ULTRA-PRECISION FLUID JET AND BONNET POLISHING FOR NEXT GENERATION HARD X-RAY TELESCOPE APPLICATION

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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]. The 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 Nickel and Borosilicate Samples

A7075 aluminum alloy was cut into 100mm diameter and 30 mm thick plano samples and turned by a single-point diamond turning machine. 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 (SPDT) again in order to obtain consistent surface conditions.

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

FIGURE 1. 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. CeO2 slurry was used, with particles ranging between 0.6-1.0um, and a concentration of 80g/L. The samples were subsequently polished by BP on the same machine. Slurry of nano-sized SiO2 particles (7-30nm 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 CeO2 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.

2.2 Surface Texture Measurement

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

3 RESULTS AND ANALYSIS

3.1 Fluid Jet Polishing of SPDT Nickel

The fluid was pressurized at 18bar, 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 0.1mm and feed rate of 500mm/min. The resulting surface texture showed no residual marks from the prior diamond tool machining, and improvement in the surface roughness from 3.05nm rms down to 1.47nm rms (see Figure 3a and 3b). Figure 2 shows power spectral density analysis performed on the surface texture before and after FJP. The two high powered frequencies associated with the SPDT processing step were completely eliminated.

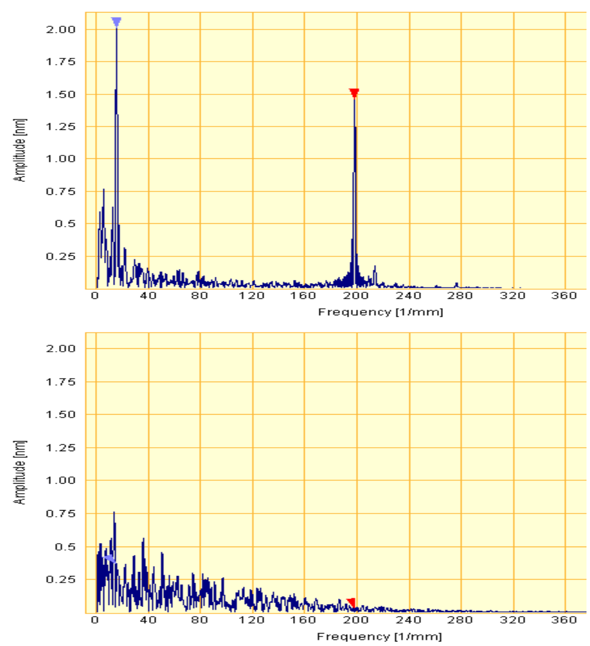
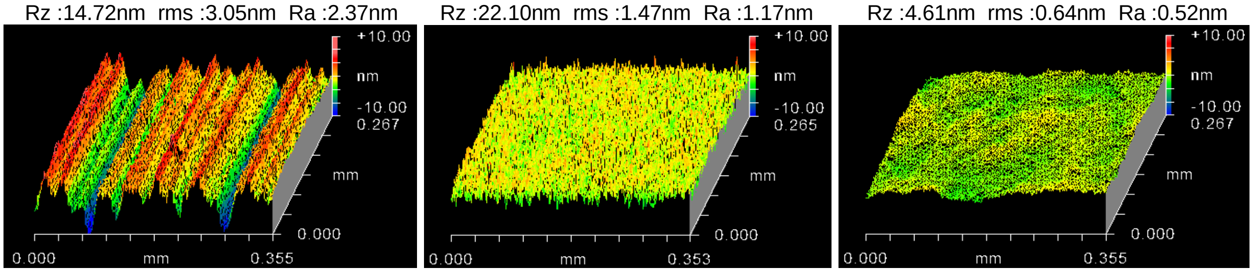


FIGURE 2. PSD analysis of electroless nickel surface before and after FJP.

The edge of the zone polished by FJP was imaged with a stitching optical profiler. Figure 4 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 strong frequency that could lead to diffraction or stray light effects on the final replicated mirror.



(a) Diamond-turned *(b) FJP polished* *(c) BP polished*

FIGURE 3. Surface texture of electroless nickel surface at various machining stages (optical profiler).

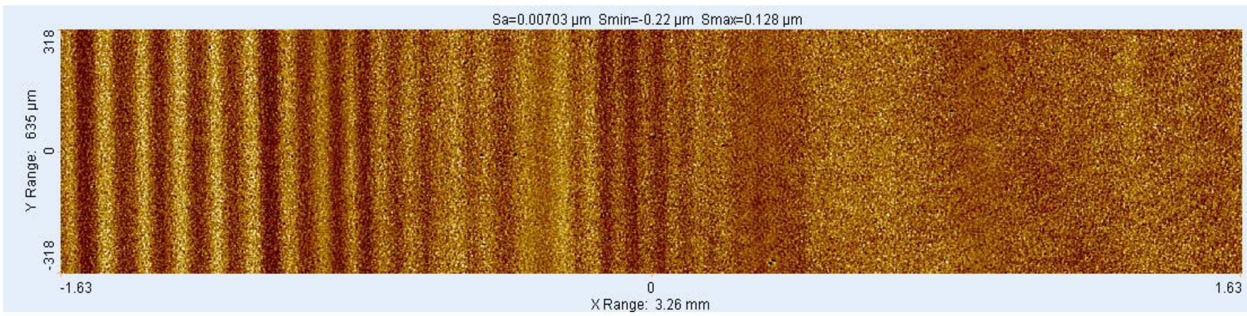


FIGURE 4. Surface texture of electroless nickel surface at edge of FJP zone (stitching optical profiler).

