Shaping of thin glass X-ray telescope mirrors using air bearing slumping and ion implantation

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ABSTRACT

Air bearing glass slumping followed by ion implantation for fine figure correction constitutes a promising process for fabricating thin glass segmented mirrors for future high-resolution x-ray telescopes. We have previously demonstrated the feasibility of both air bearing slumping and ion implantation figure correction to produce mirrors with good figure and without introducing mid spatial-frequency errors or roughness. In this work, we describe a mechanically-robust slumping tool design that can be adapted to Wolter I mirror shapes; and we describe progress on understanding ion implantation for use as a figure correction process, by using in-situ curvature measurements in a tandem ion accelerator.

Keywords: x-ray mirrors, slumping, ion implantation, glass, air bearings, figure correction

1. INTRODUCTION

The next generation of x-ray telescopes, in order to achieve sub-arcsecond resolution with large apertures, requires thin and lightweight optics with excellent figure, low micro roughness, and low mid spatial-frequency errors. Fabricating thin mirrors with these attributes is a significant challenge since typical methods of shaping mirrors, such as grinding and polishing, do not work well for compliant substrates. Glass slumping has been shown to produce excellent figure[1], but as always, room for improvement remains. A process for fabricating thin glass grazing-incidence mirrors is proposed, where flat glass is curved using a non-contact slumping method, followed by figure correction using ion implantation.

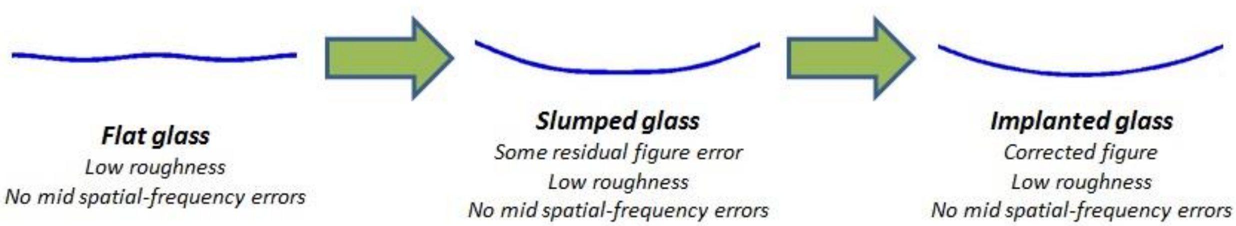

Figure 1. Mirror fabrication process. Flat glass is slumped to achieve a figure close to the desired shape. The slumped glass is then implanted to correct the figure.

During air bearing slumping, a sheet of glass is supported between two porous mandrels (air bearings) by thin films of air, each between 10 and 50 μm thick. As the glass and mandrels are heated, the glass replicates the low-order figure of the mandrels but not the mid- to high- spatial frequencies of the mandrel. Thus, by performing non-contact slumping, the glass achieves close to the desired figure without introducing roughness or mid-spatial frequency errors, which are unlikely to be removable using ion implantation[2] or other correction techniques[3,4,5].

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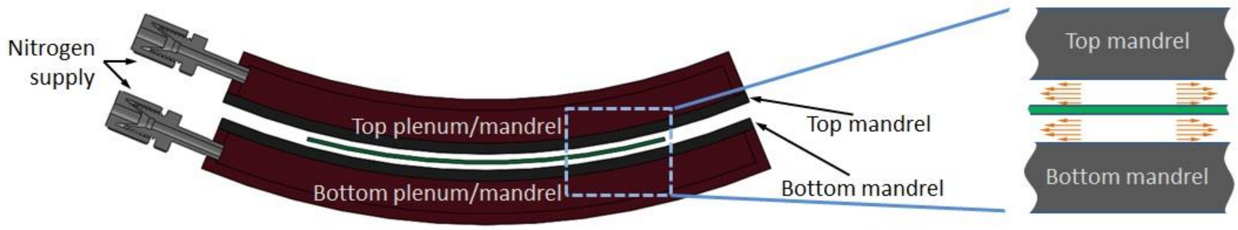

Figure 2. Conceptual diagram of air bearing slumping. Nitrogen is forced through porous SiC mandrels into a thin gap between the mandrel and glass. As the glass is heated, this air film forces the glass to replicate the mandrel shape.

