Active Control of Edges and Global Microstructure on Segmented Mirrors

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ABSTRACT

In this paper we address two interrelated issues important to primary mirror segments for extremely large telescopes - edge-control, and the detailed topography over the segment surface. Both affect the intensity and distribution of stray light and infrared emissivity. CNC polishing processes typically deploy spiral or raster tool-paths, tending to leave repetitive features. We compare and contrast two novel families of pseudo-random tool-paths for Precessions CNC polishing. We then show how CNC control of the three-dimensional tool-path can optimize edge-profiles. Finally, we demonstrate fluid-jet polishing used to clean up residual edge defects.

Keywords: Polish, Edge, Random, Microstructure, Texture

1. INTRODUCTION

The development of the European Extremely Large Telescope project has recently been described by R. Gilmozi [1]. In a parallel paper, J. Spyromillio [2] overviewed the telescope design in more detail, describing the three-mirror anastigmat baseline design, with a 42 metre aperture. The primary is ellipsoidal, the 6m secondary convex, and the tertiary mildly aspheric. The primary will comprise 984 segments deployed in the telescope, with a total requirement of 1,148 segments including a full complement spares. The primary segments are hexagonal, off-axis aspheres, each some 1.45 metres point-to-point.

This requirement for mirror-segments is unprecedented in terms of mass-production of metre-scale, high-quality, aspheric optics. Clearly, traditional production methods will not provide a viable solution, and in this paper we report on some aspects of our investigation of alternative computer-controlled, active, small-tool techniques.

Manufacture of segments for extremely large telescopes raises numerous challenges, particularly:-

i) control of global form (with requirements on metrology)

ii) control of edges (with requirements on metrology)

iii) nature of the resulting surface texture

iv) acceptable manufacturing time.

Taking a pre-machined blank, our preferred process-route incorporates ultra-precision grinding of the off-axis aspheric form [3], followed by CNC polishing. A stage of fine smoothing is also being assessed for its potential to accelerate process-convergence. The polishing and smoothing processes are based on Zeeko Ltd's standard *Precessions*™ family of processes. This paper provides an update of the process development being undertaken in support of segment fabrication.

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2. THE ZEEKO FAMILY OF PROCESSES

Zeeko *Precessions* comprises three main processes: *Zeeko-Classic*, *Zeeko-Grolish* and *Zeeko-Jet*.

1. *Zeeko-Classic* [4,5] utilizes an inflated bulged membrane, which is covered with a standard polishing cloth (e.g. polyurethane). It is spun about its axis, and pushed against the surface of the part with a controlled Z-offset to provide a contact-spot of tunable footprint.
2. *Zeeko-Grolish* [6] is itself a range of processes that are intermediate between grinding and polishing. Examples of grolishing methods that adapt the Zeeko bonnet technology include the use of 3m Trizact diamond-impregnated tiles, nickel-bonded diamond pellets, and metal pads used with loose abrasive.
3. *Zeeko-Jet* [7] uses a narrow jet of polishing slurry that interacts directly with the part with no intermediate tool.

There are two standard modes of operation – 'pre-polish' where a constant skin of material is removed from the surface, and 'form correction', which rectifies measured form-errors. In regard to the latter, simple algorithms are available to moderate the pre-polish mode to control form. However, in later stages of form-correction, empirical influence functions are measured on a witness sample. These are input to a routine that performs a numerical optimization of the polishing regime. In contrast to de-convolution, the optimizer enables a number of variables to be handled simultaneously, including the effects of boundary conditions (edges).

Given a local removal process, the polishing spot needs to be scanned across the surface of the part in a pre-determined path. Typical paths include spiral, adaptive-spiral, raster and crossed-raster. Adaptive spirals progressively morph a regular spiral near the centre of the part into a different shape that matches the boundary of the part, so that a non-circular part can be fully filled. However, all these tool-paths are regular in nature, and so tend to leave residual periodicities in a surface at the nano or sub-nano scale. Therefore, a new pseudo-random CNC tool-path has also been developed, which provides elements of the averaging provided by traditional hand-work. This is described in Section 4 as, not only can it eliminate periodic micro-texture, but it also has potential advantages for edge-control.

