Automated optical fabrication:
first results from the new "*Precessions*" 1.2m CNC polishing machine

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ABSTRACT

The requirements of space and defence optical systems and ground-based astronomy (especially extremely large telescopes) are providing optical fabricators with new challenges. These challenges particularly concern process speed, determinism and automation, and tighter tolerances on surface form and texture. Moreover, there is a growing demand for complex off-axis and 'freeform' surfaces and for larger components of the ~1m scale.

With this in view, we first report on form-correction on a smaller analogue of the IRP1200 – an IRP400 in service in industry. We then report on the design, commissioning and preliminary process-development results from the first of the scaled-up 1.2m capacity CNC polishing machine from Zeeko, Ltd. This machine delivers the 'Classic' bonnet-based process, together with two new processes – fluid-jet polishing and the hybrid soft-grinding/polishing process called 'Zeeko-Grolish.' We indicate how this trio of processes running on the same machine platform with unified software can provide an unprecedented dynamic range in both volumetric removal rate and removal spot-size. This leads into a discussion of how these processes may be brought to bear on optimal control of texture and form. Preliminary performance of the 1.2m machine is illustrated with results on both axially-symmetric and more complex removal regimes. The paper concludes with an overview of the relevance of the technology to efficient production of instrumentation-optics, space optics and segmented telescope mirrors.

1. The trio of Precessions processes

The advent of extremely large telescopes poses the well-known challenge of manufacturing hundreds to thousands of hexagonal mirror segments that must match in base-radius, and which may be spherical or off-axis aspheric segments, depending on the telescope design. Generically, there are three main approaches for polishing large aspherics: stressed-mirror polishing, stressed-lap polishing and local polishing. High removal rates are clearly important in order to deliver plant-throughput on many segments. Stressed-mirror and stressed-lap methods tend to achieve this through the large surface-area in contact between mirror and tool; local polishing through high surface-speeds, developments in abrasive technologies, (and possibly, high applied forces).

We have previously described the basic operation of the *Precessions*™ CNC polishing process e.g.[1-11] first implemented in a 200mm capacity automated machine-tool. The basis of its operation is the precision-control of both the position and orientation of a local-removal tool as it traverses the surface of the part being polished. In the '*Zeeko-Classic*' process, the tool comprises an inflated membrane, covered with a polishing 'cloth' such as polyurethane or Multitex. This is pushed against the surface of the part and spun about its axis of symmetry in the presence of a pumped supply of polishing slurry or grinding compound, creating a variable contact-spot. The bonnet can attack the surface of the part with spin-axis orthogonal to the surface ("pole down polishing"), or off-set and precessed around the local normal

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("precession polishing"). Zeeko Grolish uses the same bonnet and dynamics, but substitutes a bonded-diamond cloth such as 3M Trizact™ and coolant for the polishing cloth and slurry. Zeeko-Jet employs a jet of abrasive fluid directed towards the part, usually precessed about the local surface-normal. The main features of Zeeko-jet are i) to reach areas inaccessible to physical tools (tight concaves, corners, steps etc) and ii) to permit very small spot sizes <1mm (suitable for removing local defects, correcting edges, etc).

In all three processes, the precession technique i) averages texture because of the cumulative effect of the different surface-directions of polishing , and ii) gives a near-Gaussian removal-profile ("influence function") due to the averaging of speed-gradients over the contact spot. Having characterized the influence function and the surface error-map, numerical optimization is then used to calculate the dwell-time map across the surface to minimise residual form errors. The process can operate in 2D (rotationally-symmetric parts with rotationally-symmetric errors), 2.5D (rotationally-symmetric parts with non-rotationally-symmetric errors) and 3D (non-rotationally-symmetric parts including free-form). The software is universal given any influence-function and readable error-map.

The dynamic range of the trio of processes is considerable, as a wide panorama of process-variable can be brought to bear. Other things being equal, the process speed tends to go as the square of the spot size. A given bonnet radius can deliver a factor of ~3 in spot-size by changing the Z-offset (i.e. degree of compression), giving an order of magnitude range in volumetric removal rate. The range of spot-sizes can be changed by selecting bonnets of different radii (currently available from 20mm to 480mm radius). At the low end of removal rate, the slurry particulate composition can be changed, and the slurry can be diluted indefinitely. These provide the capability for arbitrarily low volumetric removal rates down to very small fractions of a mm^3 per minute, and nanometre-level removal. At the intermediate level, a 40mm or 80mm radius bonnet with polyurethane would be expected to deliver from a fraction to a few mm^3 per minute volumetric removal rate. At the top end, Trizact can deliver high removal rates, and we have previously reported [10] 140-150 mm^3 per minute with a 480mm radius bonnet. The material used in this experiment was Cervit, and the pole-down spot-size of 125mm used was physically constrained by the 125mm diameter of the Trizact pads. Overall, the process dynamic range is well in excess of 10^4, and largest on the big machines as they support large bonnets yet retain the low-end sensitivity.

