# Ultra-Precision Polishing by Fluid Jet and Bonnet Polishing for Next Generation Hard X-Ray Telescope Application

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## Abstract

Super-smooth ultra-precision freeform surfaces, with form error less than 100 nm and roughness below 0.3 nm rms, are increasingly becoming a requirement for various applications from industrial processes to space telescopes. An example of such application are electroless nickel plated aspherical mandrels used as molding dies for replicating thin hard X-Ray mirrors up to 600 mm in diameter.

It is known from the literature that the smoothest roughness obtainable by polishing on plano surfaces is through the float polishing method. But while this is a well proven method, it cannot be applied to any shape other than flat. In many cases manual polishing is relied upon to obtain super-smooth surfaces, after a prior machining step such as diamond turning. Thus, there is a need to find a process that enables the automation of the final polishing step.

This paper reports on an on-going study of sub-aperture fluid-jet and bonnet polishing techonologies, through a 7-axis CNC polishing machine. The ultimate goal is to attain surfaces of a quality close to that obtained by float polishing. Presently, form error less than 200 nm and roughness below 0.7 nm rms have been achieved.

**Keywords:**

Optics, Corrective Polishing, Molding die

## 1 INTRODUCTION

Single-point diamond-turning is a well-established method to create precise axially-symmetric forms on ductile materials, including flats, spheres, aspheres and cylindrical shapes. A typical example is the production of large off-axis aspheric mirrors for the three-mirror astigmatic configuration [1]. Other applications include various infrared mirrors, and mandrels for producing the cylindrical forms of Wolter-type X-ray mirrors. The main limitation of this method has been the resulting micro-structure which is cyclic in nature ('turning marks') and which produces diffraction and stray light effects. For this reason, molding dies for X-ray mandrels in particular are post-polished to achieve both the form and texture required.

Namba et.al have previously described their work on replication-mandrels for Wolter Type 1 mirrors used in soft X-ray microscopy [2] and hard X-ray telescopes [3]. Their mandrels were produced by single-point diamond turning, but required post-polishing by hand to remove the high spatial frequencies on the surface. As they pointed out, this is extremely difficult on aspheres, and leads to an inevitable trade-off between quality of the surface texture achieved and destruction of the aspheric figure. Clearly an automated method to remove the diamond-turning signature without destroying form could be an important step forward.

Fluid-jet polishing (FJP) is a method in which slurry of polishing particles is pressurized and projected through a nozzle towards the surface to be polished. The jet impacts the surface of the part directly, i.e. with no physical tool contact. Booij et.al [4] have shown the linear dependence of removal rate with slurry concentration. They have also shown the non-linear dependence with impact-velocity, due to the combined effects of i) a minimum velocity-threshold below which no removal occurs, ii) the increased rate of particle-delivery with increased velocity and iii) the square relation between particle kinetic energy and velocity. They conclude that, using appropriate abrasive and particle size with the right flow velocity, FJP can achieve ductile-regime removal with stable volumetric removal-rate. L. Yang et.al have also investigated fluid jet polishing and concluded [5] that the removal process is a mixture of shear and collision mechanisms.

Bonnet polishing (BP) is a method based on a more traditional approach. A reinforced rubber tool is kept under constant back pressure, and pressed into a workpiece to generate a contact area [6]. A polishing cloth is stuck on the bonnet, and slurry sprayed onto the surface. The abrasion rate can be controlled by changing various parameters such as pressure, bonnet spindle rotation speed, precess angle, and tool offset.

Both of these processes can produce stable sub-aperture footprints, and can be controlled by the Precessions corrective polishing software to improve form-error on freeform surfaces [7].

In the work reported in this paper, the FJP process has been used to attenuate diamond-turning marks on plano electroless nickel coated samples. This process was complemented by subsequent smoothing of the surface roughness with the BP process, using slurry of nano-sized particles. The BP process has also been used to correctively polish sections of a borosilicate mandrel, which is being investigated as an alternative to electroless nickel for making X-Ray molding dies. The method described potentially opens up new applications for diamond-turned surfaces, as well as improving the performance of glass optics.

## 2 EXPERIMENTAL PROCEDURE

### 2.1 Electroless Nickel and Borosilicate samples

A7075 aluminum alloy was cut into 100 mm diameter and 30 mm thick plano samples and turned by a single-point diamond turning machine [8]. A layer of nickel-phosphorus alloy 0.1 mm thick was deposited on the diamond-turned aluminum alloy samples by electroless nickel plating in industry. The hardness of the electroless nickel and aluminum alloy were 568 Hv and 183 Hv respectively. All samples were single-point diamond turned again in order to obtain consistent surface conditions.

