New results extending the Precessions process to smoothing ground aspheres and producing freeform parts

D.D. Walker [a,b], A.T.H. Beaucamp [b], V. Doubrovski [b], C. Dunn [a], R. Freeman [b], G. McCavana [b], R. Morton[b], D. Riley [b], J. Simms [b], X. Wei [b]

[a]Optical Science Laboratory, Dept Physics and Astronomy, University College, Gower St, London WC1E 6BT

[b] Zeeko Ltd, Precise Group, The Stables, East Lockinge, Wantage, Oxfordshire, OX12 8QJ

ABSTRACT

Zeeko's *Precession* polishing process uses a bulged, rotating membrane tool, creating a contact-area of variable size. In separate modes of operation, the bonnet rotation-axis is orientated pole-down on the surface, or inclined at an angle and then precessed about the local normal. The bonnet, covered with standard polishing cloth and working with standard slurry, has been found to give superb surface textures in the regime of nanometre to sub-nanometre Ra values, starting with parts directly off precision CNC aspheric grinding machines.

This paper reports an important extension of the process to the precision-controlled smoothing (or 'fining') operation required between more conventional diamond milling and subsequent *Precession* polishing. The method utilises an aggressive surface on the bonnet, again with slurry. This is compared with an alternative approach using diamond abrasives bound onto flexible carriers attached to the bonnets. The results demonstrate the viability of smoothing aspheric surfaces, which extends *Precessions* processing to parts with inferior input-quality. This may prove of particular importance to large optics where significant volumes of material may need to be removed, and to the creation of more substantial aspheric departures from a parent sphere.

The paper continues with a recent update on results obtained, and lessons learnt, processing free-form surfaces, and concludes with an assessment of the relevance of the smoothing and free-form operations to the fabrication of off-axis parts including segments for extremely large telescopes.

1. Introduction

The *Precessions*™ CNC polishing process has been described in the literature (e.g.[1-9]) at various stages during its development. It is based on precise control of the position and orientation of a spinning, inflated, membrane-tool (the "bonnet") with respect to the surface of a part which may be (in the historical order of process-development) flat, spherical, aspheric or free-form. The user cements one of the standard polishing 'cloths' familiar to practicing optical workers onto the pre-dressed bonnet, and the process is reversible so that the same bonnet may be re-used. The cloth is then dressed on the machine.

Before polishing starts, the machine advances the tool towards the part until first contact is sensed by a sensor in the polishing head (the 'ZTOP' process). The tool is then advanced into the part by a pre-calculated distance in order to generate a contact spot of the required size.

The polishing action is then mediated by the combination of the 'cloth' with one of the standard polishing slurries such as cerium oxide or aluminium oxide, with additives (e.g. acidification) as required, depending on the material of the part being worked. In this way, accumulated craft-expertise is not discarded; rather, it is re-deployed on the automated machine-tool.

Optical Manufacturing and Testing VI, edited by H. Philip Stahl, Proc. of SPIE Vol. 5869,
58690E, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.617067

The process as reported in the aforementioned references provides two principal modes of operation – 'pre-polishing' and 'form-correction'. Pre-polishing typically uses a pole-down spinning tool. The input-quality is typically a part taken from an aspheric CNC grinding machine, and the output quality is a surface approximately true to the ground (e.g.) aspheric form, but with sub-surface and surface damage removed. The form-correction operation takes as input the form-error of the pre-polished part, plus a family of the near-Gaussian empirical influence functions delivered by a precessing spinning tool. A numerical optimization method is used to compute the tool-path to correct the form-errors.

Polishing is statistical and averaging in nature. Now, diamond-grinding and single-point diamond-turning machines aim to be deterministic in the sense that the tool/part contact-zone is highly localized, and advancing the tool by 1μm into the part will remove 1μm depth of material. In contrast, polishing is statistical in being mediated by a myriad of mobile particles, and averaging in operating over an area of action that is a significant fraction of the size of the part. In the case of the *Precessions* process, the tool itself is also compliant, breaking the direct link between tool-positioning and depth of material removed. This means that control-of-form to deliver residual-errors down to small fractions of a micron can be achieved with a machine-tool having orders of magnitude larger positional errors. In fact, with the *Precessions* process, it is the Z machine setting-accuracy that has the largest effect, as this controls the compression of the bonnet, the spot-size, and hence the volumetric removal rate. The quantitative dependence of spot-size with bonnet-radius and machine Z-offset has previously been reported [7]. The upshot is that a machine setting accuracy of ~5 microns is adequate to handle all reasonable operating conditions down to the smallest spots currently used.

