# Precessions Aspheric Polishing:- New Results from the Development Programme

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## ABSTRACT

The *Precessions* process for producing aspheric and other optical surfaces is undergoing rapid development. In this paper, we summarise the considerable success achieved in controlling the repeatability of the process on both the 200mm and 600mm machines, and illustrate this with examples of aspherics that have been produced. We particularly describe our approach to fine form-control. This has required the development of various strategies to moderate the volumetric removal rates, in order to give the required sensitivity of removal. We conclude with a discussion of the scaling laws that apply when adapting the process to smaller and larger sized parts. This is illustrated by predicting the process-parameters for mass-producing segments for extremely large telescopes.

## 1. Introduction

Earlier stages in the development of the *Precessions*™ small-tool polishing process have been reported elsewhere [1,2,3,4,5,6]. Suffice here to note that it is a fully-automated polishing process, based on precise CNC control of the position and orientation of a compliant tool with respect to the surface of a (typically aspheric) part. Therefore, the process is *position* rather than *pressure* based. The influence function of the tool is characterized experimentally by polishing depressions in witness samples of material. This is performed for different examples of its continuously-variable footprint ('spot size'). The resulting data, together with the measured error-profile of the part, is subject to a numerical optimization process that computes run-parameters for a polishing cycle in order to minimize the residual form-error. For form control, the optimizer computes the radii of a series of concentric polishing zones, and the dwell-time and spot-sizes for each. The machine CNC transforms the result into a spiral tool-path for execution on the machine.

Given such a machine with its operating software, we focus in this paper some of the issues that are important for control of form, and consider the implications of scaling the technology.

Many of the polishing tests conducted over the last year have been obtained with machines undergoing trials in industrial production environments, often in the hands of personnel not associated with the development of the technology or machines. The results presented here are typical of what may regularly be achieved, following the experience of many hundreds of surfaces produced during the development programme and trials at various sites.

## 2. Some Requirements for Fine Form Control

### 2.1 Conditioning the tooling

The first – and possibly most important – factor governing fine form control is the interface between the tool and the part. The heart of the tool comprises an inflated rubber spherical membrane (the 'bonnet'), covered with a suitable polishing surface, which is rotated about its axis by the tool-spindle ('H' axis). The tool attacks the surface at an angle to the local normal to the surface (the 'precession angle'), and precesses around this normal in discrete steps.

A key requirement for fine form control is that the tool runs true, both in rotation about its own axis, and in rotation about the intersection of the two CNC rotation axes of the machine ('A' and 'B'). This is accomplished in three stages: the first during machine build, the second during installation by the user of a new bonnet, and the third when the user applies a new polishing surface to a bonnet.

The first stage is to ensure that the machine's 'A' and 'B' rotation axes intersect at a virtual pivot point, which in correct alignment is coincident with the centre of curvature of the bonnet. This is achieved by mounting a precision spherical ball in place of the bonnet. The ball is then clocked to run true whilst driving the 'A' and 'B' axes, by adjusting the alignment of the tool-head at its mounting interface.

The second stage is to mount the bonnet (assumed here to be new) and then to pressurize it to its approximate working pressure (typically 0.5 to 1.5 bar). Again, the 'A' and 'B' axes are driven, and the bonnet is trued-in using a single-point cutting tool or a grinding wheel, in the presence of water as a coolant. On the smaller machines the 'C' axis (part rotation) can be driven sufficiently fast that it can carry the tool directly to true in the bonnet. On the larger machines this is not the case, and then a small independent motor-driven grinding spindle is bolted to the stationery 'C' axis turntable.

The third stage is to apply the (removable) polishing surface to the bonnet. This would typically be a standard polishing material such as a polyurethane (e.g. 'Polytex'), or cloth-like surface (e.g. Multitex). In both cases, the material is first pre-formed to the bonnet's spherical radius using a stainless steel spherical mould, and then trimmed to size. In the case of polyurethane, it is then glued in place, and trued-in exactly as per the bonnet. We do not find it necessary to true-in Multitex, providing that the adhesive layer is of uniform thickness. This may conveniently be achieved by using a spray adhesive.

### 2.2 Conditioning the slurry

The constancy of the slurry supply to the part is paramount in controlling form. Bulk slurry is held in a tank furnished with an agitator propeller which draws material up from the base of the tank and homogenizes the mixture. The tank also has a thermostatically-controlled heater, as slurry temperature has been found to change removal rate. The slurry is pumped to the polishing machine, directed towards the part via two jets, and is gravity-fed back to the tank. Flooding the part with slurry is necessary to keep a constant-temperature working environment within the machine enclosure.

When the machine is first switched on, the slurry is left flowing with the H-axis spinning for some 15-20 minutes, after which the thermal environment of the machine has stabilized.