A hollow borosilicate glass cylinder was obtained directly from industry, with dimensions 200 mm diameter and 200 mm length. The process used to make the mandrels ensures uniform surface texture across the sample, around 0.5 nm rms, but poor straightness in the range 3-5 μm. The cylinder was cut into rectangular sections 50 mm by 100 mm

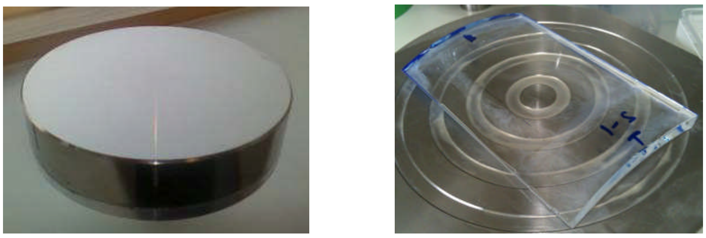

Figure 1: Electroless nickel and Borosilicate samples.

### 2.2 Fluid Jet and Bonnet polishing

The diamond-turned plano samples were polished by FJP on a Zeeko IRP200 CNC polishing machine. $CeO_2$ slurry was used, with particles ranging between 0.6-1 μm, and a concentration of 80 g/L. The samples were subsequently polished by BP on the same machine. Slurry of nano-sized $SiO_2$ particles (7-30 nm diameter) was drip fed onto the surface directly above the bonnet, while the rest of the surface was regularly fine sprayed with pure water to prevent crystallization of the slurry over the sample.

The borosilicate samples were polished by FJP and BP using the $CeO_2$ slurry described above. The objective of FJP was to assess the effect of pressure on surface texture, while that of BP was to assess corrective polishing capability.

### 2.3 Surface roughness measurement

Surface micro-topography of the samples was measured with a three-dimensional optical profiler. Form error on the borosilicate samples was measured with a Form Talysurf profilometer.

## 3 EXPERIMENTAL RESULTS AND DISCUSSION

### 3.1 Fluid Jet polishing of diamond turned samples

The fluid was pressurized at 18 bar, and expelled in laminar flow through a small nozzle (1mm diameter).

The CNC machine was programmed to raster the workpiece with a track spacing of 0.1 mm and feed rate of 500 mm/min. The resulting surface texture showed no residual marks from the prior diamond tool machining, and improvement in the surface roughness from 3.05 nm rms down to 1.47 nm rms (see Figure 4a and 4b).

Figure 2 shows power spectral density analysis performed on the surface texture before and after FJP. The high powered frequencies associated with the diamond turning were completely eliminated.

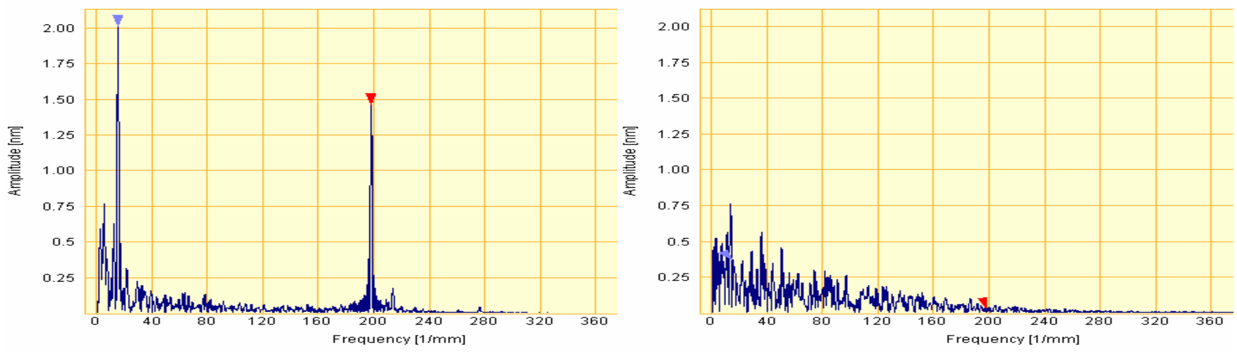

Figure 2 : PSD analysis of electroless nickel plano surface before and after FJP.

The edge of the zone polished by FJP was imaged with a stitching optical profiler. Figure 3 shows very clearly the progressive overriding of directional tool marks from prior diamond turning (left hand side) with a random FJP texture (right hand side). This effect is very desirable since it produces a surface with no outstanding frequency which could lead to diffraction effects on the replicated mirror.

