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Advanced Abrasive Processes For Manufacturing Prototype Mirror Segments For The World's Largest Telescope

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Abstract. This paper describes the application of loose-abrasive processes to the manufacture of 1.4 meter, off-axis aspheric, hexagonal mirror-segments. These are prototypes for the 39 m European Extremely Large Telescope (E-ELT). The application of active forces to correct the overall form of segments in the telescope, means that the overall form-accuracy achieved in polishing can be less critical than for a non-active mirror. However, it is a requirement that the base-radii and conic constants of mirror-segments are very closely matched, so that the combined image is not degraded. This means that abrasive processes have to operate with respect to an *absolute* rather than *relative* datum. Furthermore, there are stringent requirements on mid-spatial frequency defects on segment surfaces, and on edge-roll. These control stray-light, and ultimately detectability of faint astronomical targets. We describe the CNC abrasive techniques we have developed in response. We then demonstrate the success of the approach, which represents the first time ever that segments have been processed entirely in the hexagonal shape:- a milestone in loose-abrasive processing. Finally, we address up-scale for the unprecedented number of segments required for the E-ELT build-phase.

Introduction

This paper aims to inform the wider abrasives community, by giving an overview of a challenging abrasive manufacturing project. The methods developed are known to be transferrable to other applications. The context is the European Extremely Large Telescope (E-ELT) project, currently in its planning and technology-demonstrator stage. It is led by the European Southern Observatory (ESO), of which the UK is one of 15 member states. The telescope will ultimately be located in Chile.

The E-ELT was originally conceived as a 42m aperture f/1 optical/infrared telescope [1] with a segmented (or, 'tiled') main mirror. The design has 984 hexagonal primary mirror segments, and 1,148 including one spare of each family of segments (given the 6-way symmetry). Segments are 1.234m across the flats, or ~1.43m across the corners. Segments vary in perimeter-shape, as regular hexagons can't tessellate a curved surface with equal gaps. The segments of maximum asphericity (i.e. maximum departure of the surface of a segment from its best-fit sphere) are those near the edge of the 42m aperture, and the asphericity of each segment there is ~ 200μ peak-to-valley.

The prototype project, as described in this paper, is in the context of this original 42m design, and follows the ESO segment manufacturing specification [2]. The telescope has more recently been de-scoped on cost-grounds to a 39.3m aperture at f/0.95, with the same sized segments. The smaller aperture and faster design gives about similar maximum asphericity. This design has 798 segments in the telescope, and 931 including spares.

The prototype segments are particularly challenging in regard to the long radius of curvature (84m +/- 200mm), off-axis aspheric form, edges, and the requirement to *match* segments in terms of base-radius and conic constant. The first segment manufactured can have a base-radius anywhere between 83.8m and 84.2m. For all subsequent segments, any drift in base-radius from that of the first segment simply constitutes a term in the overall error-budget required to meet the form specification.

This ESO specification [1], including specifications for mid-spatial frequency and edge defects, is summarized in Table 1 below. The mid spatial frequency performance of a segment is established by removing ESO-specified low-order terms from the full-aperture measurement data (predominantly astigmatism, i.e. the first bending-mode, which imposes a cylindrical term into the form).

Table 1 Outline summary of specification for Prototype Mirror Segments

Maximum form-error, surface, worst segment [nm]	50
Maximum form-error, surface average segment [nm]	25
Maximum mid-spatial frequencies, surface, worst segment [nm]	15
Maximum mid-spatial frequencies, surface, average segment [nm]	7.5
Maximum edge-roll, surface, worst segment [μ]	200
Maximum edge-roll, surface, average segment [μ]	100

The established method to manufacture hexagonal mirror segments for large telescopes is based on stressed-mirror lapping and polishing of the blank to a true spherical form, whilst in the circular state. The applied stresses are then relaxed, after which the mirror approximates to the desired off-axis aspheric form. The analytical basis for this was reported in 1980 [3]. The part is then cut to the final hexagonal shape, preserving pristine edge-definition, but this causes some global warping [4] as stresses re-distribute. The mirror is then finished by non-contact ion-figuring in vacuum. The method was used successfully to produce the thirty-six segments for each of the two Keck telescopes, and a comparison of test and theoretical predictions of mirror stressing has been reported [4].

