Removal of Mid Spatial-Frequency Features in Mirror Segments

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BoX™ grinding technology has been adopted in our E-ELT segment process. The mid-spatial frequency features generated can be removed by several 'smoothing' processes. We have reported here a novel method that can smooth these features whilst avoiding edge down-turn. This process can be scaled up to E-ELT segment fabrication time-scale. It has been experimentally demonstrated that the surface quality is good enough for subsequent Zeeko form correction technology to achieve form specifications.
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1 INTRODUCTION

The primary mirror of the European Extremely Large Telescope (E-ELT), under development by the European Southern Observatory (ESO), will consists of 984 hexagonal segments of 1.4 m across [1, 2] in its current implementation. This telescope, upon completion, will be ~ 4 times larger in aperture than any telescope in operation. There are many technical challenges in construction. One of these is to manufacture the 1,148 mirror segments required (including one complement of spares) in the proposed 6 years' time. This amounts to one segment per two days.

Some prior work has been published on producing large aspheric surfaces [3]. We have adopted Zeeko's *Precessions* bonnet polishing as the core technique for pre polishing and form correction. The machines have a wide range of users worldwide, support loose and bound-abrasive abrasive grinding, and demonstrate fast corrective polishing. Overall, the dynamic range of removal is large, and the process is versatile in accommodating different tooling and removal mechanisms.

One candidate process-chain for segment fabrication involves grinding the off-axis asphere directly into the hexagonal substrates using the Cranfield University BoX™ ultra-precision grinding machine, using a spiral tool-path. The Zeeko *Precessions* sub-aperture bonnet polishing then provides capability for polishing the surface and correcting the form [4, 5]. Use of bonnets has the distinct advantage that the membrane or rubber naturally moulds itself around the asphere, avoiding the aspheric misfit problem that can be encountered with rigid, or even semi-rigid, polishing tools. However, it has the disadvantage that it is not effective in removing the mid-spatial-frequency features left from the BoX™ grinding operation. In principle small bonnets and spot sizes could be used but the removal rates would be too slow for a commercial process [6].

For this reason, we have investigated various possible intermediate smoothing processes [7, 8], and one promising candidate is reported in this paper.

2 BACKGROUND

BoX™ grinding machine can be used to produce aspheric surfaces with very fast speeds; typical removal rates are 200 mm^3/s. This may be compared with other dedicated large optics generators, such as the Large Optics Generator ('LOG'), whose typical removal rate is 28 mm^3/s [9]. Typical surface quality for the BoX is $P_t = 1$ μm and R_a= 50-100 nm can be achieved. Subsurface damage has been measured at ~ 8 μm for Zerodur. Given such a machine, the subsequent polishing time is greatly reduced compared with classical grinders, as minimal stock has to be removed to penetrate the subsurface damage layer and correct the aspheric form.

In order to grind aspheric surfaces, only a single edge of the 'cup wheel' contacts the working surface. This miminises form-errors, but the small contact-area introduces mid spatial frequency features, as shown in Figure 1. Those with spatial frequency > 1/mm can be effectively removed by a compliant polishing tool, although features in the range of 0.5-0.029/mm are still visible after polishing of 160 hours. In order to remove these features, a 'spatial filter' that has a stop-band covering this frequency should be applied. This 'spatial filter' should

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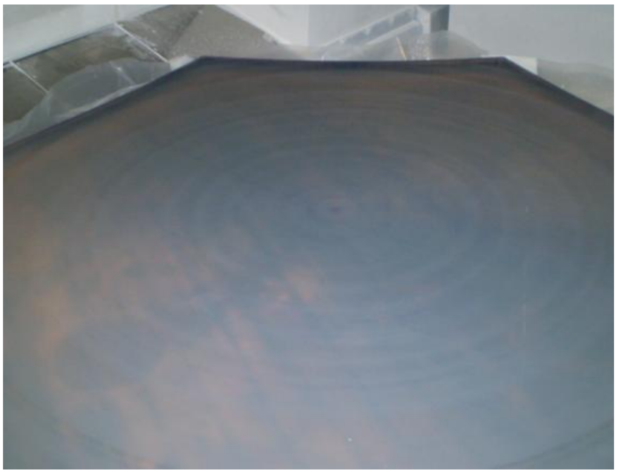

FIG. 1 Surface being ground on BoX™ showing mid-spatial features.

be of rigid or semi-rigid nature to bridge over the varied components of higher spatial frequency.