3. EDGE CONTROL

3.1 Introduction

The quality of edges is important for ELT segments, because edge-roll effectively reflects or scatters light (particularly near-IR) from building and telescope structures at room temperature towards the science detector, and the infrared emissivity varies as T^4. Hence small areas of edge-roll can have a disproportionately large effect on infrared background. This in turn is critical for key science projects, such as detection of extra-solar planets. A 1cm wide band along each edge of the E-ELT primary mirror occupies some 3% of the total pupil area.

In a traditional polishing process, the rate of material-removal is greater when the tool overhangs the edge of the part. A. Cordero-Davila et. al. [8] have explained this by proposing a new model in which the pressure is higher at the edge. They applied the model to a circular tool that polishes a circular part, and achieved good correspondence between the model prediction and measured edge-roll.

We are currently developing the segment process-chain in regard to edges, and we report some interim results. We are working on three main strategies, which can be used individually or in combination:

1. Use of wasters around edges
2. Active control of edge-profiles by optimizing polishing process parameters. This is the preferred solution.
3. Controlled turning up of the edges during most of the process, followed by a final edge-rectification stage

When using the *Zeeko Classic* process, there are two main causes of edge-roll, as follows:

1. The inflated membrane of the bonnet wraps around the edge of the part as the contact-spot overhangs the edge. However, the mechanism is different from the traditional polishing lap where an overhanging tool concentrates a constant tool-mass over a smaller contact-area. Because the bonnet is inflated with air at constant pressure, the

polishing pressure remains essentially constant as the polishing spot overhangs the edge. Rather, it is the angle-of-attack of the tool at the edge that changes

2. When the machine is performing a raster tool-path, the path needs to turn around at the end of each traverse. The finite limits on machine accelerations and decelerations can then give unwanted extra dwells at the edge of the part.

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3.2 Possible use of wasters

In traditional lapping, a waster may be used to overcome the increase in applied pressure as the tool overhangs the edge of the part. In the case of the Zeeko Classic process, a waster can provide a surface to support the overhanging part of the polishing membrane. In this case, wrapping of the membrane around the edge of the part can be avoided, giving constant angle-of-attack, and minimizing edge-roll. Furthermore, a waster can provide a zone into which the tool-path can move, avoiding unwanted accelerations and decelerations occurring on the surface of the part, which can also lead to edge-roll. The ideal waster material is the same as the respective segment, as polishing conditions will be identical, and differential thermal expansion avoided. Nevertheless, there are other possibilities that may be more favorable for cost and convenience.

Experiments have been conducted on a small Zerodur sample with various materials including Zerodur, aluminium and PTFE waster materials, waxed in place before grinding. Several microns of edge-defect remained after polishing with aluminium wasters, potentially caused by different chemical mechanisms for polishing Zerodur and aluminium. After removing some 8.5µm stock using a Zerodur waster, negligible edge-roll was observed (Figure 1). After removing some 7.5µm stock using a PTFE waster, there remained a turned-up edge of approximately 2µm. This may have been due to compression of the PTFE under grinding-forces, leaving a slight up-stand on the waster during polishing. However, the up-stand rather than down-turn gives the potential for post-processing using smaller bonnets or fluid-jet polishing.

The issues with Zerodur wasters in large sizes (for full-size segments) is the material cost of the wasters, the handling risk in attaching and detaching them, and the danger of the wasters ‘pulling’ the surface of the mirror segment leading to form-errors when the wasters are removed.

