Conference Presentation

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Active edge control in the Precessions polishing process for manufacturing large mirror segments

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ABSTRACT

The segmentation of the primary mirror is the only promising solution for building the next generation of ground telescopes. However, manufacturing segmented mirrors presents its own challenges. The edge mis-figure impacts directly on the telescope's scientific output. The 'Edge effect' significantly dominates the polishing precision. Therefore, the edge control is regarded as one of the most difficult technical issues in the segment production that needs to be addressed urgently. This paper reports an active edge control technique for the mirror segments fabrication using the *Precession's* polishing technique. The strategy in this technique requires that the large spot be selected on the bulk area for fast polishing, and the small spot is used for edge figuring. This can be performed by tool lift and optimizing the dell time to compensate for non-uniform material removal at the edge zone. This requires accurate and stable edge tool influence functions. To obtain the full tool influence function at the edge, we have demonstrated in previous work a novel hybrid-measurement method which uses both simultaneous phase interferometry and profilometry. In this paper, the edge effect under 'Bonnet tool' polishing is investigated. The pressure distribution is analyzed by means of finite element analysis (FEA). According to the 'Preston' equation, the shape of the edge tool influence functions is predicted. With this help, the multiple process parameters at the edge zone are optimized. This is demonstrated on a 200mm cross-corners hexagonal part with a result of PV less than 200nm for entire surface.

Keywords: Edge effect, Precessions polishing, Tool influence function, Edge control

1 INTRODUCTION

The edge effect significantly dominates the performance of segmented-mirror telescopes, especially for the next generation of ground telescopes such as the Thirty Meter Telescope (TMT) [1], the Giant Magellan Telescope (GMT) [2] and the European Extremely Large Telescope (E-ELT) [3]. This is because the total length of the edge of these segmented optical systems is much longer than those of the conventional system with one mirror. For example, there is nearly 4000m of total length of edge in the E-ELT's primary mirror. These edges are distributed across the whole pupil. The edge-roll degrades the stray-light and IR-emissivity performance. These are key parameters for the key scientific objectives, such as the detection of extra-solar terrestrial planets. The edge figuring process is particularly challenging in the fabrication of a segmented mirror. The traditional technique pioneered by Keck is to oversize the segment during the polishing process. When the surface meets the specification, the segment is cut to a hexagonal shape, however, this introduces a risk process step and distorts the surface, requiring ion figuring which is slow [4].

In traditional lapping, 'Wasters' around the edges of a part are used to overcome the increase in applied pressure as the tool overhangs the edge. After the prescription of the surface of the part has been achieved, the 'Waster' pieces are then detached. Thus, edge roll of the part can be avoided. The ideal waster material is the same as the part, as the polishing condition and thermal expansion will be identical. Traditionally, 'Wasters' are a very effective edge control approach for small parts. However, there are several risks to this approach in manufacturing large segments which are: (1) The issue of waster-adhesives 'pulling' surfaces, that lead to form-distortion on large parts and subsequent form rectification would be required. (2) Risk of damage to the edges when detaching the wasters. Accidental detachment: if a waster became detached under polishing forces, it could have disastrous consequences. (3) Risk of damage in cleaning adhesive from edges after waster-detachment. (4) Handling risk: There are nearly 6000 pieces of glass (for 931 hexagonal segments in the E-ELT) to be machined, installed and handled in production. An effective waster should accommodate the largest spot (for example, R160mm bonnet/60mm spot) and will weigh approximately 5Kg. This would be difficult to handle manually and would need an automated process to be employed.

With the above points taken into account, the direct processing of the edges without wasters is preferred. An active edge control technique therefore is developed for mass fabrication of segments using the *'Precession'* polishing process. The principle of this technique has been already introduced in previous papers [5, 6]. In this paper, the edge effect in the *'Precession'* polishing process is simulated by infinite element analysis (EFA). In order to compensate for the edge material removal, the process parameters at the edge zone are optimized.