2. Proof-of-Concept: Form-Correction with a Zeeko 400mm (Horizontal-format) machine

An IRP400 machine installed at LightWorks, Inc. has been used to correct form on a 315mm diameter F/1.25 parabolic mirror deviating by 140 fringes from its nearest sphere. Insufficient material was left around the edge to be finished on the machine, so the edge was finished conventionally. The progression from 7-8λ p-to-v to 0.166λ p-to-v in nine corrective runs is illustrated in Figures 1-4, and demonstrates excellent convergence.

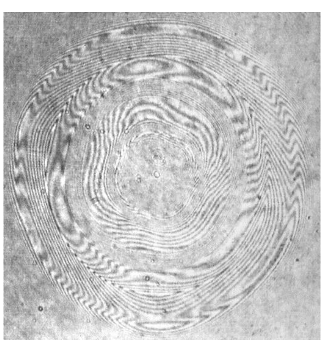

Fig. 1 Initial form 7-8λ p-to-v form error

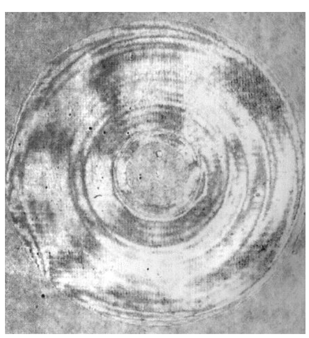

Fig. 2 After two correction runs 1.25λ p-to-v

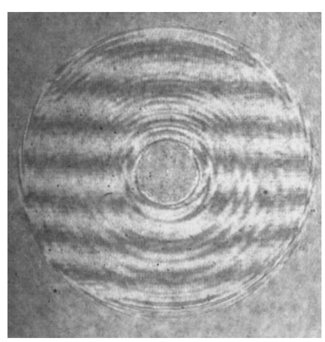

Fig. 3 After four correction runs 0.4λ p-to-v

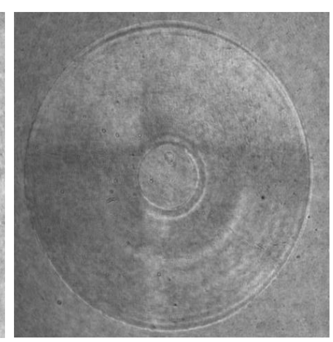

Fig. 4 After nine correction runs 0.166λ p-to-v

3. Construction of the IRP1200mm machine

This machine is designed to process parts up to 1200mm diameter, and can be configured for the Zeeko Classic or Zeeko Jet processes, or both with a simple mechanical interchange. Some details from an engineering perspective have previously been reported.[11] Figure 5 shows the CAD model of the functional parts, and Figure 6 the finished machine.

In the standard 200mm machines, the part is typically waxed into a fixture mounted in the Schunk chuck of the machine, and the axis of the part is horizontal. In larger machines including the IRP1200, the part is on a horizontal turntable with the axis vertical. For processing smaller parts on the large machines, standard fixturing can still be used, as Schunk chucks can be adapted to fit the turntable. For large parts, the part would either sit directly on the 1400mm diameter turntable with radial chocks to absorb the lateral forces of polishing, or a Whiffle tree (or similar support system) can be used.

The IRP1200 machine is built on a 6000kg polymer-granite cast base of size 2.8m by 2.5m, which gives excellent stability and damping. The part does not move during the process, except in rotation. This minimizes dynamic forces on the part, which would arise if, for example, a raster motion were implemented by rastering the part. Two symmetrical X slide-ways carry a polymer-granite bridge, which is hollowed to reduce moving mass. Rolling element bearings are used throughout the machine. The pair of ball-screws either side of the machine are driven by identical motors, and incremental encoders maintain precise synchronism of the two drive servos via the control system. The bridge carries the pair of Y slide-ways, and single-sided ball-screw, motor and linear encoder. The Z-axis carriage is mounted off the Y-axis, and carries the virtual pivot assembly (A and B axes of rotation). These two axes intersect at a point in space on the axis of rotation of the spherical polishing membrane (the ‘bonnet’), and coincident with its centre-of-curvature. On removing the polishing bonnet the jets for the fluid-jet polishing mode are exposed.

