Non-touch thermal air-bearing shaping of x-ray telescope optics

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ABSTRACT

Molding glass by using air bearings is a promising procedure for inexpensive and high precision glass shaping. Thin glass sheets are sandwiched between air bearings and pushed flat while being thermally cycled. In this study, a novel device for shaping glass is created and tested using 0.5 mm thick, 100 mm round, Schott D263 wafers. Numerous samples were shaped with varying values for bearing-to-glass gap and maximum temperature, and were measured with a Shack Hartmann metrology tool. Glass was shaped with bearing-to-glass gaps of >50 µm, 36±2.5 µm, and 30.5±2.5 µm. The best peak-to-valley (P-V) flatness achieved is 6.7/3.6±0.5 µm for front/back of the glass sheet, using a gap of 36±2.5 µm. The average steady-state P-V achieved is 12 µm. Using the same device parameters, the best repeatability achieved over the whole 100 mm wafer is 2.7±0.5 µm P-V and 9.5 arcseconds RMS slope error. When looking at 60 mm sections, the repeatability improves to <1 µm P-V and 5±0.5 arcsec.
Keywords: slumping, molding, glass, wafer, shear force, non-contact, air bearing

1. INTRODUCTION

Because glass is brittle, thermal glass shaping techniques involve heating the glass until it becomes malleable or free-flowing. Methods of mass producing sheet glass include the float glass method, the slot-draw method and the overflow downdraw method, also known as the fusion method.

The float glass method works by floating molten glass on top of molten tin. This results in tin penetration and varying chemical characteristics through the thickness of the float glass [1]. In addition, the glass exiting from the melt tank is unstable and starts reacting with ambient gases [2].

The slot-draw method forces hot glass through a narrow slit. The glass sheet is supported laterally using rollers and passed through an annealer. This method requires that the slit be machined to very high tolerances. It is also very difficult to maintain the geometry of the slit over time due to wear. In addition, effects such as condensation and devitrification cause surface defects and perturbation to the overall glass sheet. [3]

For the above reasons, the fusion method is preferred for precision flat glass, and is used for flat panel displays [3]. In this process, melted glass overflows the edges of a triangular prism-shaped trough, which points downward. The overflowing glass travels down both sides of the trough and fuses at the bottom edge [3][4].

Although this method results in much flatter and uniform glass than the float method, we have found it to be insufficient for x-ray telescope mirrors. We measured 100 mm round Schott D263 wafers with a high precision electronic micrometer and found there to be a thickness variation of 10±2.5 µm. Using a Shack-Hartmann metrology tool, we found the glass to have a cylindrical bow with a peak-to-valley (P-V) of larger than 30 µm (the maximum measurable range). For comparison, the ideal surface precision of curved and flat substrates for x-ray optics should be well under a micron.

To improve the flatness of the fusion glass, we proposed a method wherein the glass wafer is placed between two horizontal flat-ground porous ceramic air bearings with a small bearing-to-glass gap (<50 microns). The assembly is then heated up to 600°C in an oven, which is beyond the softening point of glass. The malleable glass is pushed flat by the nitrogen flow from the bearings. Figure 1 illustrates this process. To keep the glass from falling out of the bearings, the entire assembly is tilted back-and-forth using gravity to position the glass under servo control. [5][6][7]

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In this study, the design and results of a novel glass shaping device that uses the proposed method is presented. For this initial study we focused on producing flat substrates. Later we plan to develop technology for producing curved Wolter x-ray optics using innovations developed during the flat substrate research.

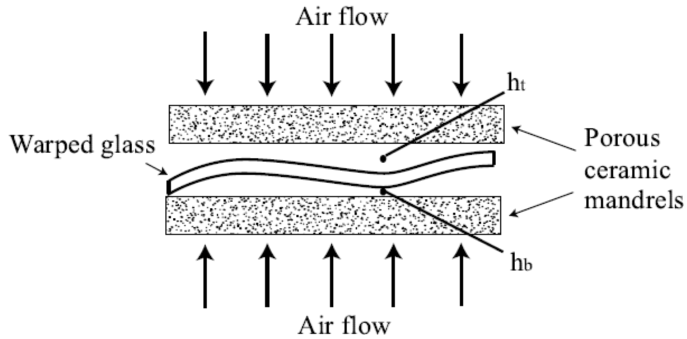

Figure 1. Schematic of air bearing glass slumping process.

