Recent development of *Precessions* polishing for larger components and free-form surfaces

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ABSTRACT

Since the 2003 Annual Meeting, the *Precessions* process has become accepted as an efficient method for polishing and figuring moderate-sized axially-symmetric aspheric parts in industry. In this paper, we report on some very significant new advances beyond this capability. The first is the demonstration of the process on substantially larger diameter parts than worked hitherto – in particular, a precision-ground 500mm diameter deeply-concave aspheric mirror. We describe the consequences of polishing large parts with the axis of the part vertical, in contrast to the horizontal axis of the smaller machines. Issues include slurry puddling and settlement in concave forms, process-uniformity, adequate support of the part and handling. We then report on recent work developing the *Precessions* process for non axially-symmetric surfaces including free-form. The correct relationship of the process with metrology has proved to be complex on several fronts, one example being differing descriptions of form either along a surface or its projection. We present our experience using profilometry and interferometry on precision-ground and polished surfaces, and in achieving absolute form with known base radius. Finally, we remark on the potential power of *a priori* predictions of achievable surface quality when optimizing optical system designs.

1. Introduction

The *Precessions*™ polishing process has been reported extensively elsewhere [1,2,3,4,5,6,7,8,9]. For the benefit of summarizing in this paper, it is an automated polishing process, in which a 7-axis CNC machine tool controls the three-dimensional position of a spinning, inflated, membrane-tool (the 'bonnet') as it traverses the surface of a part. When the tool touches the surface and is then moved further into the surface, it creates a localized 'polishing spot' of contact, and the size of this spot can be varied by changing the position of the tool relative to the part (rather than modifying the applied pressure as in some other techniques). Industry-standard polishing cloths are used, as are standard slurries.

The two principal modes of operation – 'pre-polishing' and 'form-correction' – have been reported in the aforementioned references and recently summarized [9]. The former operates on a precision ground part and polishes it to a high-quality optical finish. The second mode – 'form correction' – uses the same tool, but with the rotation axis inclined to the local normal and precessed in discrete steps around it. The near-Gaussian influence function of the tool is empirically characterized, as is the error-profile of the part. Numerical optimization is then used to determine the tool-path to correct the form error. *Precession* polishing can also achieve excellent textures, and in experimental work, values down to Ra~0.5nm have

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been achieved on BK7 [6] (limited by the noise-floor of the Wyko RST500 texture interferometer used). However, Ra~2nm is more routine in an industrial environment, particularly when no 'clean-up' finishing pass is used.

2. Experience with the Form Talysurf

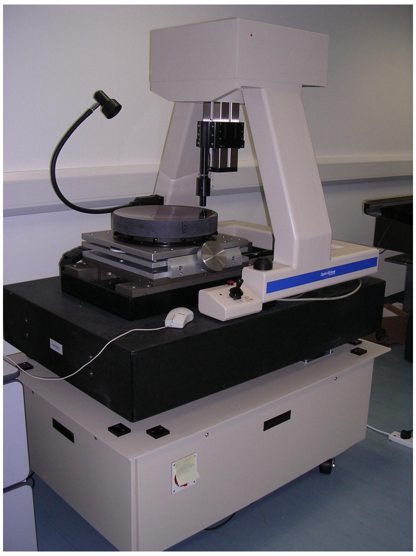

Figure 1 Extended-range Form Talysurf

Much of the process development with the 200mm capacity machines has relied on the absolute profilometry provide by the industry-standard PGI 1240 Form Talysurf from Taylor Hobson. This has a 200mm traverse, and can be equipped with a computer-controlled Y stage for raster measurements. It is therefore well-matched to the 200mm Zeeko machine.

For larger axially-symmetric parts, we use Taylor Hobson's Extended Range Form Talysurf (Figure 1), which has a 300mm traverse. The accuracy is on the order of 0.3 microns peak-to-valley over the full range.