The control system is a Fanuc high-end CNC with NURBS interpolation, with synchronised control of X, Y, Z, A, B C, plus the H-axis spindle-speed control and programmable head pneumatic-pressure. Motors are DC servo motors using absolute linear encoders on X,Y,Z and absolute rotary on A,B,C, and incremental on H. Linear encoders are high-resolution (1μm) units from Heidenhain. The C-axis motor is an open-frame ring motor and H utilises a frameless DC servo motor. The capabilities of the axes in the standard IRP1200 is presented in Table 1.

	X axis	Y axis	Z axis	A axis	B axis	H axis	C axis
Peak torque	70 nm	35 nm	35 nm	N/a	N/a	113 nm	>2000 nm
Continuous torque	24 N	12 N	12 N	N/a	N/a	14 nm	250nm
Travel	1280 mm	1280 mm	500 mm	± 360º	± 90º	continuous	continuous
Maximum velocity	0.25 m/s	0.25 m/s	0.25 m/s			2000 rpm	150 rpm
Maximum acceleration	2.5 m/sec².	2.5 m/sec².	1.25 m/sec².				

Table 1 Specification of Axes on Standard IRP1200

The machine is mounted in an integral enclosure with a rear services compartment, and side-opening doors providing a 1400mm wide clear access. With the bridge moved in X to the rear of the machine, there is an unobstructed downward path to the part on the turntable. To facilitate optical tests in-situ (e.g. if the machine were located under a test-tower), panels in the roof of the machine can be slid back to provide an access hatch with clear aperture 1250 x 1250mm.

Whilst parts could be loaded from an overhead gantry crane using the aperture in the roof of the machine, it is anticipated that more usually, parts will be loaded/unloaded via a trolley that indexes under the C-axis, via the recess in the base.