The use of cloth-plus-slurry can deliver superb textures down to the sub-nm regime, and can deliver volumetric removal-rates that make the process commercially attractive. Nevertheless, cases arise where still higher removal rates are desirable, for example when working large parts, or parts with large form errors, or which exhibit substantial sub-surface or surface damage. With this in view, a new hybrid process which we term "grolishing" – has been developed, which is intermediate between grinding and polishing. This greatly extends the versatility of the machines and process.

Our previous papers have presented results with bonnets of radii of curvatures of 40 and 80mm, although the R=20mm bonnets have also existed for some time. More recently, the Zeeko technology has been very successfully retrofitted to a 4m-class CNC machine tool. This project stimulated development of larger bonnets, up to R=480mm. The three smaller bonnets, together with the largest of the range (R=480mm) are shown together in Figure 1. A ~1m part being worked on the 4m-class machine is shown in Figure 2.

2. The "Zeeko-Grolishing" process

2.1 Diamond pads used

This process uses standard commercial abrasive products, where the abrasive is bonded onto a flexible self-adhesive backing. Three products from 3M have been investigated – metal-bonded diamond pads, resin-bonded diamond pads, and Trizact ™ diamond tiles.

The bonnets were degreased before attaching the pads, and the self-adhesive bond was used. In all three cases, the pad-flexibility was found adequate to enable effective adherence of a 30-35mm diameter pad to the spherical surface of an 80mm radius bonnet. If larger pads are required, then cutting into petals may be needed. 125mm Trizact ™ pads with 4 petals attached to R480 bonnet, and 154mm 3M resin-bonded pad with four petals attached R320 bonnet, have been successfully trialed. The self-adhesive backing provided an excellent bond.

All work to date has used pole-down polishing ("pre-polishing" mode). However, we know of no reason why polishing at an off-set precession angle should not be used, providing the pad-size is adequate to encompass the track of the polishing spot along the 'line of latitude' around the bonnet.

2.2 Diamond pad dressing

Of the three pads trialed, Trizact ™ required dressing (or, 'breaking in') before use, to expose the active diamonds. Our preferred method is to use a 6μ aluminium oxide dressing pad from 3M, mounted on a piece of flat glass on the turntable of the polishing machine. Satisfactory results can be obtained by simply setting the C axis (part rotation) and H axis (tool rotation) in motion, and offsetting the tool with respect to the C axis in order to utilize an annular area of the dressing pad. The bonnet is then advanced in Z to plunge the bonnet covered with the diamond-pad into the dressing-pad, creating a contact-spot. A dressing cycle-time of a few minutes usually suffices. A coolant such as "Bluekool" or distilled water is used. As a refinement, dressing-uniformity can be improved if the machine 'A' axis is programmed to rock sinusoidally during the dressing process. As the A axis coincides with the virtual pivot (which intersects the centre of curvature of the bonnet), this evens the dressing over the diamond pad.

Figure 1 R= 20, 40, 80 and 480mm bonnets. Intermediate sizes >80mm also exist.