### 2.3 Touch-on and probing

As the form-control process is based on CNC control of tool-position rather than applied-force, it is essential to establish the exact location of the surface of the part in the co-ordinate-frame of the machine. This is critical because the spot-size is controlled by advancing the bonnet towards the part by a specified distance with respect to first-contact ("touch-on"), thereby compressing the membrane. To enable this, the polishing-head is furnished with a sensor that detects touch-on, achieving a repeatability of 2-3μm. This is then repeated by probing along a diameter of the part, in order to generate an error-compensation file for the CNC. This file is used to compensate for residual mechanical and thermal errors in the machine, and possibly uncertainty in the absolute radius of curvature of the part, etc. This last error-source is particularly significant when an interferometer is used for metrology, as this method gives no absolute measurement of radius of curvature unless special procedures are used (e.g. defining distances in the test setup with calibrated metrology rods). The probing procedure ensures that the bonnet accurately tracks the surface of the part, or deviates from this locus in a prescribed way in order to modify spot-size as required for the specific polishing run. In successive polishing runs on the same part only the initial touch-on procedure is repeated and not the probing.

### 2.4 Achieving an appropriate level of process sensitivity

Typically, pre-polishing (improvement of surface texture and removal of sub-surface damage) will need to remove a 'skin' some 5-20 μm deep from the surface of a precision-ground part. We have already reported [3] on the excellent performance of the machine in preserving form of aspheric parts during pre-polishing. Clearly, this mode demands a high volumetric removal rate to achieve a short process time. In subsequent fine form-control one would like to achieve progressively shorter cycle times still. However, this can not be continued indefinitely as dwell-times for specific radial zones quickly become too short for a mechanical machine to execute accurately, and so removal-errors accrue. This is particularly the case near centre, where dwell-times can be very short (~1 second) due to the small circumferential length of the zones. For this reason, it is sometimes advantageous to moderate the overall volumetric rate to give greater sensitivity for fine-removal, and there are several strategies used to achieve this. An example of a case where the process 'bottomed out' due to too high a removal rate is given in Case Study 3 below.

i) Polishing cloth. We find that polyurethane is excellent for removing grinding marks and mid-spatial frequency defects. However, on proceeding from pre-polishing to fine form-control, Multitex cloth gives the better ultimate surface-texture. We have determined experimentally that Multitex delivers a removal rate some 56% that of Polytex polyurethane, when using CE40 cerium oxide slurry. We find that the influence functions are essentially identical in form but different in depth with these two bonnet-surfaces, as shown in Figure 1 and 2. These two results were acquired under polishing conditions identical other than the surface of the bonnet.

ii. Slurry concentration. This can be varied to change the removal rate. For example, in a typical experiment with Multitex cloth (7mm nominal full spot-size from a R=40mm bonnet running at 800rpm), the removal depth was reduced by a factor of 0.56 on diluting the cerium oxide slurry from a specific gravity of 1.070 to 1.010.

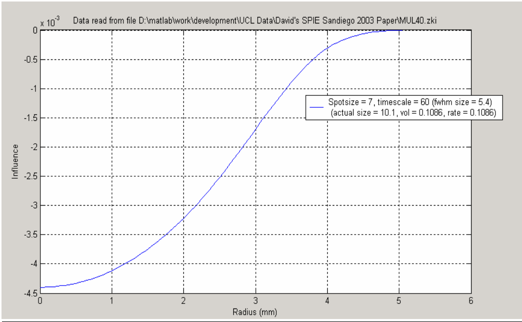



Figure 1 Measured influence function with Multitex – 0.45 µm deep

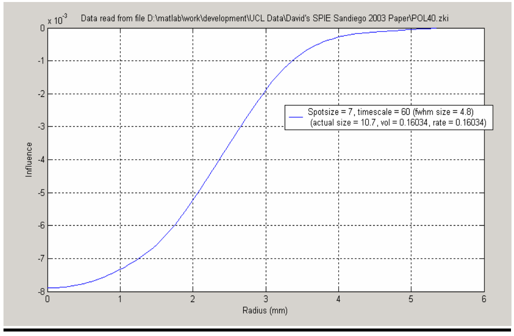



Figure 2 Measured influence function with Polytex – 0.8 µm deep

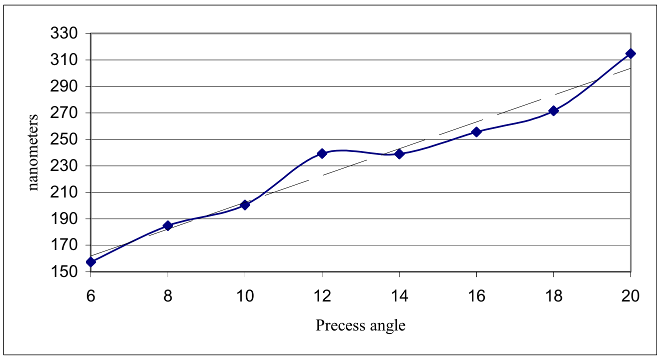



Figure 3 Variation in depth of measured influence functions with precess angle

iii Precession angle. The surface speed can be reduced, and with it the removal rate, by reducing the precession angle. A series of measured influence functions is shown in Figure 3.

This approach is limited by the maximum spot sizes that the lower angles can deliver within the restriction S < 2r in Figure 18.

iv. Spot size. A smaller spot size delivers a reduced volumetric removal rate according to an (approximately) square law. A good strategy has proved to be to use the largest spot-size(s) for the coarsest removal, followed by smaller spots for finer removal.

iv. Pressure. The bonnet-pressure can be reduced for finer polishing control, although this is limited by the tendency of bonnets to fold-in (‘pop’) and create ‘W’ influence functions at low pressures.

v. H-axis speed. This can be reduced for finer control, although this is limited by residual once-per-revolution errors in the bonnet, as mentioned below.