2 THE EDGE EFFECTS UNDER BONNET TOOL POLISHING

With the inflated bonnet tool in the *'Precessions'* polishing process, the pressure on the part is dominated by internal air pressure and the elastic deformation of the bonnet tool. For an elastomeric bonnet (solid rubber tool), the mechanical properties are similar to an inflated tool. When such a flexible tool overhangs the edge of the part, the pressure distribution at the edge is complex. Figure 1 shows a sketch of the pressure distribution at the edge zone of the part and the consequent edge roll down. It can be seen that the pressure on the edge becomes extremely high.

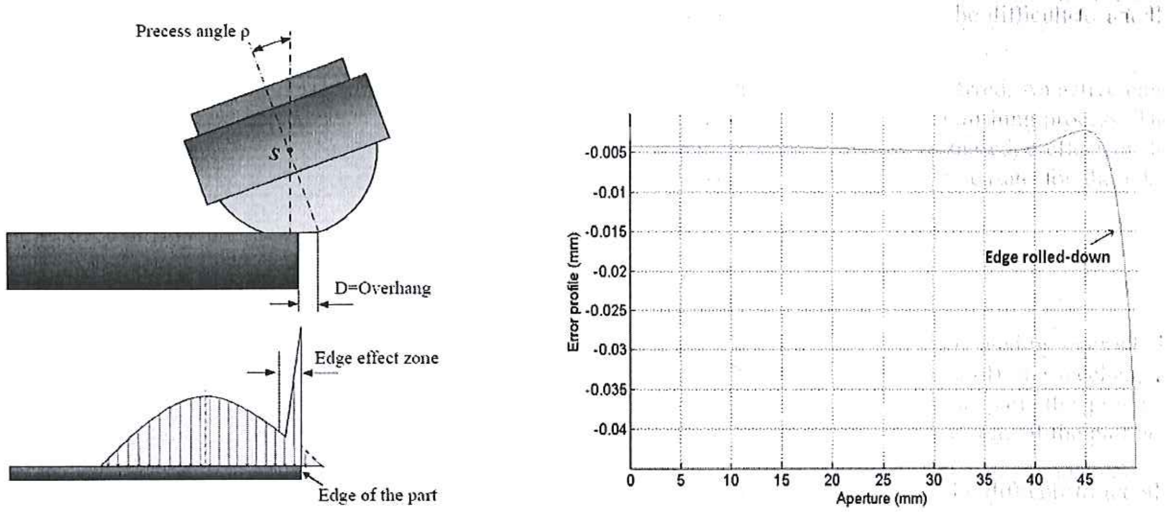


Figure 1 A conceptual sketch of the pressure distribution between the bonnet and the part (on the left) and the typical edge profile when the bonnet projects beyond the edge of the part (on the right)

In general, edge effects under 'bonnet' tool polishing are caused by the following: (1) When the spot overlaps an edge, the area in contact decreases, thus the pressure increases (for constant force). This causes the edge zone turndown. (2) The membrane of the 'bonnet' tool wraps around the edge of the part, which turns the edge zone down. (3) When the spot falls short of leaving the part completely, a zone near the edge of the part undergoes less polishing than on the bulk area of the part, which turns the edge zone up. (4) The rotating tools give a bow-wave of slurry when the tool 'attacks' the edge of the part. This turns the edge down. There is interplay between these, but they cannot be made to compensate. If the extreme edge of a segment is rolled-down at any process stage, the entire surface must be re-worked to rectify it. The amount of material removal according to the Preston equation is based on the assumption that the contact spot is fully inside the part [7]. When the spot extends beyond the edge of the part, the constant pressure between the tool and the part no longer exists. Therefore, how to analyze the pressure distribution at the edge zone accurately is crucial for edge control in the *'Precessions'* polishing process. There are several modeling and experimental approaches that have been presented to analyze the edge effect for different polishing techniques [8, 9]. According to the complexity of the edge effects under 'bonnet' tool polishing discussed above, we calculated the pressure distribution over the polishing spot at the edge zone was calculated by means of finite element analysis (FEA). Therefore, the shape of the edge tool influence functions can be predicted.

