting this error from the measured wavefront to obtain the machined surface profile. We call the first method the ME method, and the second method the EM method.

When the machined surface profile is close to the system errors, the difference between the two methods is that the residual terms to be solved are, respectively, $(M_{EM})_0$ and $(M_{EM})_{\pm 6\times j}$. The original results of each measurement are W_i, where i ($i = 0, 1, 2, 3, 4, 5$) labels the measurement sequence and a subscript designates the calculation method—i.e., $[W_i]_{EM}$ means the EM method, and the square bracket means that several results are included.

The EM method is shown as left side of Figure 6 [Figure 6: see original paper]: the initial measurement results $[W_i]_{EM}$ at the six equally divided angles are rotated to the same marked position and averaged, which eliminates the additional wavefront errors in the test results and leaving only the N order terms and the rotational symmetric terms. The image alignment of the calculation process relies on the markers on the mirror. The system errors E_{EM} and the machined surface profile M_{EM} can be calculated by:

$$E_{EM} = \sum_{i=0}^{5}[W_i]_{EM}/6 = (E_{EM})_k^l + (M_{EM})_0$$

$$M_{EM} = \sum_{i=0}^{5}([W_i]_{EM} - E_{EM})/6 = (M_{EM})_k^l \pm (M_{EM})_0$$

The ME method: as shown in left side of Figure 6 [Figure 6: see original paper]. In this method, the machined surface profile M_{ME} and the system errors E_{ME} can be calculated by:

$$M_{ME} = \sum_{i=0}^{5}([W_i]_{ME} - \bar{W})/6 = (M_{ME})_k^l + (E_{ME})_0$$

$$E_{ME} = \sum_{i=0}^{5}([W_i]_{ME} - M_{ME})/6 = (E_{ME})_k^l \pm (E_{ME})_0$$

To evaluate which of the two methods is better, separating higher-order angular terms for comparing the methods is necessary. The 12-angle rotational measurement is carried out after the 6-angle rotational measurement, as shown in Figure 7 [Figure 7: see original paper], according to each of the two methods, and the calculated system errors of the EM method in the 6-angle rotational measurement can then be obtained (Eq. (14) below):

$$E_{EM-12} = \sum_{i=0}^{11} [W_i]_{EM}/12 = (E_{EM})_k^l + (M_{EM})_0 \pm (M_{EM})_{\pm 12\times j}$$

and the calculated machined surface profile of the ME method in the 12-angle rotational measurement can then be obtained (Eq. (15) below):

$$M_{ME-12} = \sum_{i=0}^{11} ([W_i]_{ME} - \bar{W})/12 = (M_{ME})_k^l + (E_{ME})_0 \pm (E_{ME})_{\pm 12\times j}$$

The calculated machined surface profile and system errors between the 6-angle and 12-angle rotational measurement give the $6\times(2j-1)$ order rotational terms without the rotational symmetric terms. The summary of $6\times(2j-1)$ order rotational terms of the machined surface profile is expressed by Equation (16) below, which is the difference between Equations (10) and Equation (14). The summary of $6\times(2j-1)$ order rotational terms of system errors is expressed by Equation (17) below, which is the difference between Equation (12) and Equation (15).

$$\Delta M_{\pm 6\times(2j-1)} = (M_{EM})_{\pm 6\times(2j-1)}$$

$$\Delta E_{\pm 6\times(2j-1)} = (E_{ME})_{\pm 6\times(2j-1)}$$

As approximations, these equations can be considered to reveal mainly the error contained in the 6th order angular terms (the 18th order angular terms and the higher order angular terms are negligible). After the above calculations, the 6th order angular terms can be obtained to evaluate the ME and EM methods. Figure 8(a) [Figure 8: see original paper] shows $(M_{EM})_{\pm 6}$ and $(E_{ME})_{\pm 6}$ for Equation (17). The machined surface profile error (RMS 2.89 nm) is obviously larger for Equation (16), and Figure 8(b) [Figure 8: see original paper] shows than the system errors. Thus, the ME method can provide a more accurate surface profile than the EM method. Accordingly, the calculated result of the ME method by the 12-angle rotational measurement was used to compensate the surface profile.

The relationship between the number of measurement and the machined surface profile in multiple rotational measurements is shown in Figure 9 [Figure 9: see original paper]. The results of different rotation times indicate that the 6-time rotational measurement can provide a good enough result, so that a higher-number rotation time is not necessary.