Scale-up for segment mass-production at the scale of ~ a thousand presents unprecedented challenges, as such large off-axis aspheres have never been manufactured with the combination of quality, quantity and speed before. This demands a new way to look at the manufacturing cycle. Issues arise in i) manual processes and handling, e.g. for attachment and removal of the stressing fixtures, ii) risk associated with cutting hexagonal when the part has already accumulated significant processing and so added value, and iii) the time and handling associated with ion figuring (requiring vacuum).

For this reason, we report on a new approach [5]. Ultra-precision bound-abrasive CNC machining of the off-axis asphere, and then smoothing, polishing and form-correction, are all performed on the blank in its *final hexagonal state*. During the polishing, smoothing and form-correction cycles, the part stays on its support-system on a Zeeko IRP1600 CNC polishing machine at OpTIC, with metrology conducted entirely *in-situ*. This approach requires the minimum of manual interventions, no stressing of the part, and all stages are conducted entirely in air.

All the processes deployed on full-size segments have first been exhaustively tested and optimized on witness hexagons (200-400mm across corners), using the Zeeko IRP1200 machine at OpTIC.

Grinding the base-asphere

The ultra-low expansion ceramic segment blanks are supplied by the blank manufacturer machined to the final external hexagonal dimensions, and to the final thickness of 50mm plus a small allowance for subsequent processes. The blanks are also supplied with the specified rear cavity, for integration with a flexural support that resists lateral forces.

The segment is first mounted at Cranfield University in the UK onto an over-size, diamond-turned aluminum platen, flat to a few μm. This is then mounted into the Cranfield University BoX^{TM} ("Big Optics") CNC grinding machine [6]. The off-axis asphere is then ground into the hexagonal part. This high-stiffness machine is optimized for low-slope optics, having only four motions:- part and tool rotations (C, H), tool radial-traverse (R) and tool-height (Z). Grinding of segments has demonstrated pristine edges, and surfaces with ~ 2 μm peak-to-valley form-error over 1 metre, when measured on the grinding support. Sub-surface damage is ~ 10 μm or less, and mid spatial frequency errors are up to a few hundred nm in amplitude. A large coordinate measuring machine (CMM) is available at Cranfield to measure the resulting form.

Processes using loose abrasives

Smoothing the asphere by pre-polishing. The objective is to remove the mid-spatial ripples from grinding, and present a reflective surface to optical testing. This has been performed using:-

1. an R80 (80mm radius of curvature) compliant spherical bonnet furnished with a polishing cloth (e.g. polyurethane)
2. 100 and 150mm diameter rotating hard pitch-button tools, both of these used in the presence of re-circulated Cerox Super 1663 cerium oxide slurry. The mis-fit of the pitch tool with the asphere limits the maximum tool-size. Empirical evidence shows that a 150mm diameter rotating pitch tool starts to leave its own mid-spatial frequency artefacts on segments, whereas a 100mm one does not.

The maximum misfit for the 100mm diameter pitch tool, traversing over an outer E-ELT segment, is ~ 800nm. The corresponding figure for a 150mm tool is ~1.6μ. Now the particle size of the cerium oxide used is ~ 1-2μ. We believe that the particles act as an effective interface layer, preventing imposition of mid-spatials, when particle-size exceeds misfit. This has the implication that larger tools could be used, providing that the abrasive particle size is increased in proportion to the misfit. C5 and C9 (5μ and 9μ) aluminium oxide are obvious targets, and we return to this later in this paper.

Corrective polishing. Corrective polishing (Fig. 1) takes as input the Error Map – that is, the measurement of the surface form, subtracted from the target form. The Zeeko Tool Path Generator (TPG) software then computes the Dwell Time Map – that is how long the tool should dwell on each pixel of the surface to give the optimum reduction in error. The Dwell Time Map is then interpreted as a Surface Speed Map, itself interpreted as variable traverse-speeds along (e.g.) a raster tool-path. The correction can leave small mid-spatial residuals, and these are managed by interspersing with pitch-tool smoothing runs.

The full-aperture measurement of the segment is performed using a nulling optical system in a 10m high interferometric Optical Test Tower (OTT – Fig. 2), complemented by a non-contact autocollimator / pentaprism profilometer – the NOM (Fig. 3). A stitching sub-aperture interferometer is also carried by the Zeeko machine to give improved spatial resolution of edges, and to infill a small central obstruction in the OTT data.

