Deformable secondary mirrors for the LBT adaptive optics system

H. M. Martin\textsuperscript{a}, G. Brusa Zappellini\textsuperscript{b}, B. Cuerden\textsuperscript{a}, S. M. Miller\textsuperscript{a}, A. Riccardi\textsuperscript{c} and B. K. Smith\textsuperscript{a}

\textsuperscript{a}Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
\textsuperscript{b}Large Binocular Telescope Observatory, University of Arizona, Tucson, AZ 85721, USA
\textsuperscript{c}INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy

ABSTRACT

We describe the manufacture of thin shells for the deformable secondary mirrors of the LBT adaptive optics system. The secondary mirrors are thin shells, 910 mm in diameter and 1.6 mm thick. Each mirror will have its shape controlled by 672 voice-coil actuators. The main requirement for manufacture of the shell is smoothness on scales too small to be adjusted by the actuators. An additional requirement is that the rear surface match the reference body within 30 µm peak-to-valley. A technique was developed for producing smooth surfaces on the very aspheric surfaces of the shells. We figure the optical surfaces on a thick disk of Zerodur, then turn the disk over and thin it to 1.6 mm from the rear surface. Figuring is done primarily with a 30 cm diameter stressed lap, which bends actively to match the local curvature of the aspheric surface. For the thinning operation, the mirror is blocked with pitch, optical surface down, onto a granite disk with a matching convex surface. Because the shell may bend during the blocking operation and as its thickness is reduced to 1.6 mm, figuring of the rear surface is guided by precise thickness measurements over the surface of the shell. This method guarantees that both surfaces of the finished shell will satisfy their requirements when corrected with small actuator forces. Following the thinning operation, we edge the shell to its final dimensions, remove it from the blocking body, and coat the rear surface with aluminum to provide a set of conductive plates for capacitive sensors.

Keywords: telescopes, adaptive optics, deformable mirrors, optical fabrication, optical testing

1. INTRODUCTION

The Large Binocular Telescope\textsuperscript{1-3} has two 8.4 m primary mirrors and two 0.91 m Gregorian secondary mirrors. The secondary mirrors are the deformable mirrors for the LBT adaptive optics system. This design provides maximum sensitivity at wavelengths longer than about 2 µm because the adaptive correction is made without any warm re-imaging optics, tip-tilt mirror, or separate deformable mirror that would add thermal background. The deformable secondaries also deliver corrected images to any instrument in the focal plane.

Each adaptive secondary mirror consists of a Zerodur shell, 911 mm in diameter and 1.6 mm thick, whose shape is controlled by 672 voice-coil actuators, consisting of electromagnets that act against small permanent magnets bonded to the rear surface of the shell. The design is an evolution of the successful MMT adaptive secondary mirror which has 640 mm diameter x 2 mm thick shell controlled by 336 actuators similar to the LBT actuators. The actuators suspend the shell about 50 µm from a stiff ULE reference body. The shape of the shell, relative to this reference body, is measured to a resolution of 2-3 nm by capacitive sensors, providing rapid feedback to the actuators. The shell, actuators, capacitive sensors, and a sophisticated control system can support a bandwidth of 1 kHz or greater; the complete AO system bandwidth is limited by the wavefront sensing. The concept and evolution of the design have been described in a number of papers.\textsuperscript{4-12} The present paper discusses the manufacture of the shell, including optical fabrication of both surfaces, handling the thin shell, and coating the rear surface.

Two shells for the LBT secondaries were manufactured through the optical figuring and thinning of the shell, but both were damaged before being integrated with their reference bodies and actuators. The Steward Observatory Mirror Lab is in the process of manufacturing two new shells to replace the damaged ones, and the LBT Observatory plans to have a third shell made as a spare.

