Commissioning of the first *Precessions* 1.2m CNC Polishing Machines for Large Optics

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ABSTRACT

This paper reports on the commissioning of the first of Zeeko's 'IRP1200' 1.2m capacity 7-axis automated CNC polishing machines. These combo machines now support five different removal regimes, which are described. The machines differ substantially from Zeeko's more familiar 200mm machines on which we have focused before, in terms of overall architecture and detailed design. Large and small optics place different demands on part-fixturing, tooling, machine speeds and accelerations, metrology, slurry-handling, part-loading and access etc. These have had a profound effect on the development-path from 200 to 1.2m machines. Moreover, an advance in the kinematic design has extended the allowable range of surface slope-angles from typically 30^{o} up to a hemisphere. The paper presents results from the pass-off trials, the first fluid-jet experiment, and the development of tooling to address a requirement to smooth a part with a local defect.

1 Introduction

We have previously described the basic operation of the *Precessions*™ CNC polishing process [1-11], as first implemented on a 200mm capacity automated machine-tool. A series of larger machine-tools has been developed, with two 1200mm capacity machines having been built to date. The first of these was initially commissioned at the OpTIC Technium in North Wales, and recently shipped to the Harbin Institute of Technology in China prior to final pass-off there. The second 1200mm machine has been installed permanently at OpTIC for process-R&D and one-off manufacturing projects, and has recently completed its final pass-off trials. This paper reports on first results obtained with these new large machines, together with relevant work on the processes for large optics conducted on a 600mm capacity machine also located at OpTIC.

2. *Precessions* Surface-removal Processes

The overall concept of all the Zeeko machines comprises precision control of the position and orientation of a local-removal tool, as it traverses the surface of the part being worked. This can be used in two basic ways:

- 'Pre-polishing' a part from the ground state (improving texture) with the objective of preserving form. In the case of a rotationally-symmetric part, this is achieved by 'synchronous polishing'. That is, the tool rotates 'pole-down', and part and tool are rotated at almost the same speeds, as the tool is traversed back and forth many times across a diameter of the part. In this special case, uniform removal can be achieved without creating a central hole as the tool overlaps the centre of the part.

- 'Form correction' using an input surface-measurement and empirical characterization of the removal profile (tool 'influence function'), with numerical optimization of dwell-times and, if required, other variables.

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Since the work reported in our early references, the versatility of the technology has been considerably increased, both in terms of the software tools available, and the variety of removal techniques that can be employed.

Regarding the form-control optimization software, this originally operated in only 2D. That is, the algorithm could rectify rotationally symmetric form-errors on parts designed to be rotationally symmetric. The tool path used to execute this was a spiral. Next came the 3D process, where free-form errors on symmetric or free-form parts could be corrected using a raster tool-path. The latest development has been termed 2½D, and corrects non-rotational errors on parts designed to be rotationally-symmetric. This is achieved by using a spiral tool-path, but where the C axis speed (part rotation) is modulated through the cycle of each rotation, in a similar fashion to a phase-locked loop. When the C axis slows, the effective dwell-time is increased and proportionally more material is removed. This method is particularly powerful in correcting folding errors such as astigmatism or trefoil.

In terms of removal processes, the first process implemented on the original Zeeko CNC machine tools was the one now termed '*Zeeko-Classic'*. Further processes have been developed, and the current complement is summarized below.

- *'Zeeko-Classic*'. This is the standard work-horse. The tool comprises an inflated membrane ("bonnet"), covered with a standard polishing 'cloth' such as polyurethane. It operates in the presence of pumped, re-circulated slurry, typically cerium oxide.

- *'Zeeko-Grolish'* (*loose-abrasive)* In this case, the working surface cemented to the surface of the bonnet is hard, and typically a metal such as aluminium or copper foil. The loose-abrasive slurry is typically carborundum or diamond, and applied locally rather than by a recirculation pump.

- *'Zeeko-Grolish'* (*fixed-abrasive)* Here, the bonnet is covered with a flexible backing carrying bound diamond pellets (e.g. the 3M Trizact™ product). This process is typically run within a containment vessel on the machine turntable, so that the part and the active area of the tool are submerged in coolant.

- *'Zeeko-Jet*' In this mode, slurry is pumped at high pressure through jets, and removes material by direct impact with the surface of the part. Hybrid machines (such as the two 1200mm machines built to date) accommodate both jet and bonnet based processes with a simple interchange.