### 3.2 Bonnet polishing of diamond turned samples

The surface texture obtained from FJP was not sufficiently smooth for hard X-Ray application. Subsequent smoothing by BP was thus investigated. A powder of ultra fine nano-particles with average size 7 nm was mixed with pure water at a concentration of 20 g/L. The slurry was delivered above the bonnet at a rate of 12 L/H. To prevent drying of the slurry on the surface, which can cause crystallization, the surface was sprayed with a fine mist of pure water every few seconds. The slurry and water were thus delivered in total loss mode.

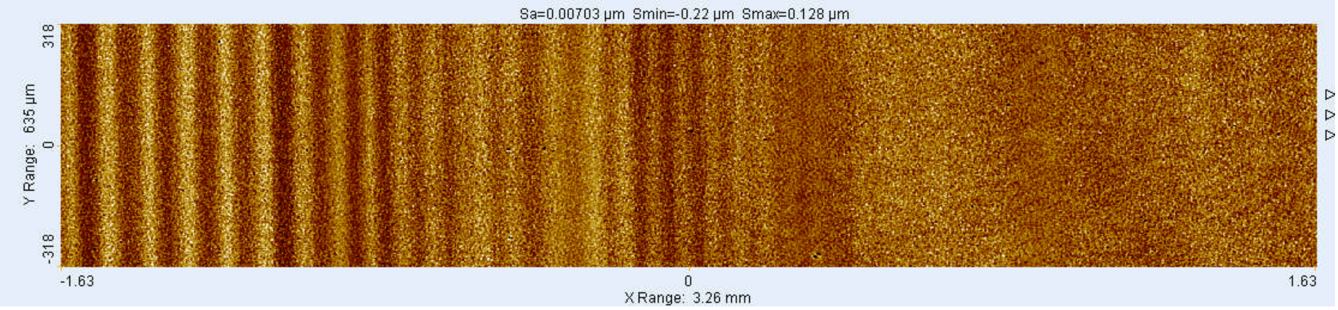

Figure 3 : Surface texture of electroless nickel plano surface at edge of FJP zone(stitching optical profiler).

Rz:14.72nm rms:3.05nm Ra:2.37nm Rz :22.10nm rms :1.47nm Ra :1.17nm Rz :4.61nm rms :0.64nm Ra :0.52nm

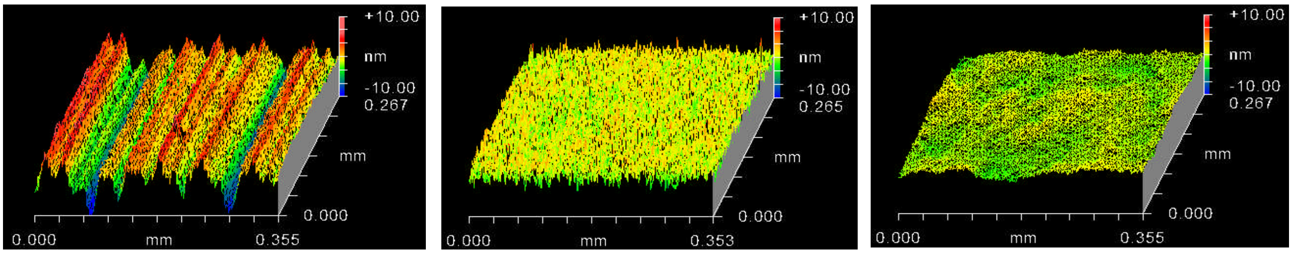

Figure 4 : Surface texture of electroless nickel plano surface at various machining stages (optical profiler).

Bonnet pressures in the range 0.2 to 3 bar and spot sizes in the range 5 mm to 15 mm were experimented with. The best pressure was found to be 1 Bar, and the best spot size 15 mm. The surface texture was evaluated after each raster pass of the tool on the surface. Using FFT Auto filtering, the evolution of waviness (low-pass) and roughness (high-pass) could be assessed. The result is shown on Figure 5. The roughness was very effectively reduced by the polishing to circa 0.3 nm rms. The waviness was slower to remove, and reached a lower limit of about 0.65 nm rms.

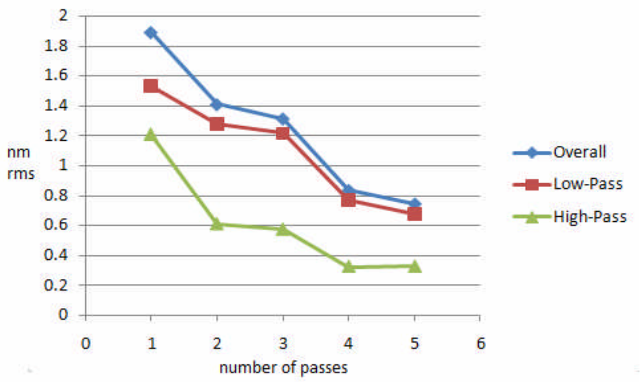

Figure 5: Surface texture variation on elect. nickel sample.

