

# The ‘*Precessions*’ tooling for polishing and figuring flat, spherical and aspheric surfaces

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**Abstract:** The *Precessions*<sup>TM</sup> process has been developed for the control of texture (‘polishing’), preservation of form during polishing, and control of form (‘figuring’), on flat, spherical and aspheric surfaces. In this first and introductory paper, we summarize the need for aspherics, review some aspheric technologies, and then distill a ‘wish-list’ of attributes for an aspheric process. Within this context, we focus on special properties of *Precessions* tools, their use in a family of 7-axis CNC polishing machines, and present experimental results.

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## 1. Introduction

Aspheric surfaces provide the optical designer with additional degrees of freedom in a ray-tracing optimization, compared with all-spherical solutions. In general this allows independent correction or balancing of various aberrations and – ultimately – some or all of the following: fewer elements, more compact packaging, lower mass and superior imaging performance.

Producing aspherics poses several challenges using traditional polishing methods, i.e., where a physical tool contacts the optical surface in a process mediated by a wet slurry of particulate abrasives. First, the part radius-of-curvature varies across the surface, and so a rigid tool can make intimate contact at only one zone. Imperfect contact introduces pressure low and high spots, leading to zonal errors. This tends to force the craft optician to use a range of small tools with consequent reductions in volumetric removal rates. The optician usually incorporates compliance in the tooling by a variety of means, such as a sandwich construction with a foam layer. The result is that the tooling and the way in which it is used, is carefully tailored to each stage of each job individually, compounding the reliance on craft skills. The process is then qualitative and iterative, with many cycles of metrology and processing required to converge on final form. This is because of the inherent unpredictability of manual polishing, mitigated only in part by the skill of master craftsmen.

## 2. Approaches to computer-controlled polishing

Several organizations have taken steps to automate the classical process, or to develop competing processes. Since the mid 1980s the Steward Observatory has developed its very successful *stressed lap* for large astronomical telescope mirrors [1]. In this approach, a ~ one-third size tool is actively deformed as it moves across the part to match the local target form of the conic section being polished. In a different approach, a full-size flexible tool ('the Active Lap'), furnished with computer-controlled pressure actuators, performs short strokes across the part. This has been demonstrated on an 83cm convex aspheric and described by Kim et al. [2]. In practice the most successful results with the Active Lap were obtained by configuring the tool to produce an 'edgeless' Gaussian-like pressure hot spot, and rocking the tool to traverse this across the surface of the part.

A 2-D analogue of the Active Lap was developed by Zeiss [3], comprising a flexible linear strip furnished with pitch polishing pads and force actuators, which was oscillated along a diameter of a large mirror. Geyl and Paseri [4] from REOSC reported successful computer-controlled polishing of the 8.2m diameter primary mirrors for the VLT using proprietary flexible laps, where the tool-pressure, part rotation-speed, and the tool-stroke, were all controlled. Litton Itek adopted the small-tool approach with their Computer Controlled Optical Surfacing facility [5] for large optics. They figured light-weighted mirrors using a dwell-time control of a small rapidly-orbiting pitch-tool, with suction to prevent print-through.

Despite the application of computer control, these and similar methods require skilled workers, for example to customize tooling where necessary for different parts, to specify

operating parameters, and to operate the equipment itself. The end-to-end processes may be expensive, but this is warranted for large, high capital-value optics.

Regarding non-classical processes, Kodak for example, has reported [6,7] results on ion-figuring, in which kinetic energy is transferred from argon ions impinging on the glass surface. This process will not polish a rough surface and tends to give a low removal rate, and so is normally used for deterministic form-control of near net-form surfaces that are pre-polished. In contrast, laser ablation [8] has been demonstrated successfully to polish rough glass. Nearer to classical polishing, Föhnle et al. [9] have developed a fluid slurry jet and demonstrated material removal. In the magnetorheological finishing process (MRF) [10] the spinning part is brought into contact with a slurry containing magnetic particles. The slurry is locally stiffened by the action of a controllable magnetic field. This process demonstrates a high level of predictability, but is not effective in removing mid spatial-frequency errors.

### 3. Guidelines for development of the *Precessions* process

Given a number of competing technologies, it is possible to draw some threads together, which have provided guidelines for developing the *Precessions* process [11, 12].