For parts between 300mm diameter and about 500mm, we can reconstruct the radial profile from a 300mm scan, allowing correctly for the tilt-term. For an asphere, the pre-requisite is that the exact axis of symmetry of the part is marked with a small fiducial dimple, in the *same operation* as the precision-grinding process that created the base form. The fiducial is picked up in the profilometry data, which enables that data to be reflected about the true centre, giving two opposite sections of the mirror which overlap around centre. For a 500mm part, for example, the overlap is 50mm on the radius. The two sections are of course identical but reversed, and so have equal but opposite slope errors. The slope-term can then be modified bringing the overlap into numerical coincidence.

An extension of the method (which we have not ye used) is to perform two overlapping *measurements* of the two opposite and overlapping sections of the part (rather than merely reflecting the *data*). The measurement would then be shifted in X to bring the fiducial into coincidence, and the slope-term adjusted to bring the overlaps into coincidence in a least-squares sense.

2. Experience polishing larger parts

Results polishing a 184mm diameter Cassegrain mirror on a 200mm capacity Zeeko machine were reported previously [7], together with an analysis of the scaling laws for scaling to larger sizes.

The principal difference in the process for polishing larger parts is that the machines with capacity beyond 200mm diameter use a horizontal turntable for the part (i.e. the axis of rotation is vertical), rather than the part being in the vertical plane as with the 200mm machine. Otherwise, the configuration of all the axes is identical in both cases, so the entire mechanical assembly and coordinate frame is effectively rotated through 90^{o}. The same software therefore works with both formats.

The larger machines with horizontal turntables conveniently enable the use of a multi-point support system under the part, such as a hydraulic or mechanical Whiffle Tree. This format also simplifies handling, as a clear vertical path is available in the machines for lifting tackle.

A concern with the horizontal format for the part is the possible accumulation and settlement of the re-circulating polishing-slurry in concave surfaces. This led to a series of experiments using a commercial air-knife (Figure 2), which comprise an extruded hollow section with air-jets along the length, designed to provide a laminar flow of air. This proved satisfactory in expelling slurry from the concavity of a deep (f/1) mirror. However, subsequent work has identified other sources of process variability which have since been resolved, and the current position is that the air-knife is not being used. Nevertheless, with the continuation of the process-development to finer levels of control, it is anticipated that the air knife may indeed play a role in ensuring high levels of process-uniformity.

