# Fluid Jet and Bonnet Polishing of Optical Moulds for Applications from Visible to X-Ray

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**Abstract**

Electroless Nickel (ENi) and binderless Tungsten Carbide (WC) are widely used to make replication moulds for optics ranging from consumer camera lenses to high-accuracy X-ray mirrors. Aspheric shape generation is generally performed by diamond turning in the case of Nickel, and micro-grinding in the case of Tungsten Carbide. Both machining methods fail in general to meet the ultra-precision criteria required by an increasing number of applications. A 7-axis CNC machine equipped with sub-aperture fluid jet and precessed bonnet polishing technology was used to develop deterministic finishing processes on both Electroless Nickel and Tungsten Carbide. Corrective polishing to less than λ/20 (<31nm PV) form error can be achieved, as well as the ability to smooth surface texture down to 1nm Ra or less.

## 1 Introduction

Because of the increasing demand for low-cost and high-accuracy optical systems in consumer products such as digital cameras, the preferred manufacturing method of many optical components is quickly evolving from direct glass generation to glass press moulding. Moulds are often made from a ceramic material such as binderless tungsten carbide. The aspheric or freeform shape generation into the mould is usually performed by grinding with resinoid bonded diamond wheels. In the case of higher accuracy or larger size optical components, Electroless Nickel may be used instead and machined by diamond turning. However, these generation methods results in cyclic micro-structures which may cause diffraction or stray light effects.

Since these techniques generally fail to achieve ultra-precision criteria, a finishing step is required. Precessions™ is an innovative CNC process based on precessed bonnet and fluid jet polishing, described previously in the literature at various stages of its development [1-2]. Details of the process are provided in the following sections.

### 1.1 Precessed Bonnet Polishing

The position and orientation (precess angle) of a spinning, inflated, membrane-tool are actively controlled as it traverses the surface of the work-piece. The work-piece may have any general shape, including concave, flat, or convex, aspheric or free-form. While a classical polishing tool is pressurized against the surface of the part, with no attempt to control actively the Z position of the tool in a local or global coordinate frame, in this technique the Z position and precession (but not directly the contact-force) are actively controlled by the CNC machine tool.

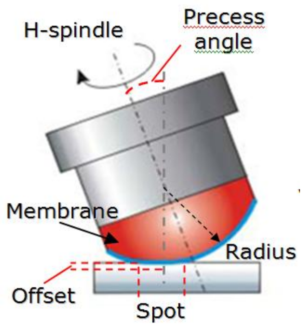

Figure 1: Precessed Bonnet

### 1.2 Fluid Jet Polishing

Fluid-jet polishing is a method in which a slurry of polishing particles is pressurized and projected through a nozzle towards the surface. The jet impacts the surface directly, with no physical tool contact. Booij et.al [3] found a linear dependence of removal rate with slurry concentration. They also found non-linear dependence with impact-velocity, due to the combined effects of 1) a minimum velocity-threshold below which no removal occurs, 2) the increased rate of particle-delivery with increased velocity and 3) the square relation between particle kinetic energy and velocity. They concluded that, using appropriate abrasive and particle size with the right flow velocity, FJP can achieve ductile-regime removal with stable removal-rate.

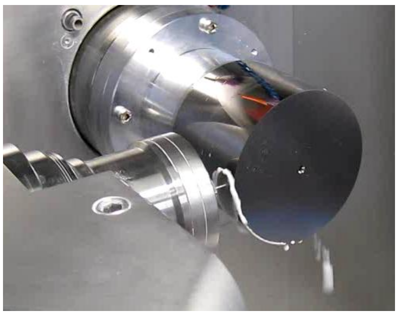

Figure 1: Bonnet (left) and fluid jet (right) polishing on 7-axis CNC machine.

## 2 Application to Tungsten Carbide

Table1: Experimental process parameters.

| | |
|---|---|
| Work-piece<br>Grain size | Binderless WC<br>0.2 µm |
| Polishing tool<br>Radius<br>Shore hardness | Polyurethane<br>4.5 mm<br>90 A |
| Tool-path mode<br>Point spacing<br>Tool offset<br>Head speed<br>Precess angle<br>Surface feed | Raster<br>0.25 mm<br>0.1 mm<br>2000 rpm<br>20 deg<br>500 mm/min |
| Diamond abrasives<br>Grain size<br>Density | Mono-crystalline<br>0.25; 1.0; 3.0 µm<br>1 wt % |

Flat WC samples of diameter 25mm were generated with a grinding wheel moving at an angle across the spinning surface, to replicate aspheric mode conditions. Surface roughness of 8-9nm Ra and form error about 900nm P-V were obtained. The samples were then bonnet polished with a range of abrasives fed by a peristaltic pump above the polishing tool while it moved across the surface, and using the process parameters shown in Table 1.