Section 2 discusses the general requirements and manufacturing plan. Section 3 describes the fabrication and quality achieved for the optical surfaces. Section 4 describes the blocking, thinning and edging operations and Section 5 the procedures for deblocking, handling, coating and packing. Section 6 describes the current status of shell production.
2. REQUIREMENTS AND MANUFACTURING PLAN

2.1 Requirements

Table 1 lists the optical prescriptions for both surfaces of the shell. The mean thickness is 1.6 mm. The different radii of curvature for the two surfaces, coupled with the asphericity of the front surface and the mean thickness, make the center and edge equally thick at 1.52 mm.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Diameter (mm)</th>
<th>Curvature</th>
<th>Radius of Curvature (mm)</th>
<th>Conic Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>911</td>
<td>Concave</td>
<td>1974</td>
<td>-0.7328</td>
</tr>
<tr>
<td>Rear</td>
<td>911</td>
<td>Convex</td>
<td>1995</td>
<td>0</td>
</tr>
</tbody>
</table>

The accuracy requirements for the optical surface differ significantly from those for a rigid mirror. The 672 actuators will control the shape of the shell on large and intermediate scales. The shell is expected to deliver diffraction-limited images, so errors on small scales that are not well controlled by the actuators must be very small. Other errors, especially at intermediate scales, are limited to amplitudes that can be corrected using a small fraction of the actuators’ force range. The goals for figure accuracy have evolved over time, but they include an accuracy of about 9 nm rms surface error after correction with the actuators, with correction forces not exceeding about 20 mN rms over the 672 actuators. The secondary mirror is the stop for the system, so it must be accurate over the full polished surface.

In addition to requirements for accuracy of the optical surface, there are requirements imposed on the rear surface to ensure a fairly uniform gap between it and the spherical reference body. The gap must be small (typically 50 µm) in order to maximize sensitivity of the capacitive sensors; natural damping by viscous flow of air in the gap is another advantage of a small gap. The gap must be uniform to a fraction of the typical gap, so the shape of the rear surface of the shell must be accurate to about 30 µm peak-to-valley including power. (It is assumed that the figure of the stiff reference body is essentially perfect and that its radius error causes less than 20 µm variation in the gap.)

The accuracy requirement of 30 µm peak-to-valley would seem to be moderately tight for power (equivalent to a 1 mm error in radius of curvature) and trivial for irregularity. But the control of both power and irregularity is complicated by the fact that the shell is 1.6 mm thick. One of the two surfaces can be figured on a thick disk, before thinning. Having tried it both ways, we prefer to figure the optical surface on a thick disk. The rear surface must therefore be controlled on a thin, flexible shell that can easily bend by tens of µm during the figuring process. The goal is to make the rear surface match the reference body when the optical surface is held in its correct shape by the actuators.

The manufacturing plan described below achieves this goal.

2.2 Manufacturing plan

The overall manufacturing plan for the procedures carried out at Steward Observatory is outlined below. It starts with a substrate of high-quality Zerodur that is thick enough (150 mm) to be mounted on a simple support, and oversized in diameter (962 mm). The plan continues through coating of the rear surface and preparation for shipment to Italy, where the magnets will be attached to the rear surface and the shell will be integrated with its reference body and actuators.

1. Generate, grind, polish and figure the optical surface on a thick, oversized substrate.
2. Block (attach with pitch) the concave optical surface to a stiff blocking body with a matching convex surface.
3. Machine the rear surface down to a thickness of about 3 mm.
4. Grind, polish and figure the spherical rear surface to the final thickness. This step is guided by measurements of the mean thickness and thickness variations over the shell.
5. Edge the shell to its final diameter, core out the center hole, and bevel and polish the edges.
6. Remove the shell from the blocking body.
7. Mask the rear surface before coating, protecting the magnet locations and the defining the geometry of the conducting surface for the capacitive sensors.

8. Aluminize the rear surface.

9. Pack the shell for shipment.

These steps are described in more detail in Sections 3-5.

3. OPTICAL FABRICATION

We generated the optical surfaces to an approximation of the aspheric shape, and refined them by loose-abrasive grinding. Both loose-abrasive grinding and subsequent polishing were performed using a 2 m computer-controlled polishing machine equipped with a 30 cm diameter stressed lap. The stressed lap, designed for polishing highly aspheric surfaces, changes shape actively to follow the local curvature of the surface. The 30 cm lap, shown in Figure 1, consists of a 13 mm thick aluminum plate with actuators around its perimeter that apply bending and twisting moments. The plate is stiff enough to provide strong passive smoothing of errors with periods less than about 100 mm. Errors on larger scales are addressed by varying the lap’s dwell time, rotation rate, and pressure. This method is augmented by local polishing with passive laps of 50-100 mm diameter.