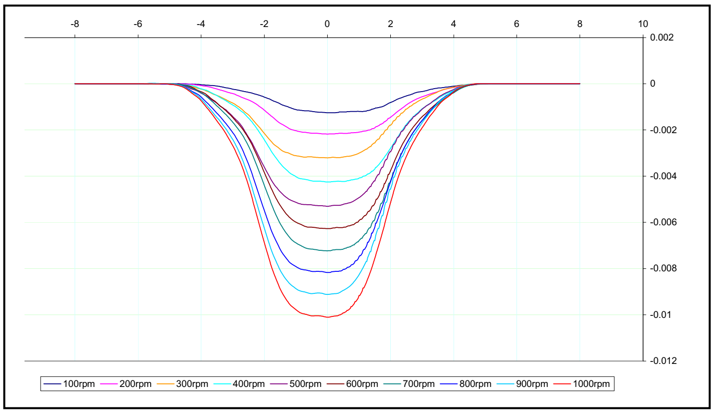



Figure 4 Linear variation of measured influence functions with H-axis speed, in the range 100-1000rpm.

The process has previously been shown to be highly linear with H axis speed and linearity plots were presented [3]. We here show in Figure 4 the actual influence function family corresponding to a group of different H-axis speeds.

It will be seen that the forms of the influence functions are very well matched. This means that the process can be moderated by changing H axis speed and scaling the dwell times, without the need to acquire separate influence functions for each speed. This has proved very important in moderating the process to control form near the centre of the part.

**2.5 Mounting the part**

On smaller machines, it is standard practice to block parts for mounting. However, for larger parts (for example, on the IRP600 machine) this is not satisfactory due to the introduction of mounting distortions. In this case, a different support strategy is required. The larger machines have a vertical C axis (i.e. the part lies in the horizontal plane), and they provide the capability to move the part to a station with an unobstructed upwards-looking path for lifting or interferometry.

Distortions of the part can therefore have two effects, as follows:-

1. Errors in the on-board metrology, if used.
2. Errors in the compression of the bonnet (Z offset), giving varying spot-size and so varying volumetric removal rate. Note that a radial component of distortion will be compensated by the probing routine, but that any azimuthal component (or local print-through of individual supports) will not.

A reasonable approximation is that the bonnet is operating in a pressurization-dominated (rather than elasticity-dominated) regime, so that volumetric removal rate is proportional to spot-area. The relative variation in volumetric removal rate with touch-on can then be calculated from simple cord-geometry and is shown in Figure 5.

As regards the introduction of polishing errors, the effect of mounting distortions on metrology is usually the dominant (albeit indirect) factor, in the case when the part is measured on the polishing support system in-situ on the machine. Beyond this, the effect of mounting distortions on polishing-rate comes into play. These are quantified in Table 1 below, where $\Delta Z$ is the change in Z height of the part's surface (giving a change of $\Delta Z$ in bonnet compression) that corresponds to a 5% change in volumetric removal rate.

For example, when polishing with a 4mm spot-size from an R=40mm bonnet, the effect of a 2.5 μm peak-to-valley mounting distortion in the part, is to modulate the volumetric removal rate by 5% over the surface. Therefore, if a polishing run removes a nominal 1 μm of stock material, mounting distortions will introduce a form-error of approximately 20 nm peak-to-valley.

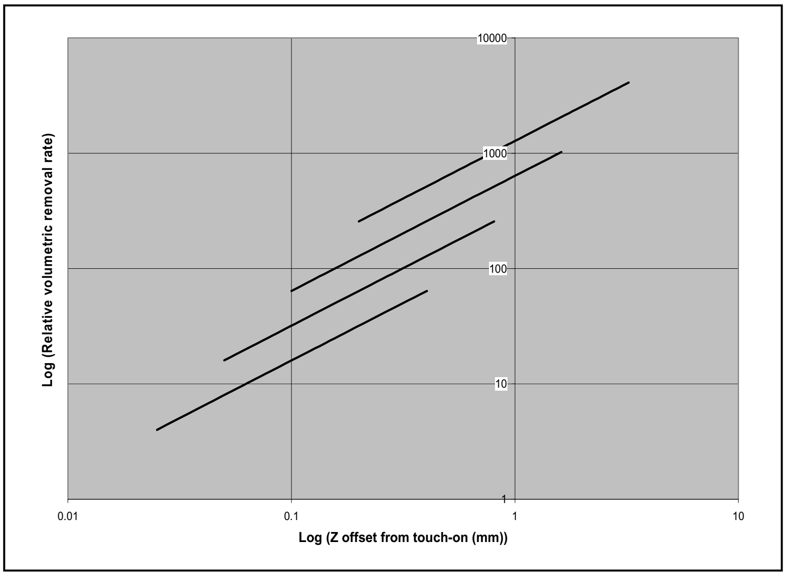



Figure 5 Calculated variation of relative removal rates with Z-offset for bonnet radii: 160mm (top), 80mm, 40mm and 20mm (bottom)

| Bonnet size<br>Range of spot diameters | R=20 mm<br>2-8 mm spots | R=40 mm<br>4-16 mm spots | R=80 mm<br>8-32 mm spots | R=160 mm<br>16-64 mm spots |
|---|---|---|---|---|
| ΔZ for smallest spot & 5% variation in vol. removal rate | 1.3 µm | 2.5 µm | 5 µm | 10 µm |
| ΔZ for largest spot & 5% variation in vol. removal rate | 20 µm | 41 µm | 82 µm | 164 µm |