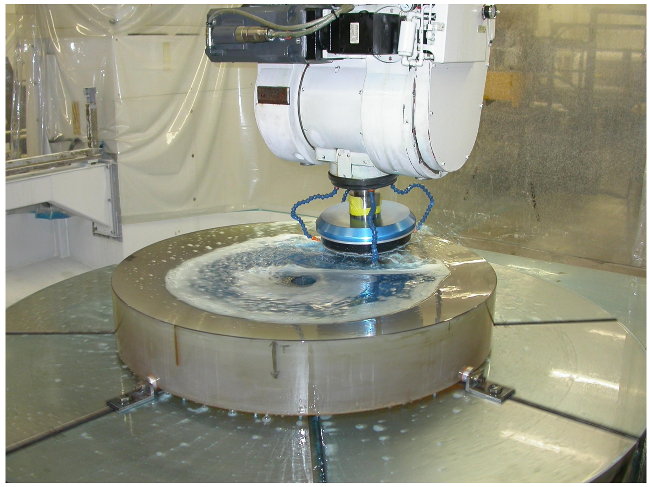

Figure 2 Zeeko technology retrofitted to a 4m-class CNC machine tool, grolishing a ~ 1m diameter part

2.3 Volumetric removal rates and stability

10μm metal-bonded diamond pads were observed to give volumetric removal rates that declined monotonically with time, reducing to a very low level after approximately 2 hours. It is believed that this was due to dulling of the diamonds.

In contrast, the Trizact TM product once dressed, continually exposes fresh diamonds until the pad has ended its useful life. It therefore tends to retain a reasonably uniform removal rate (Figures 3, 4). However, there is a subtlety to this – if, during extended cycles of grolishing and surface-measurement, the machine ZTOP is re-established at each cycle, the removal rate tends to increase. This due to a growth in the spot-size, as shown in Figure 4.

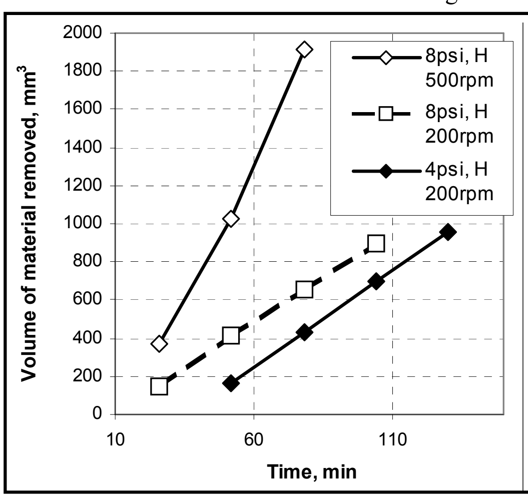

Figure 3 Volume of Cervit removed versus time. 9μm Trizact, 80mm bonnet, 20mm spot. For specified bonnet pressures and H axis speeds.

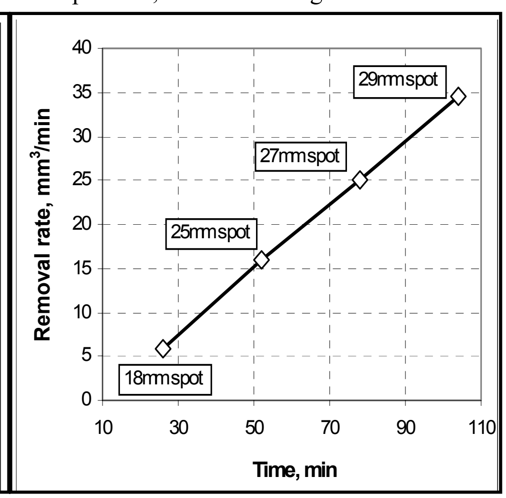

Figure 4 Volumetric removal rate for Cervit versus time, showing growth in spot-size. 9μm Trizact, 80mm bonnet inflated to 8psi.

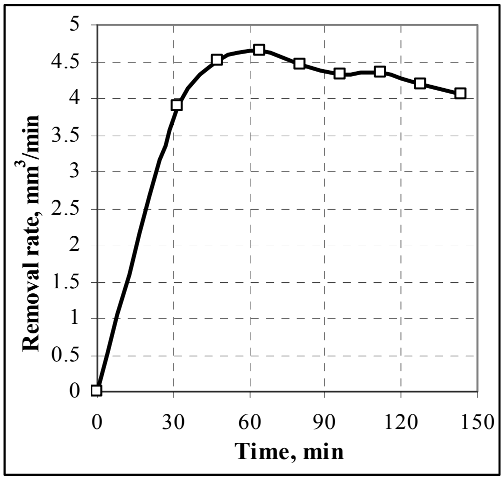

Figure 5 Removal rate versus time for BK7. 9μm Trizact, 80mm bonnet, 20mm spot.