3. MODELING OF THE EDGE INFLUENCE FUNCTIONS

3.1 Analysis of the pressure distribution on the edge

The Finite Element Analysis is widely adopted for analyzing stress, displacement and strain in complicated structures. The Bonnet tool polishing model can be defined as a contact problem of two surfaces in FEA. A set of contact pair is created between the surface of the tool and the polishing surface of the part. During the polishing process, the back surface of the part is fixed on the support system. Thus, all degree of freedom (DOF) of the back surface is constrained with 0 displacements. The top surface of the Bonnet tool is fixed on the polishing machine. The Bonnet tool is depressed by the Z-offset to deliver a spot-size along the Z-direction. Thus, the top surface of the tool is constrained with 0 displacements along X-axis and Y-axis and -0.7mm displacement along Z-axis. The pressure on the part is caused by elastic deformation of the tool. To simplify the problem, a thin layer of polishing cloth is omitted in the modeling. A 100mm x 100mm square, 10mm thick, Zerodur part was chosen in this model. The Bonnet tool was designed as a molded unit in Natural Rubber (BS-1154: 2003). The material properties for the modeling are listed in Table 1. The FEA model for a R80 Bonnet (80mm radii) and analysis result of pressure distribution are shown in Figure 2 and Figure 3.

Table 1 The materials properties for the modeling

	Density (kg/m^3)	Yong's modulus (N/m^2)	Poisson's ratio
Zerodur	2.53×10^3	9.30×10^{10}	0.30
Natural Rubber (BS-1154:2003)	1.12×10^3	1.34×10^6	0.24

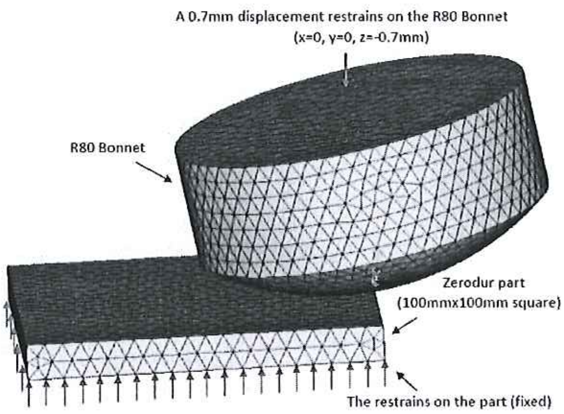


Figure 2 The FEA model for R80 Bonnet

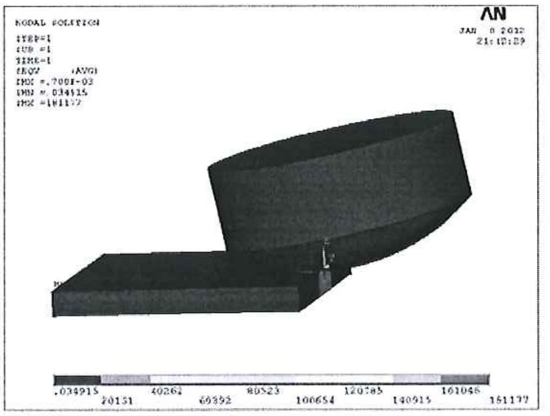
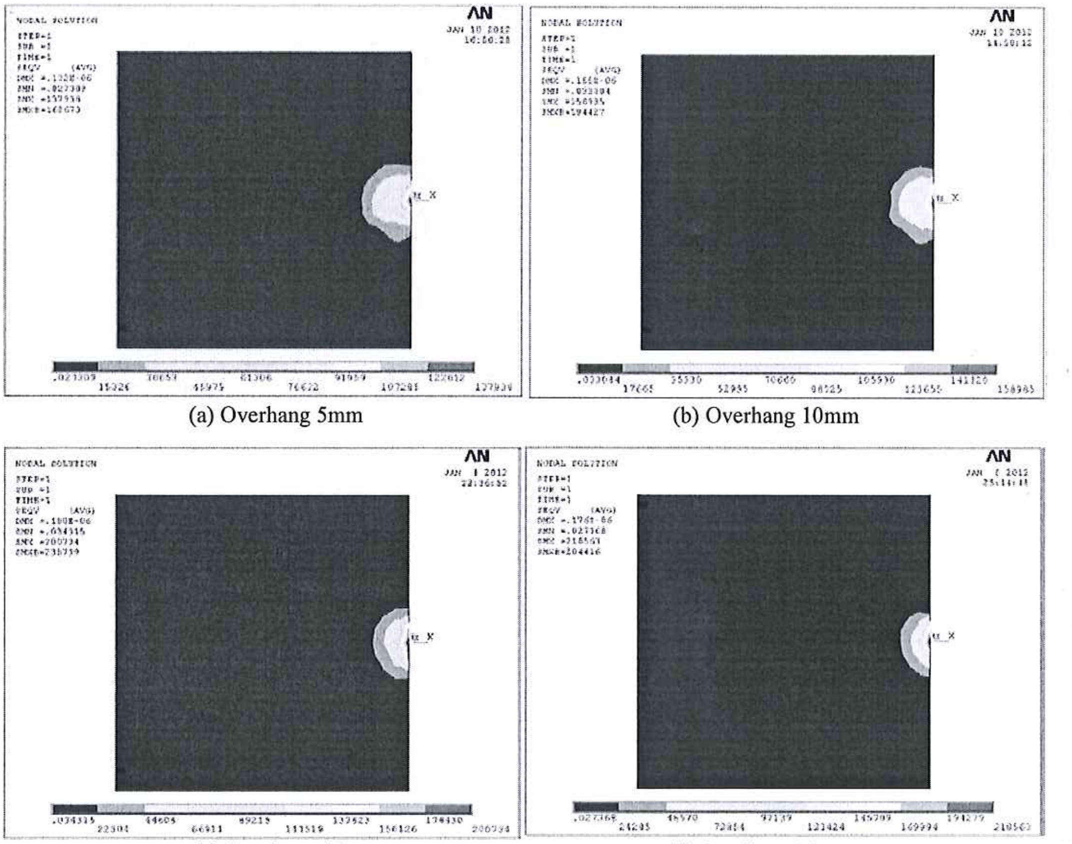