3.2 Bonnet Polishing of SPDT Nickel

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 SiO2 nano-particles with average size 7nm was mixed with pure water at a concentration of 20g/L. The slurry was delivered above the bonnet at a rate of 12L/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.

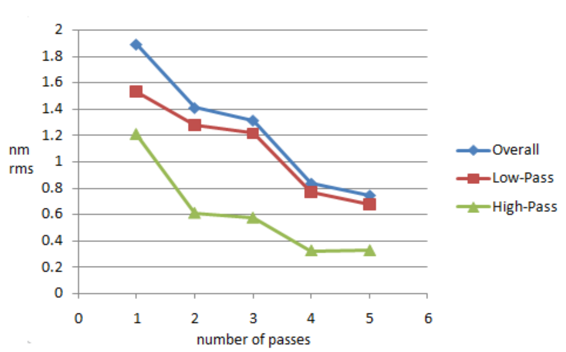


FIGURE 5. Surface texture variation on electroless nickel sample.

Bonnet pressures in the range 0.2 to 3.0bar and spot sizes in the range 5mm to 15mm were experimented with. The best pressure was found to be 1Bar, and the best spot size 15mm. 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 0.3nm rms. The waviness was slower to remove, and reached a lower limit of 0.65nm rms.

The best surface texture obtained on a sample was 0.64nm rms (see Figure 3c). The main issue was identified as residual waviness from the bonnet polishing tool, in the region of 0.6-0.7nm rms. This value is not yet 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

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 shows that the effect of pressure on roughness was almost linear, while waviness was degraded only slightly at lower pressures. The removal rates were very low because of the small size of the nozzle (only 1mm diameter). Removal rates were in the range 0.0004-0.008mm^3/min.

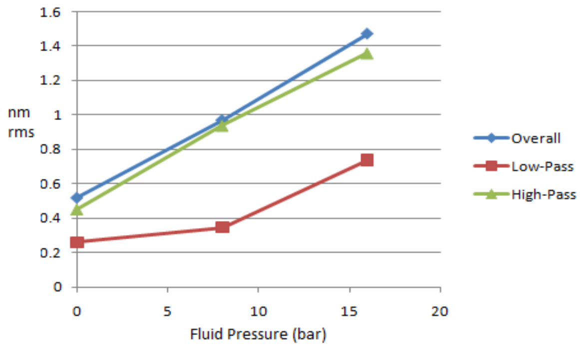


FIGURE 6. Surface texture on borosilicate sample as a function of FJP polishing pressure.

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 0.04mm^3/min) FJP will be used in the future at pressures of 8-10Bar to correct form error on the surface while leaving waviness in the range 0.3-0.4nm rms and roughness in the range 0.9-1.0nm rms. Subsequent polishing by BP with nano-particles may then reduce the roughness back to circa 0.3nm rms (see 3.2).

3.4 Bonnet Polishing of Borosilicate

Form correction was carried out on a borosilicate sample with BP using the 0.6-1.0um CeO2 slurry. The precessions software was used for this purpose [7]. After 3 corrective iterations, the form error was reduced from PV 3.2um down to 0.18um (see Figure 7).

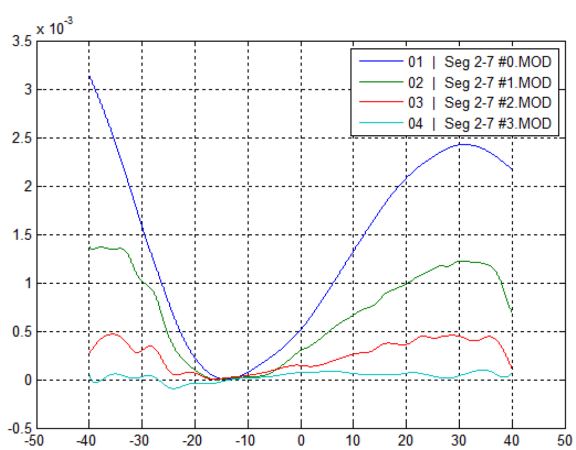


FIGURE 7. Improvement of form-error on borosilicate cylindrical sample.

4 SUMMARY

A study of automation of hard X-Ray molding dies polishing by FJP and BP was carried out. The following conclusions were drawn:

1. Surface roughness in the range 0.6-0.8nm rms can be 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 PV 3.2um down to 0.18um.
3. By using the automated process to get surface texture down to circa 0.6-0.8nm rms, it is possible to reduce the time of final hand polishing to 0.3nm by as much as 75% [3].

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