- For an economic industrial process, there are clear benefits to a reduction in the reliance on skilled craft-workers (in short supply), and to a technology that avoids the need for custom tooling for specific jobs. A generalized and automated process is therefore highly desirable. Process predictability is a prerequisite.
- A process that has the versatility to polish rough surfaces without destroying form, and also to correct form, can potentially reduce investment in capital equipment and recurrent costs and improve efficiency.
- There are clear advantages if the removal process were to provide a mathematically well-behaved tool-imprint ('influence function') on the part surface, as discontinuities or anomalies at the center or edge of the notional tool, or due to any aspheric mismatch, can introduce local defects.
- The 'softer' the removal process, the more homogeneously it 'maps' onto the local topography of the part. It then provides less spatial filtering, and therefore, more mid-to-high spatial frequency surface features are retained. Ion-figuring is at the 'soft' end of the spectrum and shows a high level of retention of surface texture. Laser ablation is an exception, as the energy density is sufficient to induce surface melting. Hard pitch tools can offer superb polishing, but introduce surface defects due to the aspheric mis-match between tool and part. One partial exception is the Steward stressed lap, as it achieves conformance to the local profile and dynamic stiffness, but not on generalized aspheres. Moreover, whilst the tool as a whole conforms to the local profile, the individual pitch facets comprising the surface, do not. In a more 'universal' process, the spatial filtering inherent in some controllable 'stiffness' is highly desirable, and the linear membrane of the Zeiss process provides this function.
- A process that can exploit the vast accumulation of craft know-how can short-circuit development cycle-times, particularly on unusual or fragile materials.

### 4. Tooling for the *Precessions* process

The baseline of the *Precessions*<sup>TM</sup> process is a physical sub-diameter tool operating in the presence of a polishing slurry. The process has been validated using a test-rig, but for polishing complete surfaces the tooling is hosted by a 7-axis CNC polishing machine that has been custom-designed for the purpose. The tool comprises an inflated, bulged rubber membrane of spherical form (the 'bonnet'), covered with one of the usual proprietary non-pitch flexible polishing surfaces familiar to opticians. The membrane moulds itself around the local asphere, retaining good contact everywhere. Such a membrane has the property that the polishing pressure (tool hardness) and the contact area (polishing spot size) can be varied

independently by varying:

1. the internal pressure of the working fluid within the tool (air in our case)
2. the axial position of the tool with respect to the part, and therefore the degree by which the membrane is compressed against the part

The variable spot size might be 5-15% of the diameter of the part, although this is not a limit. In order to achieve a high volumetric removal rate despite the small area in contact, the tool is spun about its axis (at up to 1500rpm) to increase surface speed.

A static pole-down spinning tool exhibits zero surface-speed at center, rising linearly to a maximum at the periphery. This is reflected in the influence function, as shown in the experimental data of Fig. 1, measured with a Wyko 6000 interferometer. This influence function does not lend itself to effective form control, on account of the ‘cross talk’ between zones on the part that are separated by the diameter of the contact-spot.

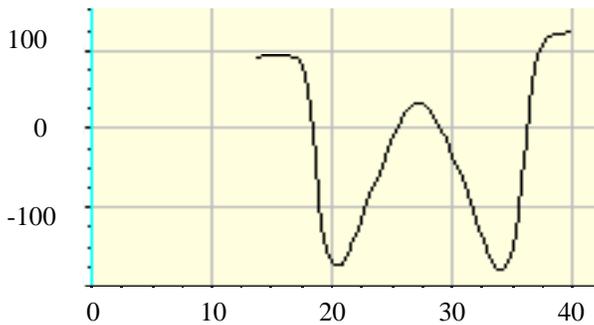


Fig. 1. Measured influence function (microns depth versus mm on the part) of a pole-down spinning tool

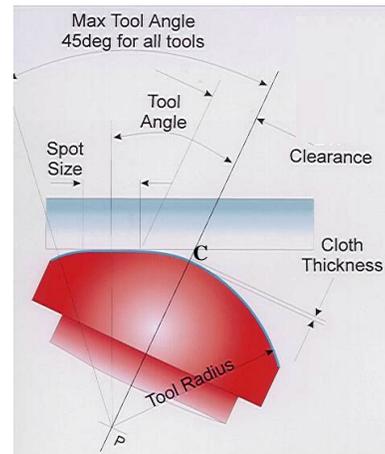


Fig. 2. Processing bonnet

For this reason, the rotation-axis of the tool is inclined to the surface’s local normal, at an angle of typically 10-25 degrees. The tool polishes on the side of the bulged membrane, and the zero-point of surface-speed is shifted outside the contact spot. The tool-axis is then *precessed* (see Fig. 2) in (typically four) discrete steps about the local-normal to the surface of the part. In practice, the entire polishing run is repeated for each of the four precession positions.

