Super-smooth optical fabrication controlling high spatial frequency surface irregularity

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ABSTRACT

Modern advanced optical systems often require challenging high spatial frequency surface error control during their optical fabrication processes. While the large scale surface figure error can be controlled by directed material removal processes such as small tool figuring, surface finish (<<1mm scales) is controlled with the polishing process. For large aspheric optical systems, surface shape irregularities of a few millimeters in scale may cause serious performance degradation in terms of scattered light background noise and high contrast imaging capability. The conventional surface micro roughness concept in Root Mean Square (RMS) over a very high spatial frequency range (e.g. RMS of 0.5 by 0.5 mm local surface map with 500 by 500 pixels) is not sufficient to describe or specify these surface characteristics. For various experimental polishing conditions, we investigate the process control for high frequency surface errors with periods up to ~2-3mm. The Power Spectral Density of the finished optical surfaces has been measured and analyzed to relate various computer controlled optical surfacing parameters (e.g. polishing interface materials) with the high spatial frequency errors on the surface. The experiment-based optimal polishing conditions and processes producing a super smooth optical surface while controlling surface irregularity at the millimeter range are presented.

1. INTRODUCTION

The control of mid to high spatial frequency errors to reduce surface scatter is vital for advanced large precision optical systems. Not only do the errors affect the sharpness of the point spread function, but the surface scatter is also affected. This is especially true when considering the total integrated scatter which is inversely proportional to the system wavelength squared, thus, degrading the performance of systems with short wavelength applications.

Surface figure and finish specifications are usually given by the RMS figure error over a low and high spatial frequency bandwidth respectively. Both are often measured using phase shifting interferometry techniques, and the surface finish measurements utilize a high magnifying power interference objective. Although these two RMS based specifications could be still used for most commercial grade optical surfaces, advanced precision optical systems are often given a structure function or Power Spectral Density (PSD) surface specifications. A bidirectional reflectance distribution function (BRDF) can be used to specify the surface scattering performance, which is also directly related with PSD via Rayleigh-Rice formula.[1, 2] The use of the structure function or PSD to specify wavefront error between the ideal optical surface and the measured surface provides good evaluation of the actual surface errors as a function of spatial frequencies.[3]

The low-spatial frequency errors are usually controlled with optimized computer controlled optical surfacing runs which provide varying tool dwell time and/or tool stroke speed according to the surface figure error distributions.[4] However, the mid- to high-spatial frequency errors, which are smaller than the tool size, mainly depend on the polishing parameters such as polishing interface material, compound, pressure, and accumulated polishing time. For super-smooth optical fabrication, it is important to connect these polishing parameters to the final surface PSD covering the mid to high spatial bandwidth.

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The high-spatial frequency errors measured with typical sub-aperture phase-shifting interferometers are often limited to a narrow spatial frequency bandwidth (as shown in Figure 1) due to their limited field of view (e.g. 0.5 by 0.5mm). The Micro-Finish Topographer (MFT) was used to measure the samples under investigation (The measurement bandwidth of MFT is shown in Figure 1 and more detailed information is provided in Section 2.2). A broad bandwidth from mid to high spatial frequency was considered to monitor and analyze the measured surface PSD in this study.