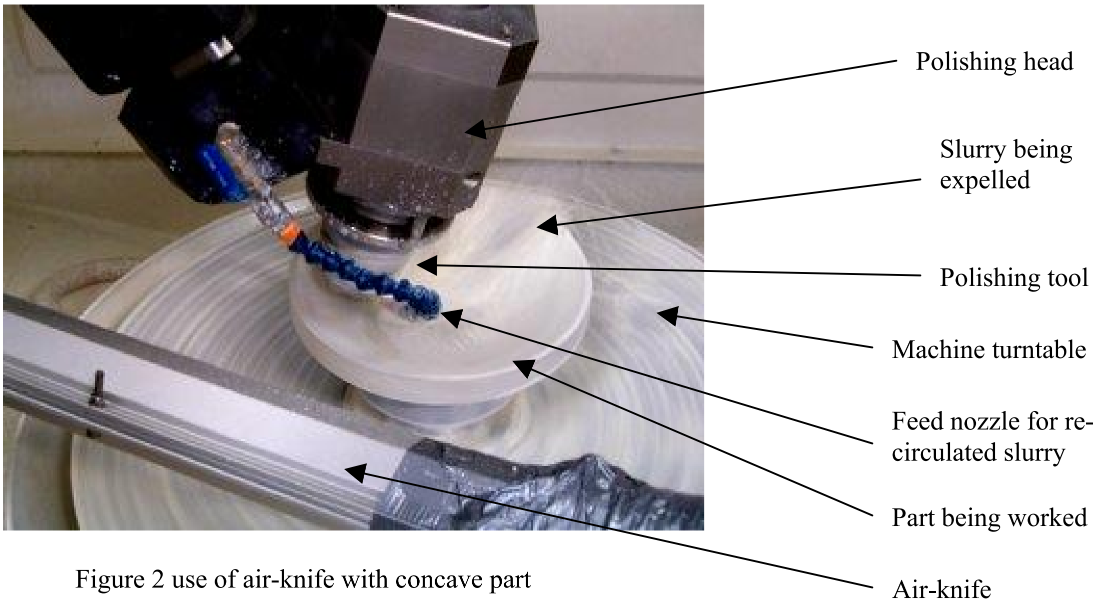

Figure 2 use of air-knife with concave part

We have previously reported [9] on the polishing of a 500mm diameter ellipsoid of revolution with 1000.0mm base radius and -0.158 conic constant. The aspheric departure from a sphere which oscullates about vertex was 82 μm. In this data we present some complementary details.

The part proved challenging, largely due to the difficulty of relating the coordinate frame in interferometric metrology data to that of the CNC polishing machine. Two complicating factors comprise the presence of i) scaling uncertainties and ii) geometric distortion in the interferometer transmission sphere. A mere 1% error in the absolute determination of the position of a surface-defect, means that the positional error is 5mm. Using a 5mm or 10mm polishing spot to correct a raised zonal error, then misses the peak and either deepens the adjacent valley, or creates a W profile of double the spatial frequency. Furthermore, when using an interferometer in this way, there is an ambiguity in the base-radius of the part. This complicates process-development, as a small error in base-radius determination can disguise a process variability in the central region of the part as a discrepancy in the outer zones. For these reasons we advocate the Form Talysurf, which is a contact profilometer giving absolute X-Z coordinates. This data is directly imported to the *Precessions* code, which then optimizes tool-path, dwell-time and spot-size in the 2D process.

Another general observation is that some metrology devices effectively operate along the curved *surface* itself. 'Z' is then in the radial direction, describing the distance of each point on the surface from a spherical reference. This applies to both the interferometer with a transmission sphere, and the swing-arm profilometer, both of which are effectively R-θ devices. Other instruments effectively operate on a *projection* of the surface onto a plane. 'Z' is then measured with respect to an orthogonal set of coordinates, giving the distance of the surface at each point from the plane. Examples are X-Z profilometers and coordinate measuring machines. In the surface-case, moreover, the length of the surface in the data-set is actually *longer* than the diameter of the part, as it follows the curve! In importing data to the polisher, it is crucial to differentiate between these two cases on an instrument-by-instrument basis.

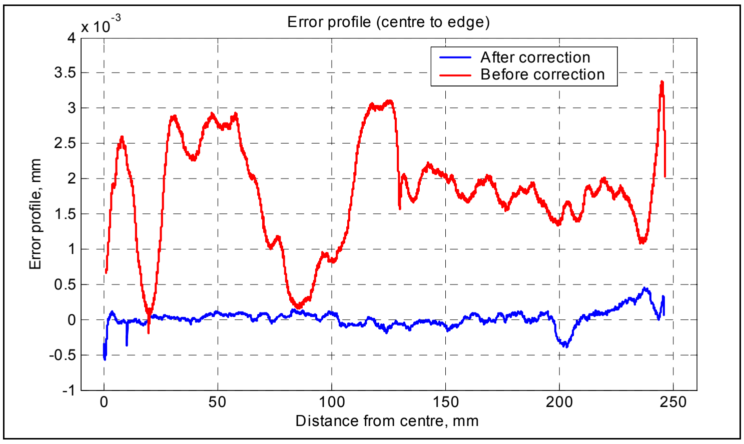

Figure 3 before and after processing 500mm part: see [9]

Any Gaussian process will leave some residual on the scale-length of the FWHM of the Gaussian polishing spot. We have therefore developed a process to clean up these residuals.

This process uses a ring tool which mounts in the machine's Schunk chuck instead of the usual polishing bonnet. The tool is passively articulated in order that it remains in intimate contact with the part, as the machine's A and B axes track local surface-slope. The tool is then pressurised against the part, and spun using the tool-spindle.