The rotation-axis of the tool is orientated in space with respect to the local slope of the part by the CNC A and B rotation axes which coincide at a virtual pivot P, located at the center of curvature of the bonnet. Changing the A and B angles then preserves the same location of the polishing spot on the surface of the part. The distance shown as ‘Clearance’ in Fig. 2 is then the clearance between the edge of the contact-spot on the part, and the axis of rotation of the tool. This clearance must always be positive, in order to prevent ‘double polishing’ on either side of the rotation axis, which would distort the influence function.

The effect of precession motion is best illustrated by first considering the four precession positions separated on the surface, as would be the case if the bonnet were rocked about its pole (in Fig. 2(c)).

This is shown in Fig. 3, where the concentric circles represent the contours of surface speed, centred on zero speed at C. In practice, the virtual pivot brings the polishing spots for the four precession angles into coincidence on the surface of the part, as shown in Fig. 4.

Following from Preston’s law, the depth  $D(r)$  of material removal is given by:

$$D(r) = k \cdot P(r) \cdot S(r),$$

where  $P(r)$  and  $S(r)$  and  $k$  are respectively the pressure and speed distributions, and Preston's constant.  $r$  is the radial distance from the point  $C$  of zero speed. Now,  $S(r)$  is linear with  $r$ . When the virtual pivot is used to coalesce four precessed polishing spots, the speed gradients  $S(r)$  are of opposite sign for opposite pairs of precession positions. Therefore, the speed-contours essentially average. As a consequence, the form of  $D(r)$  – the influence function – is dominated by the pressure distribution  $P(r)$  exerted by the bonnet. The surface speed (revolutions per minute) can then be used to moderate the depth of the profile without significantly affecting its form.

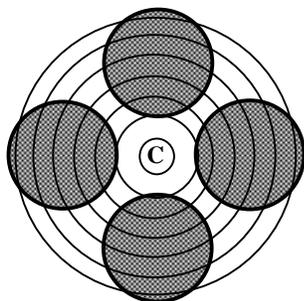


Fig. 3. Speed contours across four precessed polishing spots, shown spaced on the part

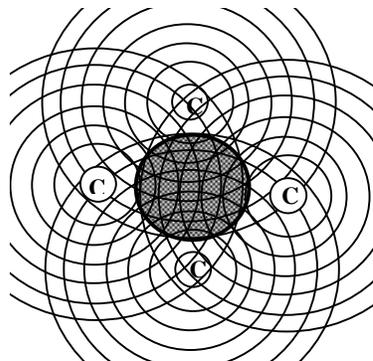


Fig. 4. Speed contours across four coalesced polishing spots

The bonnet contacts the part away from the bonnet's rotation-axis. Hence, the tool at a single precession position lays down an arcuate pattern of low-level marks (Figs. 3 and 5). Different individual precession positions correspond to different directions of attack, and so different directions of the arcuate marks on the part. By precessing in four  $\times 90^\circ$  steps, (Fig. 4) the marks produced at each individual precession position are smoothed out, resulting in excellent texture from the overall process.

BK7 glass was polished with Multitex cloth on a bonnet, and cerium oxide slurry. Texture was measured using a Wyko RST500 surface texture interferometer, giving  $R_a \sim 0.5\text{nm}$  (Fig. 6). We have found that the stiffer polyurethane is effective at removing mid spatial frequency errors, but the softer Multitex gives slightly better ultimate texture. The surface layer on the bonnet can therefore be selected to tune the spatial-frequency response of the tool.

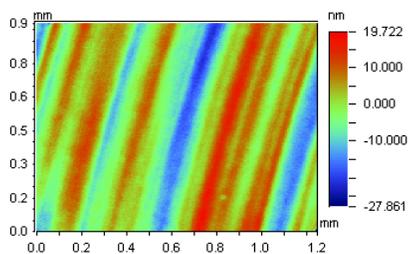


Fig. 5. Surface texture produced in the special case of polishing at *only one* precession position. The figure corresponds to a small sample of one of the circles in Fig. 3.

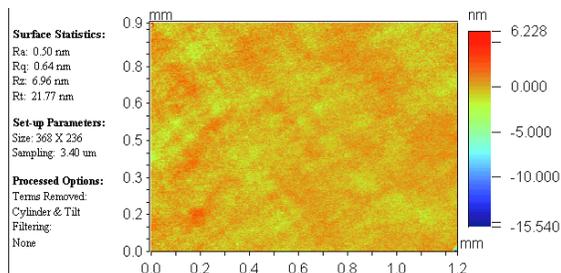


Fig. 6. Surface texture  $R_a=0.5\text{ nm}$  from four coalesced spots corresponding to the usual four precession positions i.e. a small sample of the four superimposed circles in Fig. 4.

