Advanced Technology Solar Telescope 4.2 m Off-axis Primary Mirror Fabrication

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Abstract: Advanced optical surfacing technologies are applied for the Advanced Technology Solar Telescope 4.2 m off-axis primary mirror fabrication. A newly developed Stressed lap and IR deflectometry system are demonstrated for a highly deterministic manufacturing process.
OCIS codes: (220.0220) Optical design and fabrication; (220.4840) Testing

1. Introduction

The Advanced Technology Solar Telescope (ATST), recently renamed as the Daniel K. Inouye Solar Telescope, has a unique optical system design employing an off-axis parabolic primary mirror to achieve its challenging science goals as the National Solar Observatory's future flagship solar telescope in Hawaii. The off-axis design eliminates the common central obscuration due to an on-axis secondary mirror and its supporting spider, which easily becomes a source of problematic scattered stray light. The large 4.2 m primary mirror with visible wavelength adaptive optics provides diffraction limited high resolution, enabling observations of the Sun's small scale magnetic activities (e.g. ~20 km on the Sun's surface) [1]. Also, the large mirror collects more photons to analyze narrow slices of solar spectrum, and captures fast events (i.e. temporal imaging) on the Sun.

As the telescope requires both a diffraction limited imaging performance and very high contrast imaging, all the way from the low-order surface figure to the mid-to-high spatial frequency error control become critical [2, 3]. The Optical Engineering and Fabrication Facility at the University of Arizona has been re-constructed with substantial major upgrades to fulfill the precision Computer Controlled Optical Surfacing (CCOS) capability requirement for the ATST's thin (aspect ratio: ~50) 4.2 m diameter Zerodur primary mirror fabrication.

2. Advanced Optical Surfacing and Metrology Technologies

As the 4.2 m off-axis parabolic mirror (Conic constant: -1, off-axis distance: 4 m, and radius of curvature: 16 m) has a highly freeform shape with more than ~9 mm peak-to-valley aspheric departure as shown in Fig. 1 (center), the deterministic CCOS process for a stable surface error correction requires a tool conforming to the locally varying surfaces as the tool moves on the mirror. While some small tools (e.g. <1/20 of the workpiece diameter) or Rigid Conformal lap [4] could be utilized during the final figuring phase, in order to achieve more efficient smoothing effects [5] from a large and stiff lap, a next generation Stressed lap shown in Fig. 1 (left) has been developed at the Steward Observatory Mirror Laboratory, University of Arizona. The computer controlled Stressed lap (0.6 m contact area diameter) continuously controls its aluminum plate (i.e. lap) shape at 100Hz to maintain the intimate fit between the lap and the local optical surface during fabrication.

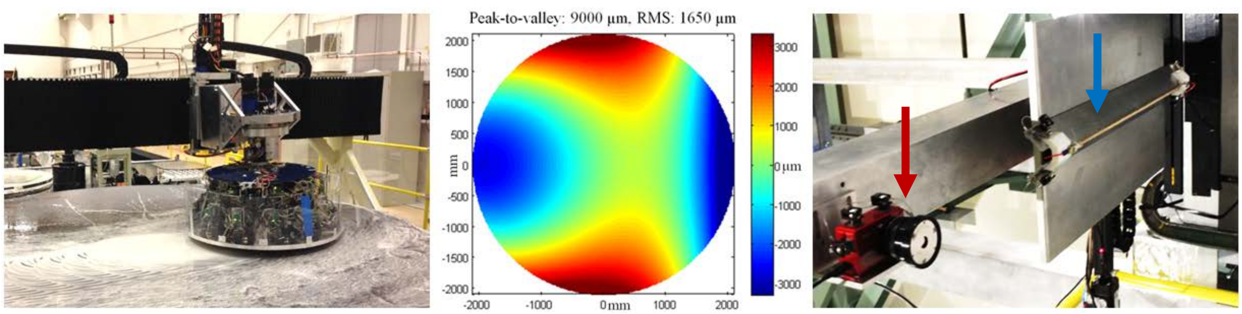

Fig. 1. Newly developed 0.6 m Stressed lap (left) on the 4.2 m ATST off-axis primary mirror, aspheric departure map of the ATST mirror with parent vertex towards –x direction (center), and the Scanning Long-wave Optical Test System [6] (right) using an IR camera (red arrow) and tungsten ribbon IR source (blue arrow) to guide a fine grinding phase by providing high dynamic range precision metrology data before polishing.