The major challenge with air bearing slumping is the instability of the glass, which requires position control of the glass. In this work, we describe a robust device to control the position of the glass at 600 °C using non-contact sensors and actuation. Several mechanical and sensing improvements have been made over previous design iterations[6].

Air bearing slumping is followed by ion implantation figure correction. High energy ions (200 keV to 6 MeV) are implanted into the glass substrate, causing a sub-surface stress without roughening the surface. This stress results in local curvature changes of controllable magnitude, thus allowing correction of the figure. Correction of spherical curvature of flat glass and silicon wafers has been demonstrated, and it has been demonstrated that roughness is kept within 1 Å for both glass and silicon substrates after implantation[2].

Correcting figure of grazing-incidence optics first requires a strong understanding of the ion implantation process; specifically, finding a set of process parameters that result in a large, highly repeatable, highly controllable, and stable stress state. In-situ measurements of sample curvature during ion implantation provide a rapid and cost-effective means of understanding the ion implantation stress control process. In this work, we describe an in-situ curvature measurement device that has been designed, built, and installed on an ion accelerator located at the MIT Plasma Science Fusion Center (PSFC).

2. AIR BEARING GLASS SLUMPING

We have developed a mechanically robust slumping tool that can be adapted to a grazing incidence slumping tool. In addition, improvements have been made to the glass positioning sensors to reduce noise and provide reliable position measurements. A photograph of the current slumping tool is shown in Figure 3.

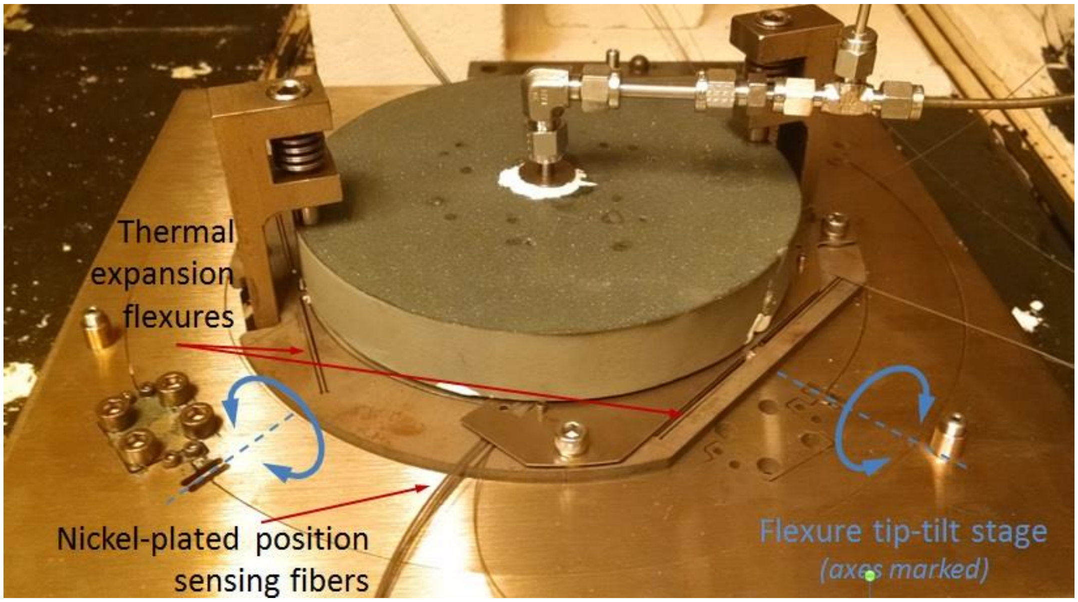

Figure 3. Slumping tool with view of: top plenum and mandrel; flexure tip-tilt stage; metal-to-ceramic connection plate; and fiber sensors.

2.1 SiC plenum and ceramic-to-metal connection

The air bearings used as mandrels are made of porous, recrystallized silicon carbide. The backsides of these mandrels are pressurized using a plenum. Previously this plenum was made of stainless steel, which led to leaky plenums and significant thermal expansion between the plenum and mandrel. In this design, silicon carbide plenums are cast and then ground to the final dimensions, such that the air bearing mandrels can be bonded in using a silicon carbide adhesive. The result is a mandrel and plenum made entirely of silicon carbide, which does not leak and does not have differential thermal expansion issues.