- *Specialised tooling* The standard bonnet interface (a Schunk chuck) can carry a variety of specialized tooling such as ring-laps, hard tools etc. Also, metallic buttons etc. have been successfully mounted on standard bonnets. Possibilities for specialized tooling are endless, giving considerable versatility.

3. Construction of the IRP1200mm machine

These machines are designed to process parts up to 1200mm diameter, and can be easily re-configured for any of the above processes. Some details from an engineering perspective have previously been reported.[11, 12].

The IRP1200 machine is built on a 6000kg polymer-granite cast base, which gives excellent stability and damping. Two symmetrical X slide-ways carry a hollow polymer-granite bridge. The bridge carries the pair of Y slide-ways and drive/encoder system. The Z-axis carriage is mounted off the Y-axis, and carries the virtual pivot assembly (A and B axes of rotation), which, in turn, support the tool-spindle ('H' axis). The A and B axes intersect at a point in space ('virtual pivot') located on the axis of rotation of the tool spindle, and the new design allows for full hemisphere coverage. The centre-of-curvature of the spherical polishing membrane ('bonnet') is arranged to coincide with the virtual pivot. In the case of the fluid jet mode, two angled jets are focused on the virtual pivot and rotate around the H axis.

When the bridge is moved back to the limit of its travel, there is a clear vertical path above the turntable. By sliding aside a split cover at the top of the machine, an optical test can then be conducted in-situ. This also provides a capability for loading from above should this be required.

Figure 1 The second IRP1200 machine, in the new National Facility for Ultra Precision Surfaces at OpTIC. The IRP600 is in the background.

With 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 mounted on the horizontal turntable with the axis vertical, typically with shims and radial chocks, or via specialized fixturing such as a whiffle tree. For processing small parts on the large machines, standard Schunk chuck adaptors are also available.

The two principal process differences between the 200 and 1200 machines are i) the orientation of the part which is vertical on the small machine, and ii) the limited C axis speed of 100 rpm (part rotation) on the large machine, due to inertial and dynamical considerations. The main consequence of this is that synchronous polishing implies a small tool rotation speed as well, and so a lower removal rate than would be desirable for a large part. Fortunately, there are effective alternative, e.g. 3D rastering.

4. Pass-off tests with the 1200mm machines

4.1 The first 1200mm machine

Pre-shipping pass-off tests of the first IRP1200, now at Harbin, have been presented previously [12]. In summary, the first test was to spiral-polish an 82mm diameter flat window, and 0.024λ rms form eror was achieved over 75mm diameter. Immediately after the final polish, the measurement result was subject to continual change due to environmental effects, with as much as 0.015λ rms of variation between successive measurements. The second part was 125mm concave spherical part, set off-axis on the turntable of the polishing machine, and polished in freeform (raster) polishing mode. 0.021λ rms was achieved over a 116mm clear aperture.

4.2 The second 1200mm machine

At the time of the San Diego conference, the second 1200mm machine had been installed at OpTIC (Figure 1), but only one polishing run had been conducted.[12] This machine has recently completed its final pass-off tests and acceptance, with results summarized below. All these tests used a 40mm radius bonnet, pre-dressed, and covered with polyurethane.

4.2.1 Test 1: Process stability

The first test was to establish the repeatability of influence functions, as shown in Figures 2,3.

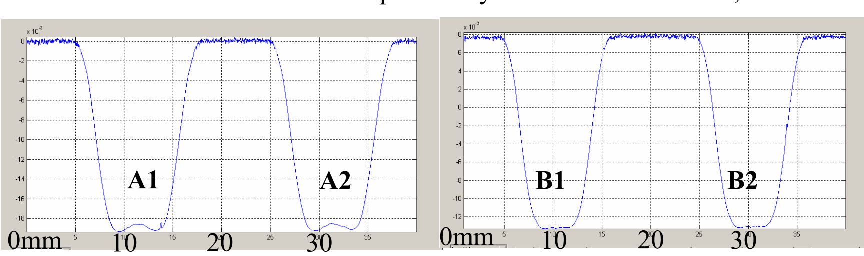


Figure 2 Two comparative pairs of influence functions; each pair under identical conditions
Left pair: Z offset = 0.45 mm
Right pair: Z offset = 0.55mm