Figure 4 Standard 80mm radius polishing bonnet

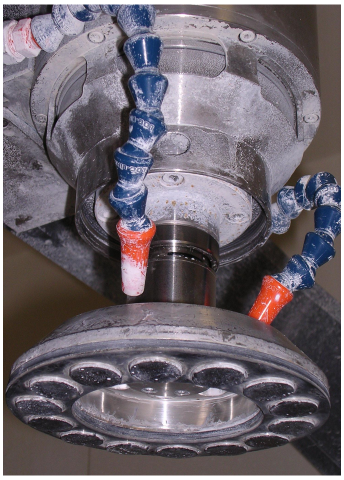

Figure 5 Compliant ring tool; pitch-loaded polyurethane

The ring tool carries a compliant Neoprene layer on which hard polishing facets are mounted. Based on Nyquist sampling theory, the facets are sized to span at least two cycles of all the spatial frequencies which are to be suppressed.

Figure 3 shows the 500mm ellipsoid part measured on the extended-range Form Talysurf before polishing (upper trace). The standard bonnet (Figure 4) was used, and the tool-path to control form was computed using the *Precessions* optimization. The ring-tool (Figure 5) was used to remove residual mid spatial frequency defects. The result is shown in Figure 3 (lower trace).

3. Interferometric Fringe Quality

The Form Talysurfs have proved extremely powerful both as a process-development tool, and in the production environment at customer sites. Indeed, in our experience, the manufacturing tolerances of most aspheric lenses we have encountered at customer sites fall within the capabilities of this metrology instrument. Nevertheless, it is limited in its ultimate precision. Moreover, whilst equipped with a Y stage it is possible to raster a full 3D *form*, it is limited in its ability to portray the *quality* of a surface. For this reason, various experiments using interferometers are in progress.

An interferogram was previously presented [7] of one side of a 300mm diameter Cassegrain aspheric mirror (non-null test), and its spherical 150mm diameter central plug, polished on a 600mm capacity Zeeko machine. Both these interferograms showed very clean fringe-visibility with little evidence of high spatial-frequency defects.

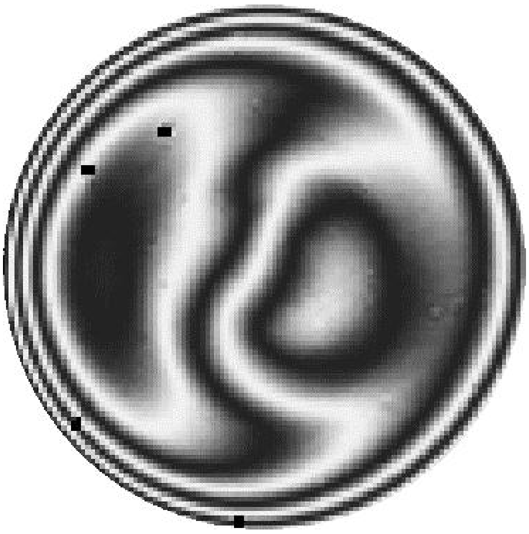

Figure 6 Non-null Zygo fringes on the 60mm diameter central region of an aspheric lens

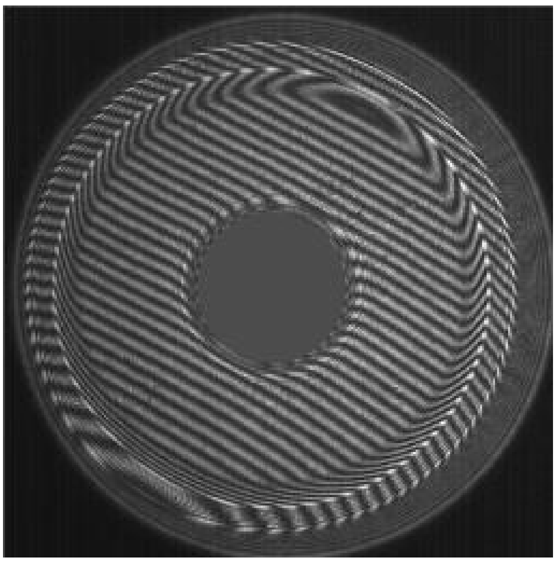

Figure 7 Raw Fisba fringe-data for near-spherical Cassegrain mirror from which 1 μm of material has been uniformly removed.