1.1 Prior art in glass shaping using air bearings

Akilian et al. developed the first air bearing glass shaping tool, shown in Figure 2, which was later used by Husseini et al. The glass was hung between two vertical air bearings, which were spaced apart using shims. The entire assembly was placed in an oven and heated to 600°C. [5][6]

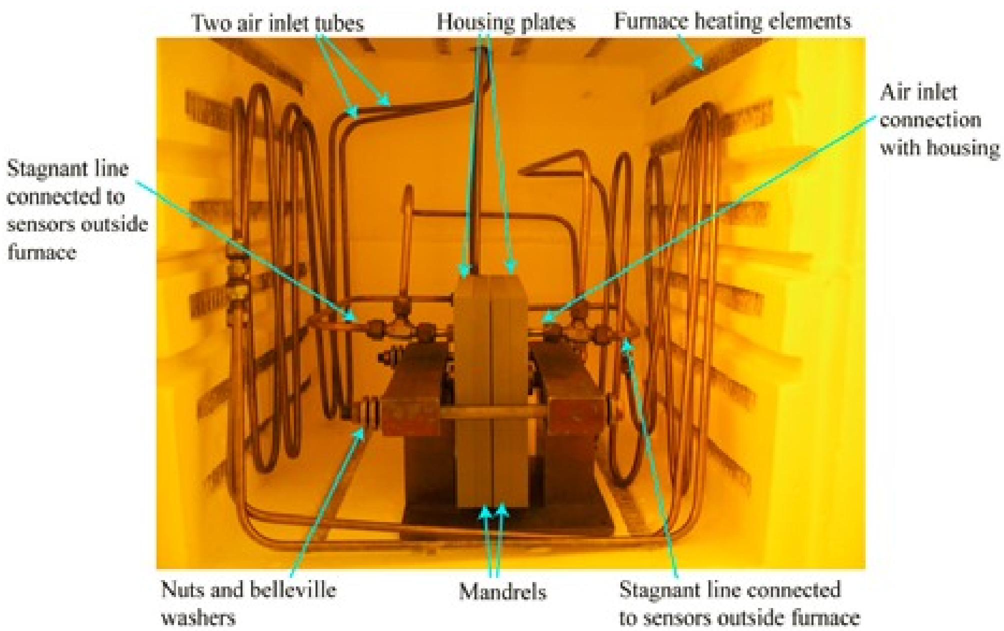

Figure 2. Akilian's air bearing glass shaping tool (vertical configuration).

Although the device produced <3 µm P-V errors in the center 60 mm section of the shaped glass, the vertical configuration had issues due to the method of constraint of the glass, which introduced non-repeatability since the glass had to be hung manually, and the effect of gravity, which caused larger errors in the vertical direction. This configuration was also thought to be difficult to automate and apply to volume production. Thus the decision was made to switch to a horizontal configuration, essentially rotating the device by 90°. However, some form of control is required to keep the glass sheet from sliding out of the bearings, as the system is inherently unstable.

Husseini et al. created the first tool for a horizontal slumping device. This design attempted to avoid the use of shims by means of gap sensors and actuators. However, the device had numerous issues including fracture of the bearings at metal-ceramic bond locations, lack of thermal expansion compensation, and other structural and assembly issues. [6][7] Unfortunately, this design had to be abandoned after a great deal of effort.

In a second attempt, using a custom adapter, Akilian's original tool was rotated 90^{o}, while still being spaced apart with shims. To hold the glass, a simple solid retainer that would physically confine the glass sheet was attempted. However, this resulted in the edges of the glass sheet being pressed against one or two edges of the retainer, which resulted in buckling of the glass sheet. The ripples were large enough to be visible. Higher pressures were also attempted in an effort to force the glass sheet to stay flat, but this instead resulted in larger ripples. From these trials, we concluded that any form of normal force against the edge of the glass sheet would result in unwanted deformations. [7]

