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SURFACE TWIST CHARACTERIZATION AND COMPENSATION OF AN ELLIPTICALLY BENT HARD X-RAY MIRROR*

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Abstract

Adaptive optics, including bendable and bimorph mirrors, have been widely used for hard X-ray dynamical focusing and wavefront correction. A recently developed elliptically bent mirror based on a laminar flexure bending mechanism has shown excellent performance. In this work, the mirror surface twist of the bent mirror was characterized using a Fizeau interferometer under different bending conditions. By applying a shimming correction, the surface twist was successfully reduced from 5.3 µrad/cm to 0.09 µrad/cm. The twist angle variation from no bending to the maximum bending is about 0.05 µrad/cm. Simulation results show that these numbers are significantly lower than the required values to ensure optimum optical performance. The study helps confirm the bender design and guides the twist compensation procedures.

INTRODUCTION

The Advanced Photon Source (APS) at the Argonne National Laboratory (ANL) is under a major upgrade with more than two orders of magnitude increase in brightness [1]. The low emittance of the APS upgrade (APS-U) source will enable nanometer focused beam with high coherent flux, which requires optics with ultra-high quality. Many APS-U beamlines also demand variable focal spot sizes to adapt to different sample feature sizes. Such a zoomable beam can only be achieved by combining multiple optics [2] and using deformable optics, e.g., bendable mirrors and bimorph mirrors [3].

A high-precision compact flexure bending mechanism has been recently designed in-house at APS to provide elliptical (or hyperbolic) shaped mirror surfaces [4, 5]. A prototype bender mirror was fabricated and has demonstrated excellent performance in achieving variable shapes and focal spot sizes [3, 6]. In this paper, the surface twist of such a bender mirror is characterized using optical metrology. Then a practical twist compensation procedure is introduced and demonstrated.

BENDER MIRROR PROTOTYPE

A photograph of the bender mirror prototype is shown in Fig. 1. The mirror has a trapezoidal shape with a length of 300 mm, a narrow-end width of 19.32 mm, a wide-end width of 36.28 mm, and a thickness of 12 mm. It is a single-crystal silicon substrate coated with Pt on the optical surface. The bending moment is applied on each end of the mirror by the flexure mechanism driven by a piezo linear actuator pushing a 65 mm long bending arm, the position of which is monitored by a capacitive sensor. There is also an array of capacitive sensors mounted underneath the mirror to record the surface profile of the bottom surface.

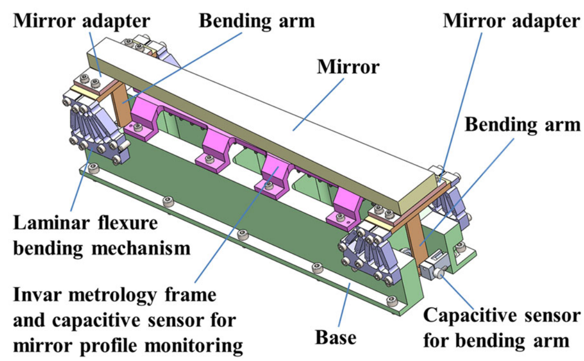

Figure 1: Photograph of the bender mirror prototype.

Although the mechanical design has shown excellent bending performance, a possible surface twist can exist due to the manufacture tolerance and the uniformity of the epoxy bonding the mirror to the adapter plates. There is no motorized or manual twist adjustment in the prototype design.

SURFACE TWIST TOLERANCE

Surface twist tolerance was studied for a typical bender mirror designed for focusing APS-U source as an example. The mirror can provide a minimum focal spot size of 200 nm. The effect of surface twist was simulated using ray-tracing software ShadowOui [7] and shown in Fig. 2.

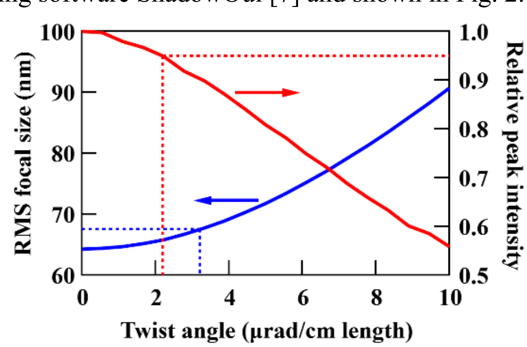

Figure 2: Simulated effects of mirror surface twist on the focal spot size and peak intensity.

As the twist angle increases, the focal spot size increases, while the relative peak intensity decrease. We specify the tolerance of the twist angle to ensure that both the focal size broadening and peak intensity reduction are less than 5%. Figure 2 shows that the twist angle needs to be smaller than 2 µrad/cm.

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METROLOGY SYSTEM

The mirror surface profile was measured using a Fizeau interferometer (AccuFiz®, 4D Technology) in the APS Metrology Laboratory (Fig. 3), which has a 100 mm aperture and uses visible laser with a wavelength of 632.8 nm. The output images have 1200×1200 pixels with a pixel size of 91.1 µm.