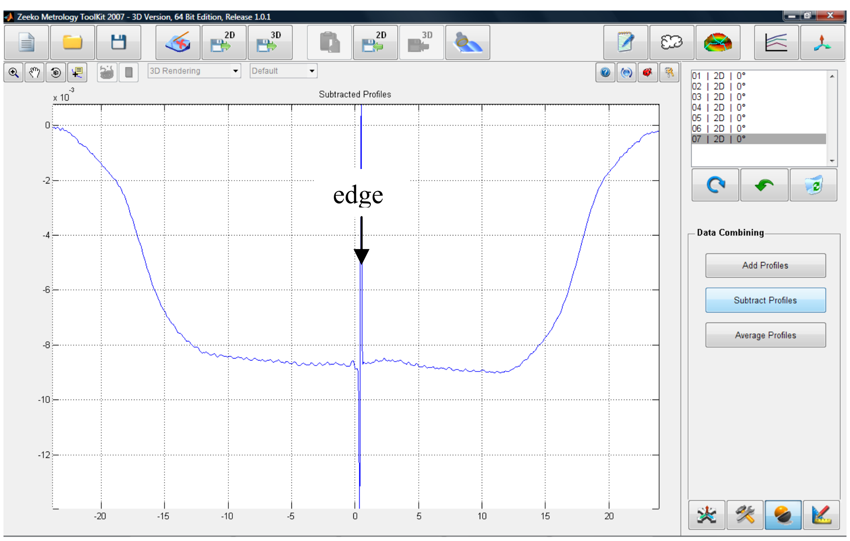


Figure 1 Profile for material-removal with Zerodur waster on Zerodur sample (subtraction of before and after polishing)

With the above points in view, we retain wasters as a backup solution, but prefer direct processing of edges without wasters as the baseline solution. We recognize that a combination may prove beneficial.

3.3 Active Control of Edges

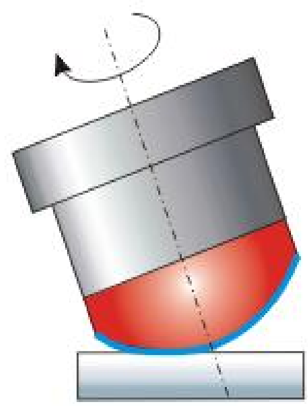
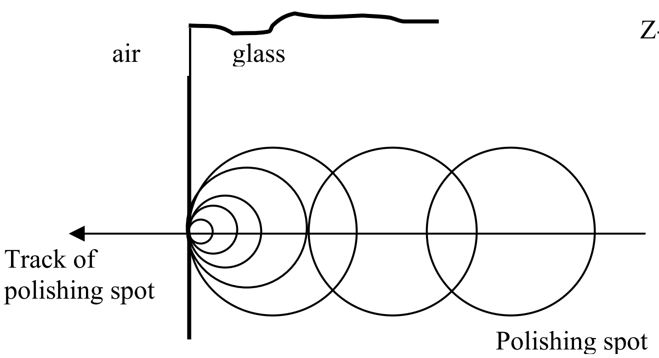


Figure 2 Precessed bonnet

The polishing spot-size delivered by a *Zeeko Classic* bonnet varies according to the radius-of-curvature of the bonnet, and the compression of the bonnet against the surface of the part. This compression is controlled by advancing the bonnet towards the surface of the part, with first-contact being detected using a sensitive load cell. Advancing through a further calculated distance, called the "Z-offset", creates a polishing spot-size of known diameter.

As normally used, the machine CNC tracks the bonnet around the surface of the part along a pre-computed tool-path, maintaining constant Z-offset and so compression of the bonnet and spot-size. However, the CNC can be programmed to vary the Z-offset along the tool-path.

In *active edge control*, this capability can be used progressively to raise the bonnet, decreasing the polishing spot-size, as the spot approaches and encroaches the edge. This is shown in Figure 3, where the edge algorithm is illustrated when configured to place zero spot size precisely at the edge.



