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Research on Fabrication of Mirror Segments for E-ELT

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ABSTRACT

The next generation ground-based giant telescope, the European Extremely Large Telescope (E-ELT), under development by the European Southern Observation (ESO) [1], will have nearly 1000 hexagonal segments of 1.45m across the flats. Fast processing of these segments with high form and edge specifications has proven to be a challenge. The Zeeko *Precessions* sub-aperture bonnet polishing plays an important role providing capability for polishing the surface and correcting the form to meet this target [2,3].

BoX™ grinding has been adopted. This technology has the advantage of fast generating of aspheric surface with very low subsurface damage (SSD) [4]. This will avoid the need of removing thick layer of stock at polishing stage to remove SSD. However the result grinding signatures has proven to be problematic for direct polishing with Zeeko's standard bonnet technology. A novel 'grolishing' process which stands between 'grinding' and 'polishing' has been developed to deal with mid-spatial features left by BoX™ grinding. This tool is designed base on Zeeko's R80 bonnet which will fits directly into the company's IRP series machines. The process parameters have been optimised to have signatures less than 10 nm PV. The edge profile is 1μm upstand within 40 mm edge zone.

The 'grolished' surface can be directly pre-polished together with all the form corrections. To meet the fabrication time target, R160 bonnet is used with 50 mm polishing spot, this will provide removal rate of 9.8 mm^3/minute, which can be employed at pre-polishing stage and some form correction. Process parameters have been developed to leave slow upstand at edge zone without any form of sharp edge downturn. The following form correction stage, which employs smaller polishing spot of about 20 mm diameter, will continue to remove form errors of spatial frequency between 0.02 – 0.05 1/mm. Furthermore, the upstand edge will be, to a large part, removed at this stage. It is demonstrated that the form specs can be achieved after this process. The following smoothing process will improve surface textures and remove edge errors. Local edge rectification is normally necessary to bring the edge at same level. A final smoothing process will bring the bulk area and edge zone to meet all the specifications.

Keywords: E-ELT, Segment, Zeeko IRP, Grolishing, Edge control

1. INTRODUCTION

The next generation ground-based giant telescope, European Extremely Large Telescope (E-ELT) has been considered to be the most challenging project worldwide. Together with adaptive optics [5], segment mirror fabrication is one of the challenges in engineering. The proposed process chain must aim to be able to deliver segment mirrors to meet the high optical specifications within the fabrication time scale. At the starting of the process chain, we employ Cranfield University's BoX™ ultra-precision grinding machine, which can generate aspheric surface with less subsurface damage (SSD). There are different technologies reported to have the capacity of polishing mirrors upto 1.5 meters [6]. We have adopted commercialized Zeeko's bonnet polishing technology for these segments' pre-polishing and form correction since it has been demonstrated fast form error removal by its worldwide customers.

In order to speed up the process and reduce the risk of segment damage during transport, the first effort is to build *in-situ* test system. This system, as shown in Figure 1 (a) was a test tower of 10-meter in height, which have sensors distributed to monitor temperature variation along optical path and around. A top spherical mirror was to shorten the optical path and a relay system is to direct the beam into interferometer. Along the optical path, there are separate optical components set to compensate spherical error, astigmatism and coma. A CGH system is also employed to compensate for remain

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mismatch between the aspherical surface with that of the reference wavefront. Vibration-insensitive interferometer from 4D Technology has been adopted to cope with the challenging metrology environment. Since the test tower builds to accommodate the Zeeko IRP2400 polishing machine, the testing of the surface is enable with the opening of top cover and supporting system providing finesse alignment necessary for metrology.