Table 1 Calculated height variations ΔZ corresponding to 5% change in volumetric removal rates

Usually, mounting distortions are most troublesome with large parts. The removal strategy is normally to remove the bulk material with a large bonnet/spot-size, followed by progressively removing smaller depths of material with smaller bonnets/spot-sizes. Fortunately, this places bulk-removal in the regime where form-errors are least sensitive to mounting distortions, and fine removal where mounting distortions have least effect.

Note that a tilt term (i.e. a wedge in the mounting of the part, or in the substrate material) will simply add a linear term to the removal-profile, thereby tending to be self-compensating.

## 3. Some representative polishing results

### 3.1 Case Study 1

This example (Figure 6) is a 300mm diameter, fused-silica Cassegrain mirror with a 150mm diameter perforation. The radius of curvature is 2045mm concave with conic constant of –1.204627. The aspheric departure from the nearest-fit sphere was approximately 3.4 µm peak-to-valley. At the time of submitting this paper, work was in-progress. Figure 6 shows the part being prepared for polishing on the turntable of the IRP600 machine at UCL.

The annular blank and a central plug were both delivered pre-polished to a spherical form. The asphere was then polished in using the IRP600. In addition, the plug was polished to remove a constant depth of material (~3µm). In the absence of a null lens (one is to be procured) the interference fringes after polishing on one side of the asphere were inspected on the Wyko 6000 interferometer display – Figure 7.

In addition, the concave plug was polished and inspected on both the knife-edge test and Wyko (Figures 8 and 9 respectively). The central obstruction in the plug was due to the central area having been used to produce an influence function for the optimizer, and the slopes were too steep for the interferometer to handle. It was consequently masked.

In both interferograms, the fringes are clean with little evidence of high spatial frequency defects, and the knife edge test on the plug is clean other than very low-level zones arising from 'cusping' – the ripple due to the superposition of the overlapping Gasussian influence functions for successive radial zones. This effect can be made arbitrarily small by choosing the zone-spacing and spot-size appropriately, as described previously [2].

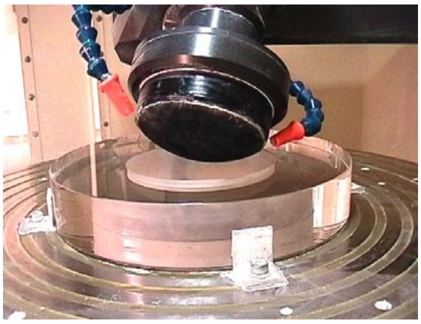


Figure 6 Polishing setup for 300mm part mirror

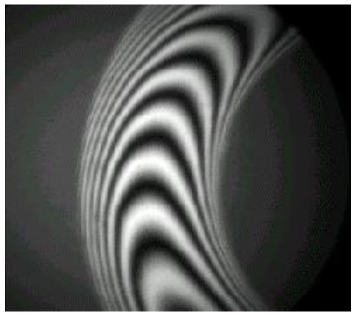


Figure 7 Interferogram of one side of 300mm part after aspherising

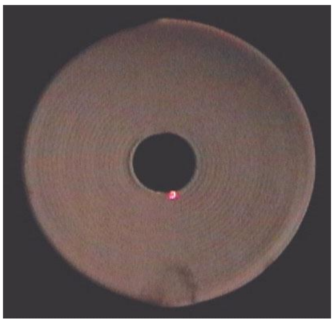


Figure 8 Knife edge of central plug After polishing spherical

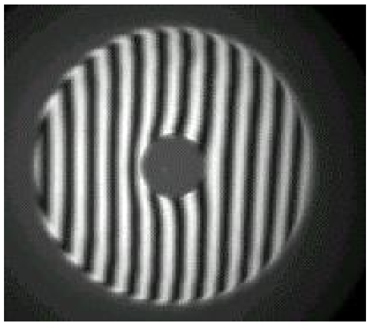


Figure 9 Interfero gram of central plug after polishing spherical

### 3.2 Case Study 2

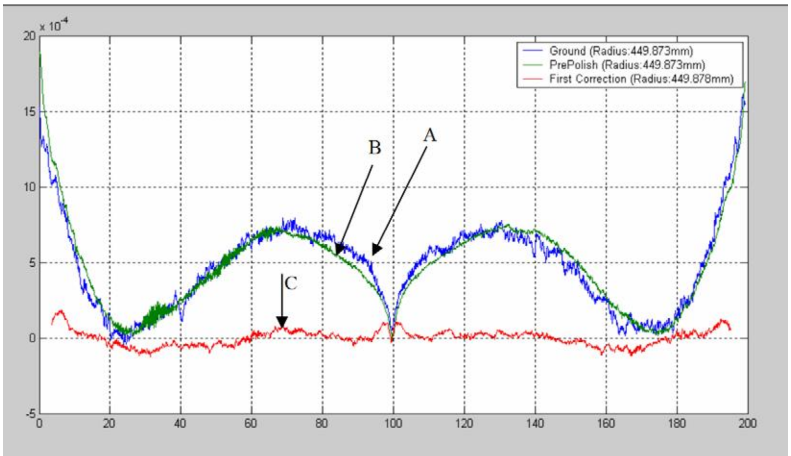



Figure 9 Pre-polish (30 minutes) and form-correction runs (90 minutes)

Figure 9 shows a typical axially-symmetric convex aspheric part some 200 mm in diameter, with a radius of curvature of 450mm, measured using a Taylor Hobson Form Talysurf stylus profilometer. The substrate material was fused silica.