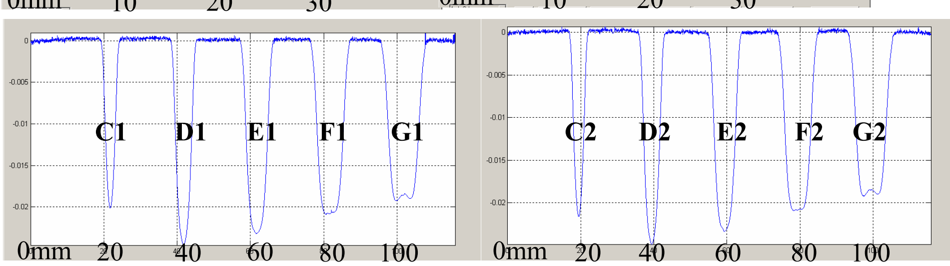


Figure 3 Two comparative sets of influence functions with Z offsets of:
0.15mm (C)
0.25mm (D)
0.35mm (E)
0.45mm (F)
0.55mm (G)

4.2.2 Uniform removal in Spiral and Raster mode

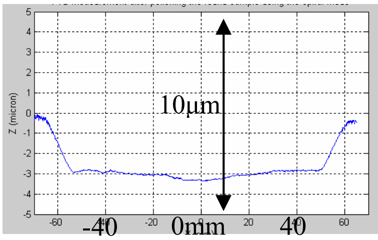


Figure 4 Result of spiral polish of circular part in synchronous mode

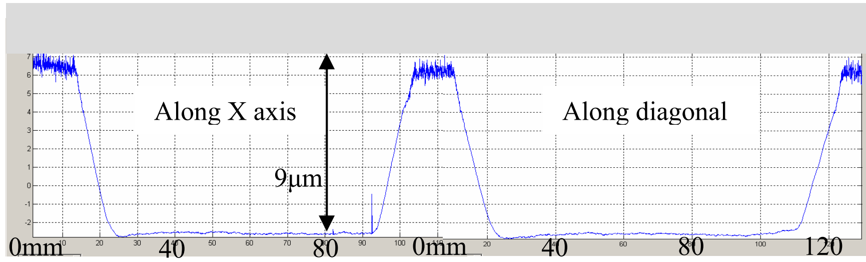


Figure 5 Result of raster polish of rectangular part, with profilometer scans along X axis and diagonal

In these tests, sub-areas of the samples were polished, in order to leave unpolished lands by which absolute removal depth could be established.

The spiral polish test (Figure 4) was conducted on a 100mm diameter sub-area of a 138mm diameter part, with a 15mm spot size. This created a small depressed area around centre, giving an overall uniformity of removal of 85%.

The second test (Figure 5) involved rastering a flat square part, prepared in advance with a wedge of approximately 150μm across the corners. The objective was to demonstrate uniform removal over an inclined surface. The part was mounted on the machine turntable, and probed using the non-linear probing routine. This uses the sensor in the H axis spindle to detect contact of the polishing bonnet with the part as the H axis is incremented down in Z. By probing several locations, a 3D map of the surface's location in the machine's coordinate frame is built up, which is then used to correct the machine motions in polishing. The polishing run was conducted with a 15^{o} precessed tool. The uniformity of removal achieved was 96%.

4.2.4 Form correction on concave spherical part

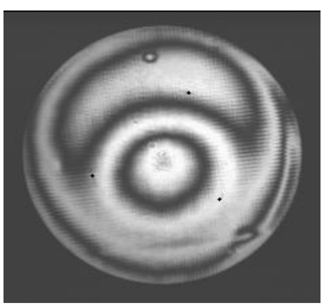


Figure 6 Spherical part before form corrrection

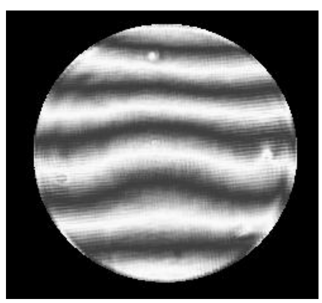


Figure 7 Form after four correction runs, meeting pass-off criterion.

The final pass-off test was to correct form on a nominally spherical part, with a requirement to achieve 1/20 wave RMS over 95% of the useable area of the surface.

The test was conducted on a 186mm concave part with radius of 291.236mm, and the input quality (Figure 6) was approximately 1/5 wave RMS. The part was polished using the 3D raster process after probing and applying the non-linear corrections. After four polishing runs, the part met the pass-off criterion (Figure 7).