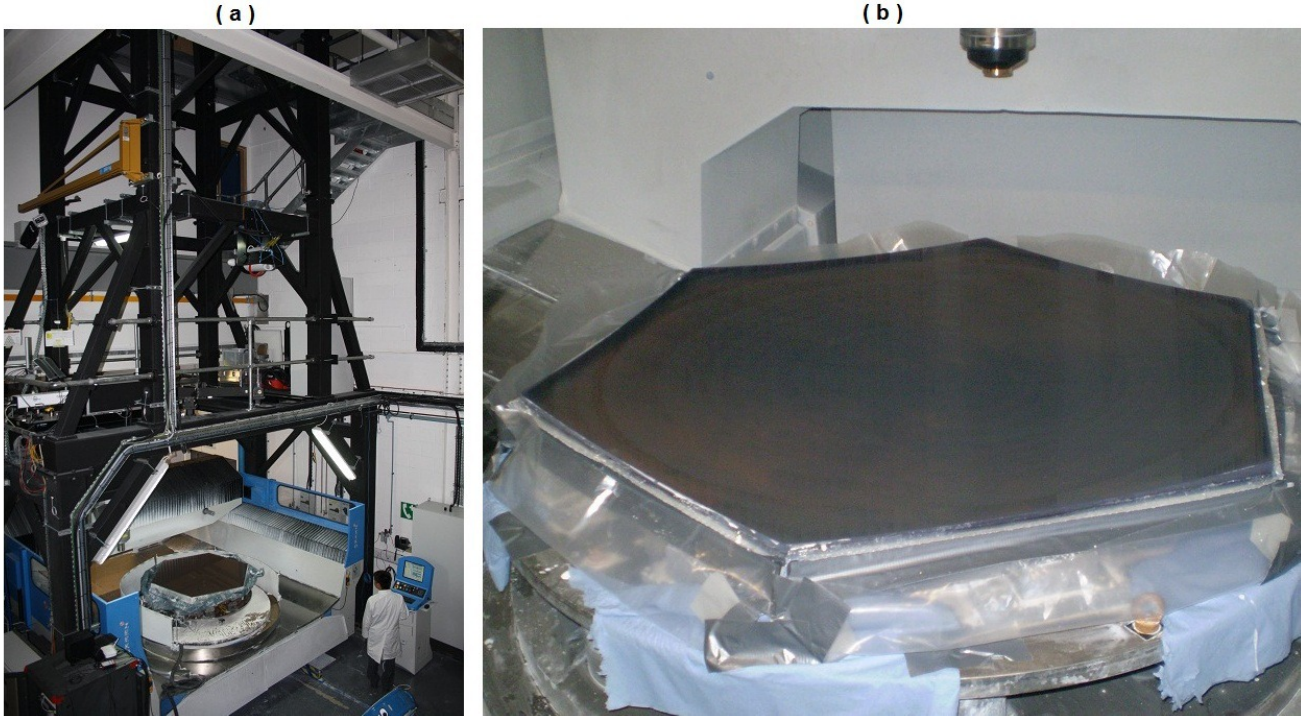

Figure 1 (a) : A full-size segment in Zeeko IRP 2400 machine with optical test tower. (b) : A test segment of 1 meter in process.

The draft of the entire process chain was considered by balancing cost, risk and time frame. It was continuously updated by experimental data from research and development progress. Although the effort of R&D has been applied to every aspect of the whole process chain, the results on smoothing, form correction and edge control have been highlighted in this paper.

2. ZEEKO SUBAPERTURE POLISHING

Zeeko *Precession* process is a well established deterministic sub-aperture polishing technology. This process employs a spinning compliant tool covered with different type of polishing foil and functioning with abrasive slurry. Since several process parameters, like tool offset, bonnet air pressure, precess angle, feedrate, slurry specific gravity etc can be adjusted and large range of functionality can be achieved with this setup. During years of development work, much classical polishing knowledge has also been inherited into this technology. The computer numerical controlled (CNC) automation has not only made this process more efficient, but also made it accessible to a wide range of customers and applications.

The principle, like other CNC technology, based on a unit removal function: Influence Function (IF). It is generated with certain pre-defined polishing conditions (parameters mentioned above) within a unit time period. Then this IF is characterized and utilized into the calculation of local dwell time base on the measurement of the surface. The tool then moves with certain path (raster, spiral etc) with the traverse speed (feedrate) moderated by the knowledge of local error.