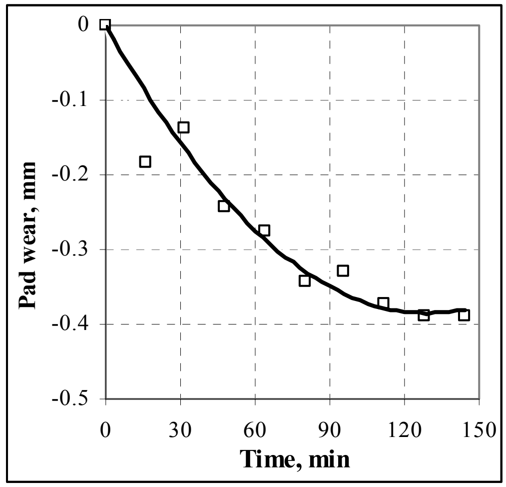

Figure 6 Measured pad wear corresponding to Figure 5

We believe that the growth in spot size is due to the observed formation of a flat land on the surface of the Trizact ™ pad as it wears, which establishes a zone of significant area at first-contact (ZTOP), rather than the point-contact which arises when the pad is spherical. However, when grolishing proceeds *without* the ZTOP being periodically re-established, the removal rate is found to be more constant (Figure 5). In this case, it appears that pad-wear (Figure 6) leads to the bonnet being less compressed. This effect tends to reduce spot-size, tending to compensates for the dilation of spot due to the flattening effect mentioned above.

Parameter / Material	**BK7**	**Cervit**	**Cervit**	**Cervit**
Initial surface finish	Ground with loose abrasive, 400 grit	Ground with loose abrasive, 600 grit	Ground with loose abrasive, 600 grit	Ground with loose abrasive, 600 grit
Bonnet radius	R80	R80	R80	R80
Bonnet pressure, bar	0.25	0.25	0.5	0.5
Polishing pad	Trizact, 9μm	Trizact 9μm	Trizact 9μm	Trizact 9μm
Spot size, mm	20	20	20	20
H-axis speed, rpm	200	200	200	500
C-axis speed, rpm	6	6	6	6
Coolant / Slurry	Bluekool	Bluekool	Bluekool	Bluekool
Temperature, ºC	23	23	23	23
Removal rate, mm^3/min	4 – 4.25	2 –3.5	8 –10	15 – 17
Removal rate stability in time	Stable	Stable	Stable	Stable

Table 1 Grolishing Cervit and BK7 with Trizact

Data given in Table 1 column 2 illustrates a typical machine setup used for the experiments on grolishing with fixed 3M abrasives. BK7 glass was grolished with 9µm Trizact ™ and the removal rate of 4 - 4.25mm^3/min was achieved with the given machine and tool parameters.

Comparing Table 1 columns 3,4 an increase in the removal rate (column 4) can be explained by a twofold increase in the bonnet pressure. Further increase in the removal rate, as indicated in column 5, was achieved by increasing the H-axis speed by a factor of 2.5 times, i.e. 500rpm against the 200rpm.

Grolishing of a single surface with the 9µm Trizact ™ followed by polishing with the 6µm and 3µm grades Trizact ™ showed that the removal rates were 140-150, 100 and 40-45 mm^3 per minute respectively. The surface finish of the workpiece was gradually improving whilst moving from coarser to finer grades of the Trizact ™, as expected. Nevertheless, grolishing of Cervit with Trizact ™ of any of the grades investigated results in a "grey" surface.

If it is required to have a more specular surface suitable for measuring with an interferometer, grolishing with the Trizact ™ can be followed by grolishing with 3M Resin bonded diamond pads. No further polishing with loose abrasives was needed to achieve a surface which can be measured on an interferometer.