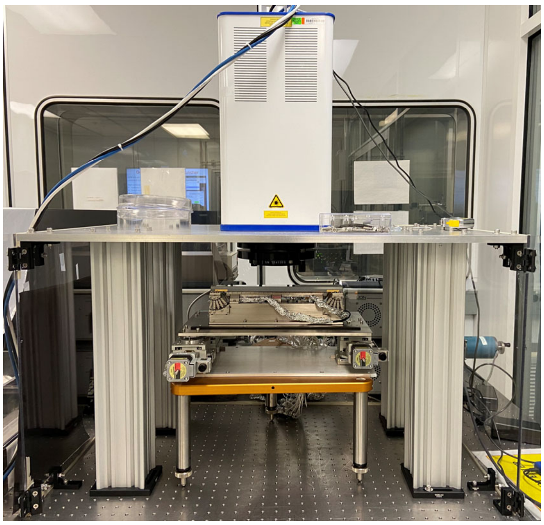

Figure 3: Photograph of the Fizeau interferometer set up to measure the bender mirror surface.

SURFACE TWIST CHARACTERIZATION

The surface profiles of the bender mirror at different bending settings were recorded, with two examples shown in Fig. 4(a) and 4(b). The bending surface curvatures of the surface were extracted by a circular fitting of centerline profiles along the mirror length [see Fig. 4(c)].

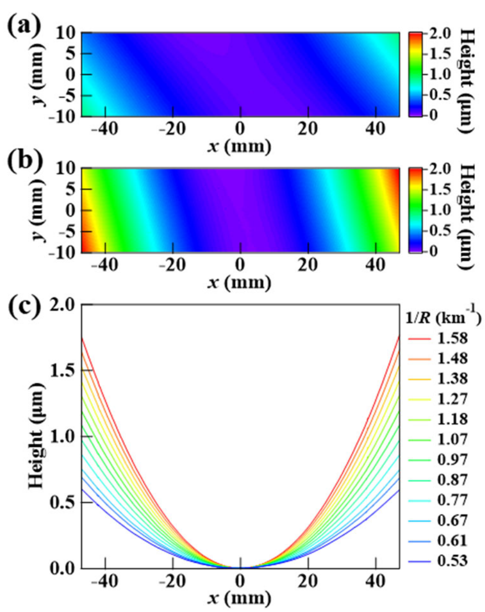

Figure 4: Mirror surface profiles with different bending surface curvatures of (a) $1/R = 0.53$ km^{-1} and (b) $1/R = 1.58$ km^{-1}, and (c) extracted centerline profiles along mirror length.

Clear surface twists exist in all 2D surface profiles at different bending surface curvatures. To quantitatively analyze the results, we extracted the twist angle, defined as the relative angle between the two end edges of the mirror, shown as the two dashed lines in Fig. 5, and normalized to the mirror length.

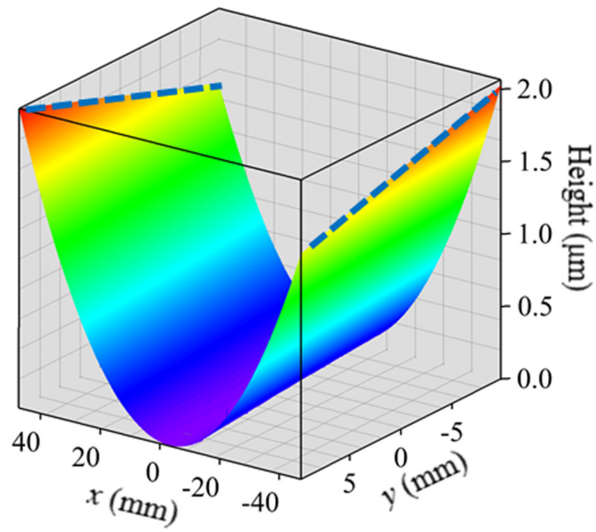

Figure 5: A 3D mirror profile with the twist angle defined as the angle between the two end edges (dashed lines).

The extracted twist angles at different bending surface curvatures are summarized in Fig. 6. The average twist angle is around 5.3 µrad/cm. The twist angle deviation from the minimum to maximum bending is about 0.11 µrad/cm. The measured twist angle is larger than the tolerance shown in Fig. 2. However, even as is, it will only reduce the peak intensity by 21% and broaden the focal size by 13%. The prototype bender mirror is already close to satisfactory, thanks to the state-of-the-art bender design and careful assembly. Further improvement can be achieved by twist compensation.

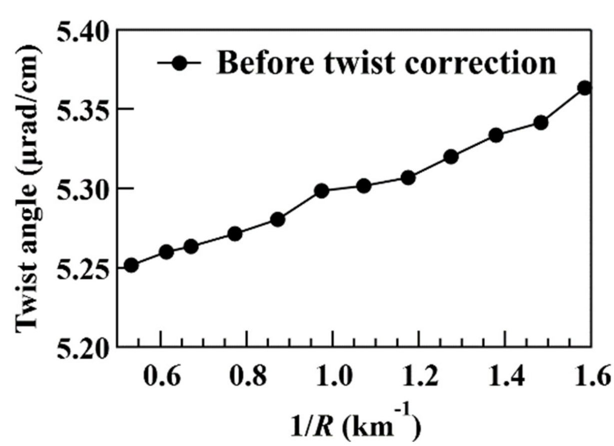

Figure 6: Extracted twist angles of the bender mirror at different bending surface curvatures before twist compensation.