The deterministic CCOS process requires high fidelity metrology data. The measurement accuracy and dynamic range often limits the manufacturing capability for a certain fabrication phase. Especially, during the fine grinding phase (e.g. 12 μm loose abrasive grinding), the ground surface is not easily measurable due to the surface scattering.

Conventional IR interferometry could be employed, but often with some limited spatial resolution and dynamic range, which degrade the optical surfacing efficiency. For instance, if the edge of the optic is turned down during the grinding phase due to the lack of metrology, recovering the edge during the final polishing phase, which is a very slow process, adds significant fabrication time to the overall project schedule. A new IR deflectometry system, Scanning Long-wave Optical Test System (SLOTS), has been successfully developed [6] and installed in the testing tower above the ATST mirror blank to provide an in-situ high resolution surface measurement with large dynamic range during the grinding phase.

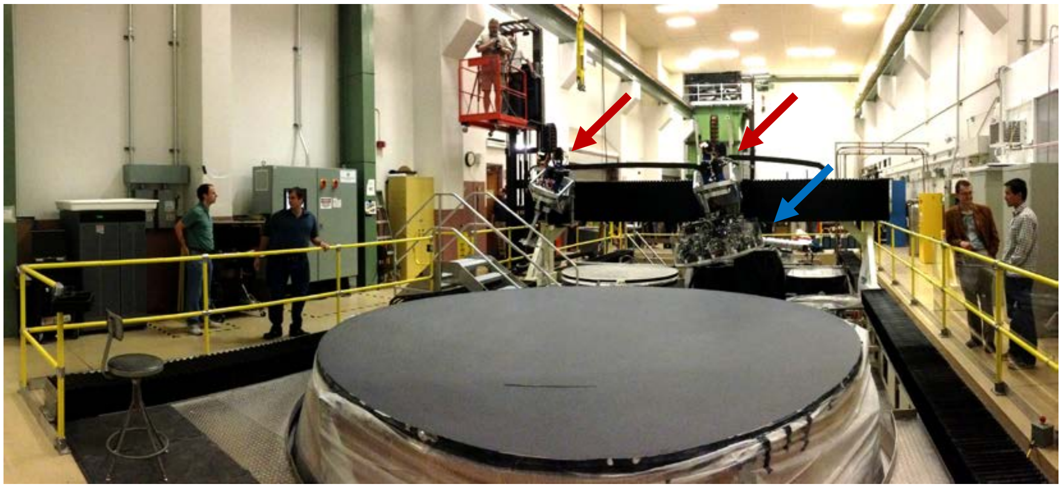

Fig. 2. A gantry type computer controlled optical fabrication machine equipped with two spindle heads (red arrows) allowing simultaneous orbital and spin tool stroke motions. The 4.2m ATST Zerodur commissioning blank sitting on 118 hydraulic supports is shown (bottom), and the whole gantry carrying 0.6m Stressed lap (blue arrow) is moved out from the mirror blank for an in-situ metrology from the testing tower above the mirror. *(Note: The panoramic image is distorted.)*

The Stressed lap has been mounted to the computer controlled fabrication machine (Fig. 2), which provides simultaneous orbital and spin tool motions. A precise dual-motion spindle head controlled by customized motion control software was developed and configured, so that the spin axis maintains the orientation of the Stressed lap towards the parent vertex of the off-axis mirror while the orbital axis provides most of the removal energy (i.e. the speed term in Preston's equation [4]). This innovative approach controlling tool's motion and orientation minimizes the required Stressed lap shape change during the orbital stroking (e.g. 15 RPM).

3. 4.2 m Zerodur Off-axis Mirror Manufacturing

The advanced CCOS capability leveraging new technologies has been demonstrated via actual grinding runs (using the parameters listed in Table 1) on the 4.2 m ATST Zerodur commissioning blank shown in Fig. 2.