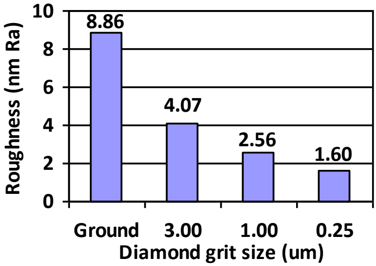


Figure 2: Roughness vs. Grit Size

Surface texture measurements with a white-light interferometer showed that the grinding marks were successfully removed from the surface after the polishing of a 200nm layer of material. Surface roughness down to 1.6nm Ra was achieved with the 0.25µm grit size (see Fig. 2&3). Further improvement down to 1.03nm Ra was obtained by applying pitch on the tip of the bonnet tool. Using the Precessions™ corrective polishing software, form error was also reduced down to 29nm P-V (see Fig.3)

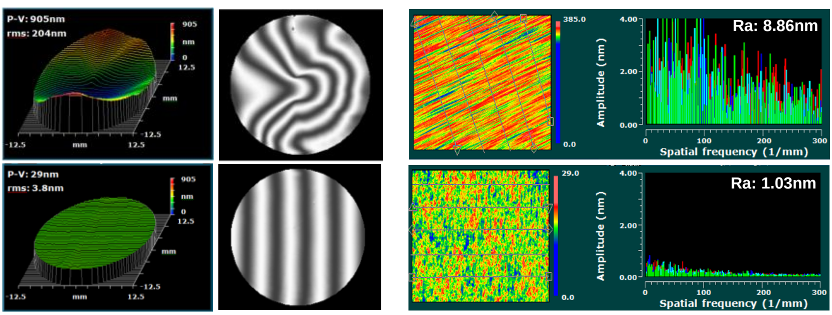


Figure 3: WC sample before and after polishing: form error (left), texture (right).

## 3 Application to Electroless Nickel

Flat ENi samples of diameter 50mm were generated by diamond turning, with surface roughness of 2-3nm Ra and form error about 400nm P-V. Using the Precessions™ software, fluid jet polishing with 200nm $Al_2 0_3$ particles at 18Bar reduced the form error to 30nm P-V in two iterations (see fig. 4). Turning frequencies were also efficiently removed from the surface (see Fig. 5a&b).

Subsequent smoothing by bonnet polishing with 30nm $SiO_2$ particles was performed to bring final surface roughness down to 0.52nm Ra (see Fig. 5c).

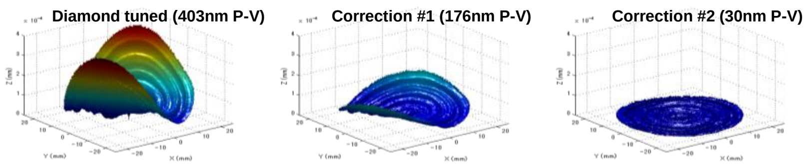


Figure 4: Iterative corrections from diamond turned state by fluid jet polishing.

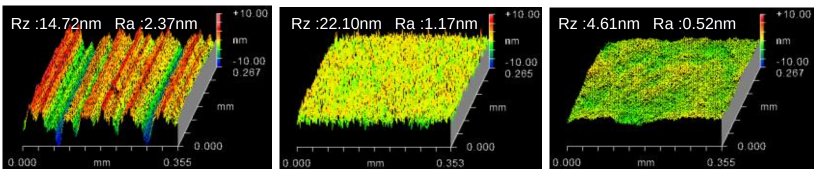


Figure 5: (a) Diamond turned (b) Fluid jet polished (c) Bonnet Polished (right).

## 4 Conclusion

Finishing processes by bonnet and fluid jet polishing have been demonstrated on both Tungsten Carbide and Electroless Nickel. These are capable of form correction to less than $\lambda/20$ (<31nm PV) and surface texture smoothing down to 1nm Ra or less. Available on a common platform and applicable to materials used most widely for optics moulding, these processes promise to unlock new doors for optics designers.

## References:

[1] Walker D., Brooks D., Freeman R., Morton R., McCavana G., The Precessions Tooling for Polishing and Figuring Flat, Spherical and Aspheric Surfaces, Optics Express, 2003.

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[3] S.M Booij, H. van Brug, J.J.M. Braat, O.H. Fahnle, Nanometer Deep Shaping with Fluid Jet Polishing, Opt Eng Vol. 41, 2002