In the normal use of full-aperture interferometry, the measurement is relative to a spherical wavefront created by the interferometer, where the radius-of-curvature can be changed by re-focusing the test. In order to assert matching of segments, a *transfer standard* was therefore manufactured – an 84m radius of curvature, over-size, Master Spherical Segment (MSS). Because of the ultimate need to maintain matching over a mass-production schedule of ~6 years, a highly stable MSS was required. Tests of aspheric segments are then bracketed by MSS measurements, so that segment data after analysis is differential *with respect to the MSS*, *which itself has been characterized absolutely by NOM profilometry.*

Optical corrective polishing is usually differential – that is, the optician aims to remove surface-errors purely as a modulation on an underlying uniform removal-depth. The absolute depth of the uniform removal is then not particularly significant. In our case, two factors conspire to make the absolute removal-depth important:-

1. Absolute depth, if excessive, impinges on the total process time, and if insufficient, will not remove sub-surface damage. For segment mass-production, the balance may be critical.
2. Excessive absolute depth makes control of edges more difficult

Therefore, the volumetric removal-rate for a run is characterized on a witness sample of the same material as the segment. In this way, it is possible to track absolute removal-depth across the surface.

Fig. 1 Segment polishing on the Zeeko IRP1600 machine

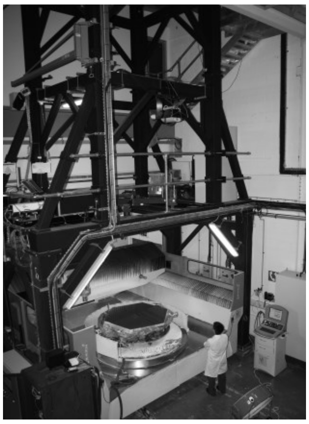


Fig. 2 Zeeko machine under OTT for in-situ full-aperture interferometry

Fig. 3 NOM profilometer mounted on Zeeko machine

Edge polishing. The most challenging aspect in the process-chain is managing edges of the hexagons in polishing, as loose-abrasive processes naturally disturb edges. In general, there are four main deleterious processes at work when polishing edges:-

1. For a removal-process naturally to give a perfect edge, the removal-spot (influence function) should progress fully off the part at the end of each raster. With a physical tool, the path of the centre of the tool always has to stop short of the edge, as otherwise, the tool would rock about the edge. This short-fall reduces edge-zone removal, which tends to turn the edge-zone *up.*
2. The deceleration at the end of each raster, and acceleration at the start, tends to increase local dwell-time and so turn the edge-zone down.
3. An overhanging physical tool presents a pressure-distribution with increasing pressure towards the edge of the part, which tends to turn the extreme edge down.
4. When the tool returns towards centre, a slurry bow-wave can turn the extreme edge down.

The principal we have adopted is as follows. First, we start with clean edges from BoX^{TM} hard grind of the asphere. Then, for each subsequent process-step we aim to leave a turned-up edge. With successive runs, this is progressively narrowed and lowered, and finally cleaned up with a pitch tool.

Turning the edges up with bonnet-polishing relies on the ability to change the polishing spot-size ‘on the fly’, by modulating the Z-offset (the amount by which the spherical bonnet is compressed against the surface). The key variables are the detailed profiles along the raster-track of i) the change in Z-offset, and ii) the traverse-speed. These have been optimized empirically.

Process Results

The MSS. The first large part to be polished was the MSS. This was produced in 200mm thick Zerodur, in order to assure long-term stability, and maximum immunity of the surface to hysteresis in the support system. Raster polishing started with a R160 bonnet delivering a spot-size of ~50mm, but most work used an R80 bonnet, giving polishing spot of 20mm full-diameter, but with high pressures and rotational surface-speeds. The part sufferd an accident in-process due to a tooling failure, which left a 7 micron deep linear feature some 60mm wide. This was removed purely by corrective polishing. Given he application as a transfer-standard, the emphasis was to achieve a smooth part, and the MSS was to be calibrated by profilometry, and used differntially. The final result was 16.8nm RMS over the useable area, 5.5nm RMS for spatial scales <250mm, and RMS for spatial scales <100mm. Fig. 4 shows the synthetic interferograms provided by data analysis, Fig 5 the unfiltered phase map, and the filtered phase maps to establish smoothness quantitatively are in Figs 6, 7.