3 TOOL DESIGN AND OPTIMISATION

In order to facilitate the tool design, analysis of surface was first carried out. A profile of the surface was obtained from interferometry data after a 'flash' (i.e. a rapid, preliminary) polishing in order to reveal the mid spatial frequency components.

A PSD analysis was then used to examine the spatial frequency components of the surface, as can be seen in Figure 2. The features, which are classified regarding their spatial frequencies, can be addressed using different processing strategies. The low-frequency errors (spatial frequency<0.02/mm) will be removed by standard Zeeko sub-aperture form correction.

The high-frequency errors (spatial frequency>1/mm) can be removed by simple compliant-tool uniform polishing, which has been demonstrated experimentally. The mid-spatial frequency errors (0.02/mm<spatial frequency<1/mm) will be removed by a 'grolishing' process, which stands between 'grinding' and 'polishing'. The diameter of the tool is chosen according to two factors: (1) The tool will cover the spatial wavelength range of the mid-spatial features to be removed. (2) The misfit between the tool and aspherical surface of the part should not introduce new mid-spatial features that are out of the specification for the part.

One of the family of "grolishing" processes uses C9 (9 micron aluminium oxide) abrasive slurry with a spinning brass-button tool. The characteristic feature with respect to the mid-spatials it is to address is shown in Figure 3. One surface is radiused to fit a standard R80 (80 mm radius of curvature) Zeeko bonnet and cemented in place, and the other is radiused to match the segment at the start of the tool-path, as shown in Figure 4.

The hard brass-button tool clearly exhibits aspheric misfit [10]. This comprises two main parts: i) the misfit as the tool progresses along the tool-path, and ii) the misfit due to rotation of the tool. The former can be effectively managed through natural tool-wear, which we have calibrated by direct measurement. The latter can be managed, providing that the process parameters are such that the abrasive size is sufficiently larger than the misfit.

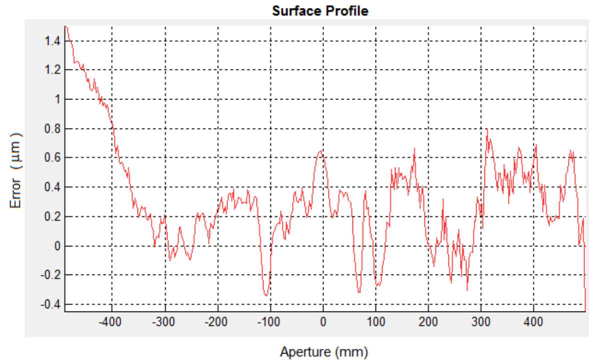

FIG. 2 Surface profile across corners.

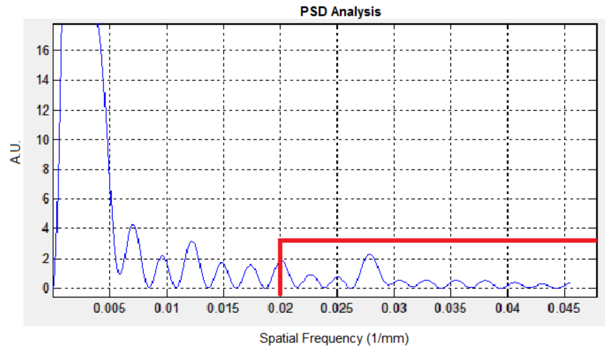

FIG. 3 Power spectral density of surface profile. Red box indicates the grolishing tool's spectral coverage range.

