Precessions 2½D Correction of an Aspheric Mirror

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Abstract: This paper for the first time maps the complete progress of an aspheric part through all stages of 2½ D form correction on the Zeeko Aii machine, from the pre-polished state with severe defects, to 0.12 waves p-to-v and 0.015 waves rms, which met the specification. Particular problems overcome included high surface-slopes at early stages, and geometric distortion in interferometer data causing significant tool-placement errors. The work has demonstrated the capability of the *Precessions* process to deliver high-precision aspheric surfaces in a deterministic manner.

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1. Definition of the project

The family of CNC sub-aperture polishing machines produced by Zeeko confronts the principal challenges of polishing aspheres and free-form surfaces, in particular, i) process variability along the tool-path and high-spatial frequency errors, due to the mismatch between a traditional tool and the part; ii) the need to pre-polish a precision ground-part without destroying the ground aspheric-form; and iii) the need to correct measured errors of form.

As described previously [1], the mis-match problem is addressed through the use of an inflated rubber bonnet tool, which is covered with a standard polishing cloth, and spun about its axis. This tool naturally moulds itself around the local surface-profile creating a spot of action. Pre-polishing of regular aspheres is usually performed using synchronous polishing with a pole-down tool, oscillated across a diameter of the part, rotating in the same direction and speed as the part. In form-correction [1], the tool is typically precessed, and a spiral tool-path used for a rotationally-symmetric asphere with rotational errors. Given the measured form and the empirical influence function(s) of the tool, the radial dwell-time map (and sometimes spot-size as well) is numerically optimized to minimize residual form errors. 3D correction [2], utilizes a raster tool-path where the surface speed (and so the effective dwell-time) is varied along each traverse. This is used to polish and control form on truly free-form surfaces and off-axis aspheres, and to rectify complex errors on rotational surfaces.

The concept of a 2½ D process was introduced early in the development of Zeeko's *Precessions* process [1], and the method fits between 2D and 3D. In 2½ D mode, the tool-path is once more a spiral, but non-rotational errors are corrected by continuously varying the speed of the part rotation ('C' axis) *during and in phase with* each rotation. The original idea was (for numerical convenience) to separate the control of axial form ("asphericity") from that of rotational form (e.g. astigmatism, trefoil, other folding modes). This could be implemented by performing two separate dwell-time optimizations, one in the *radial* direction after azimuthially averaging the rotational errors, and the other in the *azimuthal* direction after radially averaging the radial errors. In fact, the current implementation delivers a global solution, which gives additional flexibility.

In this paper we provide the first published results demonstrating the success of the 2½D method. Specifically, we show how it has corrected form on a near-parabolic aspheric BK7 Cassegrain mirror, 190mm external diameter and with a base-radius near 300mm. The centre was cored with a clear aperture specified to be greater than 180mm on the OD and less than 60mm on the ID. The target specification was $\lambda/8$ (0.125 wave ~ 80nm) P-V.

2. Metrology issues

Adequate metrology is key to successful form-control. The project was supported by two types of metrology:- the Taylor Hobson Form Talysurf stylus profilometer, and the Zygo GPI Interferometer. The Form Talysurf was used for the earlier runs, as it provided absolute measurement of base radius (normally subtracted as power on the Zygo), and was also capable of measuring the surface where the local slopes were too great to be imaged on the Zygo. The Zygo was subsequently used, configured in double pass with an f0.75 transmission sphere and auto-collimation flat.

Interferometers, when set up in the above manner, suffer from geometric distortion as the (near) spherical wavefront is effectively eventually projected onto a flat detector. There may be significant second-order Seidel distortion as well, depending on the transmission sphere used. In traditional hand-figuring, these effects are usually sufficiently small that they can be ignored, or masked by the classical optician's habit of marking the high zones on the surface to be polished watching the interferometer display, and then manually polishing those zones. However, with a CNC local polisher, the quantitative integrity of the relationship between the machine's coordinate frame and that of the metrology data is paramount, with a maximum allowable positional error on the surface of approximately 1/10 the polishing spot size. Moreover, the geometric error increases significantly as the *f* ratio of the beam reduces, and any such errors are doubled when used in double pass mode. In the case-study described, the distortion errors approached 5%, which would give a potential positioning error of the tool over the error-map of 7-10mm. This of the same order as the polishing spot size used, and hence compensation was essential if form-correction were to be effective. In order to calculate these distortions a series of fiducials were marked on either a test optic (of the same prescription) or on the actual part under test. The fiducials were marked every 10mm along three radii at 120^o on the part. Utilities within *Precessions* 2.5D were then used to calculate the distortion map from the measured data.

3. Initial condition

The part was delivered for processing by Zeeko after being pre-polished on a different machine elsewhere, and Fig. 1 shows the form as measured immediately after receipt. Only ~170mm of the clear aperture could be imaged.

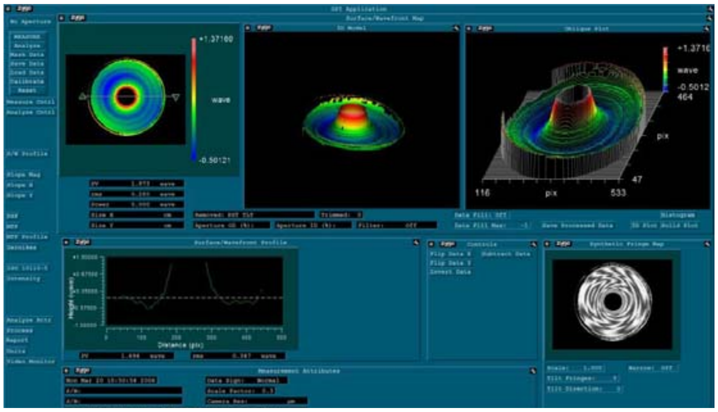

Fig. 1. Zygo measurement of the part prior to work on Zeeko machine

4. Progress of the form-correction

The corrections of form errors on the part were divided into three stages:- i) correction of base-radius, ii) targeting of specific types of error, and iii) direct convergence on the final form-specification. In all cases, the bonnet tool was used with standard polyurethane cloth and re-circulated cerium oxide slurry.