5. Assessment of tooling for the 1200mm machine

The standard tooling for the 1200 machine is the *Zeeko-Classic* family of pressurized bonnets 20-160mm radius, and the *Zeeko-Jet* fluid-jet adaptation. However, in large optics fabrication, a 'smoothing' stage may be required, where large volumes of material are removed to eliminate local surface deformities before finer operations are conducted. We have therefore used the original prototype 600mm machine at OpTIC to assess tooling for future use on the 1200.

We were recently faced with an extreme case where smoothing was required when processing a 500mm diameter aspheric Cervit part. We had started this previously [9] but deferred work pending process development The part had been originally pre-machined elsewhere to a concave ellipsoidal form with k = -0.158, nominal base radius of 1000mm and aspheric departure from the osculating sphere of 82μm. The earlier work had inadvertently introduced astigmatism due to a fixturing problem. The prototype 600mm machine does not have the X-Y capacity to raster a full 500mm diameter surface for 3D correction, and so continuing the project had to await development of the 2½ D process.

Recently, work re-started in preparation for raster-processing on the 1200mm machine. Whilst performing a 2½ D form correction with the *Classic* process and cerium oxide slurry, the C axis (part rotation) was inadvertently stopped during a polishing run. As the H axis (tool rotation) was still running, this created a single local circular depression some 25µm deep and 20mm diameter, located approximately 200mm from the optical axis. Rectifying this required the removal of some 5,000 mm^3 of stock material from the rest of the part.

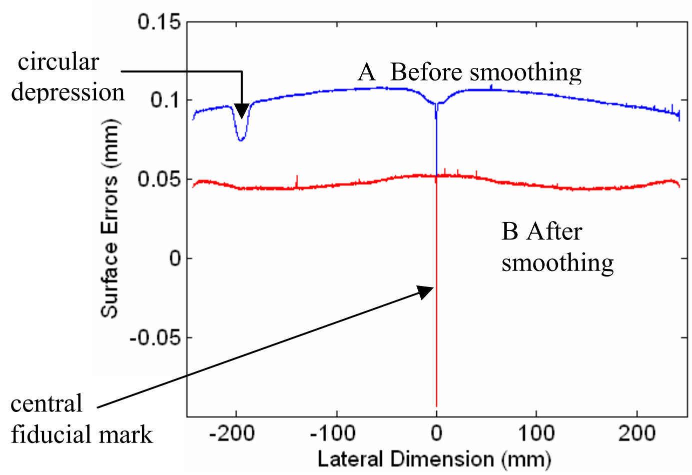
A series of experiments was conducted using the loose-abrasive grolishing process (C20 carborundum) in order to re-smooth the part and remove the depression, but without success. This was partly because of low removal rate, and partly because the compliant bonnet followed down into the depression. Consequently, a ring-tool was employed (Figure 8), which conveniently fits the standard Schunk chuck of the Zeeko machines. The tool module incorporates angular compliance through a universal coupling, and axial compliance by means of an integral compression spring.

The tool had previously been used with small polyurethane pads mounted on an annular Neoprene layer, giving some ability to conform to the asphere. These pads were replaced with stainless steel washers attached with epoxy adhesive, and the assembly was pressed against the centre of the part while the epoxy set. The size of the washers spanned the depression that was to be removed and thereby acted as a spatial filter. The tool was run with C20 carborundum slurry, applied by hand with a brush. Run conditions were as follows:

Parameter	**Value**
Machine stroke	Multiple diametric traverses
C axis speed (part rotation)	25 rpm
H axis speed (tool rotation)	20 rpm (same direction as C axis)
Applied tool-force	6.4 KgF
Button geometry	14 annular buttons each 25mm diameter