Recently, a highly aspheric lens of base radius 375mm was lifted from routine production on a Zeeko 200mm machine at a customer site. It had undergone the usual stages of precision aspheric grinding, followed by pole-down pre-polishing, and form-correction using the standard bonnet. No post-smoothing operation was performed.

The Form Talysurf is the standard metrology tool at this customer for process-feedback and acceptance, as it gives absolute XZ metrology and avoids the need for holographic null lenses. In this case the part was additionally examined in a non-null configuration on a Zygo interferometer. Due to the extreme asphericity, only the central 60 mm of the part could provide fringe data, and this is shown in Figure 6. The fringes are extremely clean.

The next experiment was to measure the form of a 350mm diameter concave Cassegrain mirror that was to hand (near-spherical) using a Fisba MicroPhase interferometer. The initial radius of curvature was measured on the Form Talysurf to be 1058.20 mm. The part was then pole-down pre-polished on the 600mm machine to a predicted uniform 1 μm depth. The tool-path was generated to leave the outer zone un-worked, in order to provide a reference by which the absolute depth of material removed could be established.

The part was then measured on the Form Talysurf, and the depth of material removed was found to be 0.94 μm. The new radius of curvature was measured to be 1058.14mm. The discrepancy of 60 μm (one part in 18,000) is almost certainly due to residuals in the Form Talysurf curve-fitting.

The part was then re-measured on the Fisba, and the raw fringe-pattern is shown in Figure 7. The un-worked peripheral land is clearly seen.

The Fisba interferometer requires calibration, and this is usually performed using a precision spherical mirror that Fisba provides as a standard.

However, in the case of the experiment reported here, the original measurement of the 350mm diameter part was used as the reference, so that the analysed data provided a *differential* measurement of the material removed in polishing. The result of this is shown in Figure 8. The residual curvature visible in this figure is due to the Fisba software balancing the focus term across the entire pupil including the un-worked land. The fringe pattern at lower right is the synthetic fringe pattern, which demonstrates the symmetry of the material removed.

