Aligning, Bonding, and Testing Mirrors for Lightweight X-ray Telescopes

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ABSTRACT

High-resolution, high throughput optics for x-ray astronomy entails fabrication of well-formed mirror segments and their integration with arc-second precision. In this paper, we address issues of aligning and bonding thin glass mirrors with negligible additional distortion. Stability of the bonded mirrors and the curing of epoxy used in bonding them were tested extensively. We present results from tests of bonding mirrors onto experimental modules, and on the stability of the bonded mirrors tested in x-ray. These results demonstrate the fundamental validity of the methods used in integrating mirrors into telescope module, and reveal the areas for further investigation. The alignment and integration methods are applicable to the astronomical mission concept such as STAR-X, the Survey and Time-domain Astronomical Research Explorer.

Keywords: X-ray optics, lightweight mirrors, segmented mirrors, mirror alignment, mirror bonding

1. INTRODUCTION

High throughput x-ray telescopes invariably involve integrating a large number of thin mirror segments into a very compact telescope[1,2,3,4,5]. The most practical approach for very large x-ray telescopes presently is to concentrically nest thin mirror segments together into modules, which are then integrated to form a large telescope. Mirrors of various approximations of the Wolter type-I optics with nested concentric shells were used, in missions such as ASCA[6], Suzaku[7], and NuSTAR[8]. It is also the approach taken by the Astro-H[9] and Athena[10] projects. The thin mirror segmented optics has the advantage in being able to pack many mirror shells together to achieve a large effective area. The goal of such effort is therefore to improve the optics resolution.

Integration of mirrors with thin (0.2 – 0.5 mm) substrates can be broadly divided into two camps of approaches. One approach is to fabricate mirror segments as precisely as they meet the telescope requirement, and mount them into telescope housings independently of each other with negligible distortion. Alternatively, the integration can couple with existing mirrors to simultaneously fix the mirror figures as well as the alignment of the mirrors. The latter approach was taken successfully by, for example, NuSTAR. Significant improvement has to be made, however, to get from NuSTAR's ~ 1 arc-minute resolution to the arc-second level. ESA's mission concept, Athena, take that concept to the extreme in that curved mirrors were not even formed before fixing them onto the telescope structure. Our group at NASA/Goddard Space Flight Center has been actively pursuing the former approach in order to avoid stack-up error and mounting distortion[11]. This approach, however, places a very stringent requirement on the figure of the starting substrate and on the method necessary to integrate them. We have developed a full suite of capabilities to fabricate substrates by precisely slumping thin sheet on accurately shaped mandrels, to coat x-ray reflective layer, to align and bond mirrors, to design

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mirror modules and to devise their methods of integration. We also develop optical metrology, x-ray testing methods and facilities. Our goal is to gradually advance telescope imaging to arc-second resolution.

The substrate we use for building such telescope, currently, is made of glass. Thin glass sheets are thermally slumped onto accurately figured mandrels. In this paper, we will report on the alignment and bonding aspects and will report mainly the method based on glass substrates. We are also developing substrates made of mono-crystalline silicon. The fabrication method of silicon substrates is different from thermal slumping and will be discussed in details separately in a paper[12]. Briefly, silicon, as a material for thin-shell x-ray optics, has several advantages over glass. It is stiffer and less susceptible to distortion during bonding. It has excellent thermal conductivity that is very important in maintaining the telescope's imaging performance in the space environment. The well-developed suite of industrial technology of silicon processing also helps. Most importantly, the single-crystal nature of silicon, as opposed to the amorphousness of glass, allows the removal of stress due to sub-surface damage from machining to recover the original shape. The principle and the detailed process of fabricating x-ray mirrors made of silicon is addressed also in these proceedings[12]. Despite the difference in fabrication, similar techniques for alignment and bonding are expected to apply to silicon mirrors, too, and specific issues will be addressed in Section 4 of this paper.

The challenge in bonding these thin mirrors is that they are not to be over-constrained unnecessarily nor the over-constraint is used as a means to modify a mirror's figure. For the discussion that follows, we will refer to mirror substrates that typically have the properties: thin (0.4 mm), lightweight (areal density of 0.5 - 1.0 kg/m^2) glass substrates, having length of 100 – 200 mm and radius of about 250 mm. They can now be formed routinely by thermal slumping, producing mirror pairs with an average half power diameter (HPD) of 6" (double reflection) for a telescope design with a focal length of 8.4 m. A metallic film is subsequently deposited onto the substrate's surface for x-ray reflection. The mirrors are then precisely aligned and are bonded onto a telescope module.

The technology in building high-resolution segmented x-ray telescope from thin substrates can be grouped into three areas: the fabrication of precise mirror substrates, the subsequent processes of delicate integration of mirrors without introducing additional unacceptable distortion, and integration of the telescope modules. In this paper, we will report the work of mirror processes without distortion, on the alignment and bonding, also discussing in depth the stability of the optics from the use of adhesives. The fabrication processes of substrates made of single crystal silicon and the current status will be reported in a separate paper in these proceedings. The issues with and module integration[13] has also been reported elsewhere. The technology can be used to implement the mission concept STAR-X, the Survey and Time-domain Astronomical Research Explorer.