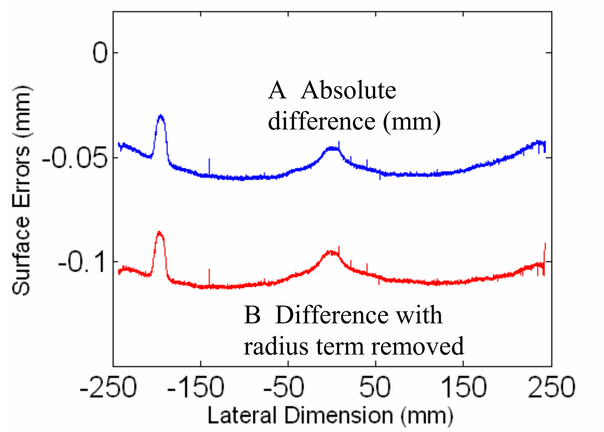
Figures 9A and B below show profilometric scans of the mirror error profile immediately before and after smoothing with C20 with the objective of removing the depression. The central hole is a fiducial ground in to the mirror at an earlier stage of processing for alignment purposes, and has conveniently been used to establish the absolute depth of material removal. Profilometry used the Taylor Hobson Extended Range Form Talysurf, which has a traverse of 300mm. Opposing 300mm scans were conducted overlapping centre by 50mm. These were stitched using the overlap region to establish relative tilt, and the central fiducial to define radial translation.

Figure 8 Ring tool on the 600mm machine, with the 500mm diameter part



Figures 9 A,B Profilometer scans before and after smoothing, on a common vertical scale, showing removal of depression

Two hours of processing with the ring lap removed approximately 50µm of stock material, eliminating the depression to about twice the depth actually required. The volumetric removal rate was calculated by numerical integration to be 81 mm^3 per minute. The process caused a drift in base radius of the asphere from 999.0 to 998.7 mm.



Figures 10 A,B Subtraction B-A of the plots in Figure 1, to show variation in removal over the surface of the part.

Figure 10A shows the difference between plots A and B in Figure 9, giving a comparison of the *absolute* difference in removal over the part. Figure 10B shows the difference after correcting for the radius term.

As can be seen, there are two contributions to the change in form – the smaller effect of radius-change, and the dominant reversion of the asphere towards spherical. Note that this reversion would have been ~ halved had the run been terminated when the hole had been just removed.

The resulting form errors (Figure 9B) are smooth, and lend themselves to future form-correction using the *Precessions* software.

The tooling described above will be implemented on the IRP1200 machine for smoothing generated parts.

6. Zeeko-Jet Mode on the IRP1200 machine

The IRP1200 machine supports the *Zeeko-Jet* mode of polishing. This is invoked by unscrewing and removing the Schunk Chuck that holds the *Classic* bonnet, and replacing it with the jet nozzle assembly (Figure 11). Two jet locations are available – the axial jet and angled jet (30^o from the normal. The jet in operation is shown in Figure 12.

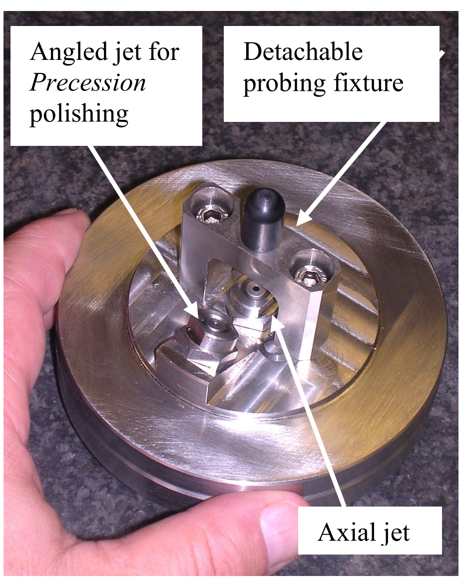


Figure 11 The *Zeeko-Jet* module, showing the axial and precessed jets, and the alignment fixture

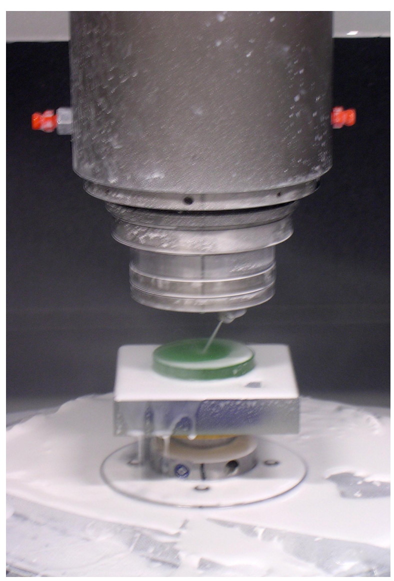


Figure 12 The Zeeko-Jet module on the IRP1200 machine at OpTIC, polishing its first influence function

In the case of the precessing mode, the jet is directed towards the virtual pivot point of the machine, which is the intersection of the machine's A and B rotation axes. The machine is adjusted so that this point is located exactly on the surface of the part.