Figure 3 The edge pressure distribution analysis result

This FEA model has been verified by a force measurement in a previous paper [10]. This model can be used to analyze the pressure distribution at the edge. The analysis results for different overhangs are shown in Figure 4. It can be seen that pressure at the edge of the part is greatly increased. The maximum pressure is 1.69Mpa, 1.94Mpa, 2.39Mpa and 2.85Mpa for 5mm, 10mm, 15mm and 20mm overhangs respectively.



(a) Overhang 5mm

(b) Overhang 10mm

(c) Overhang 15mm

(d) Overhang 20mm

Figure 4 The edge pressure distribution analysis result for different overhangs (5mm, 10mm, 15mm, and 20mm)

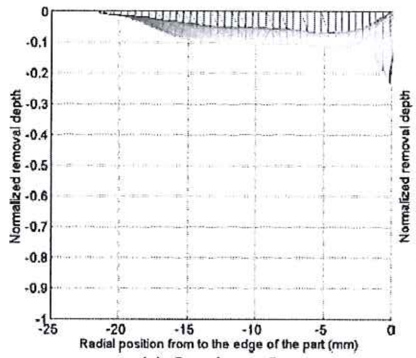
3.2 Edge tool influence function modeling results

After the pressure distribution *p(x, y)* have been obtained, the tool influence function *R(x, y)* can be calculated according to the Preston equation:

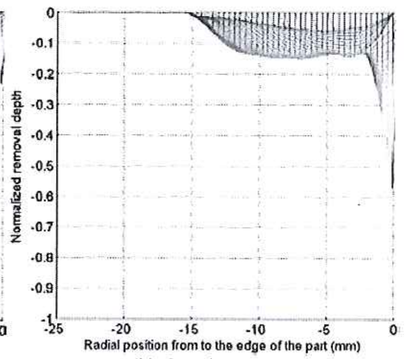
$$R(x,y)=\frac{1}{T}\int_0^T k\cdot v(x,y)\cdot p(x,y)\cdot dt=\frac{k}{2\pi}\int_{-\theta_0}^{\theta_0} v(x,y)\cdot p(x,y)\cdot d\theta$$

Where, θ is the rotation angle of the polishing tool. *k* is Preston coefficient. *v(x, y)* is the velocity distribution at polishing spot which has been calculated based on the geometry of the precess motion as stated in our previous paper [10].