4 Results

4.1 Null Compensator

The null compensator is finished in an iterative process with rotational measurements to obtain a final surface profile. Figure 10 [Figure 10: see original paper] shows the final two surface profiles of the compensator after iterative IBF. The front (Figure 11(a) [Figure 11: see original paper]) and back (Figure 11(b) [Figure 11: see original paper]) initial surface-profile RMS values of the compensator are, respectively, 63.18 nm and 41.23 nm, after the figuring of the surface profiles reduces the error to 3.84 nm and 4.29 nm.

4.2 Hyperboloidal Concave Mirror

Before performing null compensation, the initial surface of the hyperboloidal concave mirror should be machined by IBF to meet the requirements of the null test range. IBF results are shown in Figure 11 [Figure 11: see original paper]. The surface profile of the closest spherical surface reduces from an initial surface of 326.86 nm RMS to 45.57 nm RMS. After the surface profile is close to that of a sphere, the aspheric surface measurement, as shown in Figure 3 [Figure 3: see original paper], is conducted by using the null compensator. The aspherization process can been divided into two stages, as shown in Figure 12 [Figure 12: see original paper]. First is a preliminary iterative stage. Here, the main figuring is focused on the aspherical surface deviation errors based on the closest spherical surface. When the surface profile error is figured for a long time, the ion-beam footprint variation due to the heating effect significantly reduces the surface profile accuracy.

The surface profile error value of the hyperboloidal concave mirror is about 2 µm PV, and the surface profile slope at the edges exceeds the axis acceleration limitation of the IBF. Thus, the whole etching process can be divided into eight cycles. After the preliminary iterative stage, the surface profile is 41.67 nm RMS. The rotation number during the rotation measurement should be confirmed after the rough iterative stage. Second is the precise iteration: After determining the 6-angle rotational measurement to be performed, the precise iterative stage is performed, based on iterative figuring and the results of the 6-angle rotational measurement. After two cycles of iterative figuring, the surface profile finally reaches 8.27 nm RMS. As shown in Figure 12 [Figure 12: see original paper], the machined surface remains some mid-frequency errors after several rotational measurements and iterative figuring. The surface roughness is measured by using Bruker AFM, and the measurement range is 5$×$5 µm. The roughness before and after IBF are shown in Figure 13 [Figure 13: see original paper]. Many scratches can be observed from the measurement result after CMP take place as shown in Figure 13(a) [Figure 13: see original paper], and the surface roughness is RMS 0.799 nm. After ion beam figuring, the surface roughness has significantly diminished to RMS 0.160 nm (Figure 13(b) [Figure 13: see original paper]). In previous research (Chkhalo et al. 2016), they found that when fused quartz was subjected to ion beam etching under an accelerating voltage ranging from 500 to 1500 eV, and the effective roughness was improved. Furthermore, this improvement in roughness was observed to persist even when the ion beam had a low incidence angle (<30°) of incidence on the sample surface (Figure 13(c) [Figure 13: see original paper]). An increase in etching depth was also found to optimize roughness as shown in Figure 13(d) [Figure 13: see original paper]. Our experiments involving relatively maximum angle (<8°) and deep etchings (>1 µm) also satisfied this optimization criterion in the study, because in ion beam processing, we added a 200 nm base etching for each etching cycle to keep the roughness smooth, as shown in Figure 13(e) [Figure 13: see original paper] and Figure 13(f) [Figure 13: see original paper].

5 Conclusion

This paper describes hyperboloidal concave mirror fabrication and measurement of an extreme-ultraviolet telescope. The direct IBF method and the rotational compensation method were both used to improve the surface figure and diminish the roughness. By measuring the single surface figure, the averaging result at different rotation angles were used to evaluate the rotational measurement times. The rotational measurement method can greatly reduce the system errors; it balances efficiency and accuracy before the high-precision stage. The ME and EM methods of rotational measurement were analyzed, and the ME method was found to yield a more accurate calculated machined surface. In our experiment, the spherical surface profile of a null compensator reached to 4 nm RMS. Combining rotational measurement and iterative figuring, the hyperboloidal concave mirror surface profile was modified from 326.86 nm RMS to 8.27 nm RMS. The roughness has also been diminished from 0.799 nm RMS to 0.160 nm RMS.

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