The form directly off a precision grinding machine is shown in plot A, and demonstrates some 2 µm peak-to-valley form error. “Form preserving” pre-polishing on the Zeeko machine resulted in trace B.

A *single* form-control run using the Precessions optimization gave trace C. The residual form error was 0.19µm peak-to-valley, which is within the 0.2 µm calibration error of the Form Talysurf. The surface texture was also measured on a Taylor Hobson CCI (Figure 10), with a results of Ra=1.8nm.

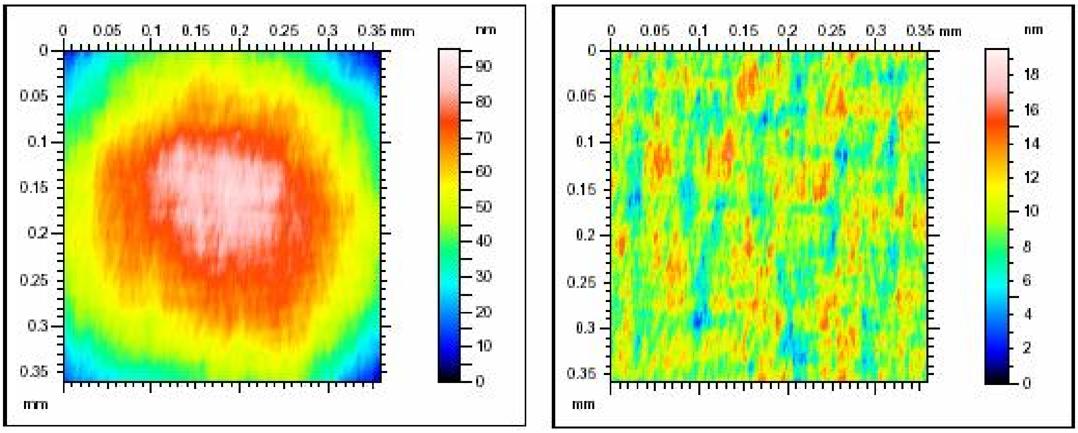


Figure 10 1.8nm Ra Texture of 1.8nm measured with Taylor Hobson CCI

## 3.3 Case Study 3

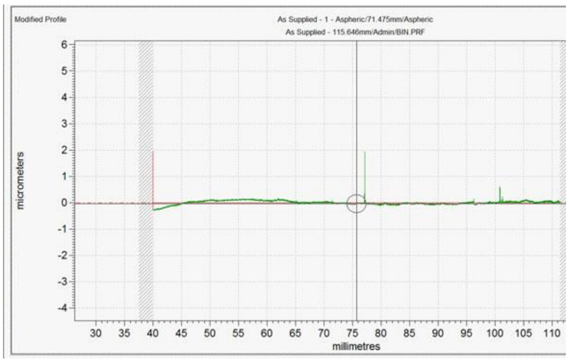



Figure 11 Cassegrain mirror directly off grinding machine

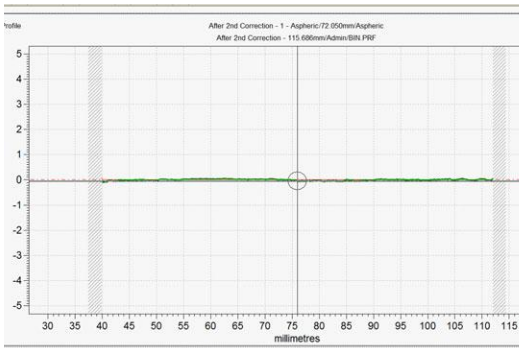



Figure 12 Cassegrain mirror after first form-correction run (15 minutes)

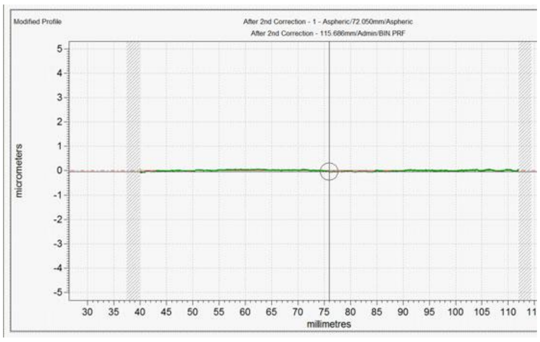



Figure 13 Cassegrain mirror after second form-correction run (7 minutes)