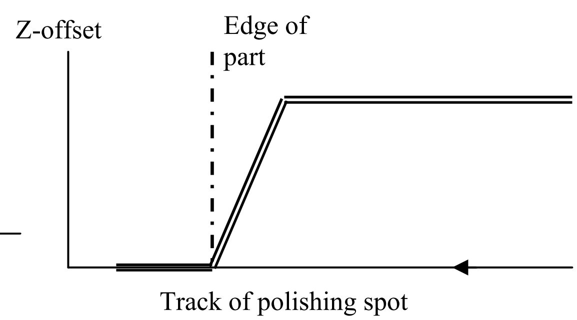


Figure 3 Operation of Tool-lift

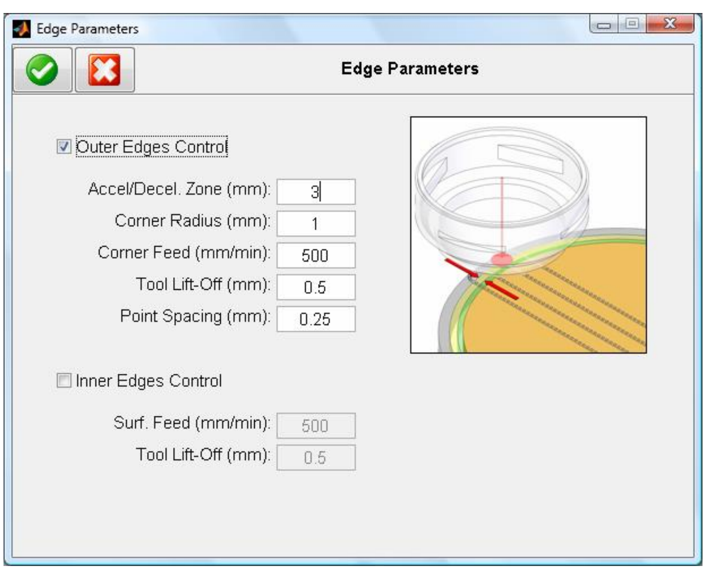


Figure 4 Graphical User Interface for Edge Utility

The relationship between the radius of curvature R of the polishing bonnet, the radius r of the polishing spot, and the compression ΔZ of the bonnet, is given by the following (for small ΔZ):

$$r^2 = 2 R \Delta Z$$

Since volumetric removal rate varies as spot area, and so with r^2, the relationship between polishing rate and ΔZ would be expected to be linear.

The existing edge-control utility utilizes this relation. It computes traverse speed and tool lift-off (and corresponding tool Z-offsets), with both varying linearly with respect to the distance from the edge of the part. The extreme values are specified by the user through the pre-polishing and edge parameters GUI (Figure 4). The variation in feed is adjusted in order to compensate for the change in volumetric removal rate as the tool is lifted up.

The effect of this edge-utility is shown in Figure 5. The part was a 100mm diameter blank, previously beveled. Some 20 microns of stock was first removed during polishing the part with a 40mm radius bonnet, programmed to leave a turned-up edge. Then, an additional 6 microns of stock was removed in five corrective runs rectifying the turned-up edge using the tool-lift algorithm. The result shows features in the final 5mm from the start of the bevel. The right edge of this part was further processed using fluid-jet polishing and finished with a pitch-loaded bonnet. The result is shown in Figure 6.