2. MIRROR ALIGNMENT AND BONDING

It is challenging to affix the mirror onto its housing without deforming the mirror beyond required level. To fix precisely, to within an arc-second, of a mirror with approximately the aforementioned dimensions, distortion in the surface or joints are to be less than a fraction of a μm. The fundamental constraints of any affixing scheme are space and mass. The spacing between mirrors, which themselves are only a fraction of a mm in thickness, ranges from less than a mm to just a few mm. Mass is also limiting. Any significant addition of mass for each mirror shall be considered seriously, as there are many mirror segments in the telescopes. The small spacing and limited mass essentially preclude the use of large mounting mechanisms. With these considerations, we settled on using adhesive to bond the mirrors onto the external telescope structure. Bonding with adhesive naturally meets both challenges of space and mass. Nevertheless, the precision requirement is very stringent for building high-resolution optics. Bonding places a requirement on mechanical strength. The precision requirement is therefore exacerbated by the necessary multiple mount points with small separations. Introducing more bond points introduces smaller spatial scale that the edges can be distorted, amplifying the slope errors for a given uncertainty in (radial) displacement. Bonding locations are also area that stress usually concentrates. Distributing the required strength by employing more mount points may further constrain the requirement of optical precision. The mechanical and optical requirements are not usually compatible with each other.

To meet these optical and mechanical requirements with the space and mass constraints, we have developed, over the past years, a bonding process with continuously improving precision[14,15]. We built and continued to experiment with small mirror modules that were tested at 8 - 10 arc-seconds. The "edge" bonding approach, in which the mirror is bonded at points on the thin surfaces along the mirror's edges, is currently sufficient to bond mirrors meeting 10 arc-second telescope requirement. To minimize the possible mirror distortion due to bonding, we devise a mechanism to gently bond the mirror to a "semi-constrained" pin, before the pin itself is fixed onto the mirror housing. We also append the mirror with clips that help to spread the load of the joint and therefore reduce stress concentration. The thermal environment is important. Even though distortion due to the small difference in CTE between glass and the housing material (nearly CTE-matched Kovar) are not that severe, a 0.1°C bulk temperature difference between the mirror and its housing is serious. We have implemented precise and stable thermal environment and the operating temperatures for bonding and metrology are held to < 0.1°C (rms) over a day.

2.1 Alignment and bonding methods

The alignment and bonding procedure involves 3 steps. (1) In the preparatory step, a mirror segment is fabricated and a metallic film (annealed) is deposited. Clips are attached to the mirror to spread the load and enlarge the area for subsequent bonding. Three clips are attached on each side of a mirror. In the latest version, only 'half-clips", are used which are attached to the mirror only at the mirror's backside. (2) The second step is to align the mirror. (3) After the mirror is properly aligned, 6 sliding pins with epoxy contact the clips and the epoxy is let cured over the next day. The sliding pins are subsequently locked down, with adhesive, in their bushings that are structural parts of the module. The complete process takes place in a stable thermal environment. Details of the alignment and bonding procedure and their foundations were described in many papers[14,15] in these conferences from previous years.

In the preparatory step, a metal clip is attached to the mirror at each mount location. The purpose of the clip is to spread the load at the joint. Epoxy is applied uniformly over a hemispherical area of about 5 mm in diameter to attach the clip to the mirror. Any stress concentration from the bonds in subsequent bonding will act on the metal clips instead of directly on the glass, minimizing the risk of glass failure from any residual micro-fracture. The clip also provide a larger area than the thickness of the mirror can provide. This larger area is important for strength purpose and it also allows a more repeatable as well as more easily executable process. The clip is only one-sided, that is, there is no epoxy on the front surface of the mirror. Experiment and model show that uneven epoxy in the case of a 2-sided clip that fully encapsulates the mirror causes additional distortion if the epoxy is not even on the two sides. The clips are made of Kovar which is CTE-matched to the Schott D263 glass. The epoxy is then cured at 40°C extensively to eliminate any instability. When it is done, the clips are essentially an extension of the mirrors.

2.2 Alignment error

The next step is to position and orient the mirrors properly. The mirror is positioned and aligned under an optical beam that covers the full aperture of the mirrors. The light enters the mirror's aperture along the optical axis and grazes the reflecting mirror surface, and reaches an imaging detector placed at the proper focal distance. The mirrors are held kinematically with the mirrors optical axis vertical to minimize any gravity distortion.

Alignment is determined from the individual focus of sub-apertures in the azimuthal direction. Each sub-aperture exposure produces a highly diffracted image in the radial direction due to the small width of the mirror's aperture. The centers of those sub-aperture images are used to map the alignment of the mirror as a function of azimuth. The sub-aperture measurements were made with a moving mask. The measurement was made in a dark enclosure.

The enclosure also serves as a thermally controlled environment. It has 75 mm thick thermal insulation. The whole environment was thermally controlled to 0.05°C (rms) with temperature-controlled air in a horizontal laminar flow. The airflow, handling air at ~ 1×10^3 cfm, did not disturb the mirror in alignment.

Each individual mirror can be aligned with the control of a hexapod. The mirror is held vertically in a kinematic mount. Finite element modeling is used to ensure that such orientation produce negligible distortion. Three small steel balls are temporarily attached to each mirror so that the mirror can be kinematically situated on a bracket, which is mounted on a high precision hexapod. The hexapod is then adjusted to orient the mirror into a focusing position. The hexapod's angular precision is 1 arc-second and its translational precision is about 1 μm. Each individual mirror in the first stage can be aligned so that the light can be brought to focus at its own focal distance, typically about 2 times the telescope focal length in a Wolter-I design. The pair of mirrors in each shell can then be brought to focus at the system's focal distance.