3. GRINDING AND THE REMOVAL OF MID-SPATIAL GRINDING FEATURES

Since the BoX™ grinding technology is involved in the process, the output surface quality was studied on a spherical surface of 3 meter radius, as shown in Figure 1 (a). The aperture of this surface is 1 meter corner-to-corner. The material is Zerodur from Schott. To reserve error components, this surface was first 'flash' polished and being measured using both CMM and interferometry method. Mid-spatial grinding features were found across different radial locations [7].

Initial experiments were carried out to remove these features through direct bonnet polishing and the effort was aborted due to the prolonged polishing time. To deliver fast removal of mid-spatial grinding features, other abrasive have been considered although there is risk of machinery contamination.

3.1 Tool design and Optimization

A PSD analysis was applied to surface measurement data to examine the spatial frequency components of the surface. 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 aspheric surface of the part should not introduce new mid-spatial features that are out of the specification for the part.
Brass material was used since its 'wear' characteristic can be utilised to account for the geometry change of aspheric surface. The rate of the wear was experimentally calibrated. The width of the tool path is chosen so that the rate of this wear is well beyond the mismatch between the tool and the aspherical surface. The disadvantage of tool wear is that the tool will gradually lost contact with the surface. This was also compensated with the introduction of surface tilt with calibrated amount.

3.2 Abrasive containment

In the grolishing process, Aluminum Oxide C9 was used instead of Cerium Oxide slurry to provide much faster material removal. Since the particle size is much larger than those of the polishing slurry, disposable containers were used so that the C9 loose abrasive did not fall into the circulation of polishing slurry. The head spindle was optimised so that it would not spray the loose abrasive outside this containment.

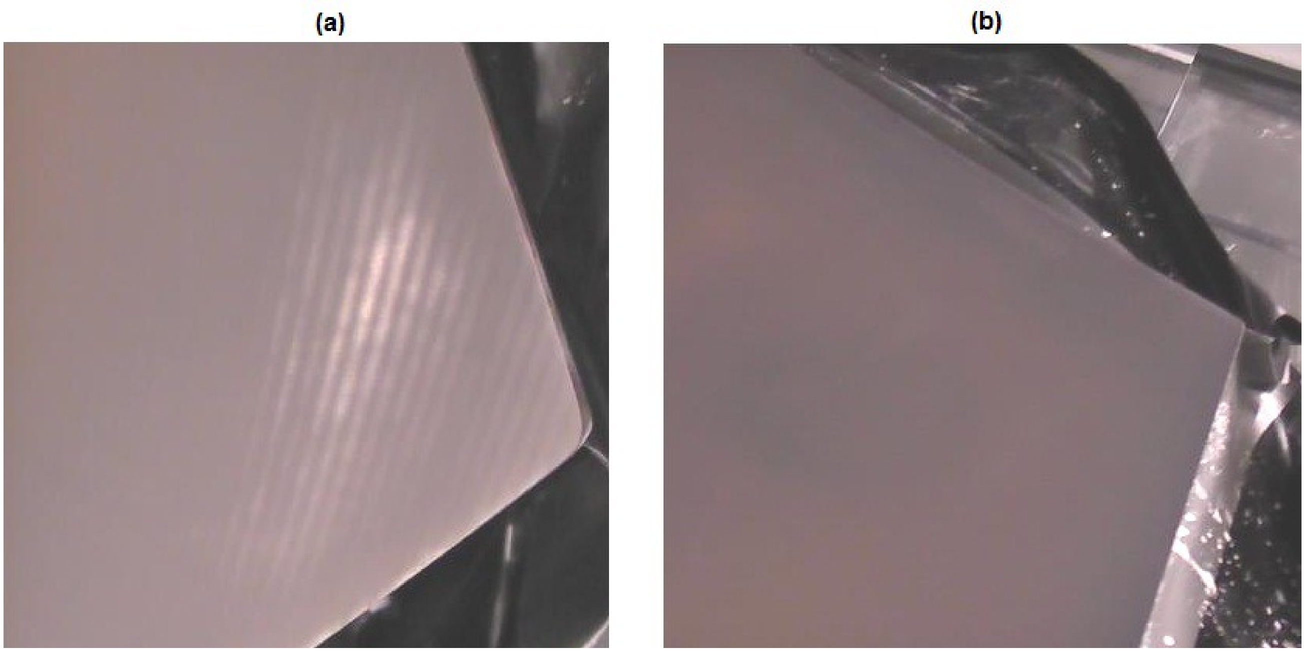

Figure 2 (a): Segment corner revealing gringding mid-spatial features with half of grolishing applied. (b): The grinding mid-spatial features have been totally removed after application of full grolishing.