Two methods of positioning the glass were conceived: (1) using the fluid shear force from the air bearings, and (2) using gravity to tilt the bearing assemblies to let the glass "fall into position." Using the fluid shear force from the air bearings involves actuating the bearing-to-bearing angle, which is significantly more difficult because it involves having to control the bearing-to-bearing gap since shims cannot be used. Thus the second method of using gravity was chosen. [7]

1.2 Comparison to traditional slumping technique for x-ray optics

A conventional x-ray mirror slumping process starts by balancing a thin glass sheet on top of a half-cylindrical mandrel inside of an oven. This technique was successfully applied to the mass production of mirrors for the NuSTAR mission by a group at the NASA Goddard Space Flight Center (GSFC). The oven is heated above the transformation temperature of the glass, which is around 600°C. This allows the glass to relax and take the shape of the mandrel. The oven must then be cooled very slowly before the glass can be removed. If the oven is not cooled slowly, then a thermal gradient will form across the thickness of the glass, which, in combination with the mismatch of CTE's of the mandrel and glass, will result in distortions. To achieve the highest accuracy, GSFC's slumping cycles therefore take several days which is a significant limitation on the mass production of telescope mirrors. [8][9]

Without any improvements, the conventional slumping process also runs into the problem with dust particles being caught in between the glass and the mandrel. Dust particles create mid-frequency spatial errors, which are visible as ripples on the surface of the glass on the order of millimeters. The dust can be eliminated through cleaning of the mandrel and glass and control of air quality, but results in the contacting surfaces fusing together. It is observed that dust particles aid in preventing stiction and allow for easy removal of glass from mandrel [10].

GSFC's approach is to apply a boron nitride slurry onto the mandrel after removal of dust particles. The coating must be made as uniform as possible, which is a non-trivial process. The coating can have non-uniform mixtures of micro-particles and larger contaminant particles. Additionally, the boron nitride tends to clump and results in non-uniform layers. For these reasons, slumped optics typically exhibit mid-spatial frequency dimples and valleys. [8]

2. DESIGN

2.1 Optical sensors

We previously reported a novel distance sensor using high temperature silica-core optical fibers to provide position feedback of the glass. The sensor works by using two optical fibers juxtaposed and directed towards the center of the glass. Light goes into one fiber, reflects off the edge of the glass, goes into the second fiber, and is read by a photodiode. We chose 0.4 mm-diameter silica fibers because of their ability to withstand high temperatures, specifically up to 600°C. The fibers have a copper coating that oxidizes at 600°C, but testing of the fibers indicates that the silica core itself survives the process. We showed that isolation of the fiber from atmospheric oxygen increases longevity [7].

These fiber sensors are not very accurate because of two limitations. The first limitation is that sensor noise greatly depends on the cleanliness of the edge surface of the glass. Since edges are typically rough and faceted, there is much noise in the sensor, which must be filtered with a low-pass filter. The second limitation is that, because the glass shape is round, movement of the glass in one axis affects the sensor reading in the other axis. To improve position sensing, a third sensor was added for redundancy. For our purposes, the sensors were sufficiently accurate to keep the glass from falling out of the bearings. A new sensor design which uses CMOS cameras is being developed which achieves significantly reduced levels of noise and avoids the offset problem.

2.2 Mechanical design

Like Akilian's device, the top and bottom bearing assemblies are clamped together with shims between bearings to set the gap. An Inconel bellows is used as a high temperature spring to provide the clamping force. Two push-pull rods are used to actuate the tilt of the bearing assemblies. These push-pull rods go through the bottom of the oven and are actuated by stepper motors. Inconel bellows are used for high temperature rotational joints, which are designed to provide high stiffness in the vertical direction but allow rotation about the x and y-axes. Plenum pressures of around 0.05 psi were used. At this pressure, the nitrogen flow rate was around 500 sccm per bearing. The device is shown in Fig. 3.