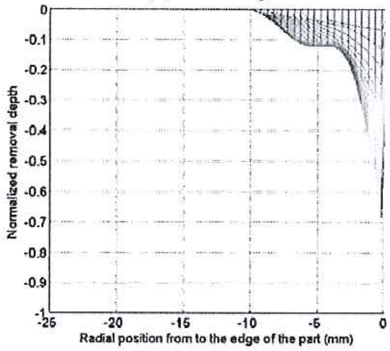
The edge tool influence functions with a different overhang have been modelled using MatLab code as shown in Figure 4. The parameters for the modeling are R80mm tool, 0.7mm Z-offset, 10° precess angle. According to the Preston equation, the absolute material removal is also determined by the Preston coefficient k, which is a constant, related to the part material, polishing liquid and temperature. To simplify the modelling result, the magnitude of the TIF has been normalised (scaling of TIF from -1 to 0) in the simulation. The modeling results of edge tool influence function are shown in Figure 5.



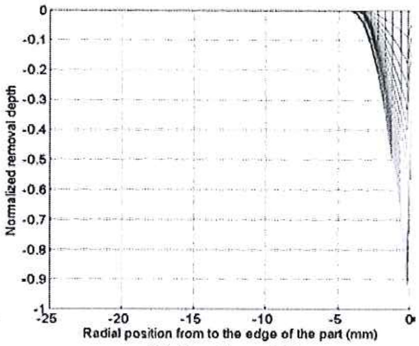
(a) Overhang 5mm



(b) Overhang 10mm



(c) Overhang 15mm



(d) Overhang 20mm

Figure 5 Normalized edge tool influences modeling results for different overhang (R80mm tool, 10° precess angle, 07mm offset)

4. OPTIMIZING OF EDGE PROCESS PAPRAMETERS AND POLISHING RESULTS

To optimize the edge process parameters, a series of edge tool influence functions (different overhangs) have been simulated. Then the edge profile was predicted by means of superpositon principle of material removal. Therefore, the process parameters on the edge of the part can be optimized. The aim of this model was to achieve the targeted material removal at the edge zone by optimazing the dwell times at each overhang position. The optimized edge parameters for R80 Bonnet are shown in Figure 6 by this means, in which Feed Rate, Tool Offset and Precess Angle have been achieved.

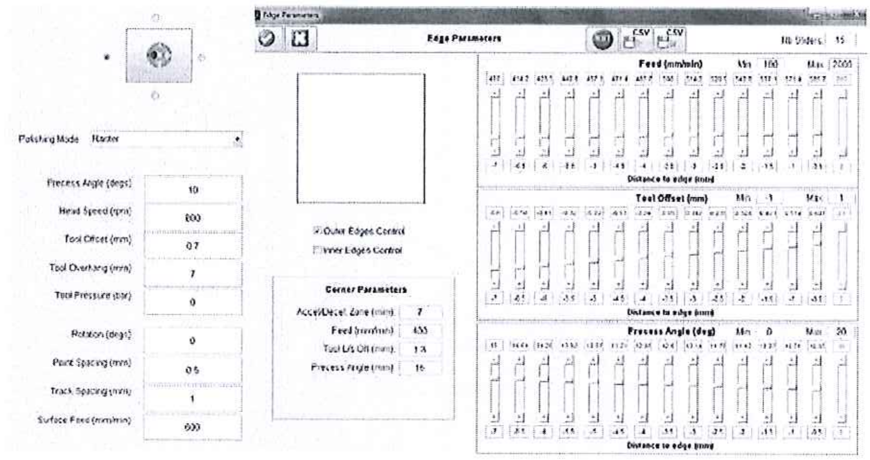


Figure 6 Optimized parameters for edge polishing (80mm Bonnet)

