Extremely Large Freeform Optics Manufacturing and Testing

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Abstract

The 4.2m Daniel K. Inouye Solar Telescope (DKIST) primary mirror has about 9 mm freeform aspheric departure. Actively controlled stressed lap and infrared deflectometry system have been developed to manufacture the extremely large freeform optics.

I. INTRODUCTION

Many next generation astronomical telescopes or large aperture optical systems leverage freeform optics as they allow segmented optical system to create extremely large optical aperture (e.g. Giant Magellan Telescope [1]) or advanced optical design without obscurations (e.g. DKIST [2]). Large optical aperture provides higher diffraction limited imaging resolution with more light collecting power. Off-axis optical design enables locating other optics such as secondary mirror outside the beam path to minimize stray light effects. The importance of large freeform optics manufacturing has been highlighted.

II. EXTREMELY LARGE FREEFORM OPTICS

A. DKIST Primary Mirror

DKIST is the National Solar Observatory's next generation solar telescope, which has 4.2 m diameter off-axis primary mirror (Figure 1), targeting ~20 km resolution on the Sun's surface to investigate small scale magnetic activities. [3]

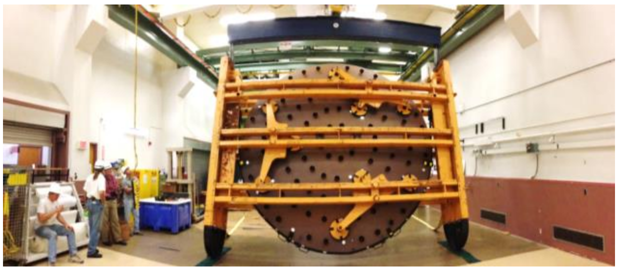

Fig. 1. The 4.2 m diameter DKIST primary mirror in the turning structure at the College of Optical Sciences, University of Arizona.

As its thermal control is critical for the solar application the primary mirror is made out of extremely low expansion glass ceramic *ZERODUR*. The largest *ZERODUR* substrate ever made (4.2 m in diameter) is shown in the mirror turning structure in Figure 1.

B. Extremely Large Freeform Optics

The optical design prescription for the DKIST primary mirror is presented in Table I.

TABLE I. DKIST PRIMARY MIRROR OPTICAL DESIGN PRESCRIPTION

Optical parameter	Value	Note
Radius of curvature	16 m	
Conic constant	-1	Parabola
Off-axis distance	4 m	Distance from the parent vertex
Mirror diameter	4.2 m	
Aspheric departure	~9 mm	Peak-to-valley departure

The primary mirror has an off-axis parabolic shape, and its aspheric departure (i.e. deviation from the best-fit sphere) represents the freeform shape component that must be fabricated and measured. The freeform departure map in Figure 2 (left) shows ~9 mm (= 14,218 λ at 633nm wavelength) of maximum deviation. The high order shape after subtracting the first 8 standard Zernike terms (Piston, Tip, Tilt, Power, Astigmatism and Coma) is shown in Figure 2 (right), also.

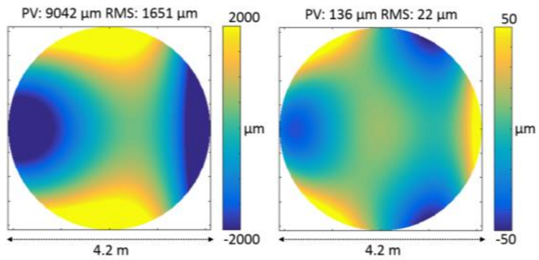

Fig. 2. Freeform departure of the DKIST primary mirror (left) and high order shape after subtracting the first 8 standard Zernike terms (right).

III. COMPUTER CONTROLLED OPTICAL SURFACING

A. Computer Controlled Optical Surfacing Machine

A gantry-type 5-aixs computer controlled optical surfacing machine (Figure 3) has been developed.