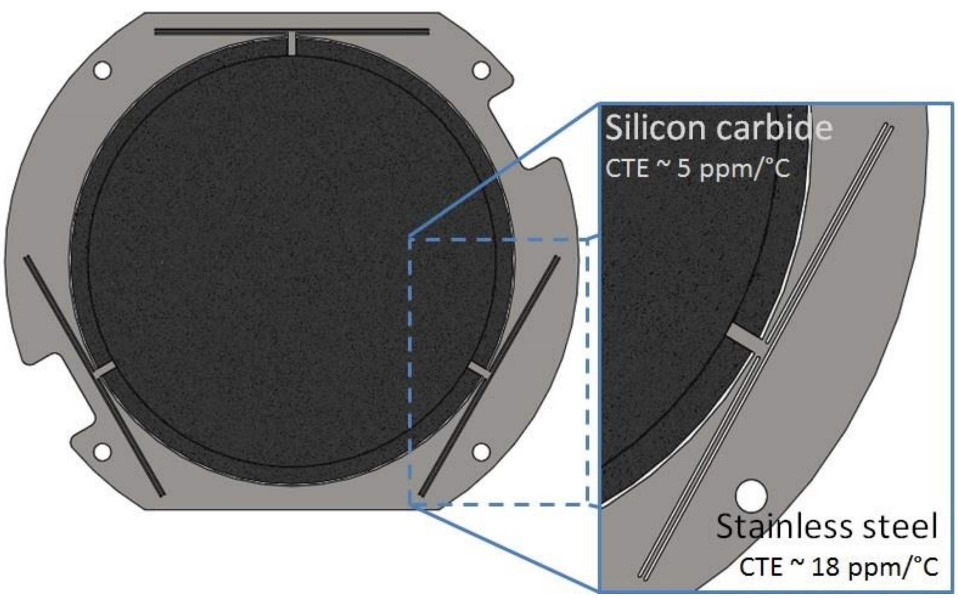

Figure 4. Metal-to-ceramic connection using blade flexures. The flexures allow about 1 mm of differential radial expansion while stiffly connecting the ceramic and stainless steel components.

The tip-tilt stage, necessary for position control of the glass, cannot be made of silicon carbide due to cost and brittleness. Thus an interface between the silicon carbide plenum and the stainless steel structure must be made, which rigidly connects the plenum to the stage but allows significant thermal growth. For this, a flexure design shown in Figure 4 was devised. The tabs are bonded into slots that have been cast into the silicon carbide plenums, using a ceramic adhesive (Aremco Ceramabond 571). The plenum to stainless steel interface plate is fabricated using an abrasive waterjet, and bonded into the plenum such that the flexures are maximally-stressed at room temperature and relaxed at 600 °C, as the stainless steel expands much more than the silicon carbide.

2.2 Flexure tip-tilt stage

Based on previous experience, it was determined that ± 2 mrad of tip and tilt is required for adequate control of the glass position, when using gravity tilt for actuation. This is well within the range allowable for a flexure-based tip-tilt stage. Flexures provide significant benefit in this application over rolling element or sliding element bearings because the high temperature severely limits bearing materials selection. In addition, the design shown in figure 3 was devised that can be made of a monolithic plate and cut using an abrasive waterjet.

2.3 Improved fiber sensing method

Previous fiber-based high-temperature position sensors relied on reflections from the edges of the glass, which are faceted and result in a very noisy measurement. A simple method was devised where a single fiber is oriented tangent to the glass edge, and emits 850 nm light toward a linear array of 7 fibers. The 7-fiber arrays feed into photodetectors, and the total intensity of light captured by these 7 fibers is measured. As the glass blocks more fibers, the intensity decreases. Edge quality of the glass is unimportant, and the resulting measurement is reliable and has low noise. In addition, to improve mechanical stability, the fibers are nickel coated, since the previous copper-coated fibers degraded rapidly at 600 °C.