Figure 1. One of the LBT secondary mirrors being polished with the 30 cm stressed lap.

During loose-abrasive grinding we measured each mirror with a swing-arm profilometer. The profilometer measures one-dimensional scans across the mirror, and is sensitive to departures from sphericity at the level of 50 nm. We measured the polished surfaces with a phase-measuring interferometer, using a two-element refractive null corrector to compensate the asphericity of the ellipsoidal surface, 130 µm peak-to-valley. In order to verify the accuracy of the null lens, on several occasions we moved the mirrors to our large test tower to make a conjugate test, with an interferometer focused at the far focus (13.7 m from the mirror) and a reflecting ball centered at the near focus (1.06 m).

We simulated the adaptive correction by fitting the actuators’ influence functions to the measured figure error. An influence function is the change in mirror figure for a unit displacement of one actuator while all other actuators are held to zero displacement. The 672 influence functions and the corresponding sets of actuator forces were calculated from a finite-element model of the shell. The residual error after the fit is the error that the shell would have after correction by the actuators. The actuator forces are determined from the fitted coefficients of the influence functions.

Polishing of the optical surfaces was completed in September 2004 for the first mirror (A) and January 2005 for the second mirror (B). Figure 2 shows the mirror’s figures at the completion of polishing, with and without the simulated
adaptive correction. We did not try to remove astigmatism while figuring either mirror because it is corrected almost perfectly by the actuators, with tiny forces. Astigmatism of 2 μm peak-to-valley is corrected with forces of 2 mN rms and a residual error of 0.1 nm rms. Spherical aberration of 260 nm peak-to-valley is present in the figure of the Shell A because of inaccuracy in the null lens. We detected this error with the conjugate test late in the process, and chose not to correct it by polishing but instead let it be corrected by the actuators. It is corrected with forces of 4 mN rms and a residual error of 1.7 nm rms.

Figure 2. Mirror surface errors at the completion of polishing the optical surfaces. The top row shows the uncorrected figure for each mirror. For the middle row, astigmatism and 3rd-order spherical aberration have been subtracted in order to show the errors at intermediate scales. The bottom row shows the residual error after the simulated correction with 672 actuators.
Mirror B has much larger non-axisymmetric errors at intermediate scales. This may be a residue of errors that were introduced when the mirror was generated and aspherized. They have little impact on the residual error after correcting with the actuators.

In both cases the residual error after correction is concentrated near the edge of the mirror. At least two factors contribute to this. First, the uncorrected figure has higher slopes near the edge, despite the fact that the substrate is oversized in order to minimize edge effects. Second, the actuators cannot bend the shell as effectively near its edge. They can produce a slope at the edge, using the outer 2 rings of actuators, but they cannot produce much curvature in the radial direction outside the next-to-last ring of actuators. The best way to reduce residual errors after correction would be to improve the figure near the edge before correction.

The simulated correction with the actuators uses 8 mN rms correction force for mirror A and 7 mN rms for mirror B. In addition to the full correction using 672 actuators independently, we also examined partial corrections that use a limited number of bending modes. The modal analysis calculates the patterns of actuator influence functions that produce the largest deflections for a given rms force. The modes are ordered from most flexible (astigmatism) to successively stiffer modes. Figure 3 shows the degree of correction and the magnitude of correction force, as a function of the number of modes. The vast majority of the correction is obtained with the first 100 modes. There is little to be gained by using more than about 100 modes, and some penalty in the form of higher actuator forces.

![Figure 3. Residual surface error and correction forces as a function of the number of bending modes used for the correction. Mirror B needs more of modes 50-100 because of its large errors at intermediate scales. The solid curve for force is the rms force (over the 672 actuators) and the dotted curve is the peak force.](image)

4. BLOCKING, THINNING AND EDGING

In preparation for thinning and figuring the rear surface of each mirror, we attached the concave optical surface to a matching convex blocking body with pitch. We used a granite blocking body, which complicated the process because of its large expansion coefficient and possible distortion as it absorbs water. We will use low-expansion glass or glass-ceramic in the future. With the optical surface face-up, we melted pitch on it in a temporary oven, and lowered the blocking body onto it.