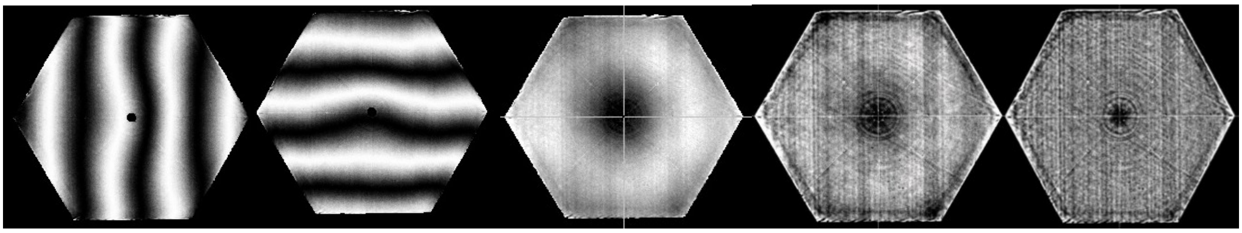


Fig. 4 X and Y synthetic interferograms for MSS

Fig. 5 Unfiltered phase map

Fig. 6 Phase map for spatial scales <250mm

Fig. 7 Phase map for spatial scales <100mm

Segment SPN01 – first phase. The first segment (designated SPN01) was ground to the off-axis aspheric form on the Cranfield BoX^{TM} machine. The RMS form error was < 1 micron, with sub-surface damage < 10 µm. It was then integrated with the 27-point hydrostatic support system at OpTIC, and mounted on the Zeeko machine for pre-polishing. The resulting surface map is shown in Fig. 8. The surface was then corrective polished down to 55.1nm RMS (Fig. 9). After removing the specified low-order terms from the data to reveal the mid spatial frequencies (and hence smoothness), the surface error was 18.6nm RMS (Fig. 10).

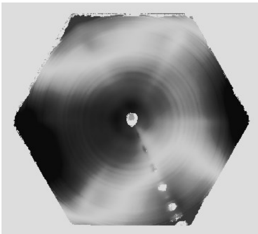


Fig. 8 SPN01 phase-map after pre-polishing

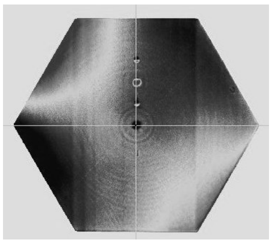


Fig. 9 SPN01 phase-map after corrective polishing

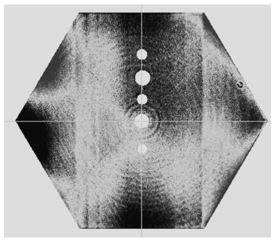


Fig. 10 SPN01 phase-map after corrective polishing and removing low-order terms

At this point polishing was stopped, as convergence was poor. This was traced to thermal effects in the 10m high air-column of Optical Test Tower, which caused random errors in metrology data. After diagnostic tests, the thermal environment was significantly upgraded.

Results – Segment SPN04. After the upgrades, the decision was made to start the next segment designated SPN04, of Corning Ultra Low Expansion (ULE) material. This had been ground on the BoX^{TM}. No CMM data was available, so the part was given a rapid 'flash pre-polish' on the Zeeko machine, removing ~ 2 µm depth of material. Interferometric testing then showed a form error >40µ P-V; entirely unexpected. However, the rear of the part from the blank manufacturer was known to be flat to only ~100 µm, rendering the few-micron flatness of the diamond-turned support plate innefective. We suspect that the segment may have rocked in grinding, although it is possible that the Twyman effect contributed to this. It is known in regard to ULE that the grinding surface stresses, known as the Twyman effect, increase dramatically in the transition from brittle to ductile mode grinding. It is notable that BoX exhibits aspects of ductile removal.