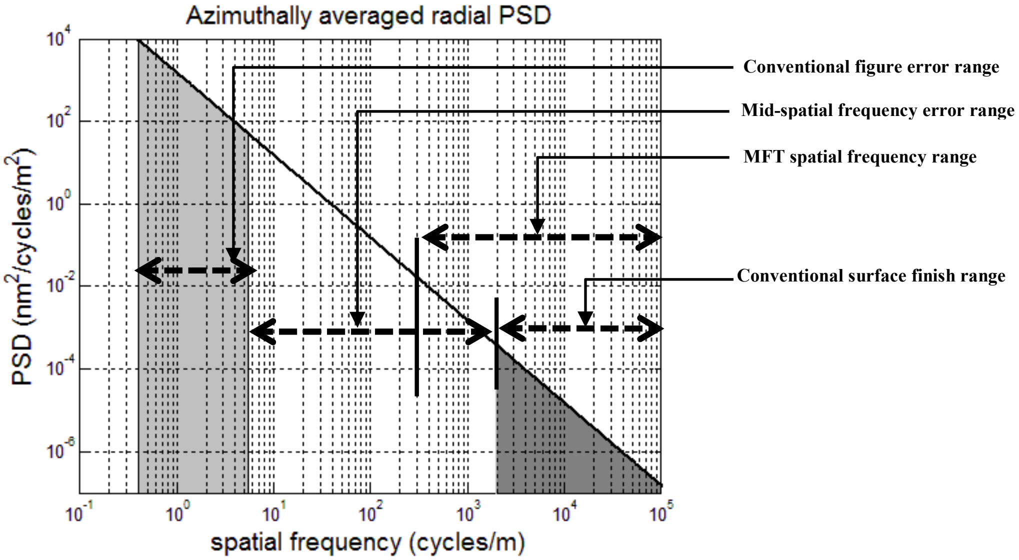


Figure 1. Exemplary synthetic PSD for meter-class optics depicting various spatial frequency errors ranging from surface figure to finish (Note: These ranges may vary depending on various factors such as optics size and metrology instruments.)

In this paper, we present the effect of polishing time and polishing interface material on the PSD and RMS surface roughness after a 5μm loose abrasive grinding on a Zerodur surface. Some theoretical backgrounds for the polishing process and the surface measurement for a PSD calculation is described in Section 2. The experimental parameters including the generating and grinding phase information are provided in Section 3. Finally, the results and concluding remarks are given in Sections 4 and 5 respectively.

2. POLISHING PARAMETERS AND DATA PROCESSING

2.1 Polishing Parameters for Super-smooth Optical Fabrication

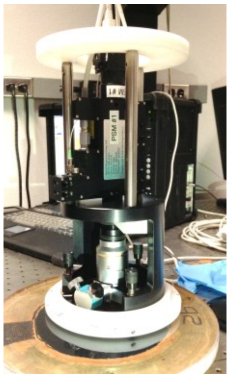
The governing equation for most polishing processes is the Preston equation [5]

$$\Delta z(x,y) = \kappa \cdot P(x,y) \cdot V_t(x,y) \cdot \Delta t(x,y), \tag{1}$$

where x and y are the coordinates on the substrate, $\Delta z(x,y)$ is the integrated material removed on the substrate surface, κ is Preston's constant defines the removal rate, $P(x,y)$ is the polishing pressure, $V_t(x,y)$ is the relative speed between the polishing tool and the substrate, and $\Delta t(x,y)$ is the dwell time of the polishing tool. Polishing optical surfaces is a complicated process consisting of both chemical[6] and mechanical[6,7,8] interactions of particles in the polishing compound and glass. In order to achieve high fidelity of the final data, the three key parameters P, V_t and Δt were carefully controlled during the PSD experiments as presented in Section 4. The accumulated polishing time to reach final surface quality (i.e. final PSD) and the PSD difference between various polishing interface materials, such as conventional pitch, synthetic pitch and polyurethane pads have been investigated.

2.2 Surface Measurement and PSD calculation

The MFT is a 3-dimensional non-contact optical profilometer which uses temporal phase shifting to determine the phase difference between the measured surface and reference in the interference microscope objectives.[9] The surface shape measurements of the Zerodur substrate were taken using the MFT as shown in Figure 2. The instrument provides the option of interchanging objectives, therefore, allowing the measurement of mid to high spatial frequency errors. A total of 15 measurements on the 10inch diameter Zerodur substrate were taken at random locations to check the isotropic characteristic of the polished surface.



MFT Specifications

Measurement type	In situ / Temporal phase shifting
Camera	FL2G-50S5M-C, 1599 X 1199 pixels, pixel size=3.45 µm
Interchangeable objectives	2.5X / 10X / 50X
Numerical Aperture (NA) for each objective	.075 / .3 / .55
Object space pixel size for each objective	2.76 µm / .69 µm / .138 µm
Spatial field of view for each objective	4.41 x 3.31 mm / 1.10 x 0.83 mm / 0.22 x 0.17 mm

Figure 2. Micro-Finish Topographer (MFT) measuring the phase difference (in situ) between the reference in the interference microscope objectives and the measurement area on a 10inch diameter Zerodur substrate.

After the measurements were taken, the errors in the MFT were calibrated by subtracting the fixed (i.e. unchanged) component in the 15 maps at random locations.[10] This assures that only surface shapes are considered when attaining the surface OPD maps.