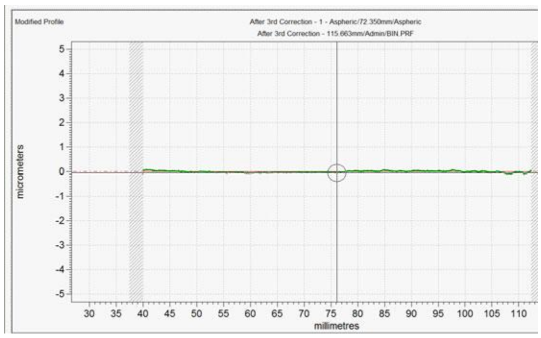



Figure 14 Cassegrain mirror after third form-correction run (5 minutes)

The Case Study 3 component (results above) was a concave Cassegrain light-weighted mirror in BK7, with a central perforation 58mm in diameter. The nominal optical diameter of the part was 184mm diameter, although there was a substantial unused land around this area on the blank. The aspheric departure with respect to the oscullating sphere was 120 µm, and 29 µm from the best-fit sphere. The global form-error off the grinder was about half a micron peak to valley. No pre-polish was required on this part. After the first polishing cycle (Figure 12), the peak-to-valley form-error was reduced to about 0.23 µm and after the second (Figure 13) 0.18 µm. This was the limit of form control with the slurry-concentration and spot size used. A subsequent run (Figure 14) actually degraded the form-error slightly to 0.24 µm. This was because the removal rate was sufficiently high that dwell-times were right on the limit of the physical capability of the machine to execute. This is a good demonstration of the need to moderate removal rates as discussed in Section 2.4 above.

### 3.4 Case Study 4

This aspheric part had a nominal diameter of 70mm, a very short radius of curvature of 44mm, and the material was SLAH66. The aspheric departure from the osculating sphere was approximately 1mm, and 165 μm from the best-fit sphere. Due to A Axis limit setting of -44.5degrees, the part could not be pre-polished over the full clear aperture and with a 10mm spot size. In order to avoid exceeding the A axis limit a reduced clear aperture of 61mm was defined. In general the form of the part has been retained after pre-polishing. The centre peak has been reduced to a general depression at centre.

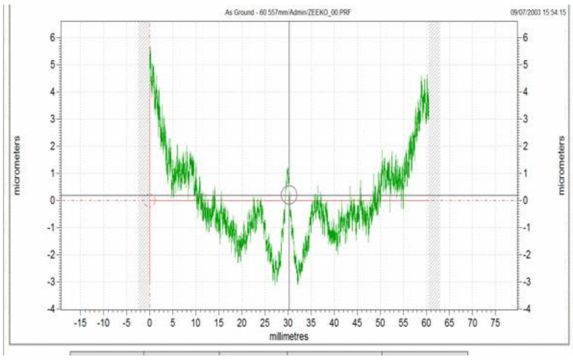



Figure 15 Short radius part directly off diamond grinding machine

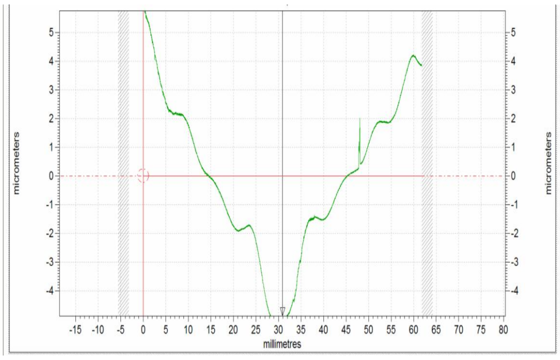



Figure 16 Short radius part after pre-polish (100 minutes)

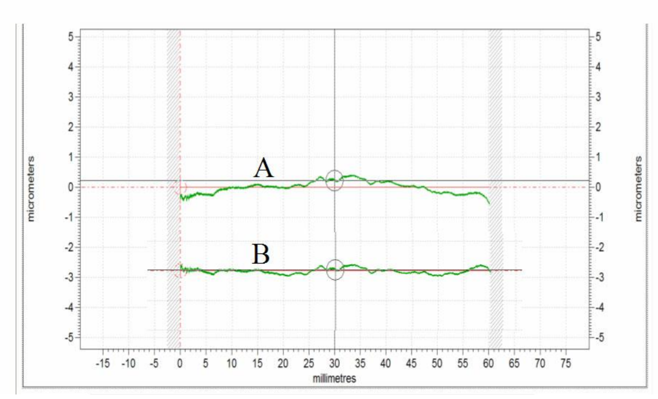



Figure 17 Short-radius part after third form-correction run (curve A), and after removing the focus-term (curve B). Process times were 90, 45 and 18 minutes for the three form-correction runs respectively.

## 4. Scaling the process to different part sizes

The polishing bonnet is mounted in the nose of the tool-head spindle, and spun about its axis (machine 'H' axis). The geometry is shown in Figure 18. Bonnets with nominal radius B = 40mm and 80mm have been produced, and a 160mm bonnet is under development. Larger bonnets are envisaged for larger machines.