The repeatability of locating the centroids of the diffracted images is better than 1 arc-second, even though the images themselves can be 2 orders of magnitude larger, due to diffraction from mm-size aperture. Nevertheless, many subtle effects concerning the stability of alignment throughout the alignment and bonding processes were found. For example, dimensional and orientation changes in the set up consisting of heterogeneous components with different coefficients of thermal expansion (steel and aluminum frames, steel balls temporarily attached to the mirrors, glass or silicon mirrors, etc.) are eliminated with the aforementioned thermal controlled environment. Positional change of the steel balls temporarily attached to the mirrors are stabilized by preparing the attachment in advance to allow sufficient curing time for the epoxy joining the balls.

Subtle effects in alignment were continuously found during the many trials. For example, the hexapods used to control the mirrors' orientation need to be moved backward and forward during the alignment and bonding process in order to permit access to the joints. The hexapods are mounted and moved on linear slides. This movement not just demands high precision of the slides but also introduces instability in the process. It was found that the alignment could change after such operation, by as much as a few arc-seconds, which is not acceptable. Repeatable change came from flexing of the support structure (which can become mechanically insufficiently as more components were added onto it) can easily be fixed by strengthening the structure. Residual random and gradual changes appeared to depend on the actual procedure. Lessons such as these are learned through multiple practice runs.

2.3 Bonding and mirror figure distortion

Bonding of the mirrors onto the mirror module is perhaps the most challenging part of the integration. Currently, the overall image of < 10 arc-second is dominated by the quality of the mirror figures, which average to about 6 arc-second (double reflection for a Wolter Type I configuration). This is expected to greatly improve as the crystalline silicon mirror technology mature. This will be discussed in Section 4 below. At any rate, the contribution from bonding is also important. Change in time scale of 8-10 hours are the most significant. This change comes from dimensional instability of the epoxy during its curing.

The alignment of mirror depends on a temporary mount that orients the mirror like a rigid body. Epoxy is subsequently applied to bond the mirrors, at the clips' surface, to a pin. The pin, which can slides in a bushing, is part of the external structure. (See references 14 and 15 for detailed configuration of the bonding.) When this is done, the mirror will have 6 extended "spider legs" in the bushings. The pins and their bushing are matched sets in that each pin has a tight fit, about 2 μm, in its corresponding bushing. Epoxy is introduced to bond the mirror's clip to the end surface of the pin, creating a bond gap of 25 μm (the pin diameter is 1 mm). The epoxy is allowed to cure in room temperature. Even though the pins ("spider legs") are not yet attached to the bushings, they are not completely unconstrained. Any displacement in the transverse direction by an amount more than that allowed by the gap in the bushings will impact the mirror. The final step is to bond in the pin to the bushing.

In our experimentation with bonding, mirrors were measured before and after bonding. The surface measurement is done with an interferometer coupled with a tilted cylindrical null[16]. A surface map is generated from the difference from the conical wavefront and the mirror surface. Experimental platforms made of 2 types of materials were used: one is Kovar, which is a nickel-cobalt alloy having a CTE compatible with borosilicate glass; and another is E60, a beryllium/oxide metal-matrix composite with matching CTE. E60 is very lightweight (density 2.6 g cm^{-3}) and has very high specific rigidity. As far as bonding goes, these two are essentially the same. The lightweight E60 metal-matrix composite will have significant advantage in a space flight mission. The mirror can both be out of alignment and also be distorted from the bonding. Epoxy curing causes a minute dimensional change. Displacement or rotation at the 3 joints at each side of the mirrors means changes of the boundary condition. These changes are low order axial change at the mirror edges and the mirror responds to the new constraints. Axial sag and other higher order axial distortions are detrimental to the performance of the x-ray mirror.

Despite the simplicity of the bonding process described above, because of the sub-μm requirement on dimensional stability of the bonding, many variables were found to be important. Dimensions such as the bond gap between the clip and the pin, or the gap between the pin and the bushing may be important variables for the bonding process, since they control the amount of free-play that the epoxy needs to fill. Too large a gap may allow too much free play for any epoxy dimensional change to affect mirror's boundary positions and distort the mirror. The shape of the epoxy and that of the head of the pin may be another variable. The alignment of the pin to that of the clip's surface may also be important if the epoxy shrink more than a few percents and the alignment is off by more than a degree, for instance. The relative timing of the application of the epoxy turns out to affect the bonding performance, too. Some of these subtle effects are described here.

1. Changes due to impacts when the pins engaged the mirror's clips. These hydrostatic impact are immediate and is usually correctable by adjusting the hexapod since the epoxy is still fluid. Such shift, typically a few arc-seconds in magnitude, relaxes after within an hour. More strongly constrained mirror

(that is, less free) would help in maintaining the orientation but at the expense of introducing mirror distortion.

2. Change due to the curing of epoxy. This is the hardest to control, as it is the nature of epoxy to undergo dimensional change when it is being cured. Presently, good alignment and stable bonding can be obtained with the application of a smaller amount of epoxy. Reinforcement with additional epoxy after that from the first application was cured can be made to improve the mechanical strength. This method worked quite well so far, producing consistently < 5 arc-second alignment precision between mirrors of different shells.

3. Dependence on shape and size of the bond at the pin-clip joint. The bond gap between the pin and the clip partially determines the amount of epoxy that can fill the gap. Currently, the gap is controlled to be 25 μm, while the diameter of the pin is 1.0 mm. Modeling has shown that a random displacement at the pin-clip boundary of 1 μm will cause significant distortion of the mirror. A series of bonding experiments were carried out with various bond gaps, up to 200 μm, showed, however, that there is little dependence on that gap. Instead, the fact that the epoxy may ooze outside the circular area covered by the head of the pin proved to be more relevant. In such cases, the epoxy does not form a disc but with some (uncontrolled) amount of excess around it. Control of this critical bonding is maintained by monitoring the gap while the pin is continuously pushed inward by an actuator. The force on the pin is also measured continuously. The displacement, the frictional and contact forces are all reliable indictors of the parameters and the goodness of the bonds.