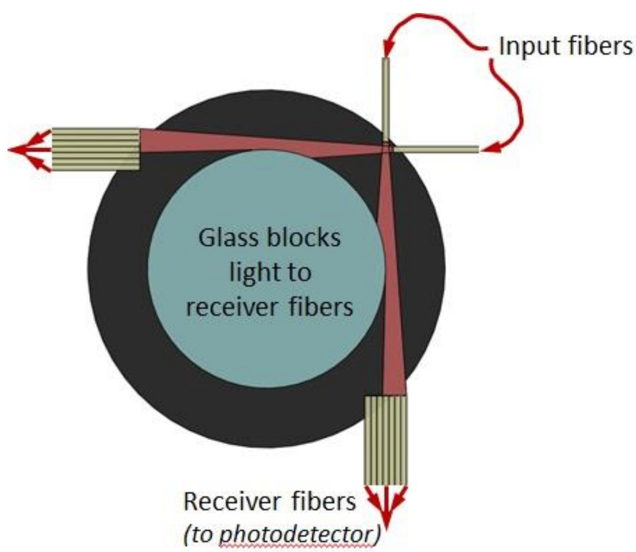

Figure 5. Fiber-based position sensing. Glass substrate simply blocks light from entering receiver fibers, resulting in a low-noise position measurement by measuring total received light intensity.

3. ION IMPLANTATION

We have developed an in-situ curvature measurement tool for measuring stress in ion implanted samples in real-time, without breaking vacuum, in a tandem ion accelerator at the MIT Plasma Science Fusion Center (MIT PSFC). Making in-situ measurements will allow for rapid data collection and a strong understanding of the ion implantation process. This is possible thanks to collaboration with a MIT PSFC lab run by Professor Dennis Whyte and Dr. Graham Wright. Both the people and the equipment from this group will be critical to forging an understanding of ion implantation in the context of figure correction of thin grazing-incidence optics.

Our previous work to demonstrate the feasibility of using ion implantation for figure correction relied on ex-situ measurements, where a sample wafer's figure was measured, the wafer sent to California for implantation in a commercial ion implanter, and subsequently re-measured to determine the change in curvature and calculate the stress. Ex-situ measurements such as this are time-consuming and expensive, since each wafer gives only one data point, and at least 15 data points are needed to give one stress-dose curve. Using commercial implanters also limits our ability to control process parameters outside of narrow ranges dictated by the needs of the semiconductor industry.

3.1 In-situ curvature measurement device

In-situ measurements have a long history of use in understanding stress arising from ion implantation. Early studies relied on single-point measurements at the end of a cantilever sample[7], while later researchers used laser scanning methods of measuring curvature[8,9]. These laser scanning techniques, while very sensitive, are also susceptible to vibration errors. More recently, in other fields, a multi-beam laser curvature measurement has been used[10], which shows minimal influence from vibration and a sufficient number of data points to achieve good averaging. Our device uses a very similar design, and the concept is shown in Figure 6.

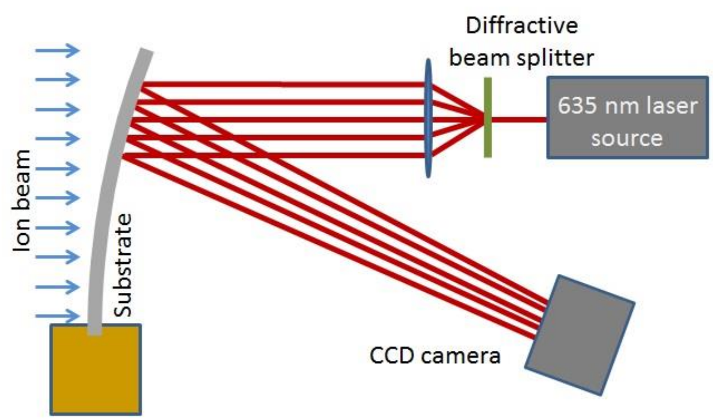

Figure 6. In-situ curvature measurement tool concept. Five parallel beams illuminate a 5 mm width of a cantilever sample, and are reflected to a CCD. The change in distance between these beams gives a measure of sample curvature.