The tool-head in its entirety describes the precession-motion about the local normal to the part. This is accomplished by synchronized rotation of the CNC 'A' and 'B' axes of the machine. These axes intersect at the centre of curvature of the spherical membrane of the bonnet. The area in contact (the 'spot size') between the bonnet and the part is controlled by advancing the bonnet into the part by a controlled linear distance (*not* by servoed force). The compression of the rubber membrane creates a polishing spot of diameter S in Figure 18. The maximum spot size with a given bonnet is limited by two effects:

1. Restrictions on physical clearance i.e. S < 2r in Figure 18.
2. The tendency of bonnets to create 'W' influence functions when very large spot sizes are attempted, unless the pressure is increased significantly (i.e. to ~2 bar or more)

As a practical guideline, S may be varied between typically 5 and 15mm for a 40mm radius bonnet; twice these values for an 80mm bonnet, etc. At the higher values in both cases there is distortion from a pure Gaussian profile (depending on the internal pressure), although these larger spots are still useful for achieving fast removal rates, particularly for pre-polishing.

We considered previously [2] the case of an aspheric of given 'difficulty', such as a parabola of defined focal ratio. We then considered the implications of scaling up the part and process in all linear dimensions by a factor of two. In summary, the area of the part and the contact-spot increase by the same factor, so the increase in volumetric removal rate compensates for the increased area of the part. The area-ratio argument implies that process-time is independent of diameter of part, if the tooling is scaled accordingly. As we observed, however, this is valid only for *constant surface speed*.

However, another effect comes into play, and that is the increased distance r of the centre of the polishing spot from the tool's rotation-axis (Figure 18). The latter is characterized by zero surface-speed, and speed increases linearly away from it. The surface speed averaged over the spots for the four precession positions is then given by:

Average surface-speed = $2 \pi r R / 60$ metres/sec.

Where $r = B \sin P$ and R= revolutions-per-minute of the bonnet.

So average surface speed = $\pi B R \sin P / 30$ metres/sec. i.e. it is proportional to bonnet radius.

We have already reported an excellent linear response between surface-speed and removal-rate [3]. Taking both the area-ratio and bonnet-radius effects into account, process-time can actually *decrease* on scaling up the process, if the scaling-strategy is to maintain tool revolutions-per-minute rather than constant surface-speed. It should be noted that there is a limit to the useable surface speed due to the onset of aquaplaning, where the tool effectively lifts off the surface of the part, and the volumetric removal rate then drops dramatically. This can be mitigated by increasing the bonnet internal pressure.

Polishing with high tool-rotation speed does, however, have a distinct advantage. If there are any residual non-uniformities of the bonnet or polishing cloth around the small-circle which progressively contacts the part, once-per-revolution polishing errors tend to be averaged. However, the short process-times concomitant on fast tool-rotation and small depth of removal has an undesirable effect; dwell times for individual zones on the part (especially near centre) can be impractically short.

Given the above, the best strategy for scaling up the process is to increase the bonnet size, maintain as high a tool-rotation speed as dynamical considerations and the onset of aquaplaning will allow, and moderate the process-speed where required by other means; in particular reduced spot-size and bonnet pressure, probably combined with diluted slurry, as mentioned above in Section 2.4.

Consider polishing the precision-ground surface, and correcting form, on one of the hundreds to thousands of 2m-class hexagonal segments required for each of the next-generation ground-based Extremely Large Telescope projects. (For examples of these projects, see [7,8,9]). In order to estimate process times, we extrapolate experimental results obtained on the IRP600 machine at UCL using an 80mm nominal-radius polishing bonnet delivering the maximum spot size achievable. Table 2 below shows an example of these experimental results, giving the polishing conditions and the measured volumetric removal rate on a Zerodur sample. (On BK7, we obtained a volumetric removal rate approximately twice that of Zerodur.)

| **Parameter** | **Quantity** | **Parameter** | **Quantity** |
|---|---|---|---|
| Actual full spot size | 31.3 mm | Measured bonnet radius | 83 mm |
| Spot FWHM | 25.9 mm | Bonnet pressure | 1.5 bar |
| H axis (tool) speed | 1000 rpm | Number of precess positions | 4 |
| C axis (sample) speed | 4 rpm | Precess angle | $20^o$ |
| Cloth | Blue poly | Slurry | Cerium oxide 460 |
| Slurry specific gravity | 1.075-1.080 | Slurry temperature | $25^oC$ |
| Total dwell time | 60 seconds | Volumetric removal rate | 2.26 $mm^3$ per min. |