The 2-dimensional PSD_{2d} can be directly computed from surface height measurements $z(x,y)$ given by an interferometer as[2]

$$PSD_{2d}(f_x, f_y) = \lim_{Area\to\infty} \frac{1}{Area} |\mathcal{F}\mathcal{F}[z(x,y)]|^2 \quad , \tag{2}$$

where FF is the 2-dimensional Fourier Transform. Based on the assumption that the surface height distribution throughout the surface is isotropic, the PSD_{2d} function can be converted into an azimuthal average of the PSD_{2d}.

3. SUPER-SMOOTH POLISHING EXPERIMENTS

3.1 Generating and Grinding Phase

The experiments involved using Zerodur substrates as the workpieces. The substrates were generated to a flat surface using cup-wheel generation. The Zerodur surfaces were then rough to fine grinded using Aluminum Oxide loose abrasives. A typical 10inch diameter Zerodur workpiece during the rough grinding phase is shown in Figure 3.

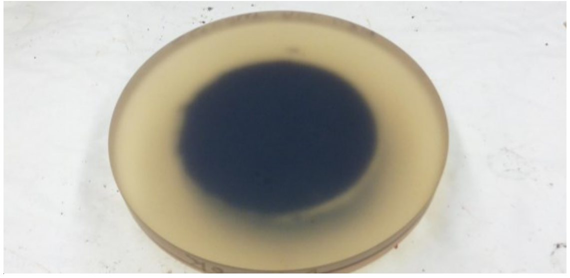


Figure 3. 10 inch diameter Zerodur workpiece during rough grinding phase (Note: The black area in the middle shows the pitch bonding layer to the aluminum puck to mount the workpiece on the polishing machine).

The rough to fine grinding removal procedure with applied loose abrasive grit size information is presented in Table 1. All Zerodur samples were processed flowing the same grinding time, tool pressure, and spindle speed listed in the table so that the final surface PSD only depends on the polishing phase parameters in Section 3.2.

Table 1. Rough to fine grinding procedure and the fixed grinding variables

Loose Abrasive Grit Size (μm)	**Piston Removal Depth (μm)**	**Grinding Time (hours)**	**Pressure (PSI)**	**Spindle Speed (RPM)**
40	100	1.7	0.25	60
25	75	1.4	0.25	60
12	50	1.0	0.25	60
5	25	0.8	0.25	60

3.2 Polishing Phase

The flat optical surface after fine grinding was polished with various polishing parameters and the surface after each polishing run was measured using MFT and analyzed. The experiments were divided into two major cases as summarized in Table 2. Repeatability was a big factor for each experiment. After each experimental result, the experiments were repeated and the resulting PSD was analyzed to make sure it converged to the same result each time.

Various polishing conditions including the environment were controlled to avoid any undesired effects from uncertain aspects. For instance, for the LP-66 polyurethane polishing pads, all the pads were equally conditioned (i.e. ran on a dummy optical surface) for a fixed amount of time until the initial roughness of the pads reached an equal state.[4] More care and maintenance has to be taken when using pitch, as pitch is more sensitive to many preparation and environmental conditions since it is a viscoelastic material. The pitch lap was pressed on the mirror being polished so that its shape fits the surface shape before the polishing in order to eliminate the uncertainty from the tool misfit during the final data interpretation. The charging of polishing slurries on the pitch lap was monitored and controlled. The relative density of the water and polishing compound mixture was also considered and maintained throughout the experiments. This gives the ratio of the density of the liquid to that of water. A hydrometer in combination with a graduated cylinder was used and more polishing compound or water was added to meet a fixed value.

Table 2. Super-smooth polishing experiment conditions

	Study-1	Study-2
Workpiece diameter	25.4 cm	25.4 cm
Tool diameter	30.5 cm	30.5 cm
Rigid aluminum backplate thickness	2.54 cm	2.54 cm
Polishing interface material	Conventional Pitch (CP) #64	Conventional Pitch (CP) #64 Synthetic Pitch (SP) #64 Polyurethane LP-66 on Pitch
Polishing compound	Opaline	Rhodite-906
Tool pressure	0.3 psi	0.3 psi
Spindle speed	50 RPM	50 RPM
Polishing time	1, 2, 3, 5, 8 hours	Until converging to a final PSD (in Table 3)

4. EXPERIMENTAL RESULTS

4.1 Study-1: Surface PSD Evolution through Polishing Time

The change in the PSD as a function of polishing time was monitored to investigate the surface error reduction during the polishing process as a function of spatial frequencies. This can help determine which surface error spatial frequencies become “smoothed” the fastest and which take the most time to plateau to a final magnitude in terms of PSD.