The measured depth and volume of material removed, as a function of the tool rotation-speed on the CNC machine, are shown in Figs. 7 and 8. The response is highly linear, demonstrating that tool-speed can deterministically control material-removal.

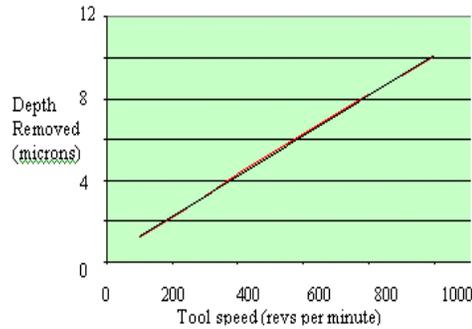


Fig. 7. Removal depth versus tool-speed

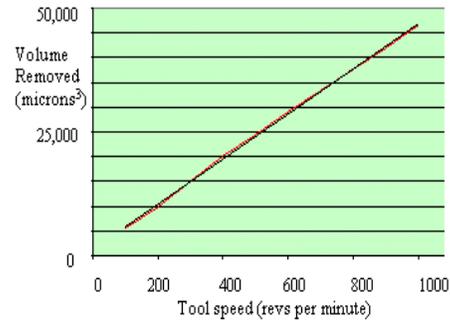


Fig. 8. Removal volume versus tool-speed

A family of influence functions produced by the rotating and precessing tool on the CNC machine is shown in Fig. 9. The spot-size is varied by advancing the tool towards the part, compressing the membrane. The influence functions are near-Gaussian, and effectively edgeless, with no sharp discontinuities. Even for polishing a curved lens, influence functions are usually measured on flat-stock. The tool-advance and dwell-times are corrected to give the desired width and depth respectively on the curved surface.

Controlling form in essence comprises moving the polishing spot across the surface of the part in a prescribed path, varying both dwell-time and spot-size (and, where needed, tool rotation-speed). The CNC machine accomplishes this by:

- i) a touch-on procedure that advances the bonnet towards the part and senses first-contact to 2 microns repeatability, using a sensitive force-transducer,
- ii) coordinated XYZ motions of the bonnet with respect to the part, and
- iii) A,B angular motions of the tool-head to follow the local slope of the part and the required angular-offset to allow the precession motions.

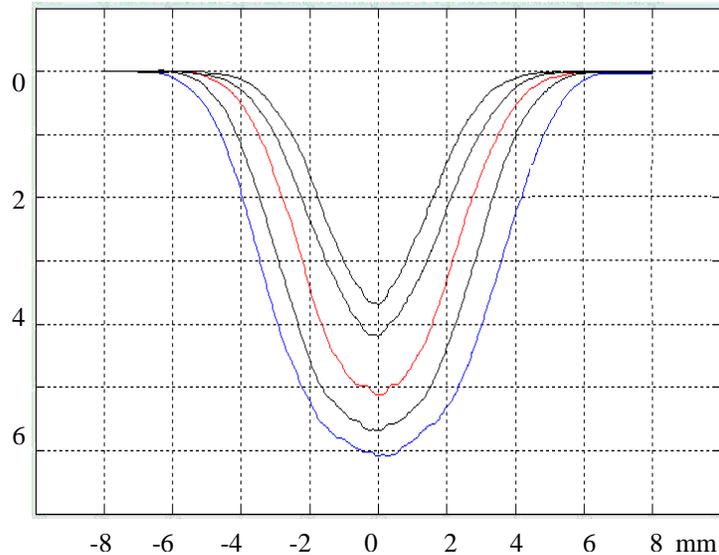


Fig. 9. Family of experimental influence functions (depth in microns)

## 5. Conclusion

The *Precessions*<sup>TM</sup> process uses novel tooling that produces a mathematically well-behaved near-Gaussian influence function. The tooling supports a range of consumable familiar to the working optician, and permits a less flexible surface to remove mid spatial frequency errors, or a softer surface to achieve ultimate texture. Implementation is a hybrid between classical polishing and CNC diamond grinding, and combines the flexibility of the former with the determinism of the latter. Variable spot-size and dynamic control means that the tooling is near-universal, even for a wide range of aspheres. Form-preservation polishing and methods of form-control will be described in a separate paper.

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