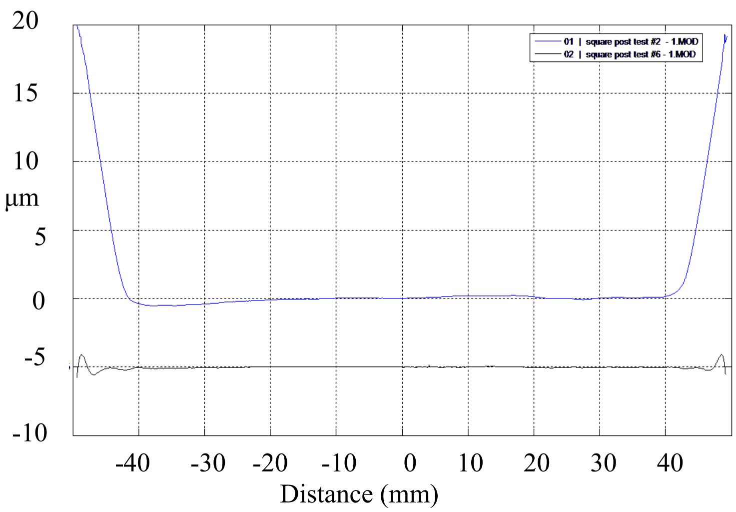


Figure 5 Edge control using tool-lift

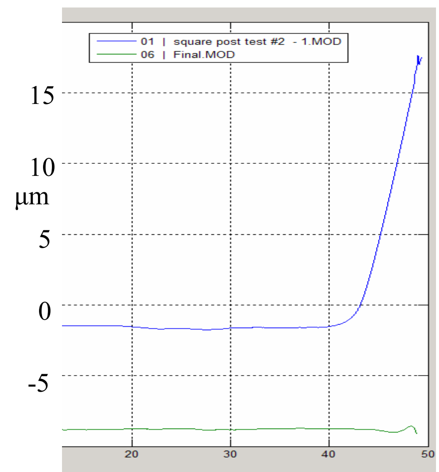


Figure 6 Post-processing of Figure 5 right-hand edge using fluid-jet polishing and pitch-loaded bonnet

An interesting feature of edge control arises when processing a hexagonal part such as the segment for an extremely large telescope. A regular tool-path such as a raster or crossed raster will attack different edges differently on account of their inclination with respect to the tool-path.

4. POLISHING WITH PSEUDO-RANDOM TOOL PATHS

The unicursal pseudo-random tool path was first developed to address the problem of mid-spatial frequencies that may be left on a surface by periodic tool paths such as raster or spiral patterns. However, it was clear that it could confer advantages to edge-control as each edge could be treated identically.

The *Precessions* process performs prescriptive polishing with the use of a dwell time map combined with a tool path. Because the raster or spiral tool path never crosses itself, the velocity of the tool can be varied along the path to produce the dwell time specified at each point on the dwell time map. The unicursal random tool path can also be used with a dwell time map because it does not contain any crossing points.

4.1 The Unicursal Random Tool Path

The unicursal random tool path is generated in NURBS space. The patterns are defined on a plane one arbitrary unit square, and then projected onto the curved surface using NURBS software. Generation of the pattern begins by defining the boundaries of the region to be polishing, which may include interior holes. Random tool path patterns can be generated to fill any continuous surface, including those with interior holes, and a completely different pattern is produced every time the algorithm is run. An example of a random tool path is shown in Figure 7.

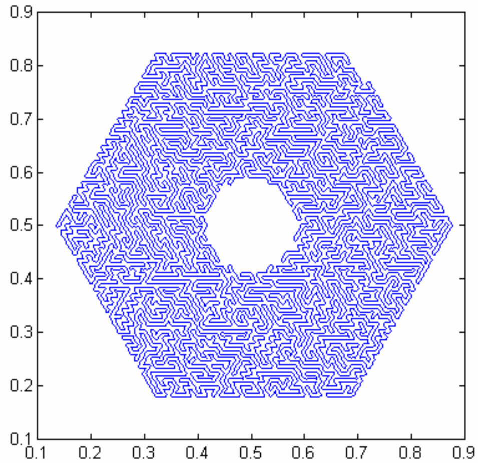


Figure 7. The unicursal random tool path never crosses itself, so that it may be used with a dwell time map for prescriptive polishing.

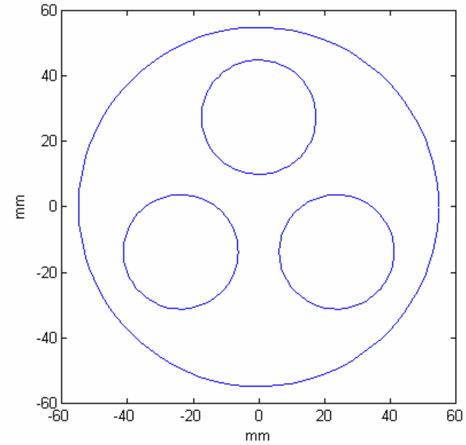


Figure 8. Three spots 35 mm in diameter were polished on each 110 mm diameter sample.