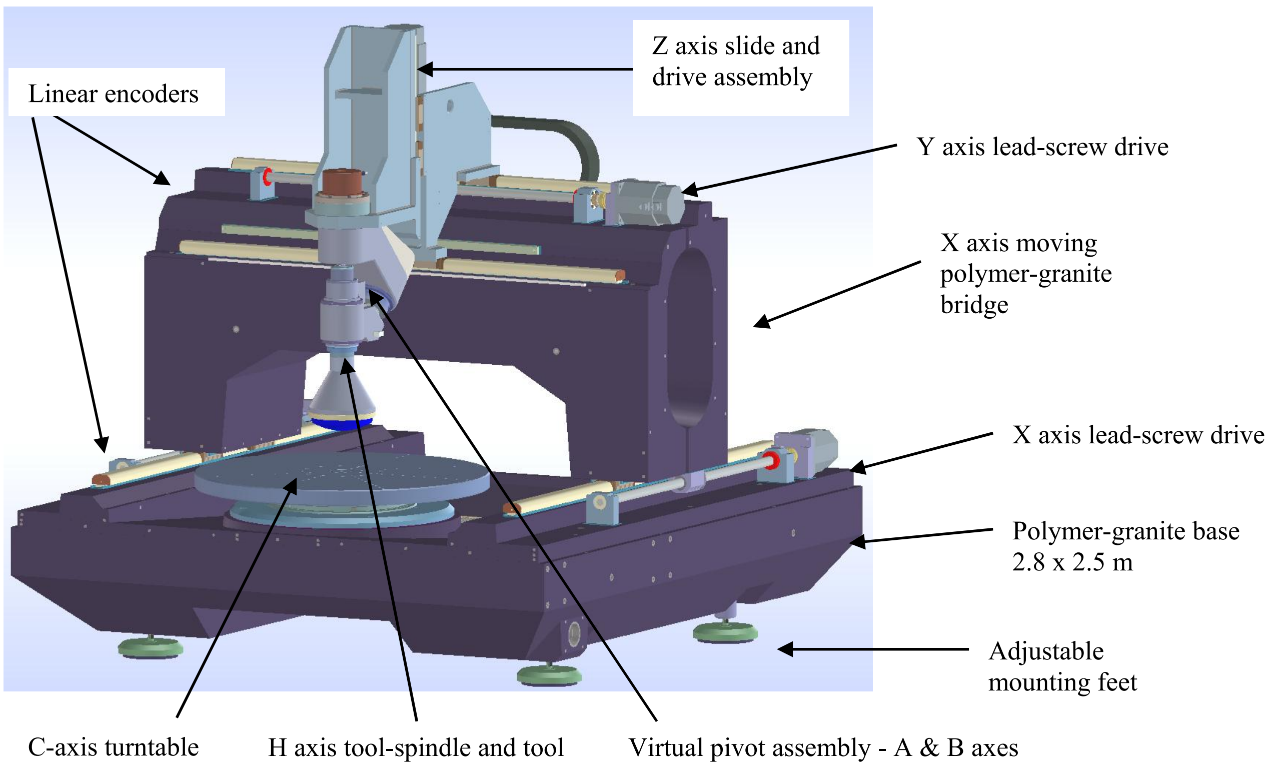

Figure 5 Solid model of principle working components of IRP1200 machine.

Figure 6 The Zeeko IRP1200 machine at the OpTIC Technium, North Wales

The slurry management system is on the left, and the control console on the right. The opening doors on the lid can be seen, allowing in-situ vertical testing.

4. Pass-off tests with the first 1200mm machine

The first IRP1200 machine has been delivered to the Harbin Insititute of Technology. It was first installed at the OpTIC Technium, St Asaph, North Wales, where it was commissioned and subjected to pre-shipping pass-off tests. The test results are presented here. It is important to recoignise that, according to the pass-off protocol, the parts after meeting the pass-off criteria, were *not* subject to a final 'clean-up' pass. This is required to remove residual local surface structure. An effective clean-up strategy is to use a standard bonnet tool, where the pad has been lightly loaded with moulten pitch.

The pass-off specification was that the parts should achieve 0.025λ rms over 95% of the useable area of the part, with allowance made for the errors of metrology. In both cases, the parts were mounted on the machine in brass blocking fixtures. These results constitute the *starting-point* for process-development on the IRP1200, not the end-point. In particular, only a single spot size was used, with no attempt to control edge-profiles by progressing through smaller spots as would be normal.

4.1 Pass-off part #1: 82mm diameter plano-plano fused silica window.

This part was supplied with a good optical polish on the front surface and basic polish on the rear surface. To provide calibration data for the corrective polishing process it is necessary to polish a series of sample influence functions ('spots'). It was decided that, since the sample was already polished, the front face would be used for this purpose, after which it would be reground to show the overall process capabilities. Due to the small size of the workpiece the R40 tooling was chosen and the 'Spotting Sites' were as in Figure 7. The spots were measured using a Zygo interferometer. The known distance between the spots was used as a means of calibrating the image size on both the interferometer and in the *Precessions* 3D software. The 'groove' was then used to perform a secondary calibration of the spot. This was performed by entering the measured depth of the groove into *Precessions 3D*, which gave a 'scaling factor' of 1.566.