4. POLISHING: THE REMOVAL OF SSD AND FAST CORRECTION OF FORM ERRORS

The polishing process can be classified as pre-polishing and form correction. The purpose of the pre-polishing is to remove stock of about 15μm of material containing subsurface damage from grinding process. A polishing spot of 50 mm was used which can carried out 9.8 mm^3/min of removal rate. The surface can be measured with interferometry after prepolishing as shown in Figure 3. The resulting surface errors were: PV 6.50 µm and RMS 1.50 µm. A peripheral of 20 mm edge zone was reserved for experiments on edge treatment so that the error shown is a sub-aperture of the whole surface. After 5^{th} correction, the surface errors were PV 214 nm and RMS 61 nm. A smoothing process was applied to improve the surface texture and removal of mid-spatial features left by polishing runs. Since the segments will be mounted on active support system so that certain low order Zernike terms can be removed. The surface errors were PV 62 nm and RMS 11 nm after these terms removed.

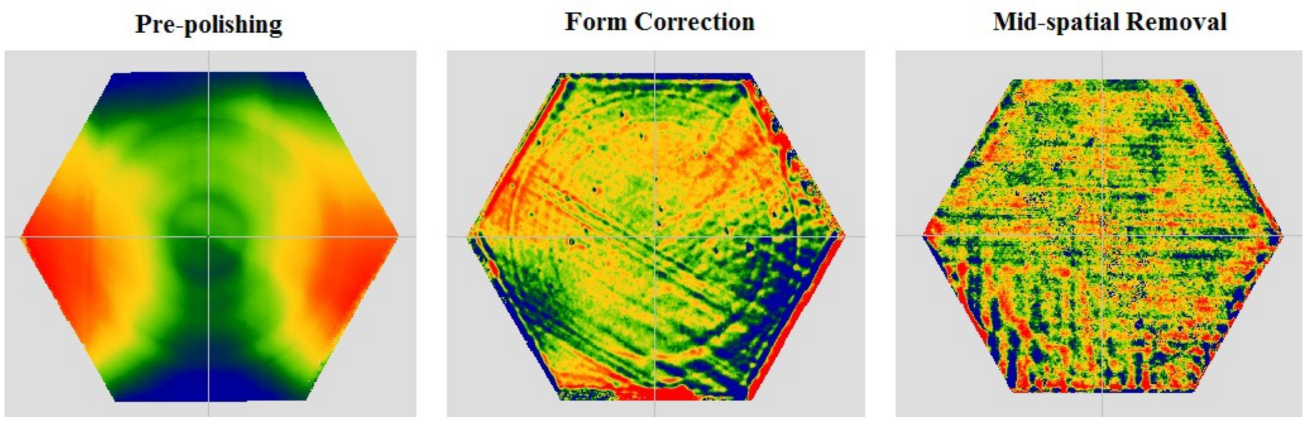

Figure 3: The surface phase maps of the test segment after being pre-polished, form corrected and final mid-spatial removal.

5. EDGE CONTROL

The edge control is widely regarded as the most challenging task of fabricating segment mirrors. The heterogeneity and non-linearity of process conditions demands a very close control of process procedures.

In order to speed up process development cycle, we have adopted much smaller segment samples (200 mm corner-to-corner). The using of these samples have the following advantages: (1) The net processing time is much shorter. (2) It is much easier to apply contact metrology to verify interferometry results. (3) Recondition these samples to starting condition can happen in-house. This has save segment transport time.