The fine ground Zerodur substrate was polished every half hour using a conventional pitch tool with Opaline polishing compound (detailed polishing parameters in Table 2, Study-1) while the surface map was measured with the MFT after every polishing run. The experiment was conducted until the surface PSD converged to a static curve, which happened after ~5 hours of accumulated polishing run time as shown in Figure 5 (left).

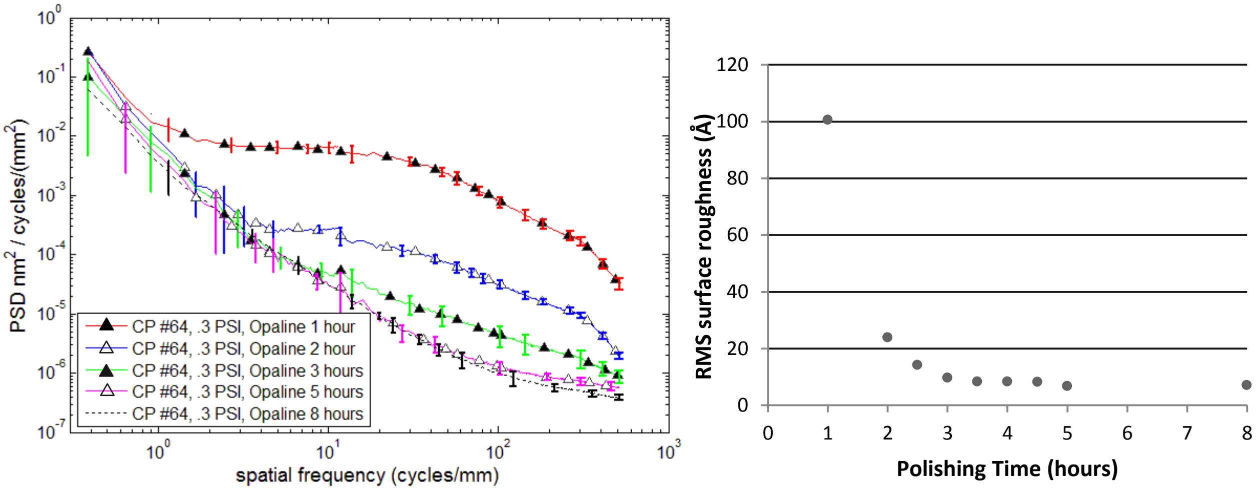


Figure 5. Azimuthally averaged PSD as measured from 1 to 8 hours accumulated polishing time (left) and the RMS surface roughness as a function of polishing time (right). (Note: The error bars represent $\pm\sigma$ (standard deviation) of the data. CP stands for conventional pitch.)

As can be seen in Figure 5 (left) and analyzing the PSD magnitude, the lower frequencies became smoothed the fastest while steadily improving over time until saturating and the higher frequencies took longer to saturate. In terms of RMS surface roughness shown in Figure 5 (right), initially, the surface roughness decreases dramatically over time then it starts to gradually decrease. This measured Zerodur surface RMS went from 100.52 angstroms to 6.82 angstroms in ~4-5 hours.

4.2 Study-2: Comparing the Final PSD between Different Polishing Interface Materials

The smoothing caused by different polishing interface materials was examined. There are numerous polishing interfaces to choose from; the interfaces vary from different blends of pitches to polishing cloths. Since polishing interfaces vary in properties such as viscosity for synthetic and conventional pitch, the interaction between the particles in the polishing compound and the interface may vary causing a unique final PSD for each polishing interface material. Most common polishing interfaces include conventional pitch, synthetic pitch, and polyurethane pads; therefore, those interfaces were chosen for these experiments. The detailed polishing parameters are summarized in Table 2, Study-2.