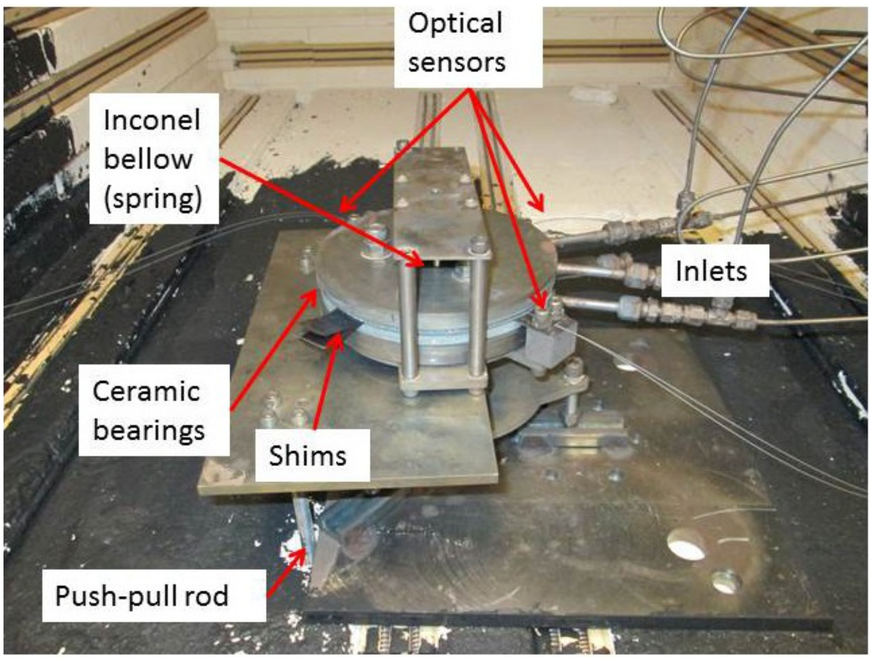

Figure 3. Horizontal slumping tool inside the oven.

3. EXPERIMENTAL RESULTS

3.1 First round of slumping (glass shaping)

Using the device built, an initial trial of 13 glass wafers were slumped with varying degrees of success. The slumped wafers were measured with the lab's Shack-Hartmann surface metrology tool, which was repeatable to ±0.5 μm P-V during these experiments. Table 1 lists the slumping parameters and results for these samples. During these experiments, the Shack-Hartmann tool was unable to accurately measure samples with greater than 30 μm of distortion. However, the general shape can be ascertained; all of the samples started out with similar cylindrically-curved shapes.

Table 1. Results of first slumping round.

Trial	Sample	Gap (µm)	Max temp (^{o}C)	Slump time at max temp (min)	Result P-V (µm) front or front/back
1	G8	>50	600	6	12.3±0.5
2	Unlabeled	>50	600	60	>30 (unmeasurable)
3	G18	>50	600	6	5.9/5.2±0.5
4	G19	>50	600	6	14.0/12.6±0.5
5	Unlabeled	>50	600	60	>30 (unmeasurable)
6	G8	>50	600	6	4.8/5.1±0.5
7	Unlabeled	>50	600	60	>30 (unmeasurable)
8	Unlabeled	>50	550	60	>30 (unmeasurable)
9	G38	>50	550	6	6.4±0.5
10	G40	>50	550	6	11.3±0.5
11	G37	36±2.5	550	6	6.7/3.6±0.5
12	G38	36±2.5	550	12	10.1±0.5
13	G19	30.5±2.5	550	6	19.5±0.5

The actual gap for trials 1-10 is unknown. This is because, while the gap was set at 50 µm, there was interference from some sheet metal parts that caused the gap to be somewhat larger than 50 µm. The sheet metal was intended to bend elastically and not interfere with the gap, but was stiffer than anticipated due to repeated thermal cycling. To correct this, more compressive force was added to clamp the two bearings together with shims in between. The shims were measured with a digital micrometer with resolution of ±2.5 µm.

Trials 1-7 were run at 600^{o}C. All attempts with short dwell times (6 minutes) at 600^{o}C were successful, while attempts with long dwell times (60 minutes) failed. It was speculated that this happened because the glass is too soft at 600^{o}C. If the glass is too soft, it may not maintain a flat shape and will instead deform to the confines of the air bearings. During shorter dwell times, the glass might not have had time to actually reach 600^{o}C, thus resulting in a better surface P-V. Other explanations have also been proposed and further research is ongoing.

To confirm that 600^{o}C is perhaps too hot, trials 8-13 were run at 550^{o}C. All samples changed shape significantly, confirming that a lower process temperature is sufficient. In addition, trial 8 was run for a 60 minute dwell time, and also failed, similar to what occurred with 60 minute dwell times at 600^{o}C. This suggests that the process temperature can be lowered even further.