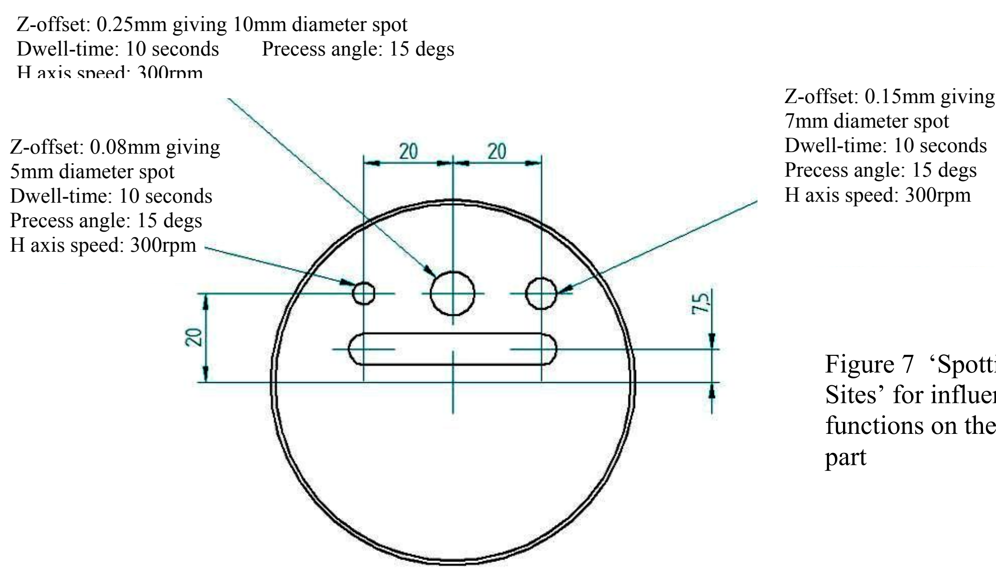

Figure 7 'Spotting Sites' for influence functions on the flat part

Each of the spots was then extracted in *Precessions 3D* and converted into influence functions that can be used by the 2.5D & 3D optimising engine. Following the 'spotting' tests both surfaces were hand lapped to a fine ground condition. The rear face was lapped to avoid the internal reflection compromising future interferometer images.

The ground surface was pre-polished. A 50 minute polishing run was performed using synchronous 'pole down' polishing using the following parameters. The first run left some surface damage and so a further run was required. The resulting depression at centre was identified as being due to the workpiece not being centered with sufficient precision on the axis of rotation.

It is common to perform the first corrective polish of a new prescription with an elevated scaling factor. This tends to cause an under-correction to occur, which is useful as it allows the operator to refine the final scaling factor for subsequent polishing runs. In this instance a scaling factor of 1.6 was chosen, based on the previous determination using the groove.

Figure 8 shows the starting condition for corrective polishing (i.e. following pre-polish from the ground condition). The final surface form error (Figure 9) was 0.024λ rms over 75mm diameter. Immediately after the final polish the measurement result was subject to continual change with as much as 0.015λ rms of variation between successive measurements. This was attributed to the change in environmental conditions between the machining location and the metrology location. The temperature difference was measured to be in excess of 5°C. The primary factor causing the form-instability was the brass blocking fixture used to mount the optic. The result given above is after stabilisation overnight.

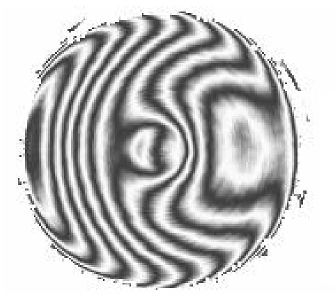

Figure 8: Starting condition for flat part (after ~100 mins pre-polish stage)

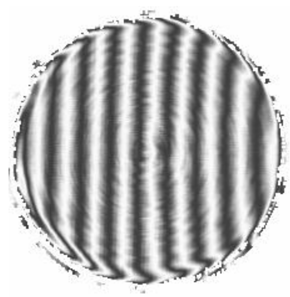

Figure 9: Final condition after 7 corrective runs (~230 mins total)

4.2 Pass-off part #2: 125mm diameter spherical concave part, polished off-axis

The objective of this test was to polish a concave spherical part (for ease of metrology), but using the 3D process – i.e. polishing it as if it were an off-axis surface. First, a similar BK7 blank was ground to the same base radius as the test optic. This was then pole-down pre-polished using the standard 2D process to provide a suitable surface for spotting influence functions. These spots were then extracted using the *Precessions 3D* software to provide a series of influence functions that could be used in the corrective polishing. In order to demonstrate 'off-axis' capability, the concave test part was then mounted off-axis on the IRP1200 turntable, with a nominal offset in Y of the centre of the part with resepct to the centre of the turntable of 122mm.

The test part was polished in freeform (raster) polishing mode. The initial run used the R80 (80mm radius) bonnet with a 20mm diameter spot size and with a 22 degree precess angle, with the H-axis running at 1500rpm. This was chosen to try and balance a high removal rate with a relatively small spot to preserve clear aperture. In order fully to remove the grinding marks it was necessary to repeat the same toolpath twice, resulting in a total pre-polish time of 84 minutes.

For corrective polishing the R40 tooling was used with a Z-offset of 0.4mm on the first run and 0.3mm on all subsequent runs. Following the first correction (Figure 10) it became apparent that the fiducialsation of the optic between metrology and machine was inadequate and that resulted in the corrections being applied in the wrong position. Given this circumstance the alignment on the Zygo was improved; however the surface had been compromised to an extent that made it difficult to recover the error.

In order to regain more clear aperture the Extended Range Form Talysurf was used to create a pseudo 3D surface by taking a series of diametric transects across the part at 30° intervals and reconstructing the 3D surface (Figure 11).
In view of the error on corrective run #1 a conservative approach was used with a scaling factor of 1.8 being used on the influence function. This was to try and ensure that the alignment problems had indeed been overcome. Correction #2 showed a small but significant improvement indicating that the alignment errors had indeed been overcome. A third run was then performed chaning the scaling factor to a more nomal value of 1.0, which resulted in a very significant reduction in overall error and a marked improvement in the increase in clear aperture.