It was observed from Figure 6 that conventional pitch outperforms polyurethane LP-66 and synthetic pitch in terms of PSD and RMS surface roughness. The magnitude of the PSD for all frequencies considered is much less for conventional pitch and the average RMS surface roughness using the conventional pitch for all repeated experiments (7.16Å) is less than the other two interfaces. The average surface roughness for all repeated experiments using synthetic pitch and polyurethane LP-66 pad is respectively 9.55Å and 14.97Å as seen in Figure 6 (right). However, it is also noticeable that synthetic pitch produces a much smaller standard deviation (from error bars) than the other two interfaces as seen in Figure 6. The synthetic pitch can lead to a more predictable surface finish when completing an optical surface.

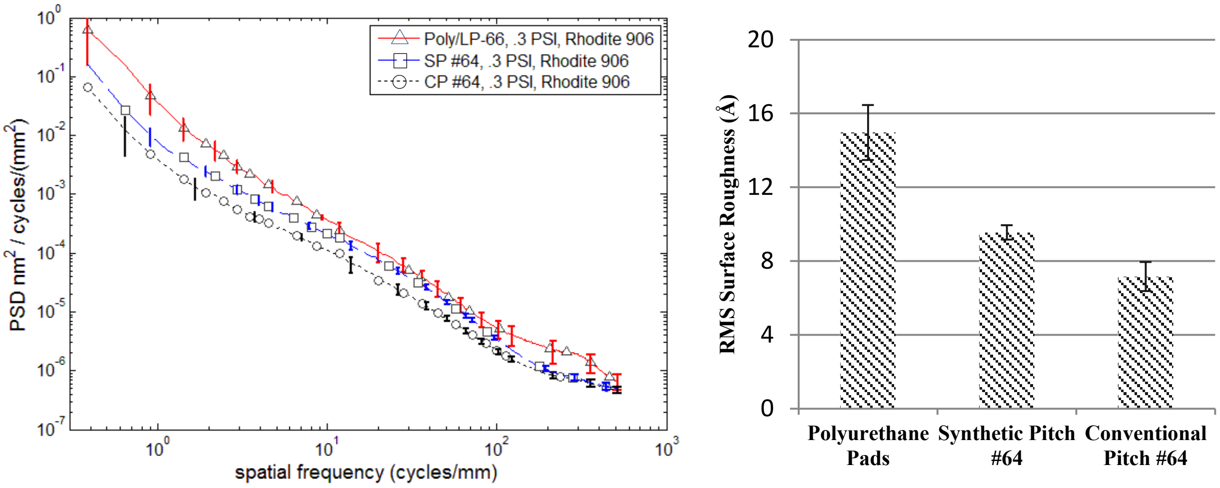


Figure 6. Azimuthally averaged PSD (left) for polyurethane LP-66 pad (Poly/LP-66), synthetic pitch (SP) #64, conventional pitch (CP) #64 and RMS surface Roughness (right) for each polishing interface material. (Note: The error bars represent $\pm\sigma$ (standard deviation) of the data.)

When comparing the time it takes to converge to the final PSD, synthetic pitch and conventional pitch excel as seen in Table 3 as both interfaces achieved this goal within ~4-5 hours. The LP-66 polyurethane pad took about twice as much as synthetic pitch to reach the final PSD.

Table 3. Polishing time to reach the final PSD after 5μm grit size loose abrasive fine grinding

Polishing Interface Material	**Polishing Time to Reach Final PSD**
Polyurethane LP-66	8 hours
Conventional Pitch #64	5 hours
Synthetic Pitch #64	4 hours

5. CONCLUDING REMARKS

The final surface PSD covering mid to high spatial frequency range is closely related with the polishing parameters. The time evolution of PSD during the super-smooth polishing phase right after the fine grinding phase was monitored. The combination of conventional pitch #64 tool with Opaline polishing compound required ~5 hours of accumulated polishing-out time to converge its final PSD. Also, it was verified that the polishing-out time depends on the polishing interface materials. In terms of the final PSD, conventional pitch showed best performance followed by the synthetic pitch. The LP-66 polyurethane pad showed the longest polishing-out time with relatively high PSD curve. For the surface RMS roughness, the conventional pitch with Rhodite-906 polishing compound achieved ~7Å RMS surface roughness.

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