Parameter / Material	**Pyrex**	**Pyrex**	**Pyrex**	**Pyrex**	**Pyrex**
Initial surface finish	Ground, 600 grit	Ground, 600 grit	Ground, 600 grit	Ground, 1200 grit	Diamond-turned, equivalent to 240 grit grinding
Bonnet radius	R80	R80	R80	R80	R80
Bonnet pressure, bar	0.5	0.5	1	1.5	1.5
Polishing pad	Trizact 9µm	Trizact 9µm	3M Metal, 10µm	3M Metal, 10µm	3M Metal, 10µm
Spot size, mm	20	25	20	20	20
H-axis speed, rpm	200	200	500	200	500
C-axis speed, rpm	6	6	6	6	6.5
Coolant / Slurry	Bluekool	Bluekool	Bluekool	Bluekool	Bluekool
Temperature, ºC	23	23	23	23	23
Removal rate, mm^3/min	6.5	8	4	6.5	4.5
Removal rate stability in time	Stable	Stable	Non-stable	Non-stable	Non-stable

Table 2 Grolishing Pyrex with 9µm Trizact

Table 2 columns 2,3 demonstrate the results of grolishing Pyrex with the 9µm Trizact ™. As indicated in column 2, the removal rate was 6.5mm^3/min. A higher removal rate of 8mm^3/min as shown in column 3 was due to the larger polishing spot size. Results of grolishing Pyrex with 3M 10µm Metal bonded diamond pad are shown in column 4. As compared with the previous two tests with Trizact ™, less aggressive removal was achieved even with higher bonnet pressure and speed. A further increase in the bonnet pressure, as shown in the column four, resulted in an increase in the removal rate even at a reduced bonnet speed. Table 2 column 6 shows the result of grolishing Pyrex with the 3M 10µm metal bonded diamond pad. The work-piece was single-point diamond-turned prior to grolishing. This result should be compared with the result in the column 4: the removal rates were similar despite the different pressures.

Results of grolishing with the 10µm 3M Resin bonded diamond pads are given in Table 3 columns 2-7. Column 2 shows the result of grolishing Pyrex with a 3M 10µm resin-bonded diamond pad. It can be seen that a much lower removal rate was achieved, compared with grolishing using the 3M 10µm metal bonded pad with the similar operating conditions in Table 2. Columns 5-7 show the results of grolishing a single fine-finish surface with the 3M resin bonded pads. It appears that for a surface with a good input surface-finish, variation in bonnet pressures and speeds produces little impact on the removal rate, and this is interpreted as the material operating in the self-quenching mode. The removal rate remained low whilst the surface finish gradually improved.

Parameter / Material	**Pyrex**	**Pyrex**	**Pyrex**	**Pyrex**	**Pyrex**	**Pyrex**
Initial surface finish	After grolishing with 3M metal 10µm	Ground with loose abrasive, 1200 grit	Diamond-turned, equivalent to 240 grit grinding	After grolishing with 3M Resin 10µm for four hours	After grolishing with 3M Resin 10µm for five hours	After grolishing with 3M Resin 10µm for six hours
Bonnet radius	R80	R80	R80	R80	R80	R80
Bonnet pressure, bar	1.5	1.5	1.5	0.5	2.0	1.5
Polishing pad	3M Resin, 10µm	3M Resin, 10µm	3M Resin, 10µm	3M Resin, 10µm	3M Resin, 10µm	3M Resin, 10µm
Spot size, mm	20	20	20	20	20	20
H-axis speed, rpm	200	200	500	500	500	1500
C-axis speed, rpm	6	6	6	6	6	6.5
Coolant / Slurry	Bluekool	Bluekool	Bluekool	Bluekool	Bluekool	Bluekool
Temperature, ºC	23	23	23	23	23	23
Removal rate, mm^3/min	0.2 - 0.22	0.4	0.25	0.025	0.05	0.035
Removal rate stability in time	Stable	Stable	Stable	Stable	Stable	Stable

Table 3 Grolishing Pyrex with Resin-Bonded Pads

3. Further work on the free-form process

3.1 Arbitrary removal function on spherical surface

The first result from the free-form process was published in [8], which demonstrated imprinting the Zeeko logo into a surface. Two more recent examples are reported here. The first represents fine control of a complex free-form removal profile on a regular surface, permitting measurement with an interferometer. The second demonstrates removal on a severely free-form surface. In this case, metrology is the limiting factor, and work to date has used coordinate measuring machines which typically provide measurement of 3D topology at the few-micron level of accuracy.