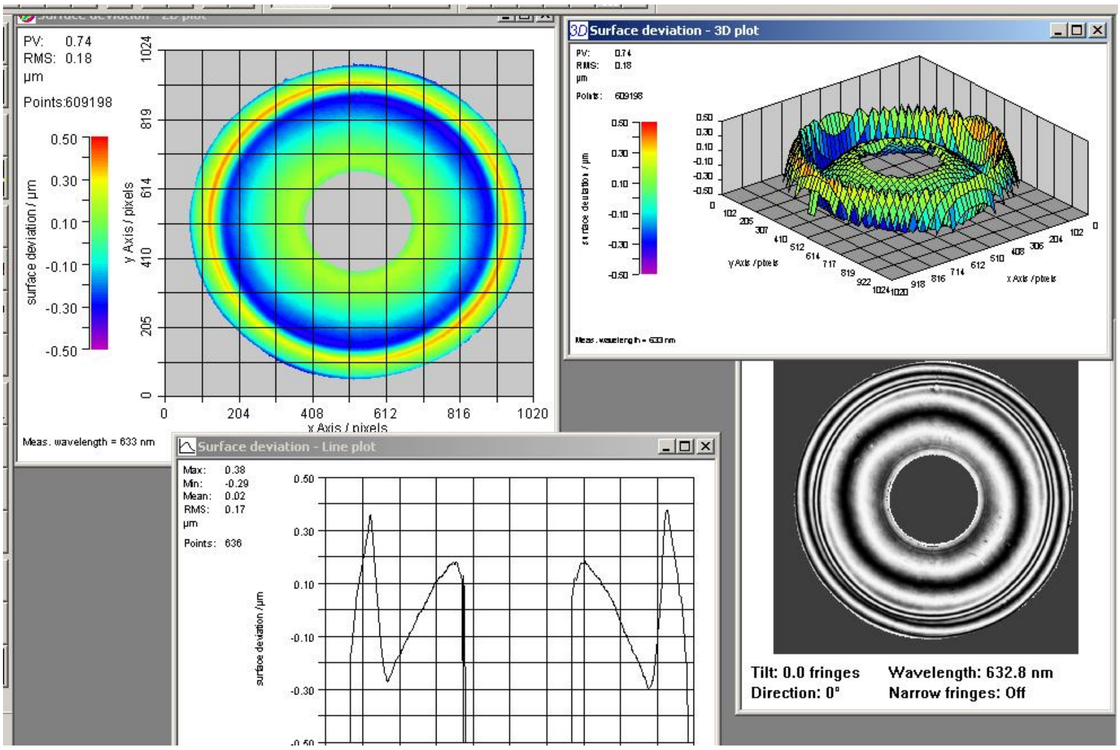

Figure 8 Differential analysis of material removed from 350mm diameter Cassegrain part

8. Free-form Surfaces

By exploiting the 7-axis CNC capability of the Zeeko family of machines, free-form surfaces can be polished using a raster tool-path. To control form, a new 3D version of the '*Precessions'* numerical-optimisation software has been developed.

The first results were recently presented [8]. These demonstrated the creation of the Zeeko logo (Z and spot) in both flat and concave surfaces, by rastering the parts with a variable feed-rate modulated to control the effective dwell-times. The predicted geometry and absolute depth were achieved within ~ 10%.

The next stage in the process development was to polish a pre-determined free-form departure into a flat surface [9]. The result is reproduced here in Figure 9, where the top left figure is the predicted removal, top right is the measured result of polishing (Zygo interferometer), and the lower figure is the difference (resulting error). 2-3 microns of free-form removal has been correctly produced with an error of approximately 10%.

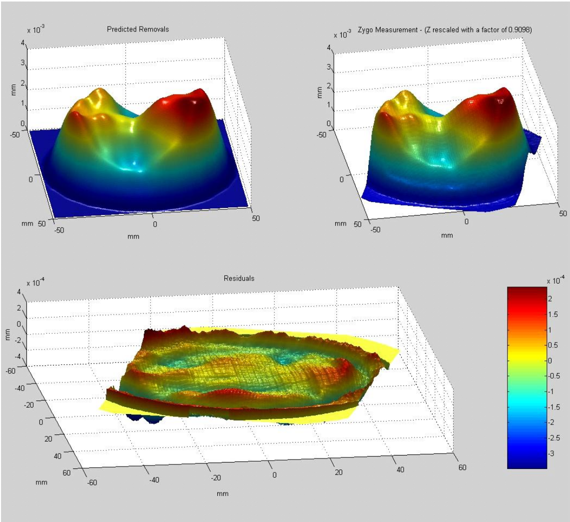

Figure 9 Free-form polishing of flat-surface [9]

Recently, experiments have started on truly free-form optical surfaces. We present here the result obtained on a section of an industrial part (Figure 10), which is a highly-distorted saddle.

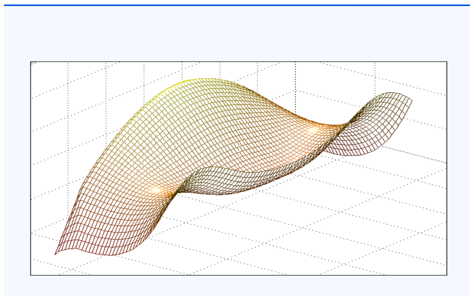

Figure 10 Surface of a truly free-form part

The part of Figure 10 was measured on a PGI 1240 Form Talysurf, equipped with a motorized Y-stage to permit rastering of the 3D profile. The resulting form-error is shown in Figure 11. The result after two runs of free-form polishing (100 minutes total), is shown in Figure 12. A p-to-v error of approximately 5 microns has been reduced to ~ 1 micron [9].