We then generated, lapped and polished the rear surface of each mirror to produce a mean thickness of 1.6 mm, monitoring thickness with an ultrasonic gauge. The rear surface is nominally spherical with a radius of 1995 mm, with a tolerance of about 30 µm peak-to-valley including power. We had concerns, initially for Shell A, that the shells might be under stress and warped by a significant amount, because of thermal expansion of the granite during the blocking process or water absorption, or both. We therefore measured the distribution of thickness over a grid of about 100 points, and inferred the shape of the concave optical surface from the spherical rear surface and the thickness variations. The inferred optical surface was significantly different from the figure that had been measured during processing of the
optical surface, confirming that the granite had indeed warped at some time after the blocking pitch “froze”, causing the shell to bend with it.

We therefore let the figuring of the rear surface be guided by the measured thickness distribution. Figure 4 shows the measurement procedure. A thin plastic mask with holes on a regular grid is placed over the blocked shell. The measured thickness values are compared with a map of the desired thickness distribution, equal to the mean thickness plus the aspheric departure of the optical surface. This method guarantees that the rear surface will have the correct shape when the optical surface is brought to its correct shape by the actuators. If there is significant bending of the shell, the rear surface must be figured to something other than the nominal radius of curvature and may require aspheric variations.

![Figure 4. Measurement of the thickness distribution over an LBT secondary shell with an ultrasonic gauge.](image)

The final operations before deblocking the shell are edging it from its oversized diameter to the final dimension, coring a central hole, and beveling and polishing the edges. Shell A was damaged while the outer diameter was being trimmed to the final dimension. Several fractures were produced, most running in the circumferential direction but one extending radially about 100 mm from the edge. While the precise cause of the damage is not known, it is thought to be related to excessive radial force on the shell and delamination between the shell and the pitch. The damaged regions were subsequently removed, leaving an 850 mm diameter shell that is intact apart for the radial fracture which was drilled out to leave a slit. Shell A is being used for integration with the reference body and actuators, so the development can continue while replacement shells are made. We expect that this shell can serve for nearly complete development and optical testing of the system, albeit over a smaller aperture.

A new procedure for trimming to final dimensions was developed and applied successfully to Shell B. At the outer diameter, most of the excess glass is removed as a whole annular piece by cutting vertically through the shell at a radius 2 mm outside the finished dimension. After removal of the outer annulus, the shell is trimmed to the final diameter with an edging wheel, using tools, cutting speeds and feed rates that are understood not to cause excessive force. The operator watches carefully for signs of delamination throughout the process. The operation is shown in Figure 5. The 56 mm central hole is produced in a similar way. Most of the material is removed as a whole disk by cutting vertically through the shell at a radius 2 mm inside the final dimension, then the hole is enlarged to the final diameter with an edging wheel.
5. DEBLOCKING, HANDLING, COATING, AND PACKING

The shell is removed from the blocking body by melting the pitch and letting the shell slide vertically off the blocking body into a special handling fixture. This operation is performed in the same oven used for blocking. The handling fixture and the procedure have been analyzed thoroughly and are known to provide a factor of safety of at least 5 against damage to the shell. This procedure was used successfully for both shells (including shell A after its damaged parts had been removed). Figure 6 shows the end of this operation.

Following deblocking, the shell is always supported in one of four ways: in the main handling fixture, on a special lifting fixture, resting on the reference body (on thin plastic standoffs), and in the shipping container. The main handling fixture is used for all handling operations performed after the deblocking and until the shell is packed for...
shipping. The lifting fixture serves to transfer the shell safely between the other supports and to support the shell in the vacuum chamber during coating.

The main handling fixture, shown in Figure 7, supports the shell axially at 18 points. Two opposed sets of supports can be mounted so that the shell can be held in the inverted position as well. The fixture is used for inverting the shell; during this operation the axial load is transferred from one set of supports to the other while the shell is supported by lateral clips that prevent it from sliding. The design has been analyzed thoroughly and provides a factor of safety of at least 5 against damage to the shell.