In the first example, the part was a convex spherical lens of 88mm diameter and radius of curvature 97mm. An arbitrary image (Figure 7) was imported into the 3D optimization software as a .bmp file. An influence function was created, measured and imported. The dwell-time map was then computed using the 3D optimizer with the objective of imprinting the ‘error’ into the part. The optimizer provided a numerical prediction of the profile, as shown in Figure 8. A single 20 minute polishing run was conducted comprising two crossed rasters with moderated traverse speeds. The result was measured on a Zygo interferometer, producing the Figure 9. About 300nm of material was removed. The residual background errors (predominantly circular zonal errors) were in the original surface.

Figure 7 Imported .bmp file

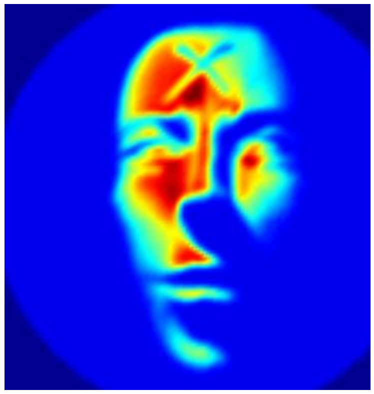

Figure 8 Predicted result

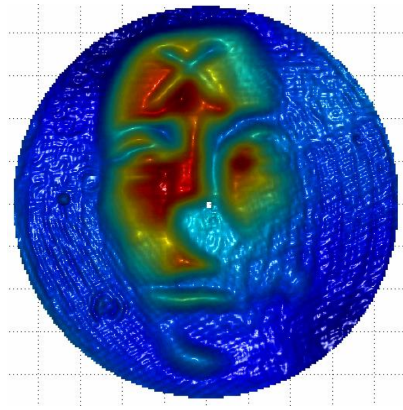

Figure 9 Zygo result of crossed-raster polished surface (with contrast enhanced)

3.2 Uniform removal on an arbitrary free-form surface

In the second example, the part was pre-ground on a CNC grinding machine to the free-form surface, exhibiting radii of curvatures ranging across the surface from 300mm to 50mm convex. All metrology was performed using a coordinate measuring machine (CMM).

A removal linearity test was performed by programming the machine to polish a uniform 60 microns off the specified polishing zone on one of the available parts. (This zone fell short of the edge by 4mm.) Two precess angles of 15 degrees were used, five passes at a feed-rate of 400mm/minute, and a total process time of two hours The removal was measured by directly comparing the before and after measurements from the CMM, and is shown in Figure 10. The depth of material removed was 57.6μm, and was perfectly uniform within the errors of measurement.

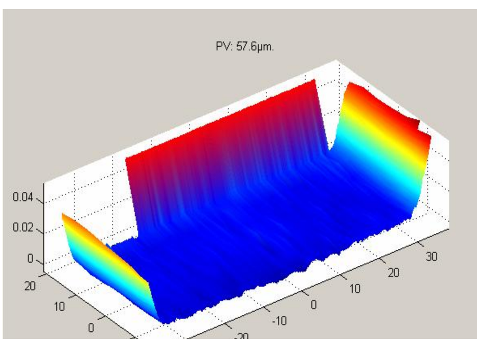

Figure 10. Uniform removal over free-form surface.

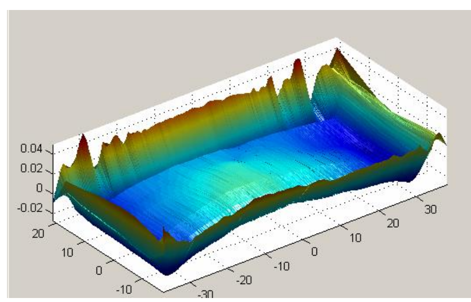

Figure 11 Removal error (μm)

3.3 Form-correction on a free-form surface

On a separate part ground to the same design as above, the measured form error after grinding was 20.4μm peak-to-valley over the optical area to be polished.