The best surface texture obtained on a sample was 0.64 nm rms (see Figure 4c). The main issue was identified as residual waviness from the bonnet polishing tool, in the region of 0.6-0.7 nm rms. This value is not sufficiently low for Hard X-Ray applications, so future research will concentrate on reducing the waviness induced by the bonnet polisher. The effect of hardness of the tool in particular will be investigated. In the meantime, it is possible to use this automated process to reduce the final hand polishing time by as much as 75 % [3].

### 3.3 Fluid Jet polishing of Borosilicate samples

The Borosilicate samples were polished at different FJP pressures and the effect on surface texture assessed with the same method as described in the previous section.

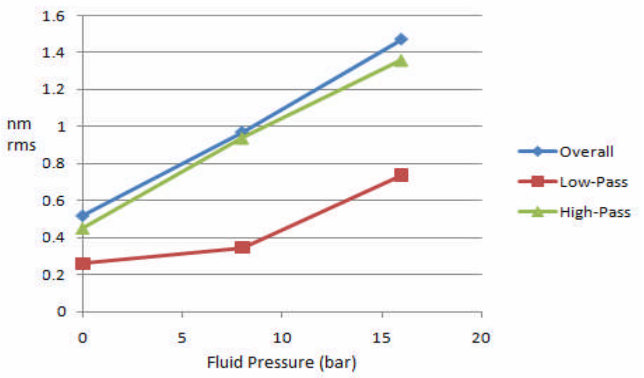

Figure 6: Surface texture variation on borosilicate sample during FJP polishing, as a function of pressure.

Figure 6 shows that the effect of pressure on roughness was almost linear, while waviness only slightly degraded at lower pressures. The removal rates were very low due to the small size of the nozzle (only 1.2 mm diameter). Removal rates were in the range 0.0004-0.008 mm$^3$/min.

A new slurry management system capable of higher flow rate was recently delivered that will enable the use of larger diameter nozzles in future experiments. It is hoped that with sufficient removal rates (circa 0.04 $mm^3$/min) FJP will be used in the future at pressures of 8-10 Bar to correct form error on the surface while leaving waviness in the range 0.3-0.4 nm rms and roughness in the range 0.9-1.0 nm rms. Subsequent polishing by BP with nano-particles may then reduce the roughness back to circa 0.3 nm rms (see 3.2).

### 3.4 Bonnet polishing of Borosilicate samples

Because of low removals from FJP polishing due to too small nozzle sizes, form correction was carried out on a borosilicate sample with BP using the 0.6-1.0 μm $CeO_2$ slurry. The precessions software was used for this purpose [7]. After 3 corrective iterations, the form error was reduced from 3.2 μm down to 0.18 μm (see Figure 7).

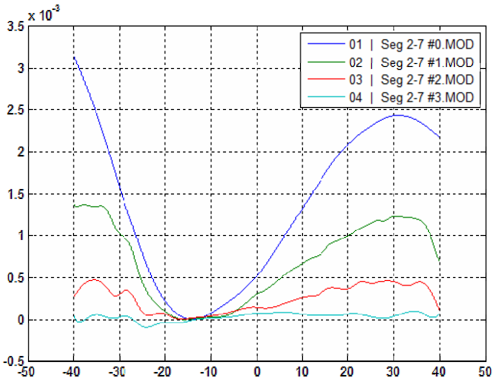

Figure 7: Improvement of form error by corrective polishing with BP on borosilicate sample.

## 4 SUMMARY

Samples of electroless nickel and borosilicate were polished for shorter wavelength applications, particularly dies for hard X-ray mirrors. The following conclusions may be drawn from the results of this study:

1. Surface roughness in the range 0.6-0.8 nm rms was obtained on electroless nickel samples by a combination of Fluid Jet polishing with micro-particles followed by Bonnet polishing with nano-particles.
2. Automated corrective polishing was demonstrated on a borosilicate cylindrical sample, with form error improvement from 3.2 μm down to 0.28 μm.
3. In order to obtain surface roughness of less than 0.3 nm rms, suitable for X-ray application, it is possible to use the automated process to get the surface down to circa 0.6-0.8 nm. This reduces the final hand polishing time by as much as 75 % [3].
4. Form correction on Borosilicate samples by FJP, followed by BP polishing with nano-particles will be investigated next.

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