A polishing experiment was carried out on a Zeeko IRP1200 machine. The part was a 200mm across-corners, R=3m spherical concave, Zerodur hexagonal sample and prepared by free-abrasive lapping on a cast iron tool. The pre-polishing was conducted with an R160mm solid rubber tool with 2.8mm offset, which aimed to achieve a high volumetric removal rate over the bulk surface. The polishing cloth was polyurethane LP66. At the pre-polishing, the edges of the part were kept up-standing by tool-lift to avoid data loss from interferometry. The form-correction was then performed with an R80mm solid rubber tool with 0.7mm spot. The wide up-standing edges were corrected at this stage. Figure 7 shows the measurement set-up for this experiment in which a 4D interferometer was used to measure the entire 3D surface and the 'Extended Range' Form Talysurf was used to examine the edge profile. After six correction runs (the total polishing time was about 65 mins) a pith polishing run was carried out to clear up the high frequency error on the surface. The measurement results are shown in Figure 8 in which PVq (99%) =189nm and RMS=26nm including the edge zone have been achieved. The fiducial masks shown in Figure 8 were applied at each step to identify physical edges of the test part. From the polishing results it can be seen that the dominant edge-defect remaining in the PV numbers is the turning-up of the corners. It is believed that the use of a rigid pitch tool must polish the edges more than the corners, because the overlap at the corner is less. This leaves raised corners. This factor indicates that it needs local treatment in the edge zone using a small tool (e.g. R20mm tool, 5mm spot size).

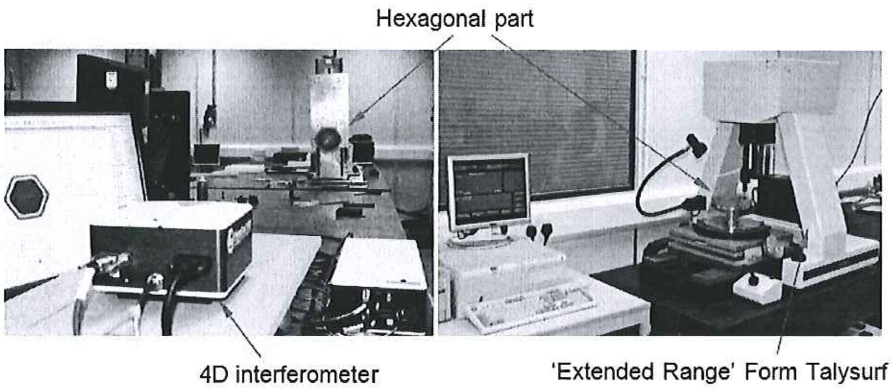


Figure 7 The measurement set-up, on the left is the 4D interferometer, on the right is the 'Extended Range' Form Talysurf

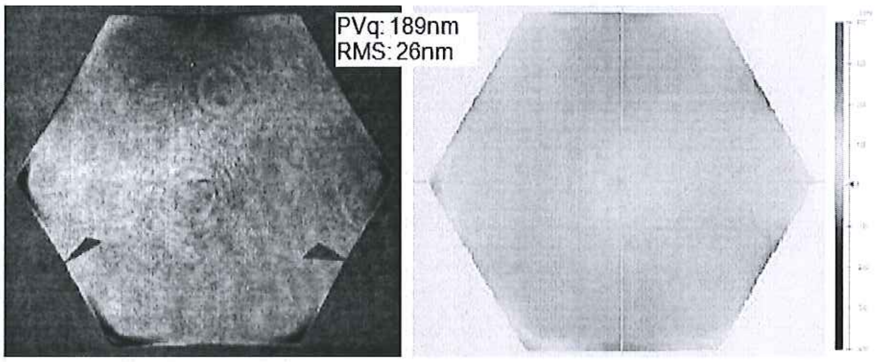


Figure 8 The measurement results for entire surface

5. CONCLUSION

This paper has investigated the edge effect under 'Bonnet tool' polishing. The pressure distribution on the edge zone was analyzed by means of Finite Element Analysis (FEA). According to the Preston equation, the edge material removal function was simulated using MabLab code. Therefore, the shape of the edge profile was predicted and the process parameters on the edge zone were then optimized. This modeling result was verified by a polishing experiment on a 200mm cross-corner, hexagonal part. A result of PV 189nm for the entire surface was achieved. To correct the raised corners, a local edge rectification technique was developed recently. This work will be reported on in a future paper.

ACKNOWLEDGEMENT

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