Two tool paths were generated corresponding to two precess positions mutually at 90°. The tool-paths were computed to polish a minimum depth of approximately 20μm to remove the grey from grinding, and superimposed upon this, to correct the 20.4μm form-error. The maximum removal depth was therefore ~40μm. The required total polishing time was 93 minutes. In practice, this was divided into three runs of 31 mins each, with the raster speed correspondingly increased. The resulting form-error was 6.2µm peak-to-valley over the polished area.

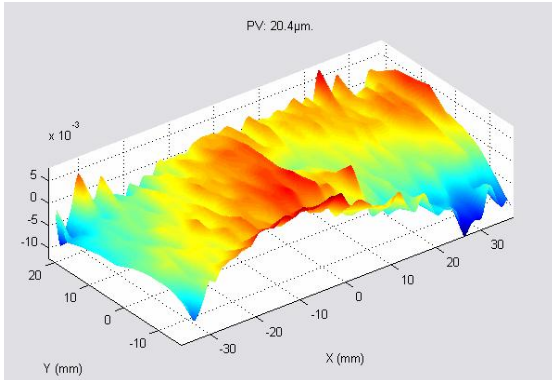

Figure 12 Form error of 20.4µm p-to-v over optical aperture of part, after free-form grinding

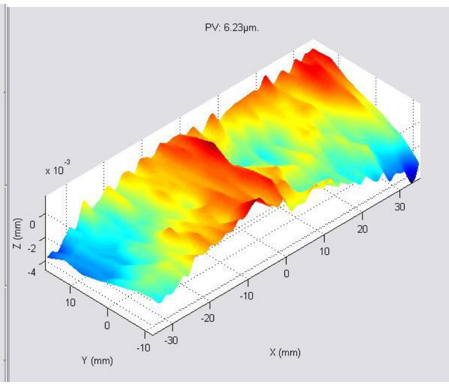

Figure 13 Form error of 6.2µm p-to-v over optical aperture of part, after one run removing a 20µm pedestal and correcting the form error of Fig. 12.

4. Conclusions

3M Trizact TM diamond tiles can produce extremely high and reasonably consistent removal rates, and results in a uniform and fine grey surface. Volumetric removal rates as high as 140-150 mm^3/min with 100mm spot sizes have been observed on Cervit with modest H-axis (tool-rotation) speeds. 3M metal bonded diamond exhibits declining removal rates. There is some evidence that resin bonded pads require in-process conditioning, but this can conveniently be provided by working a fine-grey part. As the grey is taken out, the texture improves, until removal declines when the surface is at the limiting quality for this product. This can result in a surface quality as good as 15nm rms (as measured with a Zygo Newview). The apparent self-quenching property could be useful in improving texture without disturbing form. Therefore, a 2-stage process with resin bonded diamond following Trizact TM is promising as an efficient method for controlled local bulk-removal of material, prior to final polishing and figuring.

The free-form polishing process has been demonstrated to be capable of polishing an arbitrary form into a regular surface, to remove a constant skin from a severe free-form part, and to correct form on a free-form part. The limitations polishing a free-form part are currently due to the quality of the metrology as delivered by a CMM.

The next generation of 50-100 metre aperture extremely large telescopes will require hundreds to thousands of hexagonal mirror segments, depending upon the detailed design. There is currently controversy in the community as to the optimum optical design. One option is to utilize a primary mirror fabricated from spherical segments of identical form, whereupon the remainder of the optical system must correct for the gross spherical aberration. Alternatively, an aspheric primary can be used, in which case the optical design reduces to an elegant two-mirror system. The main penalty is then the difficulty of mass-producing the different off-axis aspheric segments required to tile the parent asphere (e.g. parabola). Traditional manufacturing methods as applied to 1-off mirrors are simply too slow. The results of this paper, presenting rapid and controlled local material removal using diamond pads, and the ability to control form on free-form surfaces, provides important stepping-stones to rapid aspheric segment and other manufacturing.