The First step is to pre-polishing and removal of grinding mid-spatial features. The correction of main area form error can be started immediately after interferometry data can be obtained. During this stage, large tool with big polishing spot (about 50 mm in diameter) was used to correct form errors with low spatial frequency. There are multiple steps of these corrections. This is to keep symmetry edge upturn and avoid data loss from interferometry. Fiducial masks shown in Figure 4 were applied at each step to identify physical edges of test samples. Only the tilt term is removed from metrology data. The keeping of power term is to keep radius of curvature in registry, which is one of the method to keep the tight control of ROC distribution among segments. The PV and RMS error of the surface were 2.4 μm and 0.71 μm respectively after this stage. They reason to keep a symmetry edge upturn is that the removal of these errors, at smoothing stage, without a necessity to acquire metrology data. This will not only avoid additional process method but also time in metrology and polishing.

The next stage is to remove the broad upturn edges left by big-spot process. Since the previous process has corrected over 90% of the total error at main useful area. The tool's traverse speed can be set at a very large value (3000 mm/min) without under-correction of the main area. Like the previous stage, the total error is equally divided to balance the upstand edges. After the correction of broad upturned edges there are upturned edges of 7 mm in width and 2 μm in height and these edge upturns are spread out evenly, as shown in Figure 5. We can see from fringe pattern that the edge upturns are too steep for interferometer to resolve. These data can be cropped out in form correction.

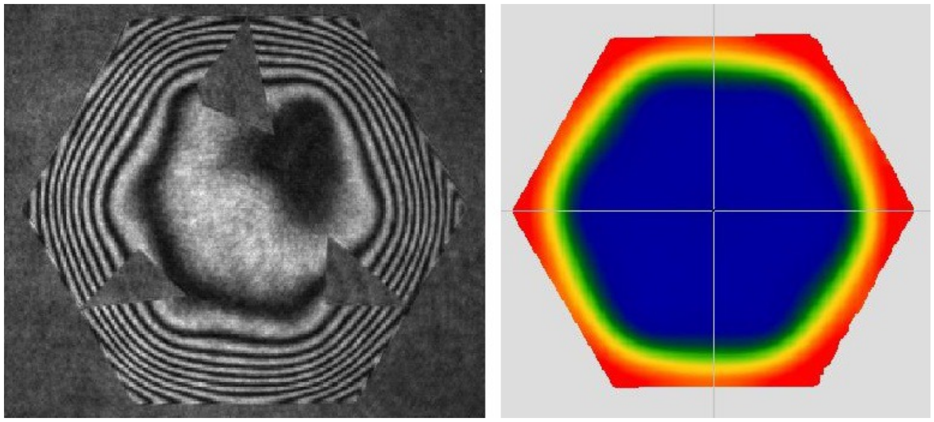

Figure 4. Fringe and phase map of test segment after low spatial frequency form correction.

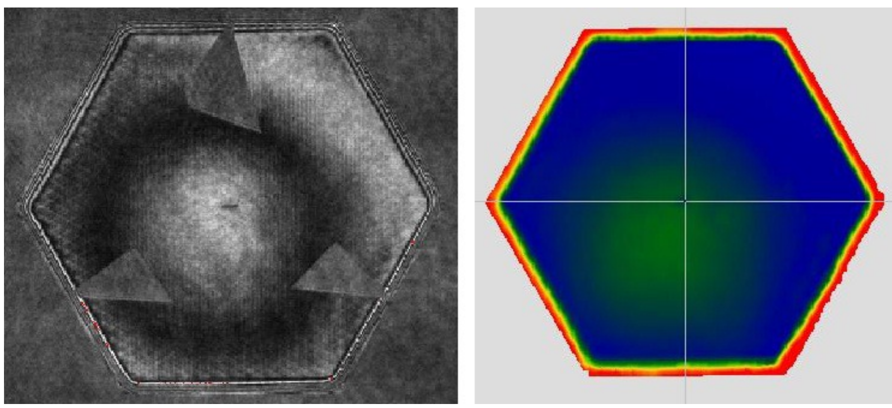

Figure 5. Fringe and phase map of test segment after form correction.

The recovery of the entire surface was performed with semi-rigid smoothing tool. These tools can serve two purposes: (1) To improve surface textures to customer specifications. (2) To remove edge upstands left by small spot process. The second task is evident from fiducial masks that are pointed directly to champers of physical edges, which can be seen in Figure 6. The surface texture was measured of being 1.5 nm Sa. The PV and RMS error of the entire surface were 115 nm and 12.6 nm respectively.