Interestingly, trials 11-13 did not result in significantly better surface P-V, even though the gap was smaller. Trial 13, especially, has the worst P-V of 19.5 µm, but also somehow resulted in a nearly perfectly symmetrical shape, which proves that the glass was floating the entire time instead of getting pinned or stuck on an edge. In addition, the symmetrical shape suggests that the worsened P-V might be the natural mode at steady state instead of being an exception. Further experiments and computer modeling are planned to help elucidate this effect.

3.2 Second round of slumping

In a second round of slumping, the primary goal was to evaluate the repeatability of the slumping tool. The glass was slumped below 550^{o}C in order to extend the life of the fiber sensors, and to avoid the instability observed at higher temperatures. Due to the lower temperature, longer dwell times are required in order to allow the glass to reach steady state. The results are shown in Table 2.

Table 2. Results of second slumping round.

Trial	Sample	Gap (μm)	Max temp (°C)	Slump time at max temp (min)	Result P-V (μm) Upward side
1	G100	28.5 ± 2.5	500	6	17.6 ± 0.3
2	G101	28.5 ± 2.5	500	30	12.9 ± 0.3
3	G35	28.5 ± 2.5	500	90	12.5 ± 0.3
4	G20	28.5 ± 2.5	550	6	8.5 ± 0.3
5	G3	25 ± 2.5	550	30	10.1 ± 0.3
6	G21	Unrecorded	529	30	9.2 ± 0.3
7	G22	Unrecorded	529	30	9.8 ± 0.3
8	G23	Unrecorded	529	30	9.9 ± 0.3
9	G24	24 ± 2.5	529	30	4.5 ± 0.3
10	G25	25.5 ± 2.5	534	30	6.0 ± 0.3
11	G26	26.5 ± 2.5	534	60	14.5 ± 0.3
12	G27	31.5 ± 2.5	534	60	11.9 ± 0.3
13	G28	Unrecorded	534	60	13.2 ± 0.3
14	G29	Unrecorded	534	60	12.6 ± 0.3
15	G30	Unrecorded	534	60	10.9 ± 0.3

Trials 1-3 show that 500°C is hot enough to slump glass, as the glasses did not seem to reach a steady state (spherical shape) even after 90 minutes of slumping. This is expected since the strain point of the glass is 529°C. Subsequent trials used 550°C, 529°C, and 534°C with 30 minutes of dwell time. Trials 5-8 were slumped with the convex side of the wafer pointing upward. Trials 9-10 were slumped with the convex side of the wafer pointing downward. Because there was little variation between trials 5-8, but significant variation between the two sets of trials, it was concluded that either a hotter slumping temperature or a longer dwell time was required. Trials 11-15 were slumped with the convex side initially downward, at 534°C for 60 minutes. This resulted in apparently steady-state shapes (spherical). Figure 4 shows the surface mapping of trial 14, which appears to have achieved a steady-state shape.

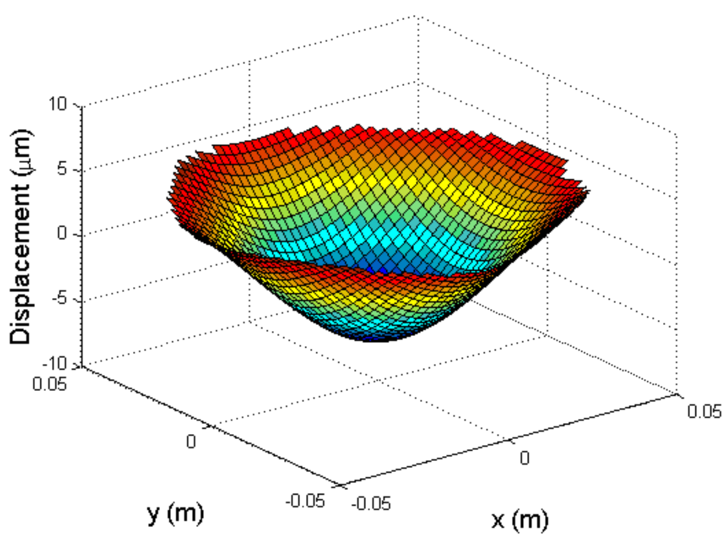

Figure 4. Trial 14 (wafer G29) surface map.