4. Dependence on the tightness of the gap of the pin in the bushing. After all the pins are attached to the clips on the mirrors, the pins are to be locked into its bushings. The space (difference in diameters) between the pin and its bushing allows different amount of free play when the pin was attached to the mirror. Too tight a gap will constrain the mirror during the previous step of bonding, while too large a gap may allow asymmetric distribution of epoxy into the bore of the bushing. We fabricated matched pin and bushing sets by lapping the bushings to tight tolerances, at about 2 μm. These lapping processes are tedious but the dimensional consistency is essential.

5. Dependence on relative timing of the two bonding. The idea of splitting the bonding of the mirror into 2 applications of epoxy is to allow the pin to settle down along the pin's axis (tangentially to the mirror surface) without much constraint first. The second bonding of the pin is only to fix the pin more gently without significant pull or push. As such, the bonding of the pin to the mirror should be done first. The order between the two applications therefore is relevant. This notion was verified in many trials in which the order was reversed or the pin is locked down before it is completely attached to the mirror.

6. Dependence on humidity. It is not surprising that the curing of epoxy depends on the environment's humidity. What is more surprising is that the strength depends critically on a level of humidity that is around normal ranges ~ 40%. It was found that too low humidity significantly weakens the bonds, and humidity control was implemented in the bonding facility to ensure sufficient strength of the bonds.

7. Wetting of nearby surfaces. Lesson was learned when poorer result was found for some mirrors that were bonded with previous mirrors bonded in. It turns out that epoxy applied for mirrors in neighboring shell in the module may migrate along the surface, over a short distance to a few mm, therefore impacting the bonding of the next mirrors. The wetting is not visible with unaided eyes, but tests were carried to show the additional stickiness depending on the distance from a previous bonding.

3. BOND STABILITY

The long-term stability of the bonded mirrors is another concern a flight telescope has to address. Mirror bonded with epoxy may suffer from instability in a different thermal environment, in an environment with a different humidity, or simply from the ageing of epoxy. In our preliminary study, we had indication that the bonding may not have reached an acceptable level of stability until after a few weeks. The curing was thermally accelerated to make sure that the epoxy is sufficiently cured. The thermal treatment also serves as a means to stabilize the epoxy against future thermal cycling test.

3.1 Temporal change

Epoxies are, in many ways, very suitable for the application. It bonds mirror with strength, occupies a small volume or area, and does the job gently so that it does not really disturb the mirror like a mechanical mechanism may do. However, being a polymer, it may suffer a very minute change in dimension, in time, to render the bonded mirrors out of alignment, or to distort the mirror. Despite the fact that the epoxy we use has a cure time of a day or less, it may still have a significant and detectable effect on the mirror since even a minute change, of the order of a μm in linear dimension may be sufficient to cause a mirror distortion. The change in dimension may also occur differently under different environment or mirror orientation. The change may not be reversible.

To examine the stability of the bonding epoxy, a long-term stability test was carried out. In the test, a glass mirror (485P2550) with radius of curvature of 243 mm and an axial length of 200 mm, was bonded onto a CTE-matched strongback. The bonding was made at 6 points at the mirror's side, 3 on each side. An epoxy (Hysol 9309) was used to make the critical joint event though other adhesive is involved (such as that used in locking down the pin attached to the mirror). The bonded mirror was left in the laboratory environment where the temperature is controlled at 20.5°C (with a variation of ± 1°C) and was monitored over a long period of time, in this case, over 500 days. The surface of the mirror was frequently measured and its sag variation, as a function of azimuth was derived. Average and variance were then obtained from the sag variation. The trends of these values are shown in Figure 1 below. Other parameters of low-order axial figure, such as tilt angle, which is an important parameter for alignment, were also derived. Their absolute values were difficult to assess, however, due to the lack of absolute reference as the mirror was transported in and out of the measuring station for measurement and storage.

It can seen that the standard deviation of the mirror's sag changes at a rate of ~ 3 nm/day. The average sag also drifts upward at a rate of 2 nm/day. The trends would continue for over 2 – 3 months, resulting in a total increase in sag variation or average axial sag of ~ 0.2 μm. A change of this magnitude, while small, is not negligible for a telescope having an angular resolution of 5 arc-second. Such change needs to be minimized. It is assumed that this gradual change is due to the curing of epoxy used in bonding the mirror. After the curing phase is completed, subsequent change is about an order of magnitude smaller, and is possibly consistent with zero. The data are not strong enough to constrain the trend, partly due to the change in orientation that we will discuss next.