The required specification was achieved (Figure 12) after 5 corrective polishing runs (totalling ~300 mins) and using a single influence function offset (spot size circa Ø10.6mm). Given the metrology alignment problem it is believed that at least one corrective run could be eliminated if the test were to be repeated. It should again be noted that a significant variation in result was observed over a period of time and with the part left untouched in the metrology station (Figure 13). This was again due to the significant variation in temperature between the machine and metrology locations. For ultimate corrective polishing capability the part should remain in a free stated and be kinematically located.

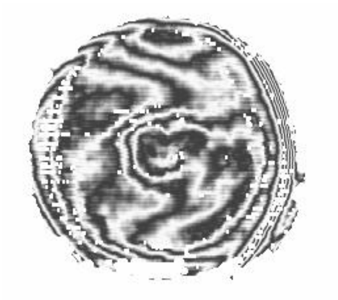

Figure 10 Interferogram of "off-axis sphere" after Correction # 1 (inadequate part-fiducialisation)

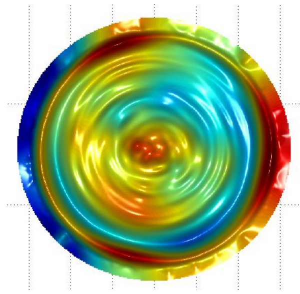

Figure 11 Surface reconstructed from Form Talysurf after Correction #1

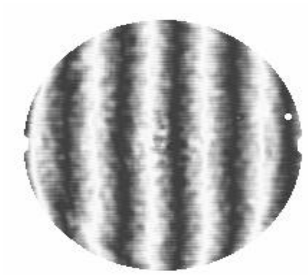

Figure 12 Interferogram immediately after Correction #5

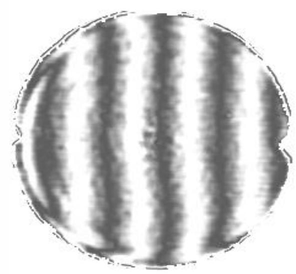

Figure 13 Interferogram after leaving part to stabilize

5. First result from the second 1200mm machine

At the time of compiling this paper, the second 1200mm machine is being commissioned at Zeeko's premises. This machine will constitute part of the new National Facility in Ultra-precision Surfaces, under construction at the OpTIC Technium. The first polishing run with this second machine was conducted on a 200mm diameter spherical part with concave radius of 194mm. This run reduced the input form error of 0.91µm p-to-v to 0.24µm p-to-v.

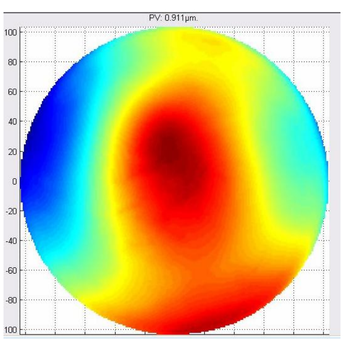

Fig. 14 200mm diameter part before polishing (0.92 µm p-to-v form error)

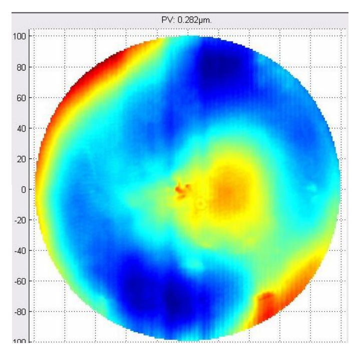

Fig. 15 200mm diameter part after polishing (0.24µm p-to-v form error)

5. Discussion and Conclusion

The successful implementation of Zeeko tooling and software on a 4m-class CNC maching-tool [10] has given confidence that the process is inherently scaleable to large sizes. The use of large tool-sizes de-sensitizes the process to mechanical positioning errors; small tools on a large machine are the most challenging case. With this in view, the pass-off tests, albeit on modest parts and small tools, have demonstrated the inherent precision of the 1200mm machines and ability to control form.

The simple pass-off tests on the 1200mm machines to date have not exploited the versatility of the process in two key respects: i) utilization of varying tool spot-sizes to address edges and ii) application of a finishing pass to smooth the final surface. In the next phase of the commissioning, these methods will be used and reported in due course.

6. Acknowledgements

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