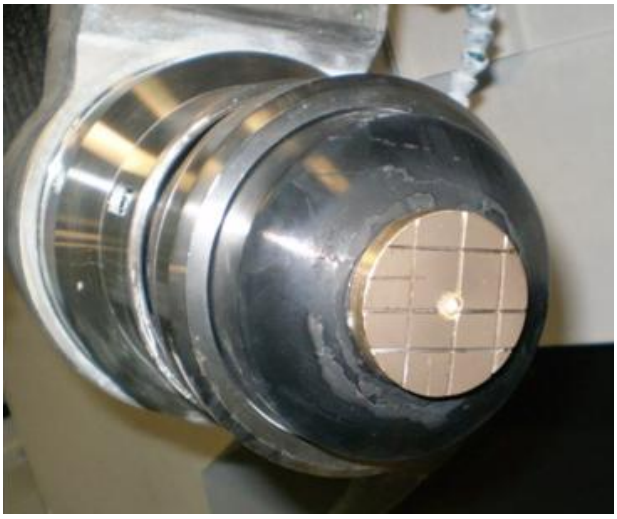

FIG. 4 Grolishing tool mounted on polishing machine.

4 FORM CONTROL EXPERIMENT

The aim of form control experiment was to examine whether the output-quality from brass button grolishing is sufficient to provide a competent input quality for Zeeko bonnet polish-

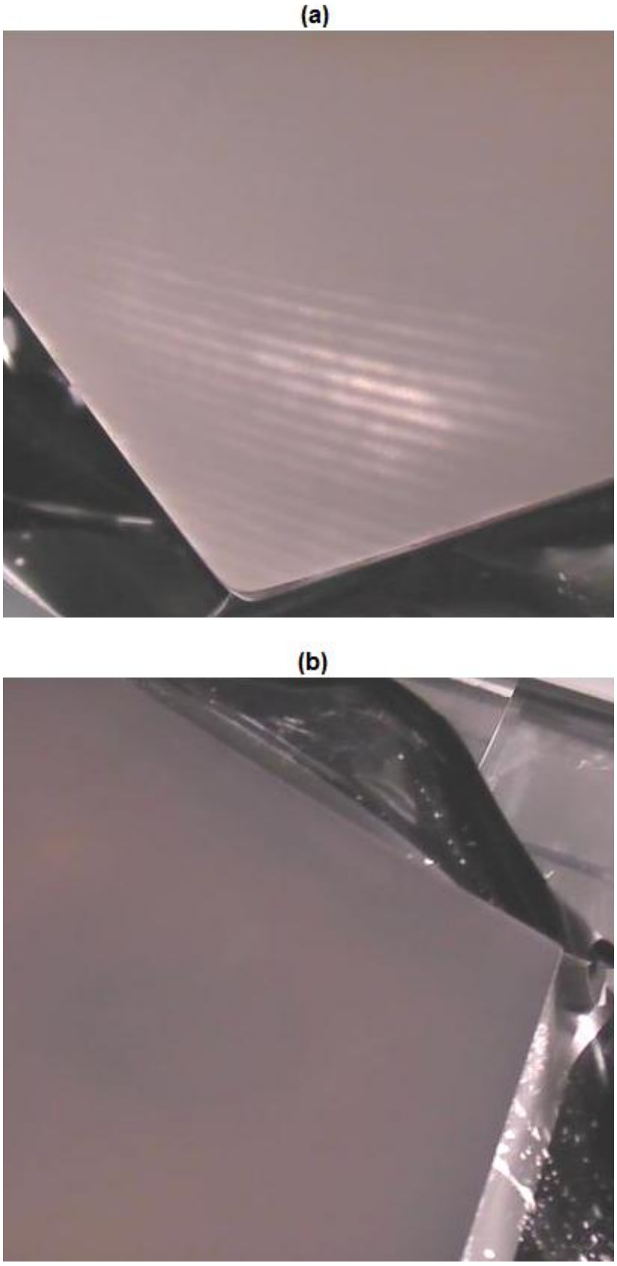

FIG. 5 (a) Surface after 1st grolishing and (b) surface after 2nd grolishing.