Wafers G27 and G29 were compared to evaluate the repeatability. Fig. 5 shows the difference between G27 and G29 surface shapes. Over the whole 100 mm wafer, the P-V of the difference between the two wafers is 2.7±0.5 μm and the RMS slope difference is 9.5 arcseconds. In other samples, larger differences from this shape appeared to be due to the center of the spherical shape being shifted slightly. These results are a significant improvement over the previously-reported vertical slumping results [5][6]; when only the center 60 mm is considered (as in the previously-reported results), the difference improves to <1 μm P-V and 5±0.5 arcsec. We judge repeatability to be the most significant performance parameter at this time, since a repeatable error shape (e.g., spherical) could always be ground out of the mandrel set.

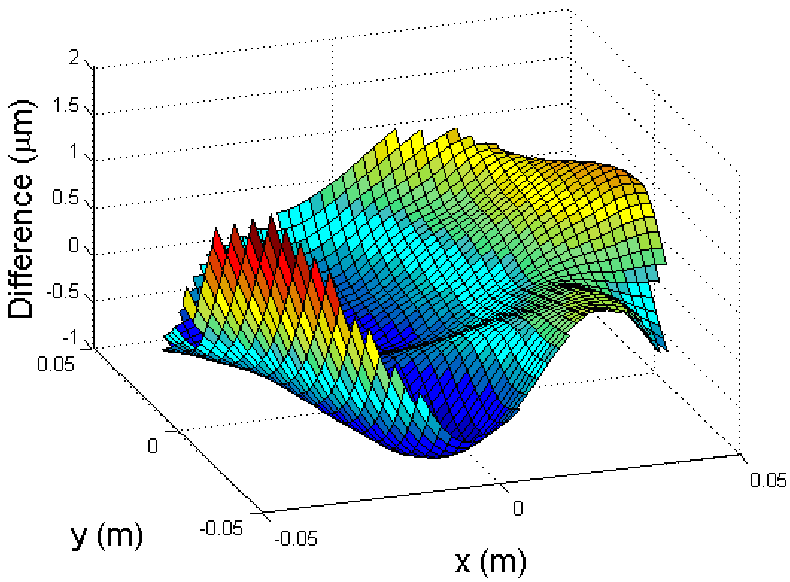

Figure 5. Difference between G27 and G29 surfaces.

4. CONCLUSION AND FUTURE WORK

It has been shown that glass can be slumped horizontally, without contact using air bearings, to micron-level precision. The lowest peak-to-valley achieved in the scope of this work was 3.8±0.5 μm. However, this was not the steady state shape of slumped glass. Steady state shapes were found to be symmetrical and spherical with a P-V of about 12 μm. However, this was for a relatively large gap of 36±2.5 μm between bearing and glass. With a smaller gap, the stiffness of the air layer rises as the inverse cube of the gap, and may result in a much lower steady state P-V for the slumped glass.

The repeatability of the slumping process was found to be much improved over the previous vertical slumping method. When aligning the centers of the spherical shapes, the repeatability over 60 mm sections was found to be less than 1 μm P-V and 5±0.5 arcsec, which is challenging to measure with our surface metrology tool. With further development we expect these errors can be reduced.

Additionally, the slumped glass exhibits only low frequency spatial errors, since dust particles are not an issue as they are with traditional methods, and mid-range frequency bearing errors are averaged out by constantly moving the glass within the bearings. We have proposed using a novel technique to remove remaining low-frequency spatial errors via ion implantation (see paper by Chalifoux et al. in these proceedings).

It has been shown that 600°C is not necessary to slump glass using the air bearing method. Lower temperatures, down to 529°C, are sufficient to slump D263 glass, although lower temperatures require longer slumping times since the glass is not as malleable. 534°C was found to provide an adequate balance between slumping time and lower temperature.

Additional work is currently being performed in the form of a new device that does not require an oven. Instead, heated air is blown into the plenum/bearing assembly, which is thermally isolated. This device has the potential to reduce the slumping cycle time to less than 1 hour. Rapid slumping cycles, and potentially cheaper mandrels, should help reduce production costs of high-precision x-ray mirrors

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