4.2 Comparing Random and Raster Tool Paths

A series of experiments were carried out to compare the characteristics of the surfaces produced by the random tool path with those resulting from a raster tool path. These experiments were carried out using a Zeeko IRP200 polishing machine on flat glass samples. Circular regions 35 mm in diameter were polished on the samples, following the design shown in Figure 8. To enable this, the random tool-path software was integrated with the standard Zeeko Tool-path Generator ('TPG') software.

4.2.1 Polishing Parameters and Removal Rates

Two samples were polished, one using the random tool path, shown in Figure 9, and the other using the raster tool path. All other polishing parameters, listed in Table 1, were held constant.

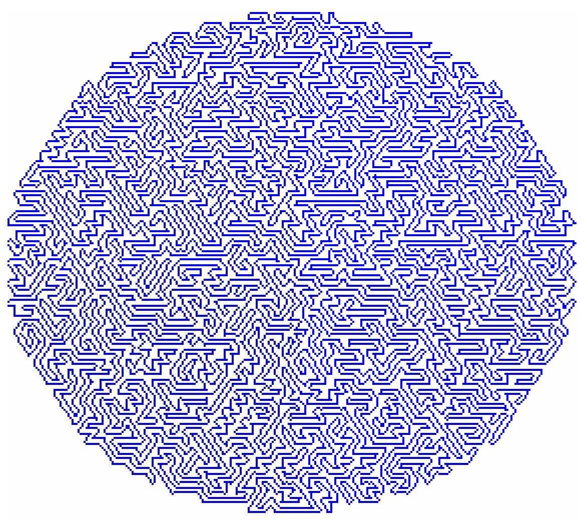


Figure 9: This random tool path pattern was used in the experiment.

Random polishing parameters						
Spot	Feed rate (mm/min)	H-axis speed (rpm)	Polishing time (min:sec)	Pattern spacing (mm)	Point spacing (mm)	Depth removal (um)
1	100	300	20:14	0.5	0.05	1.7
2	150	450	13:36	0.5	0.055	1.6
3	200	600	10:14	0.5	0.06	1.1
Raster polishing parameters						
Spot	Feed rate (mm/min)	H-axis speed (rpm)	Polishing time (min:sec)	Pattern spacing (mm)	Point spacing (mm)	Depth removal (um)
1	100	300	20:15	0.5	0.5	1.4
2	150	450	13:36	0.5	0.5	1.1
3	200	600	10:15	0.5	0.5	1.4

Table 1. Polishing parameters

4.2.2 Surface Texture

Polished spots were measured using a Wyko 1200 white light profilometer with a field of view of 1.2 by 0.9 mm.

Random polishing			
Spot	Ra (nm)	Rq (nm)	Rz (nm)
1	3.39	4.29	32.10
2	4.09	5.05	31.00
3	4.24	5.27	35.04

Raster polishing			
Spot	Ra (nm)	Rq (nm)	Rz (nm)
1	3.97	4.87	33.08
2	5.51	6.85	49.27
3	5.30	6.66	41.15

Table 2. Surface texture results

4.2.3 2D-PSD Results of Surface Texture at different feedrates

Wyko RTI4100 interferometer (tilt removed) was used for PSD measurements. Results are in Table 2. The raster results show sharp peaks at the raster spacing, plus lower amplitude peaks at higher spatial frequencies. These lower-level effects may be due to irregularities in the polishing cloth, although the precise reason is currently unknown. In contrast, the random tool-path suppresses the principle PSD peak and shows much cleaner PSD profiles.

