Faster production of high-quality telescope mirrors

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Novel polishing techniques on pre-cut segments may speed the manufacture of aspheric mirrors for large telescopes.

Large-aperture telescopes use multiple segmented mirrors, which require grinding and polishing to achieve a specific surface-form. There is growing demand worldwide for high-precision, nanometer-level control of surfaces to manufacture these mirrors on an increasing scale. However, current production processes are slow. The UK National Facility for Ultra-Precision Surfaces, which is operated by Glyndŵr University and partnered with University College London and Zeeko Ltd, has developed a novel, faster process to manufacture prototype high-specification mirror segments for the European Extremely Large Telescope (E-ELT).

The E-ELT, an optical/infrared telescope, will have a 39.3m diameter primary mirror comprising 798 hexagonal segments, each off-axis aspheric (i.e., with a surface profile that has nonspherical aspects). In total, the telescope requires 931 segments, providing one spare of each design. Our challenge is to meet the technical specification with an unprecedented production schedule of one segment every few days. The segments require a wavefront of tens of nanometers, an edge-roll (where pressure from the traditional polishing tool causes the edge to be rounded) of $<100\text{nm}$, and the dimensions necessary to create the aspheric shape.

Unlike other segment manufacturers, we grind, smooth, and polish on segments pre-cut to the final hexagonal shape. This was previously considered impractical, as the issue of edge-roll was insurmountable. Conventionally, segments are processed as round blanks, until the manufacturer has reduced form errors to less than a micron in size, and can cut the segments into hexagonal shapes. Unfortunately, this process warps the surface. Finishing by ion-figuring in vacuum (involving a high-precision beam to remove material from the mirror’s surface) preserves the edges, but is slow.

We saw that using pre-cut segments simplified the process-flow and minimized manual interventions. Cutting—with its own risks—is performed before value is added to the blank, and avoids the need for ion-figuring.

To address the problem of edge-roll, we developed the process on subscale parts, deploying a variety of techniques. These included bonnets furnished with polishing cloth or pitch and used with cerium oxide abrasive, or a brass button working with more aggressive abrasives. We performed the work on our 1.2m Zeeko Computer Numerical Control (CNC) polishing machine. Bonnet polishing used the tool-lift method, where the bonnet is progressively raised or lowered, delivering polishing spots of variable size and giving effective edge-control.1-3 We then built full-scale production equipment, including the first 1.6m Zeeko machine, to develop the process (see Figure 1). Glyndŵr designed and operated a 10m test tower to surround the machine, enabling full-aperture null interferometry, or measuring of the entire surface area (see Figure 2). We could then measure the segments in situ, further minimizing handling. The E-ELT project requires an independent test of base radius
and conic constant, so Glyndŵr has developed a scanning pentaprism profilometer—deployable in the lab, or on the bridge of the Zeeko machine—for measuring segments in situ. (see Figure 3).

The first mirror manufactured on the 1.6m machine was the master spherical segment (MSS). We characterized this oversized mirror (1.45m across corners), using rotations and shearing to decouple test from surface errors. Polishing stopped when the surface met requirements for the master:—16.8±2nm root mean square (RMS) surface, 5.5nm RMS for spatial scales <250mm, and 4.2nm RMS for scales <100mm (see Figure 4). We test aspheric segments differentially with respect to the MSS. This is necessary so that all the segments in the eventual telescope, to be manufactured over six years, will be consistent and bring light to a common focus.

We aspherically ground the first segment, SPN01, to about 10 microns peak-to-valley (PV) form error on the BoX CNC grinder at Cranfield University. In the Zeeko process, we circulated a conditioned abrasive slurry onto the workpiece. This caused the first problem: the slurry settled on the surface, increasing the local removal rate, and in the machine, decreasing the global removal rate. Enlarging the slurry tank and increasing the delivery rate resolved the problem. The second challenge was more subtle. For CNC polishing to converge, the coordinate systems for the part’s surface, the CNC machine axes, and the metrology data must all coincide. In the early days we had discrepancies, which meant that we polished in the wrong places. The third issue was removing mid-spatials (surface errors) from CNC grinding, requiring an effective smoothing process suitable for an aspherical surface.4, 5

Having rectified these issues, we polished SPN01 to about the same specification as the MSS, but with good edges. We then recalibrated the optical configuration, and improved the thermal environment of the test tower to accommodate changes in surrounding temperature (which might otherwise affect the test result). We BoX-ground SPN04, and it is currently on the Zeeko

Figure 2. A 10m test tower designed and built by Glyndŵr University around the IRP 1600 machine. The tower enabled full-aperture interferometry, for accurate surface measurements.

Figure 3. Performing a measurement in situ using a specially developed pentaprism profilometer mounted on the Zeeko IRP 1600.

Figure 4. Phase maps of the master spherical segment after form corrections.

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Figure 5. Comparison of work progress on the ‘SPN01’ and ‘SPN04’ segments. The curves show the root mean square (RMS) value of surface errors of the two prototype segments after each correction. Work on SPN01 is near completion and the data is actual. Work on SPN04 is still in progress, so that both actual and predicted data are presented.

machine. On this segment, BoX delivered 30 microns PV input form-error, which we have since successfully corrected with CNC polishing. The current status is 136nm RMS to the extreme edge, with excellent form convergence and edge definitions (see Figure 5).

The largest number of meter-class mirror segments made anywhere for an optical telescope is 36, and these were made by running a prototype manufacturing process 36 times. Worldwide, there is a gulf between today’s manufacturing for off-axis aspheres, and tomorrow’s mass-production requirements. We are now working to further speed and automate the process chain and so close this gap. Under an intensive program, we are developing the actual corrective polishing and smoothing processes, the metrology methods, and, importantly, the computational techniques required for analyzing and interpreting metrology data and computing tool-paths to improve form. In parallel, we are estimating the machines and support facilities required for mass production and developing the factory layout for an effective work-flow.

Meanwhile, we are investigating the wider markets for meter-scale optics, including high-power laser systems, remote sensing, space astronomy, and photolithography. We are looking to create a manufacturing base in North Wales and to stimulate the supply chain.

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References