Table 2 Measured volumetric removal rate on Zerodur with IRP600 at UCL

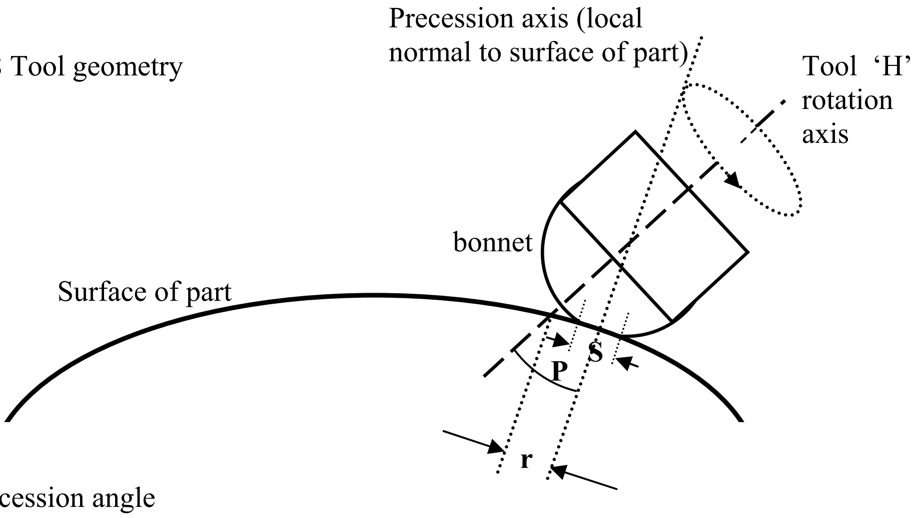
Now, consider scaling the process to a 400mm nominal-radius bonnet delivering a 156mm full-spot diameter (factor 5 in bonnet radius and spot-size c.f. 80mm nominal bonnet above). Keeping all other quantities the same, the volumetric removal rate then tends to follow the cube law (area of polishing spot times distance of polishing spot from rotation axis) – a factor of 125 for a 156mm spot, giving 283$mm^3$ per minute. The area of a hexagonal segment 2m across the flats is about 3.5 $m^2$. A 10 micron average depth-of-polish then requires the removal of 35000 $mm^3$. With a removal rate of 283 $mm^3$ per minute, this would take ~ two hours. This removal rate constitutes a relatively aggressive regime. In successive runs to control form, the volumetric removal rate would be moderated by a combination of reducing the spot-size, bonnet pressure and slurry concentration, in order to maintain an approximately constant run-time.

The above scaling should be considered as indicative of polishing conditions that might be appropriate. In reality, the process would need to be optimized by experiment, particularly in terms of H axis speed, bonnet pressure, spot-size and precession angle, in order to obtain the optimum-removal rate and surface-texture, whilst avoiding aquaplaning of the tool at high surface speeds. Pending further experimental results, it would be prudent to allow a factor of 2 in process time to allow for a possible need to reduce H axis speed. Conversely, it might also be possible to *increase* removal rate further using a larger bonnet (an 800mm radius bonnet delivering a 300mm full spot size could well be feasible on a 2m class polishing machine).

An earlier extrapolation to a 2m segment was previously reported [2]. This used experimental data from a 40mm radius bonnet that pre-dated the first of the 80mm bonnets. A polishing time of approximately 3 hours was estimated for removing an average of 10 µm from a 2m BK7 hexagonal segment. This could be scaled to about 6 hours for Zerodur. The difference compared with the 2 hours estimated here lies in three main areas. First, the earlier extrapolation assumed a lower bonnet pressure, as we did not have experience with higher pressures at that time. Second, that result assumed a moderated H axis speed, and we have noted here that speed moderation from 1000rpm may indeed be required. Third, the 40mm bonnet as used in the earlier experiment delivered a measured volumetric removal rate of only 0.105 $mm^3$ per minute on BK7. Therefore, the work reported here, based on a measured removal rate some twenty times greater (and on Zerodur), may be considered a more reliable basis for extrapolating process-speed.

In the case of scaling to smaller parts, the reverse applies. Therefore, bonnets of smaller radius B delivering smaller spot sizes S, will exhibit reduced surface speed. This is due to the reduced distance r between polishing spot and rotation axis. Therefore small parts are expected to demand faster tool revolutions per minute and increased bonnet-pressure to achieve viable process times. Fortunately, this is easier to provide on tool-spindles for small bonnets where dynamical considerations are not such a constraint.

Figure 18 Tool geometry




P = precession angle
S = full diameter of polishing spot
r = distance of polishing spot centre from rotation axis
B = radius of the spherical form of the bonnet
R= revolutions per minute of bonnet

## 5. Conclusion

The Zeeko process is undergoing extensive industrial trials and is proving to be robust and predictable on a range of aspheric surfaces. This has been demonstrated here, albeit by presenting a necessarily small sub-set of representative results from a large portfolio of tests conducted mostly in production environments. The Taylor Hobson Form Talysurf has proved to be an excellent tool for measuring aspherics down to the level of approximately one to two tenths of a micron, and side-steps the issues relating to custom null lenses (holographic or otherwise). In our experience, this level of precision amply meets most industrial applications of aspherers. However, further refinement of the process for the more challenging (particularly scientific) applications tends to be metrology-limited. For significant aspheric departures, interferometric testing with null lenses or sub-aperture stitching is currently inescapable. The inherent capability of the polishing process has previously been illustrated [2] with the example of polishing a mild asphere (for easy testing), which achieved 80nm peak-to-valley form error. Given the protocols described in this paper, there appears to be no reason that would preclude lower levels of form error, given adequate metrology.

We have also described some of the important steps in form-control including touch-on procedures and part-probing. The need to moderate the process for fine form control has been highlighted and a number of strategies described. The process is believed to be fully scaleable to both smaller and larger sizes than the current 200 and 600mm capacity machines. To achieve optimum process speeds for precision of form-control, high-speed spindles will be required at the small-sale, and lower-pressure bonnets at the large scale. We have estimated process times for 2 metre-class segments for extremely large telescopes, and find that they are commensurate with realistic production schedules.

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