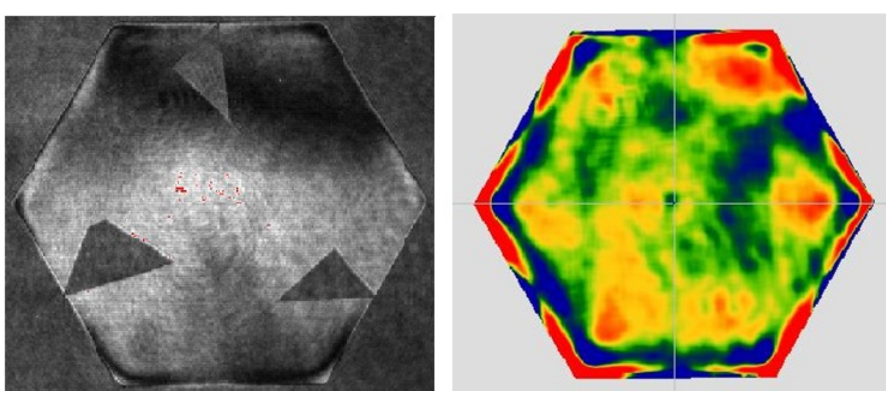

Figure 6. Fringe and phase map of test segment after texture improvement.

A separate analysis was performed regarding specifications on main useful area and edges. This was achieved by applying analysis masks to separate main area and edges. The main area was determined to be 4.75 nm. The six edges were 101 nm, 100 nm, 110 nm, 112 nm, 138 nm and102 nm. These values met the maximum allowance of edge specification which is 200 nm. The average value of the edges was 110.5 nm which was out of the specification of 100 nm.

In order to improve the edge profile whilst keep the obtained main useful area's figure, local edge rectification has been performed experimentally with the following steps: (1) The error map of each edge was generated by cutting off trapezoidal zone of 10 mm in width. (2) The part surface tilt was canceled out by machine probing. (3) Each edge was polished with characterized IF and with feedrate modulated toolpath of error information obtained. The statistics of the same edges are shown in Figure 7, which after local edge rectification reach an average PV value of 90.5 nm that meets the ESO's edge specification on mean values.

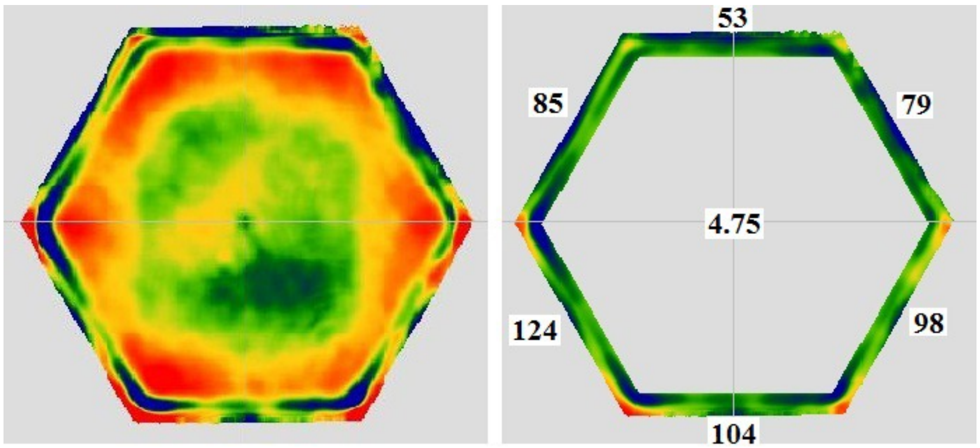

Figure 7. Phase map of entire surface after edge rectification and separate analysis of main useful area and edges (the unit is nm).

6. CONCLUSIONS

Research and development results have shown that the segments of E-ELT can be fabricated through Zeeko's IRP machines. The implementing of R&D achievements, like grolishing and edge control technologies are important steps to meet the optical specifications and fast processing of these segments to meet the planned time scale.

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