A 1 mW, 635 nm laser diode with focusing optics is used for illumination. The beam passes through a diffractive beam splitter, creating 5 diverging beams, which then pass through a lens to make them parallel. These five parallel beams illuminate a 5 mm length of the sample, and reflect to a CCD for centroid measurement. The sample will be implanted uniformly over a known area larger than the measurement area, and the substrate curvature and ion dose measured simultaneously.

The sensitivity and dynamic range of the apparatus to integrated stress is dependent on the thickness of the sample, which can be chosen depending on the experimental objective. Thin samples result in high sensitivity but low dynamic range. This device is designed to measure with an integrated stress sensitivity of 0.5 N/m on a 200 μm thick sample. The maximum measurable integrated stress is 500 N/m on a 500 μm thick sample. The as-built device is shown in Figure 7.

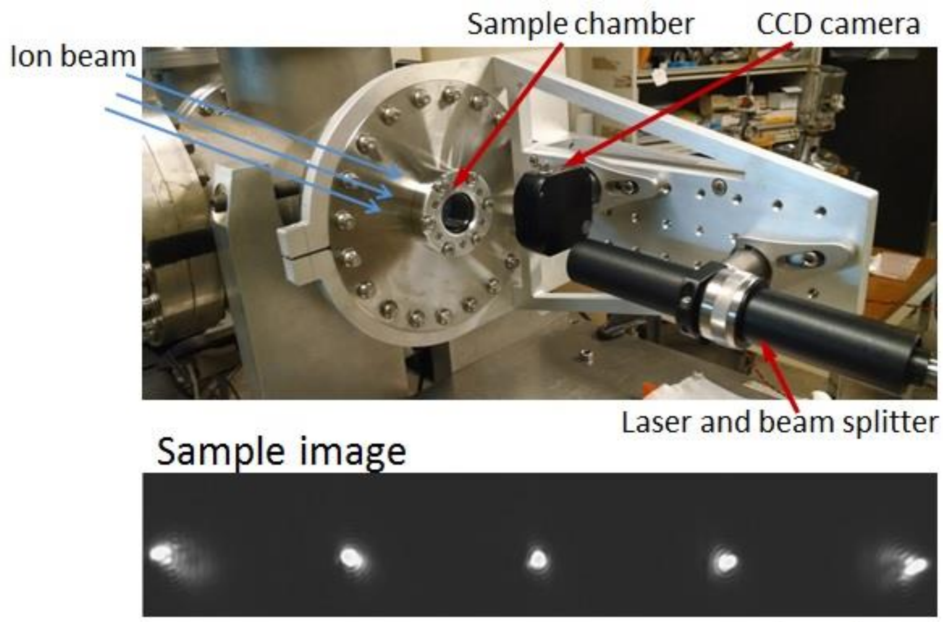

Figure 7. In-situ curvature measurement tool installed on ion accelerator sample chamber. Sample is viewed through a 37 mm-diameter window during implantation.

3.2 Experimental objectives

The objective of making in-situ stress measurements is to quickly understand process parameters that affect the stress that can be generated. Ideally, we could find a set of parameters resulting in excellent repeatability, large maximum stress, precise stress control, and high beam currents. Studying existing literature has suggested numerous potential avenues to explore, especially the effect of ion mass and energy on maximum stress generation and stress-dose gradient.

The MIT PSFC tandem ion accelerator is ideal for these studies. The sample chamber is easy to modify, many diagnostic tools are already in place, a wide variety of ion species can be implanted, and it has a large range of ion energies it can achieve. The PSFC accelerator can achieve ion energy from about 200 keV up to 6.8 MeV. By comparison, commercial implanters most often have an energy range of 50 keV to 350 keV. High ion energy may be important for depositing energy into nuclear collisions over broad depths, thus generating more stress.

4. CONCLUSIONS

Two devices have been built, which will allow significant advancement in both air bearing glass slumping and ion implantation figure correction. A robust slumping tool design will help demonstrate and test design features that can be adapted to a slumping tool for grazing-incidence optics. In-situ curvature measurement during ion implantation of samples will allow rapid collection of stress data, significantly accelerating progress on understanding stress generation from ion implantation in various substrates.

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