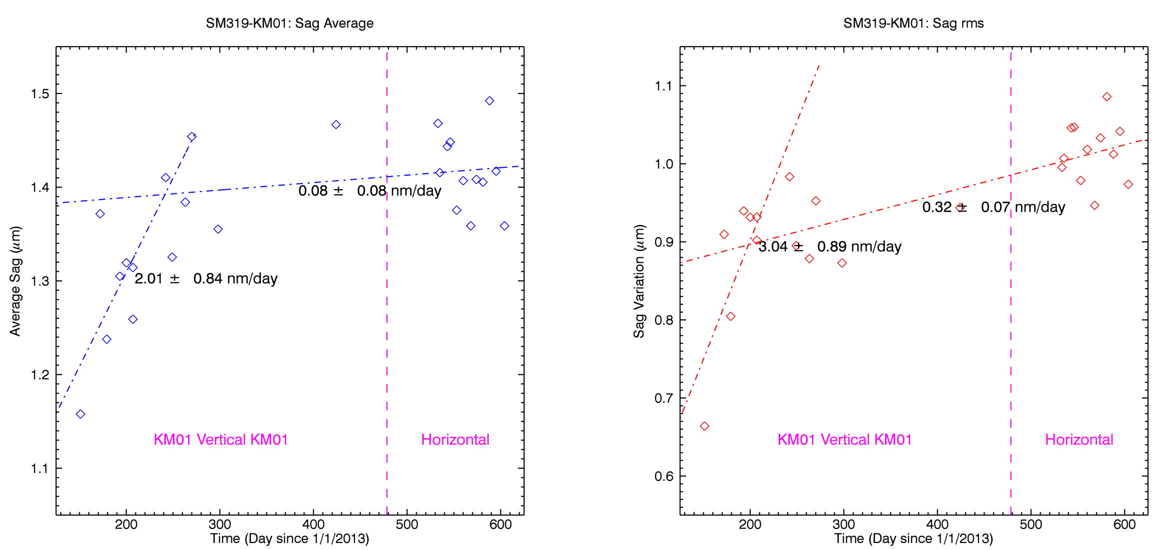

Figure 1. The trend of mean and standard deviation of sag for the long-term stability test "SM319". The mean and standard deviation were computed from the axial sag variation profile as a function of azimuth. The sag variation profiles were, in turn, derived from surface measurement of the bonded mirror. As expected, the mirror underwent a gradual change in the first 2-3 months, presumably due to the continue curing of epoxy used to bond the mirror. Subsequent change were much smaller (possibly consistent with zero.) The total change amounts to about 0.2 micrometer of sag for both the average and the standard deviation.

About one year into the study mentioned above, it was found, from separate investigations, that the mirror would act differently if it were placed with its axis lying horizontally. From finite-element modeling, it is known that a bonded mirror is distorted when placed horizontally. This is due to an elastic response of the thin glass mirror (0.4 mm thick) constrained at 6 side points. This result is verified in the comparison of data from x-ray measurement of a mirror oriented horizontally, and the optical data of mirror surface and alignment. The mirror in the stability experiment SM319 described above was then placed horizontally (mirror surface faced upward), in order to test if there is an additional change of rate. The result in Figure 1 (right) shows the measurements from such trial. Note that when the measurement was done, the mirror would temporarily be oriented vertically. It is assumed that the elastic effect occurs over a period of days, much longer than the 30 minutes when the optical measurement took place. From the data, however, there is no indication that there is any further change---the rate was consistent with zero, except that there is a jump when the mirror was place in a different orientation.

3.2 Gravity sag

Besides the curing of epoxy, there is a component of instability that could come from a visco-elastic deformation of the epoxy. The elastic component was revealed by measuring bonded mirrors after they sat in a different orientation than the standard vertical orientation for many days. As it turns out, the change could largely be recovered if the original orientation was restored for several days. The effect therefore appears to be elastic. It is easy to suspect the delayed elasticity of the epoxy used in bonding, even though the elasticity of the glass mirror itself cannot be excluded.

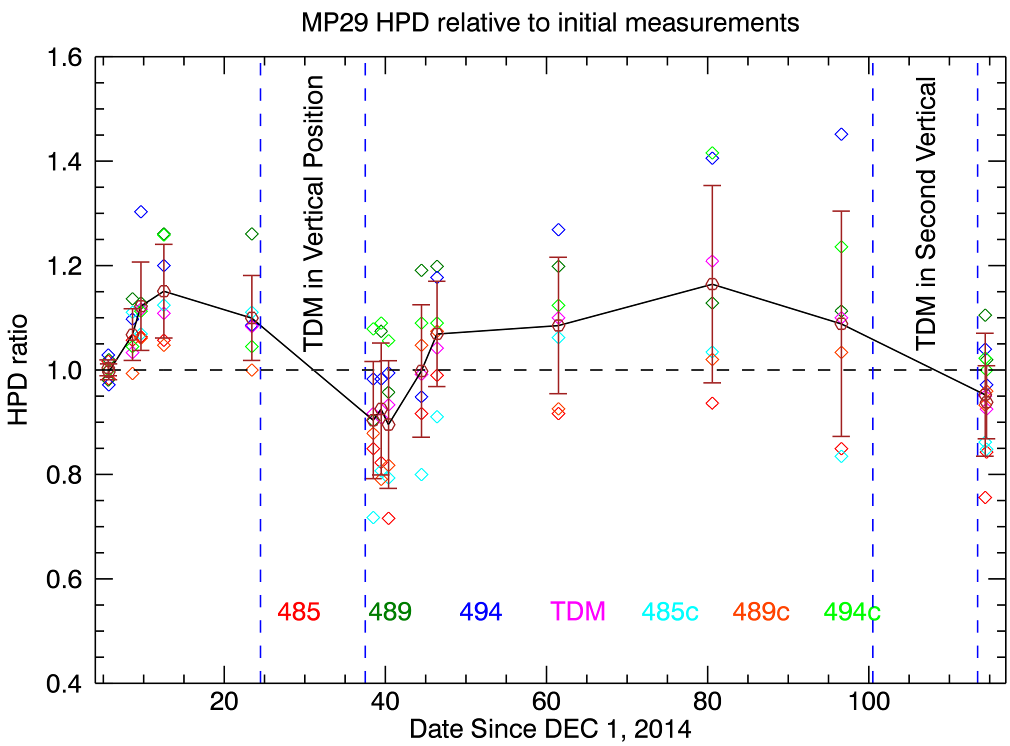

Figure 2. Change of mirror resolution in time and after storing in vertical orientation. Three mirror pairs (“485”, “489” and “494”) were installed in the TDM and each of them was measured at their respective best focus and at a common focal plane (“485c”, “489c” and “494c”). The fully exposed TDM was also measured at that focal plane. Evolution of the measured angular resolution is represented by the half power diameter (HPD), relative to the initial values. The trend for all the pairs is clear: they went up when placed in the test chamber, horizontally. The HPD before the TDM was placed in the chamber should be better. The clear improvement of relative HPD after the TDM was taken out and stored vertically for several days indicates a strong relaxation effect. This observation was confirmed in a follow-up test 3 months later.