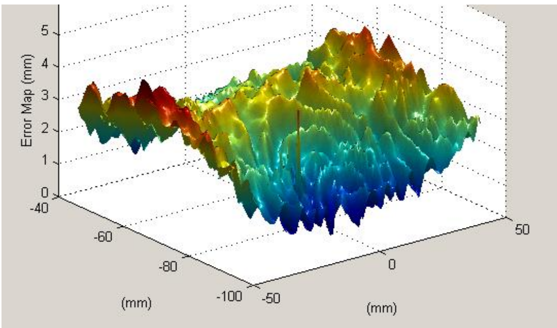

Figure 11 Initial error on free-form part [9]

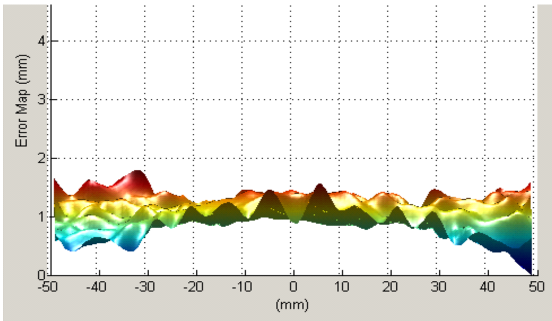

Figure 12 Error on free-form part after two polishing runs [9]

9. Conclusions

The work in this paper has confirmed that the *Precessions* process, well established on the 200mm machines in production, can be scaled up to deliver removal of material on larger parts that is deterministic up to the 90% level. The proviso is that the input metrology must be adequate in absolute terms.

Metrology has been by far the most serious issue with the 500mm part, due principally to errors in the coordinate-relationship (X and Z) between the optical metrology data and the CNC machine. We have been disappointed by infrared interferometry on grey surfaces, due to the poor SNR from the uncoated part in double-pass, and an inability to close-phase in the presence of local surface-slopes from grinding. The Form

Talysurf stylus profilometer has proved extremely effective, down to its intrinsic limit of accuracy in the 0.2 to 0.3 micron regime. Visible interferometry has revealed its own problems in relation to CNC local polishing; specifically, ambiguity in both the absolute base-radius and the lateral-scale, and second-order effects due to geometric distortion in interferometer transmission spheres. The distortion is likely to be in part due to the mapping of the concave surface onto the flat interferometer detector. However, there appear to be additional terms. These effects require calibration for surfaces with significant curvature.

The relationship between aspheric fitting in the interferometer and Form Talysurf software is clearly not fully understood, and will be rectified in the next stage of the work by analyzing the raw data from both instruments in MATLAB. To proceed with the 500mm part beyond the work reported in this paper and [9], a combination of i) use of the Form Talysurf to establish base-radius and ii) visible interferometry calibrated and corrected for geometric distortion and scale, appears to be the optimum approach. This will also permit full 3D coverage of the surface. Following this approach, and by moderating the removal rate to increase the sensitivity of the process, there appears to be no reason why *Precessions* polishing can not achieve form-control on aspherics down to the $\lambda/10$ target. Experiments are underway to demonstrate this.

The early use of small polishing spots on the 500mm part, unavoidable at that time due to the restricted tool-spindle torque available when the work was undertaken, and combined with the effects of positioning errors from the metrology, left high spatial frequency defects. These could not be recovered by active polishing as this would have demanded impractically small spots. The strategy we now advocate is to start with the largest polishing spots possible, then to proceed to smaller spots as the work progresses. This is valid from the perspective of Nyquist sampling theory, and has the added bonus of providing increased sensitivity of polishing as final form is approached. Meanwhile, we have had good success using a classical ring-tool on the CNC machine in order to smooth the 500mm part. This hybrid approach demonstrates the versatility of the machine in enabling the accumulated craft expertise to be encapsulated in an automated machine-tool. Two 1m machines are currently being designed, and the above experience is proving invaluable, particularly in terms of tool-spindle torque requirements and maximum turntable rotation speed.

Work on the 350mm part has demonstrated the uniformity and symmetry of the material removed and the cleanness of the interferometer fringes produced.

The preliminary results on raster free-form polishing are extremely encouraging, and the correct operation of the new free-form optimizer and tool-path software has been amply demonstrated.

10. Acknowledgements

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