ing. Experiments have been performed on a 1 meter corner-to-corner Zerodur hexagonal part, machined spherical on the BoX™ to R = -3 m concave, for convenience of measurement. To characterize the mid-spatial features, this part was flash-polished on a Zeeko IRP1200 machine. The process used an R160 mm bonnet covered with Greyrock polishing cloth and used with conditioned and re-circulated cerium oxide slurry. A raster tool-path was adopted, and the bonnet compression selected delivered a 60 mm spot-size.

This process created a surface measureable by a 4D interferometer mounted on a test-tower immediately above the machine. The choice of raster for the tool-path was important, as it enabled separation of linear polishing effects from the circular BoX™ features that were revealed, these having widths in the 10 to 40 mm range.

The part was then brass-button grolished. After the first grolising run and bonnet pre-polish, the circular marks had not been totally removed, as shown in Figure 5(a). This was due to the progressive tool-lifting procedure deployed at the edges and corners to prevent edge down-turn. This inherently removes less material removal within the tool-lifting zone compared with the bulk area.

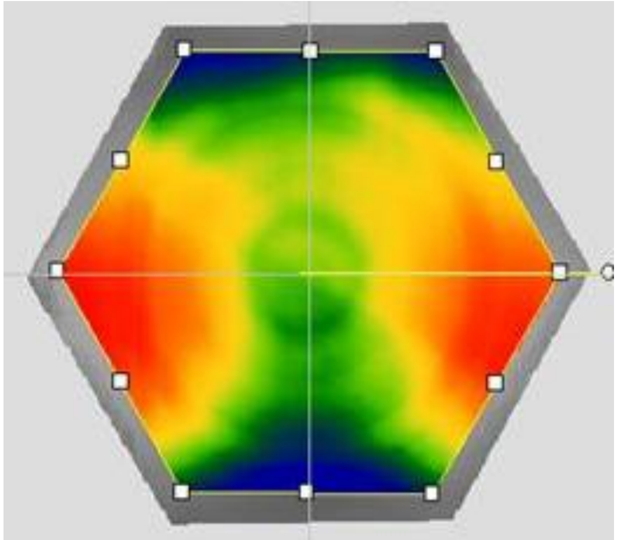

FIG. 6 Surface measured after been grolished and pre-polished.

After a second grolishing run with the same material removal rate, the mid-spatial grinding marks had been removed, as can be seen in Figure 5(b).

To measure the bulk area with the interferometer, the surface was uniformly pre-polished using Greyrock polishing cloth and cerium oxide slurry. This polishing was different from that of the previous flash-polishing, in that it aimed to remove the sub-surface damage left by the grinding process. A large spot size of 60 mm was again chosen and the removal depth was 3 μm. The surface quality was then sufficient to acquire preliminary interferometry data to start form correction, as seen in Figure 6. The PV and RMS error of this surface before corrective polishing were 5.9 μm and 1.3 μm respectively. The 50 mm-wide edge zone was reserved for separate edge process- development, so that the polished bulk area was approximately 800 mm across corners.

Five corrections were performed. The PV and RMS error were 366 nm and 62 nm respectively, after the 5th correction. A final pitch process was also applied to attenuate residual mid-spatial features left by prior process stages. The resulting surface was then as per Figure 7, with PV and RMS error of 56 nm and 12 nm after removal of the tilt, power, astigmatism and trefoil terms. This reflects the final application of the segments where such terms will be handled mechanically through a warping harness.