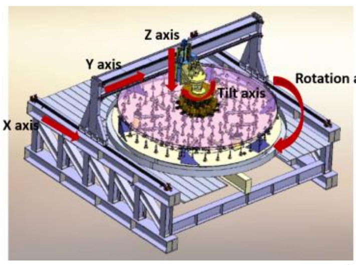

Fig. 3. Gantry-type computer controlled optical surfacing machine.

It controls the tool motion and mirror rotation to deterministically fabricate the optics using dwell time control technology. [4]

B. Stressed Lap and Infrared Deflectometry

Actively controlled stressed lap, shown in Figure 4 (left), using real-time 12 benders to change its 60 cm diameter lap shape according to various local freeform shapes has been developed. [5] In order to provide metrology data during fine grinding phase, an infrared deflectometry system, Scanning Long-wave Optical Test System (SLOTS), using ~300°C wire emitting ~10 μm wavelength light has been developed as shown in Figure 4 (right). [6]

Fig. 4. Actively shape controlled 60 cm stressed lap (left) and Scanning Long-wave Optical Test System (right).

IV. METROLOGY AND FABRICATION RESULT

SLOTS has been successfully used to provide surface shape information to guide the fabrication process. A sequence of captured infrared camera images during a scan is presented in Figure 5.

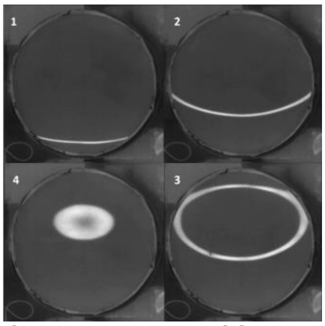

Fig. 5. Infrared camera images captured during SLOTS scanning process (clockwise from the top-left).

A series of fine grinding runs have been performed using 25 μm loose abrasive grits. Detailed fabrication parameters are listed in Table II.

TABLE II. DKIST PRIMARY MIRROR FABRICATION PARAMETERS

Fabrication parameter	Value	Note
Loose abrasive grit size	25 μm	Aluminum Oxide
Polishing pressure	0.3 psi	
Tool sizes	300 – 600 mm	Circular tool diameter
Orbital stroke speed	30 rpm	
Orbital stroke radius	75 – 150 mm	[4]
Preston's constant	~794 μm/psi(m/sec)hour	Calibrated from measurement
Mirror aspect ratio	~50	Mirror diameter / thickness

The DKIST primary mirror surface shape error (from the ideal shape) measured by SLOTS is presented in Figure 6. Three successive runs has been made between the two measurements. The Root-Mean-Square (RMS) shape error has been improved from 15 μm to 2 μm.

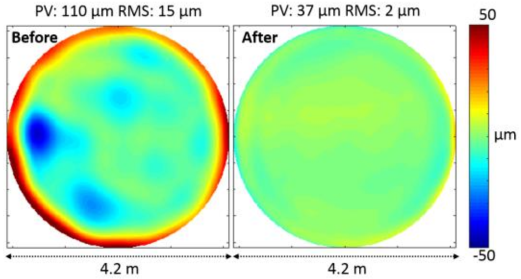

Fig. 6. DKIST primary mirror surface shape error (from the ideal shape) changes between 3 successive fine grinding runs (measured by SLOTS).

V. CONCLUSIONS

The 4.2 m DKIST primary mirror has gone through the fine grinding phase with remarkably fast convergence. It demonstrates the superb capability of the presented large freeform optics manufacturing and testing technologies. The DKIST primary mirror in polishing phase (after the successful fine grinding phase) is shown in Figure 7.

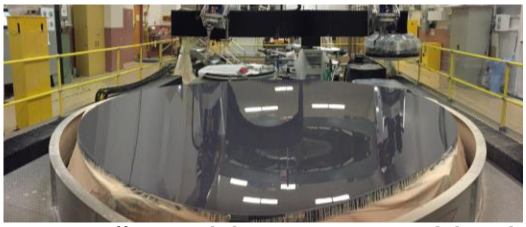

Fig. 7. DKIST off-axis parabolic primary mirror in polishing phase.

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