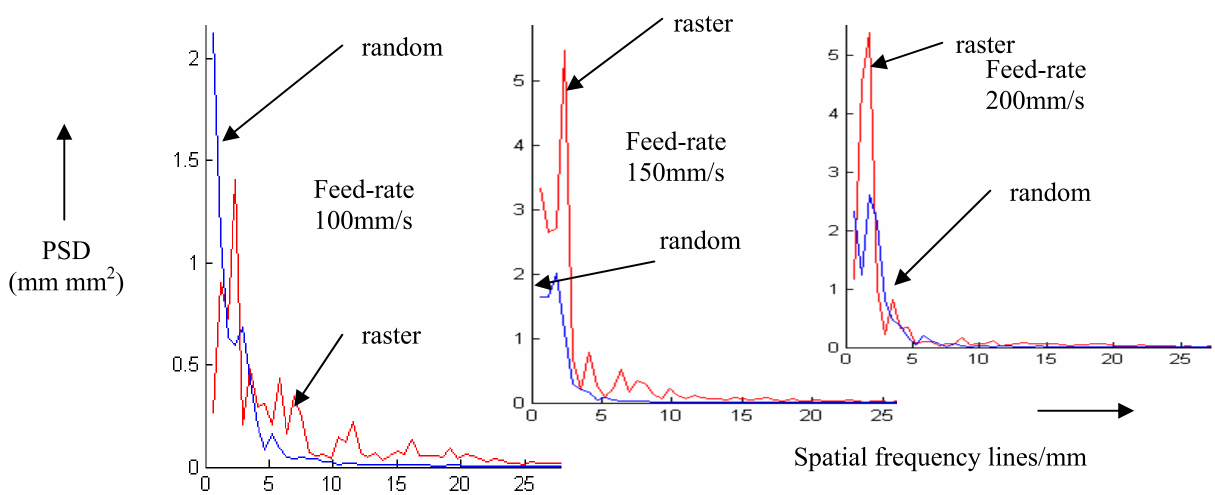


Figure 10. Comparison of PSD from raster and random tool-paths, with otherwise identical conditions.

4.3 Diminishing Mid-Spatial Frequencies Using the Random Tool Path

The rastered regions were polished again using the random tool path shown in Figure 9, and the surface text measured using a white-light interferometer. Results are shown in Table 3, which demonstrates the reduction in surface texture due to the randomization of the surface.

	Before			After		
Sample area	Ra (nm)	Rq (nm)	Rz (nm)	Ra	Rq	Rz
1	3.97	4.87	33.08	3.25	4.02	27.29
2	5.51	6.85	49.27	3.75	4.51	39.10
3	5.30	6.66	41.15	3.60	4.45	37.91

Table 3. Surface texture measurements before and after random polishing

5. Conclusion and Further Work

We have demonstrated the feasibility of controlling edges using a raster tool-path with a linear tool-lift algorithm under manual GUI control. The approach is based on polishing the overall surface but deliberately leaving a turned-up edge, and then re-processing the part to bring the raised edge down. Results were further improved using a combination of fluid-jet and a final pass with a pitch-loaded bonnet. We have also demonstrated an effective random tool-path algorithm, and pointed out the advantages over a raster in terms of texture, PSD, and the uniform handling of all edges around e.g. a hexagonal segment.

Considerable potential exists to develop our approach to edge-control further, and to qualify the technology for routine segment fabrication. That work is in progress and the list below illustrates the direction being pursued.

- In current work, the bulk surface is first processed, and then the entire surface is addressed in the edge-rectification stage. The philosophy will move to treating the edge separately, in order to reduce process time, and avoid the danger of introducing new defects into the bulk surface.
- Upgrade the Tool-Path Generator GUI to allow more versatility in controlling the tool-lift parameters, to provide an investigative capability. Note that this will still be essentially empirical in its operation, and will not require quantitative input-data on measured influence functions for the range of spot-sizes used.
- Integrate variable spot-size and tool-lift with the *Precessions* numerical optimizer (as used in the Zeeko process for the ultimate form-control). This will require quantitative input-data on measured influence functions for the range of spot-sizes used.
- Validate operation with both raster and random tool-paths.

6. ACKNOWLEDGEMENTS

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