Runs #1-5 on the Zeeko Aii machine used 1.5mm spacing on the spiral tool-path. Run #1 targeted the bulk of the power error, using the Form Talysurf metrology. The run duration was 53 mins and a fast tool-speed of 600rpm was used. The part was then measured using both the Form Talysurf and the Zygo. The absolute radius of curvature from the Form Talysurf was the used to correct the Zygo (power removed) data in preparation for Run 2. This run was 61 mins with a tool speed of 300rpm, and was used to correct the remaining power term.

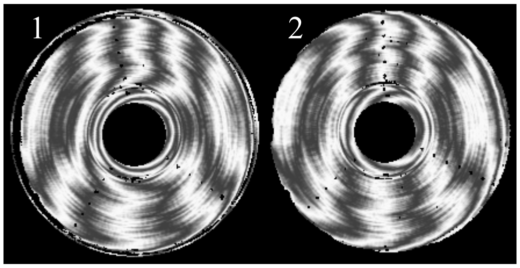

Fig. 2 First correction stage to correct base radius: results of Runs # 1 & 2 using Form Talysurf data (53 & 61 mins)

In correction Run 3, the FTS data was gain used as the error source for the correction software, due to interferometer data drop-outs due to slope errors, and to the lack of visibility of the full clear aperture at both the inner and outer edges. In Runs 4, 5, the spiral tool-path was programmed to fall short of the centre of the part in order to target the centre defect. The full 3D data from the Zygo was imported into the 2½Dform-correction software.

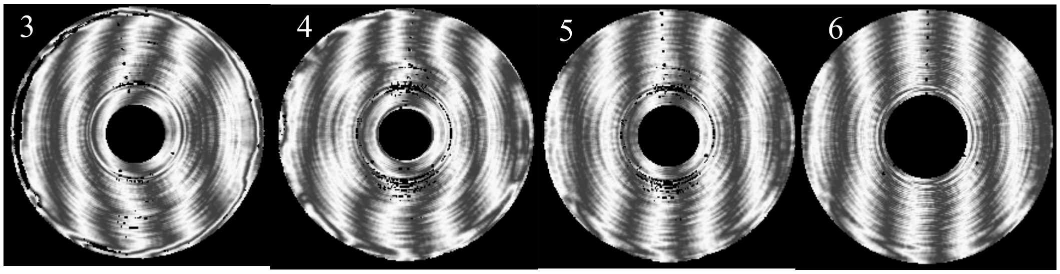

Fig. 3. Intermediate figuring stage: results of Runs # 3,4,5,6 (46, 12, 12, 15 mins)

After Run 5, it was recognized that the consistent use of the 1.5mm spacing in the spiral tool-path had left significant rings on the surface. Therefore, it was decided to perform a modest 'clean up' of the surface by running a 15 minute synchronous pole-down polish (Run. 6). The remainder of the runs targeted the final form.

The observed astigmatism during the process is believed to be due to the thermal difference between the glass cooled by the slurry and the relative warmth of the metrology area. In hindsight a longer time should have been used to allow the lens to stabilize.

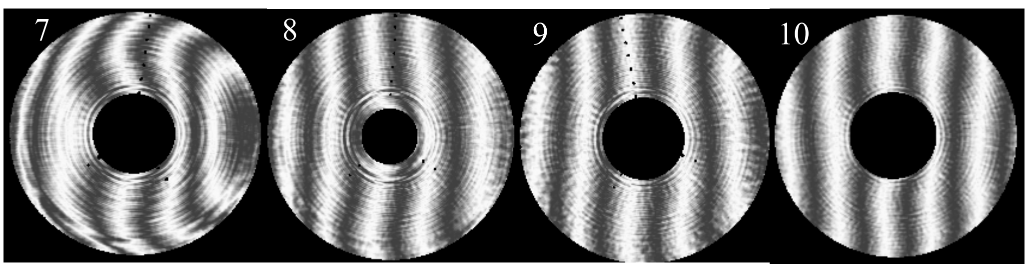

Fig. 4. Final figuring stage: result of Runs # 7,8,9,10 (26, 22, 10, 22 mins)

5. Conclusion

We have reported on the first experiment using the 2½D form-correction software to achieve 0.12λ p-to-v over the prescribed clear aperture of a component, which exceeded the specification of λ/8. A total of 4 hours 39 minutes of polishing time was required on this 180mm clear-aperture mirror, excluding metrology down-time. Various lessons have been learnt along the way, which can very usefully be applied to future components.

In particular, a modest additional investment in time spent on the pre-polish would be advisable, to ensure that the full clear aperture is achieved and radius-error (power term) minimized. This could save significant time on the subsequent correction process. Residual power should then be targeted first using the Form Talysurf (or other profilometry) to achieve the absolute base-radius required. This is difficult with interferometry unless measuring rods are used. High slopes should be targeted next. In contrast to the procedure reported here, the spacing of the spiral tool-path should also be varied between each polishing run to avoid the tool tracking down the identical path each time. This improvement will average, rather than progressively deepen, the repetitive structure on the part.

Metrology down-time can be considerable if the part has to reach thermal equilibrium after a polishing cycle. Therefore, consideration should be given to matching the temperature of the slurry to a temperature close to that of the metrology-room. This will minimize inherent distortion of the part, or differential effects due to fixturing.

4. References

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