5 EDGE CONTROL EXPERIMENT

The E-ELT has approximately 4 km of segment edges, and edge-roll will contribute materially to the degradation of stray-light and infrared-emissivity performance. Monitoring and control of edge profiles is perhaps the greatest technical

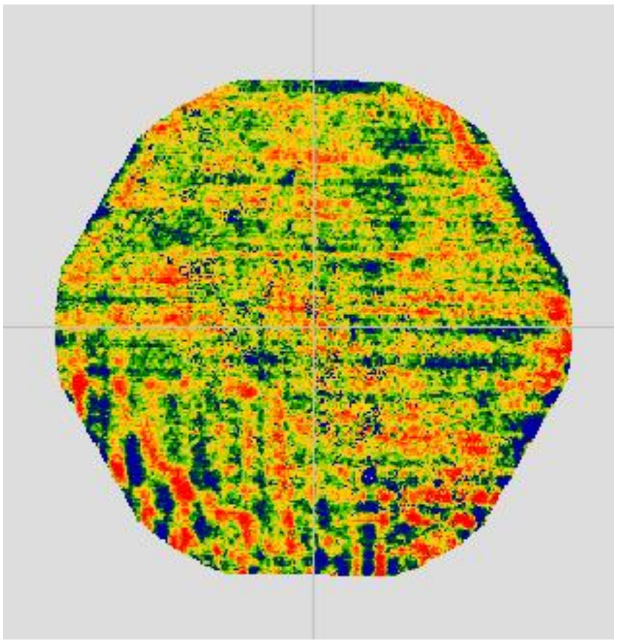

FIG. 7 Surface error map form correction and texture improvement, certain Zernike terms removed.

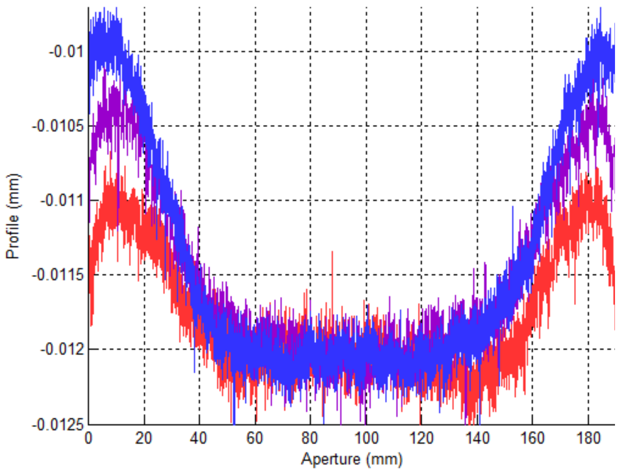

FIG. 8 Varied edge profile can be achieved through different tool-lifting scheme.

challenge in segment fabrication using small-tool techniques on hexagonal segments. Due to the rigid nature of the grolishing tool, control of edge profiles can be achieved by progressively lifting the compressed bonnet carrying the grolishing tool as the edge-zone is encountered. There is considerable flexibility in tuning edge-performance, as there is a wide range of detailed lift-profiles that can be deployed.

Linear or quadratic control of the Z-motion (tool-lift) with lateral position are the simplest. The other degree of freedom is the amount of overlap of the grolishing tool at the limiting point when the tool-path reverses.

Generally, the tool-lifting profile is selected to ensure that the tool has zero contact-force when the centre of the tool is aligned to, or approaches, the edge of the surface. Independent experiments have been carried out on another hexagonal Zerodur surface, measured using Form Talysurf contact profilometry. In these tests, it was found that a $\sim$1 μm edge upstand could be achieved within an edge zone of 50 mm width, as in Figure 8. This upturned edge zone can be addressed by subsequent corrective polishing.

6 CONCLUSION

We have demonstrated a grolishing process that can remove mid-spatial grinding features by BoX^{TM} ultra-precision grinding machine. The potential speed of the process is sufficiently to scale up to ESO's 1.4-meter segments. The edge profile and its own features have been optimised within the input-specifications for subsequent polishing processes.

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