5. Acknowledgements

We wish to acknowledge financial support from the UK Particle Physics and Astronomy Research Council and the Ministry of Defence, under the PPARC/MOD Joint Grant Scheme, and from the UK Research Councils under the Basic Technology initiative. The diamond-abrasive experiments with the 80mm bonnet were conducted on UCL's 600mm Zeeko machine located at the OpTIC Technium. C. Dunn acknowledges sponsorship of her graduate studentship from Zeeko Ltd. D. Walker acknowledges a Royal Society Industry Fellowship. The implementation of Zeeko technology on a 4m-class machine, as shown in Figure 2, was performed under contract to Brashear, L-3 Communications with the help of Andrew Clarkson and François Piché.

6. References

1. "A Novel Automated Process for Aspheric Surfaces" R,G. Bingham, D.D. Walker, D-H. Kim, D. Brooks, R. Freeman, D. Riley , Proc. SPIE 45th Annual Meeting, 2000, Vol. 4093 'Current Developments in Lens Optical Design and Engineering'; pp445-448

2. "The Zeeko/UCL Process for Polishing Large Lenses and Prisms" D.D. Walker, R. Freeman, G. McCavana, R. Morton, D. Riley, J. Simms, D. Brooks, A. King, proc. Large Lenses and Mirrors conference, UCL, March 2001, pub. SPIE, pp 106-111

3. "The first aspheric form and texture results from a production machine embodying the *Precessions* process", D.D. Walker, D. Brooks , R. Freeman, A. King , G.McCavana, R. Morton, D. Riley, J. Simms, proc. Proc. SPIE 46th Annual Meeting, San Diego, 2001, vol. 4451, 2001, pp267-276

4. "Novel CNC polishing process for control of form and texture on aspheric surfaces", D.D. Walker, A.T.H. Beaucamp, D. Brooks, R. Freeman, A. King, G. McCavana, R. Morton, D. Riley, J. Simms, proc. SPIE 47th Annual Mtg, Seattle, 2002, vol. 4451, pp267-276

5. "The *Precessions* process for efficient production of aspheric optics for large telescopes and their instrumentation" D.D. Walker, A.T.H. Beaucamp , R.G. Bingham, D. Brooks, R. Freeman , S.W. Kim, A. King, G. McCavana , R. Morton , D. Riley, J. Simms , Proc. SPIE Astronomical Telescopes and Instrumentation Meeting, Hawaii, 2002, Vol. 4842, pp73-84

6. 'The '*Precessions*' Tooling for Polishing and Figuring Flat, Spherical and Aspheric Surfaces', D.D. Walker, D. Brooks, A. King, R. Freeman, R. Morton, G. McCavana, S-W Kim , Optics Express, Published by Optical Society of America on http://www.opticsexpress.org/, Vol. 11, issue 8, 2003, pp958-964

7. '*Precessions* Aspheric Polishing:- New Results from the Development Programme', D.D. Walker, A.T.H. Beaucamp, R.G. Bingham, D. Brooks, R. Freeman, S.W. Kim, A. King, G. McCavana, R. Morton, D. Riley, J. Simms , Proc. SPIE's 48th Annual Meeting, the International Symposium on Optical Science and Technology, 'Optical Manufacturing and Testing V', San Diego, Vol. 5180, 2003, pp15-28

8. 'First Results on Freeform polishing using the *Precessions* Process', D. Walker, A. Beaucamp, C. Dunn, R. Freeman, A. Marek, G. McCavana, R. Morton, D. Riley, ASPE Winter Topical Meeting on 'Free-Form Optics: Design, fabrication, Metrology, Assembly', CD-Rom, ISBN 1-887706-33-X 2004

9. "New Results from the *Precessions* Polishing Process Scaled to Larger Sizes", D.D. Walker, A.T.H. Beaucamp, D. Brooks, V. Doubrovski, M. Cassie, C. Dunn, R. Freeman, A. King, M. Libert, G. McCavana, R. Morton, D. Riley, J. Simms, Proc. SPIE Astronomical Telescopes and Instrumentation Meeting, Glasgow, 2004