The setup procedure uses a detachable probing fixture (Figure 11). This is advanced towards the part, and first-contact is detected by the standard touch-on procedure used for *Zeeko-Classic*. The fixture is then removed, and the H axis spun during polishing to precess the jet about the impact point.

The advantage of the inclined precessing jet is that it averages the removal process, and avoids the 'centre-zero' of removal, which an axial jet tends to produce.

At the time of submitting this paper, commissioning of the fluid jet mode has just commenced, with the successful production of the first influence function. The polishing parameters were as given in the table below, and approximately follow those used by S.M. Booij [13].

Parameter	Value	Parameter	Value
Jet pressure	7 bar	Polishing time	30 mins
Jet size	1.07mm diameter	Precess angle	30 degrees
Slurry composition	9 µm Aluminium oxide	H axis rotation speed	50rpm
Slurry concentration	4Kg in 20 litres water		

The removal depth with the 1.07mm diameter jet was measured to be 3 µm using a Form Talysurf Intra profilometer, and the width was 3mm FWHM. The X and Y profiles were essentially identical and flat bottomed (Figure 13). The 3D influence function, as viewed by simple interferometry with a test plate, appeared symmetrical (Figure 14). In practice, the *Zeeko-Jet* mode will normally be used with smaller jets, with the objective of achieving narrower influence functions.

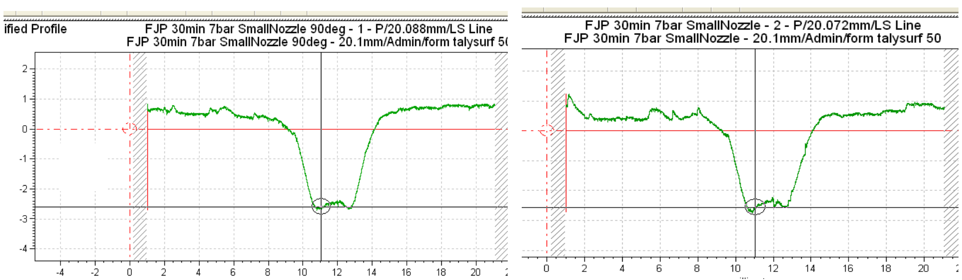


Figure 13 Form Talysurf scans in X and Y directions through the first *Zeeko-jet* influence function obtained on the IRP1200 machine

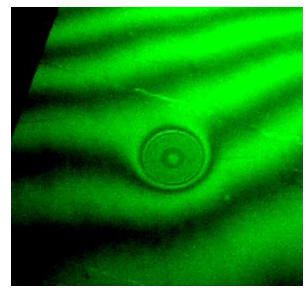


Figure 14. Test plate interferogram of first influence function

5. Discussion and Conclusion

We have reported on the five basic removal regimes now available with the Zeeko family of machines.

The second IRP1200 CNC polishing machine has successfully completed its pass-off tests at the OpTIC Technium. The repeated influence function tests have demonstrated removal-rate consistency in the *Classic* process. Similarly, the tests of uniform removal-depth over surfaces using both spiral and raster tool-paths were successful. Finally, a 186mm concave part was corrected from 1/5 wave RMS to 1/20 wave RMS in four runs, again satisfying the pass-off criterion.

Attempts to remove a 20mm diameter by 25µm deep hole in a 500mm aspheric part using a *Classic* bonnet with C20 abrasive on the IRP600 machine proved unsuccessful. The bonnet simply molded itself around the depression – the feature that of course makes it suitable for addressing aspheres. The bonnet also delivered a removal rate inadequate to handle the large volumetric removal required. We therefore report on development of a smoothing process using hard facets larger than the depression, mounted on a compliant ring tool. This successfully removed bulk material over the part to below the depth of the depression, although giving some regression in the asphere and base radius. However, the resulting errors were smooth and well suited for (future) correction. This tooling will be adopted on the 1200mm machine.

Finally, commissioning of the Zeeko-Jet mode has commenced with the successful production of an influence function; observed to be well-behaved, symmetrical and flat bottomed. Future work will optimize removal-rate and texture, and will progress to smaller jets with the objective of achieving fine control of edges of parts.

6. Acknowledgements

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