Table 1. Fine loose abrasive grinding parameters for the 4.2m Zerodur off-axis commissioning mirror blank fabrication

Parameters	**Value**
Loose abrasive fine grinding grit size	12 μm
Calibrated Preston's constant [4]	363 μm/psi(m/sec)hour
Orbital motion radius with stroke RPM	150 mm with 15 RPM
Stressed lap contact area size	0.6 m in diameter
Stressed lap pressure	0.3 PSI
Max overhang ratio [7] (= Overhang length / Lap diameter)	0.25

The initial surface map was measured using SLOTS from the testing tower while the gantry was moved out to clear the SLOTS beam path. A CCOS run targeting the measured surface error was simulated, optimized (using MATRIX software [8]), and executed using the Stressed lap with 12 μm fine loose abrasive grinding grits on the Zerodur blank for 5.3 hours. The dwell time distribution during the 5.3 hours run is presented in Fig. 3 (bottom-right). The Zerodur surface was measured after the run and subtracted from the initial surface map to produce the measured removal map in Fig. 3 (top-left).

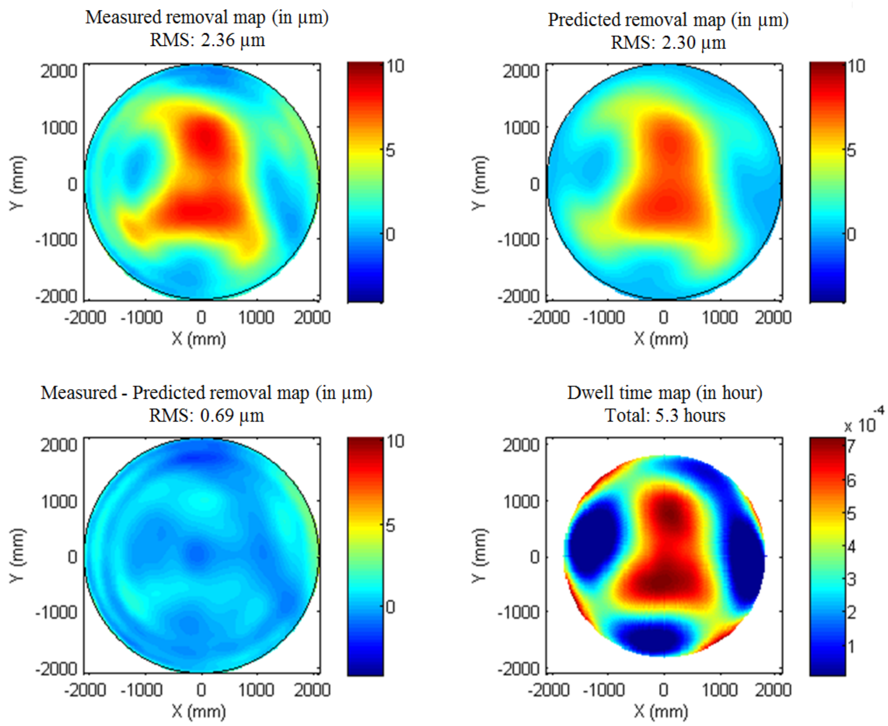

Fig. 3. Comparison between the measured (top-left) and predicted (top-right) removal map for a figuring run during the fine grinding phase using 12 μm loose abrasive grits with the 0.6 m Stressed lap on the 4.2 m Zerodur blank. The difference map between the measured and predicted removal maps is presented (bottom-left) to evaluate the deterministic figuring capability. The total 5.3 hours dwell time distribution plot (bottom-right) is also presented. *(Note: Red means more removal in the measured and predicted removal maps.)*

In Fig. 3, the measured removal map with 2.36 μm RMS (top-left) shows a good match with the predicted removal map with 2.30 μm RMS (top-right). This demonstrates an excellent deterministic CCOS capability during the early fine grinding phase, which guarantees a significantly improved initial surface figure accuracy entering the slow final polishing phase. The 0.69 μm RMS difference map (bottom-left) shows some low order differences and edge effects [7], which will be used to calibrate and further improve the current CCOS process in the future.

4. References

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