The effect of gravity sag was best seen in the x-ray data. In the x-ray test, pairs of mirrors were aligned and bonded on a Technology Demonstration Module (TDM) and their angular resolution was measured in x-ray. The measurement was made in the Goddard 600-m x-ray beam line. In an experiment "MP29", 3 pairs of mirrors, aligned to 8.4 m focal length, were tested. X-rays at 4.5 keV, from a Ti source, was used (it is known that the dependent of x-ray image on soft x-rays is very mild.) It was found that there is a change which continued for over about a week, and was recoverable if placed in the vertical position again. The temporal behavior of the imaging quality of the mirror pairs, measured as the half-power diameter (HPD), is shown in Figure 2.

In the experiment, the test module was taken out and was set in the vertical position. It was shown that the HPD of each pair degraded over ~ 5 days. When the test module was re-placed into the chamber (set horizontally, which is the only configuration for testing) the HPDs improved to their original values, before they deteriorated again. The exercise was repeated to demonstrate the validity of the observation. The simple interpretation is that the epoxy may slowly deform over many days, causing additional distortion. A placement in the vertical position somehow set the deformation back in the reverse direction. Another similar experiment, but with the vertical storage of the module in vacuum, showed the same phenomenon, demonstrating that it is not the atmospheric humidity or air that cause the relaxation.

Since the test module had to be placed with axis horizontal for the test, it is easy to see that the measured HPD did not represent the "original" performance of the optics, as it would in the free-falling spacecraft. In fact, it typically take at least one day after the TDM was installed in the test chamber before any reliable images can be taken. The pumping down of the x-ray chamber is slow (to avoid cooling the TDM unnecessarily) and it takes some time to obtain the proper pointing of the module. An example is illustrated in Figure 3, in which the HPD is extrapolated back from the first measurement by 2 days. It is gratifying to see that not only the HPDs are better (the data for the pair "494" was good enough to permit a reasonable fit), as expected, they essentially diverges from a common 8 arc-second performance. The 8 arc-second HPD is consistent with the totality of typical error terms assigned to the substrates, alignment, and bonding. It is still a matter to be investigated as why some bonding degraded more and some less. It is possible that the degree of degradation depends on the amount of epoxy or perhaps the geometry of the epoxy beads.

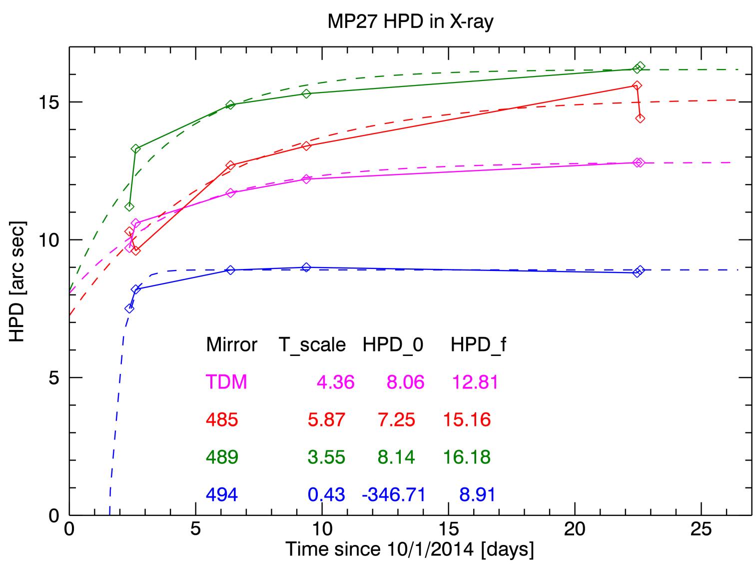

Figure 3. Gradual change of mirrors' resolution for the TDM in a static horizontal position in experiment "MP27". The resolution, represented by the HPD was measured at 4.5 keV x-ray using a Ti source. Three mirror pairs were in the module (labeled as "485", "489" and "494"). The "TDM" labels the HPD for the fully exposed module. The resolution became worse in time for all the mirror pairs. A simple exponential model is fitted to the data to extract the performance at zero time and the time scale of the change. The exponential time scale is about 5 days (data for "494" was not sufficient to give a decent fit). The extrapolation to zero time before the TDM was placed in a horizontal position gives an HPD of about 8 arc-seconds consistently. The final t=∞ values, however, vary, indicating that additional subtle parameters control the degradation in gravity. The unknown variable is possibly related to the amount or geometry of epoxy beads use in the bonding.