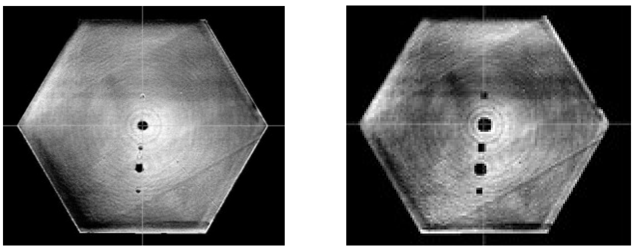
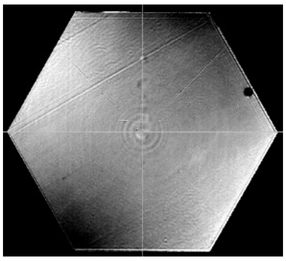


Figure 11 SPN04 Final wavefront (left); low orders removed (right)

SPN04 was completed, and formally accepted by ESO, who witnessed the acceptance tests on -site. The results were 23nm RMS surface, 10nm RMS (low orders removed), 172nm P-Vq (95%) edges, ~1nm Sq texture, and very low scratch-dig. The final phase maps are shown in Figure 11, left.

Results – Segment SPN01 second phase SPN01 was then re-mounted on the Zeeko machine and corrective-polishing continued, utilizing the superior metrology data after the Optical Test Tower improvements and re-calibration. The segment is now complete and awaiting formal acceptance tests to be witnessed by ESO. The final phase-map for the area excluding the 10mm edge-zone, and with low order terms removed, is shown in Figure 9. This comprises Test Tower data, with the CGH artefacts and central obstruction in-filled by stitching from on-machine sub-aperture interferometry. From an analysis of all the acquired data, the measured surface errors are:-



- RMS form in the useable area i.e. excluding the 10mm wide edge-zone (no low-order allowances removed):- 25.4nm ±4.8nm
- RMS form useable area with low-order terms removed:- 7.5nm ±2nm
- Six edges (PVq 95%):- Worst 263nm; Average 199nm; Best 117nm
- Quoted uncertainties represent repeatibilities; absolute accuracies estimated as 21nm (form) and 13nm (form, low orders removed)

Fig. 9 SPN01 final phase-map, low order terms removed

A new intermediate process Polishing to remove BoX^{TM} mid-spatials is slow, and so we are developing an intermediate smoothing process on an industrial robot. We are currently using a Fanuc robot with 20Kg payload and 1.8m reach (Fig. 12). A second robot with 125Kg payload and 3m reach will be installed shortly. Robot control has been integrated in the Zeeko Tool Path Generator software, and process trials are underway on 400mm across-corners hexagons. The tool is 100mm dia. brass under 0.68KgF, with C9 abrasive slurry, and 1,000rpm rotation speed. The removal rate was measured by profilometry to be 42.7 mm^3/minute, with an excellent repeatability of +/- 3% (Fig. 13). Texture was 3µ Sa, giving an output-quality well-matched to the input-quality for the Zeeko machine. Figs 14, 15 show respectively turned-up and turned-down edge-profiles across flats and corners, demonstrating the ability to tune the edge performance as described earlier.

Fig. 12 Robot facility

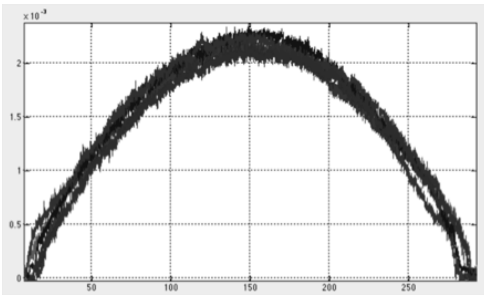


Fig. 13 Uniformity of removal over three runs

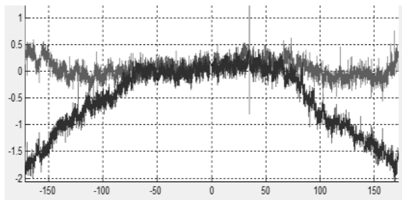


Fig. 14 Edge profiles across flats of hexagon

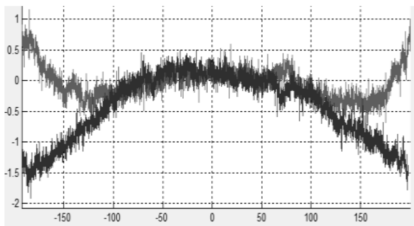


Fig. 15 Edge profiles across corners of hexagon

Conclusion

We have demonstrated a process-chain using BoX grinding, followed by CNC loose-abrasive polishing, manufacturing mirror segments approximating E-ELT requirements; the first demonstration of such quality anywhere, and moreover, with all steps conducted on pre-machined hexagons. We have also demonstrated robotic smoothing providing an intermediate process-step to accelerate the overall process-chain, though further work remains to optimize process parameters.

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