Figure 7. Main handling fixture supporting the first LBT secondary shell.

The rear surface of the shell is used as an electrical reference for the capacitive sensors that measure the shell’s shape relative to its reference body. We produce the conductive surface by depositing a thin (~ 80 nm) layer of aluminum. This simple method provides a layer that meets all the requirements. The deposition of aluminum follows a pattern that is generated by masking a set of 672 small circular areas and a set of six lines. The circular areas provide bare glass interfaces for gluing magnets to the rear surface, while the lines serve to electrically separate six sectors of the capacitor plate. The pattern can be seen in Figure 8.

The shells were aluminized in a 2.3 m coating chamber. The shell is supported by the lifting fixture, which consists of a 9-point whiffletree using magnetic clamps. Each “point” of the whiffletree is a 3-point load spreader, so the clamps include 27 permanent magnets on both surfaces of the shell. Like all support conditions, the coating support has been thoroughly analyzed for safety. The rear surface of the shell is face-down for coating. The magnets for the clamps are placed on 27 of the masked circular areas, so they do not interfere with the coating.
After the rear surface is coated, each shell is shipped to Italy for integration with the reference body and actuators, and optical tests of the system. The shipping container comprises an inner and an outer wooden box, separated by polyethylene foam. Inside the inner box is a steel frame holding the shell. The shell is sandwiched between two fiberglass foam cored panels, with a soft foam pad that bears against the concave surface of the shell with a controlled pressure. A lateral band is mounted around the circumference to provide a lateral constraint to the shell. The upper and lower panels and the foam pad provide sufficient stiffness to prevent buckling of the shell even under exceptionally high lateral loads.

Shell B was found to be damaged after shipment to Italy, and we believe the damage occurred during the process of packing it into the shipping container. During that packing operation, an aluminum spacer that was used to adjust the separation between the two panels fell onto the edge of the foam sandwich holding the shell. The spacer may have contacted the edge of the shell, causing a fracture that was not detected at the time but propagated during the shipment. Shell B is not considered usable. The shipping container has been redesigned with a more compliant foam pad so that adequate compression will be achieved without the need for adjustable spacers.

6. CURRENT STATUS OF SHELL PRODUCTION

Two replacement shells are currently being made for shells A and B, and the LBT Observatory plans to have a third shell made as a spare. The manufacturing plan for the replacement shells is the same as that described here with a few exceptions. First, the aspheric surfaces of the substrates were generated by ITT Industries to an accuracy of about 10 µm rms before being sent to the Mirror Lab for the remaining operations. This reduces the time required for loose-abrasive grinding. Second, the blocking bodies are made of Corning TSG, a low-grade equivalent of ULE. This will eliminate concerns about warping due to thermal expansion during the blocking operation or absorption of water. (We will continue to monitor the thickness distribution over the shell.) The procedure for edging the shells has already been modified and demonstrated successfully for shell B. The design of the shipping container has been modified to eliminate both the parts and the operation that are thought to have caused the damage to shell B.

The production of the second set of two shells is still in the initial phase but is taking advantage of the previous experience and progressing at a faster pace. Figuring of the optical surface of the first replacement is nearly complete, while the second has been generated and is in the polishing queue.

While the two accidents have caused significant difficulties and delays to the project, they do not show any fundamental difficulty with the method of production or the design of the LBT adaptive secondary mirrors. The accidents have pointed out a need for even more thorough analysis and oversight of every step in the manufacturing process and handling of the shells. The Mirror Lab and the LBT Observatory have implemented a number of
improvements to the manufacturing and handling procedures and will continue to develop safe procedures for future operations.

7. SUMMARY

We have developed an effective method for the manufacture of 1.6 mm shells for the LBT adaptive secondary mirrors. This method produces optical surfaces that are very smooth on the critical small scales, and rear surfaces that match the reference body accurately when the optical surface is held in its correct shape. We have developed equipment and procedures for safe handling of the shells. Inadequate procedures that led to damage of the first two shells have been corrected, and all work on the shells is being performed in a way that minimizes the risk of future damage.

REFERENCES