3.3 Thermal curing and change

Thermal treatment of epoxy in mildly elevated temperature can accelerate the curing of epoxy and stabilize the mirror sooner. After all, stability again thermal cycling of the mirror module is required to meet spacecraft operation requirements. To that end, bonded mirrors are placed in a thermal enclosure to have the epoxy cured. The curing cycle was set at 120 hours, with a 72 hours in actual thermal soak at 40°C. The temperature ramp up and cool down were carried out slowly (20°C/24 hours) to avoid differential thermal expansion between the thin mirror and the module housing or the strongback. The differential expansion did not arise from the CTE mismatch of the glass and housing material, but rather from the very different thermal time scale of the two components having very different thermal mass. The results of a series of experiment were shown in Figure 4.

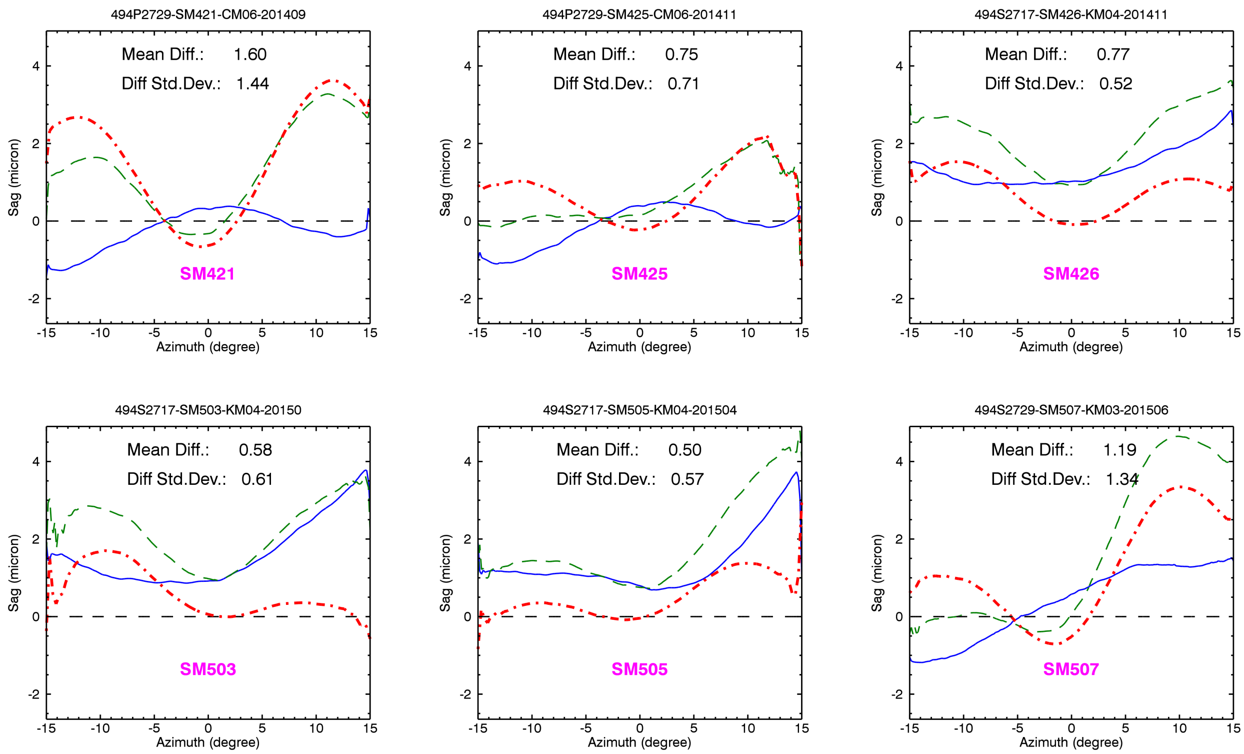

Figure 4. Comparison of sag variations before and after heating. Test results from 6 experiments are shown. Sag variations were derived from surface measurement with an interferometer. The axial sag was computed at each azimuth of the surface. The curves show the sag variation before (blue solid) and after (green dash) the bonded mirrors went through a 5-day thermal cycle. The soak temperature was 40°C. The difference curves (red dot-dash) show the characteristic "M"-like profile, possibly generated by non-uniform force, tangential to the mirror surface, at the 6 boundary points. Not all experiment showed the characteristic "M" as the selected sample did. In about 1/3 of the experiments, a failed "M" showed only half of the profile from one half of the mirror. The result is consistent with finite element modeling with random tangential forces at the bond points.

In the experiments, a glass mirror was bonded onto a CTE-matched strongback. The strongback is made of the ferrous alloy Kovar, of which the CTE is closely matched to that of borosilicate glass. The bonding was made at 6 points as described before. The surface of the mirror was measured with an interferometer before the mirror was put into the thermal cycle. The surface was subsequently measured again after the heat treatment. Their sag variations were computed and compared. From Figure 4, it can be seen that these experiments showed a pattern of distortion representing the elastic response of the mirror under the constraint at the 6-point boundary. The change in axial sag is typically small in the middle part of the mirror and increases towards the 2 sides before decreasing again, forming an "M"-like profile. It should be note that not all experiments yield this "classic" pattern, but the majority of them, about 2/3, did. A minor fraction of experiments gave a sag variation that increased on one side and decreased on the other. Finite element modeling applying random tangential forces at the 6 bonding points can reproduce the sag variation quite well. Bonding and heating processes are now being tested to determine the critical factors that regulate the distorted axial sag.