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SURFACE TWIST COMPENSATION

Twist compensation was studied by shimming the mirror bender in between the adapter plates near one end of the mirror, as shown in Fig. 7. Calculation shows that a few microns thick material is needed at the location of shimming. In this study, we used a 4 µm thick Ultralen film based on availability.

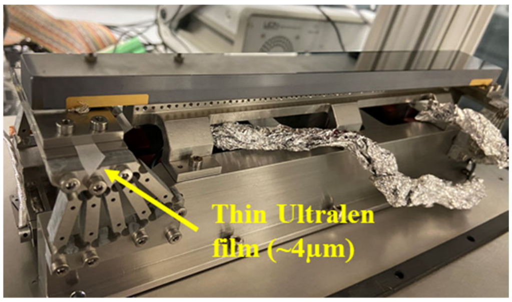

Figure 7: Photograph of the bender mirror with shimming applied for twist compensation.

The surface profiles after the twist compensation were measured and shown in Fig. 8, where the surface twist is not visible anymore. The extracted twist angles at different bending surface curvatures are summarized in Fig. 9. The average twist angle is now only 0.09 µrad/cm, significantly better than the specified tolerance. The twist angle deviation from the minimum to maximum bending is about 0.05 µrad/cm. If we simulate the mirror performance following Fig. 2, it will only affect the peak intensity and the focal size by a negligible amount (< 0.05%).

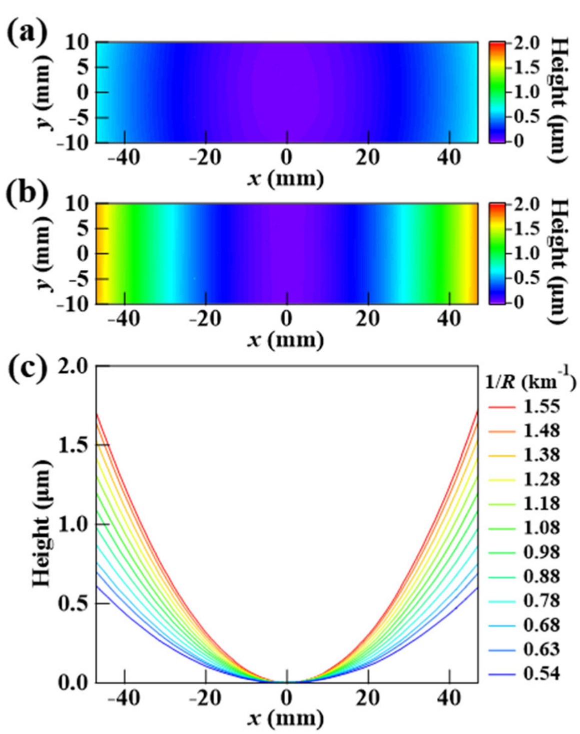

Figure 8: Mirror surface profiles after twist compensationwith different bending surface curvatures of (a) $1/R = 0.54$ km^{-1} and (b) $1/R = 1.55$ km^{-1}, and (c) extracted centerline profiles along mirror length.

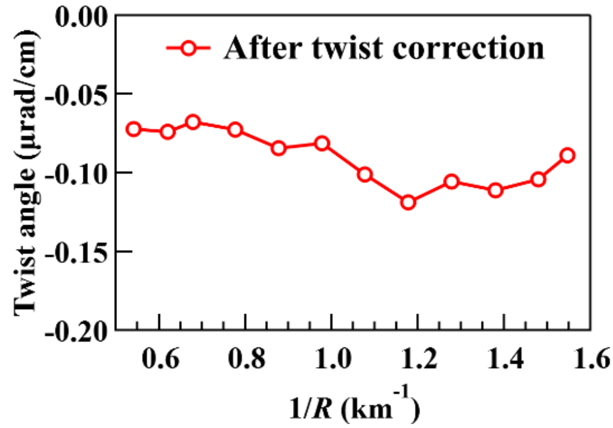

Figure 9: Extracted twist angles of the bender mirror at different bending surface curvatures after twist compensation.

CONCLUSION

The surface twist of a flexure-based bender mirror was evaluated using optical metrology. The mirror shows a slight but observable surface twist that could potentially affect the performance of APS-U nanofocusing beamlines. A practical shimming method is introduced to the current bender design for twist compensation. A final twist angle of less than 0.1 µrad/cm is demonstrated with negligible effects. The proposed method is proven to be adequate for all bender mirrors at APS-U. The study may also help the twist compensation design of future bender mirrors at other facilities.

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