4. ADJUSTMENT OF TECHNIQUES FOR SILICON SUBSTRATES

Mirrors currently developed in our group typically achieve an angular resolution of 6 arc-seconds (HPD, double reflection, in a Wolter Type 1 configuration). Even though these mirrors with glass substrates have excellent precision for x-ray astronomical telescopes, we are developing similar mirrors made of crystalline silicon substrates that can have resolution of ~ 1 arc-second. Silicon is much stiffer than glass (with Young's modulus of ~ 130 – 190 GPa, compared to glass' 72 GPa). Silicon has excellent thermal properties such as a low CTE and a thermal conductivity that is 2 orders of magnitudes higher than borosilicate glass. The good thermal conduction is important in maintaining the temperature uniformity of an integrated telescope with nested shells of mirrors. Another important advantage of crystalline silicon is that the ordered structure of the solid is well suited to be stress-relieved after machining. This important property allows the use of machining process to fabricate precise mirror substrates. We have been using a glass slumping method that requires the use of a forming mandrel as a mold for the mirror to replicate on. The most precise mirror requires mandrel of a different radius for mirrors with that radius. The use of machining fabrication methods allows making mirrors of any radius without the use of a mold. The method of substrate fabrication with crystalline silicon and the current result are detailed in a separate paper in these proceedings[12].

Basically, instead of starting with a lightweight glass sheet and figure it by slumping, silicon substrates are first figured and polished on a silicon block before being 'lightweighted', by slicing it, for example, from the block. Residual stress due to the grinding, polishing and slicing can then be removed by etching away the sub-surface damages. Due to the crystalline nature of silicon, the substrate has been shown to recover it figure after the stress are removed.

The approach to build a telescope with mirrors made of crystalline silicon substrates is essentially the same as that with mirror made of glass substrates. There are, nevertheless, several important differences in building telescopes with silicon substrates. Two areas of difference are expected: (1) Bonding, and (2) Coating. In bonding, the stiffer silicon would allow a more relaxed configuration of constraining the mirror. The means to light-weigh the mirrors, as is being developed currently, also allows the possibility to have different thicknesses for mirror with different radii. It is possible to have continuously varying thicknesses for mirrors with progressively larger radii. This feature will permit a more flexible bonding scheme to work throughout the telescope.

Coating for lightweight mirrors has to meet two basic requirements. First, since the surface of the substrate is smooth to begin with, the deposition on the originally smooth substrate must not produce a surface with large micro-roughness. For x-ray reflection in the energy band up to 10 keV, a surface is reasonably smooth with micro-roughness < 4Å. Secondly, the coated film must be sufficiently relaxed so that the coating stress produces only negligible distortion of the thin mirror. Coating stress can impart on a mirror low order axial curvature, such as axial sag.

We have studied and reported on the coating stress with different methods of deposition[17], and of different metals. High density metal such as Ir has excellent reflectivity at E < 10 keV. However, Ir has high film stress that causes low order axial distortion[18,19]. For example, magnetron-sputtered Ir (or other metals such as Cr or Pt) films of about 10 nm in thickness can have stress of a few GPa. Such high stress and thickness distorts the figure of thin substrate mirror significantly. For example, on a glass mirror segment with a radius of 250 mm, a length of 200 mm, a angular width of 30°, and a thickness of 0.4 mm, the coating distortion is about 3 μm PV for every 10 nm of Ir deposited. The coated film can be annealed to reduce the internal stress and therefore the mirror's figure can be improved[20,21]. Thermal annealing was shown to be very effective even at temperature as low as 350°C. This is fortunate as prolonged heating above 400°C will soften the glass substrate and change its figure.

Annealing iridium film coated on silicon substrates, however, will be different in two aspects. First, annealing the coated film on single crystal silicon substrates does not pose the same limitation on annealing temperature, as single crystal silicon is thermally stable at much higher temperature than glass. The annealing of film at higher temperature may produce a better result than that described above for glass substrates. The second aspect concerns the oxidation of silicon. Annealing in an environment with atmospheric oxygen will oxidize the silicon surface. An oxide layer forms on silicon thermally deforms the mirror due to its stress. Annealing films on silicon substrates at very high temperature therefore requires either an oxygen-free environment or having the substrates protected from oxide growth.

5. SUMMARY

Future high throughput optics for x-ray astronomy inevitably requires assembling large number of mirrors of thin substrates using a modular approach. Such a modular telescope is scalable, and can better meet the requirements of mass and effective area. The challenge of such approach is in achieving the arc-second resolution that can better satisfy science objectives. We have been developing technology capable of building a large x-ray telescope with arc-second angular resolution. The technology development involves developing better mirror substrates, and improving the subsequent bonding methods.

We have developed a general approach to align and bond mirrors. From many extensive experiments and tests, we found that bonding the mirrors at their edges is effective. Within this scheme, we have identified many important variables essential in making consistent and reliable bonding of the mirrors. The effects of dimensional parameters such as clip size, bond gap, and spacing between the pin and the bushing, are clarified and controlled. Procedural variables such as the timing of the applications of bonds are understood and optimized. Other subtle effects such as humidity of the environment and the migration of adhesive to its neighboring area due to wetting were regulated.

The stability of the bonds was investigated. The time scale for the mirror to stabilize to arc-second precision was found to be long, much longer than the stated epoxy curing time. Thermal curing can accelerate the progress towards stability, but even a slow ramp-up to 40°C has a significant impact on low order figure. Elasticity, possibly of the epoxy, due to the weight of the mirror, affects the imaging performance of the mirrors. The elastic effect has a time scale of a few days and the mirror performance can be recovered when the loading is relaxed.

New development in the fabrication of substrates made of crystalline silicon opens up a new domain where much higher telescope resolution can be achieved. Silicon has many advantages over glass. In addition to the better mechanical and thermal properties, faster and more cost-effective fabrication methods are possible. Associated with the new substrates, the developed methods for glass substrates, such as coating, are being adjusted to accommodate the differences.

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