Fabrication of SiC aspheric mirrors with low mid-spatial error

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ABSTRACT

Recent experience with finishing off-axis parabolas and other conic surfaces is demonstrated by some examples that illustrate surface accuracy – not only in terms of traditional metrics, but also in terms of specified ranges of spatial frequency. Particular attention is given to the topic of interferometric metrology, and the extent to which we can effectively characterize mid-spatial frequency errors. The presence of mid-spatial errors can appear even more dominant in hard ceramics like SiC as compared with glass – reasons for this are suggested. This paper will discuss how controlled force grinding, robotic polishing, and surface smoothing can be employed to minimize and mitigate mid-spatial errors in fast silicon carbide aspheric mirrors. Recent experience and results are presented on two SiC mirrors finished by Aperture Optical Sciences Inc.

Keywords: mid-spatial frequency errors, off-axis parabola, aspheric mirrors, SiC, silicon carbide, slope error, robotic polishing, optics fabrication

1. INTRODUCTION

Manufacturing optics for today's most precise reflective imaging systems requires polishing techniques which enable extreme control over surface gradients and periodic features. This is critical for x-ray optics, which, are used at grazing incidence, high damage threshold laser optics, as well as applications in remote sensing, lithography and many other precision imaging applications. Today's manufacturing techniques for producing fast aspheric optics unfortunately also results in the progressive accumulation of mid and high spatial frequency features during grinding and polishing. The amplitudes and frequencies of such features can ultimately limit image quality. Mitigation of such features can be difficult, costly, and time consuming. Corrective finishing of high performance imaging optics must address and mitigate the impact of processes, which create surface features within the mid spatial range. This presents unique challenges to deterministic finishing techniques, which endeavor to employ stable work functions and tool paths to surgically correct for surface errors. While corrective finishing technologies and techniques may correct for errors in one spatial frequency region, they may inadvertently create new periodic signatures, which can further degrade image performance. Manufacturing design must therefore address correction of the full measurable power spectrum to optimize image performance[1].

1.1 Mid-Spatial Frequency Error

There is no definitive, or globally accepted convention for Mid-Spatial Frequency Error ("MSF") yet. However, it is commonly defined as periodic "ripple" or texture in the surface or wavefront occupying the region between "Roughness" on the high spatial frequency ("HSF") side and "Shape" or "Figure" on the Low-Spatial-Frequency ("LSF") side. There are multiple conventions for defining mid-spatial error that we commonly observe in optical drawings. The mid-spatial region defined by the rms gradient optics specification for the National Ignition Facility at Lawrence Livermore National Laboratory applied to spatial scale lengths of 2.5 to 33 mm, or in terms of spatial frequencies: $0.400mm^{-1}$ to $0.030mm^{-1}$. Extreme Ultra-Violet Lithography optics conventions define a specification for Mid-Spatial Frequency Roughness (MSFR) written as the spatial scale lengths from 1mm scale to the micron scale. We most often see the MSF range defined as 1 mm to 10 mm ($1\ mm^{-1}$ to $0.01mm^{-1}$) and have adopted this as our own convention at Aperture Optical Sciences Inc. We use this (1-10mm) MSF region to characterize both surfaces & wavefront errors, and gradients of the same.

1.2 Causes of Mid-Spatial Errors & Periodic Surface Features

There are many origins of Mid-spatial and High-spatial frequency surface errors, not the least of which are created by

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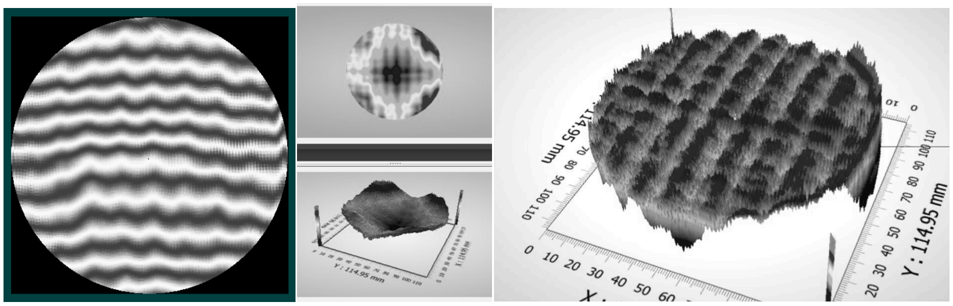
the use of small area tools traversing over defined paths to generate an aspheric form. These tool induced errors can be difficult or impossible to remove since they often persist deep into the surface and subsurface, especially on hard ceramic materials such as Silicon Carbide. Polishing is often ineffective for removing periodic errors unless the tool size and stroke are sufficiently large enough to bridge the spatial period of these errors[2]. By comparison, large tools are well suited to the shaping and finishing of flats, spheres, and in general - optical surfaces with mild, slowly varying curvature. Large tools can avoid creation of periodic errors and reduce or remove any residual errors from earlier processes. While large tools are not a general solution for all optical forms, they are well suited for shaping and finishing of some aspheres – in particular, grazing incidence optics used in X-Ray applications. However, when it comes to fast aspheres, there are few options but to employ small area tools which have the ability to follow steep asymmetric slopes to generate fast aspheric departures. An example of mid-spatial errors in an "un-smoothed" F/2 off-axis parabola is shown in figures 1a-c below.



(1a) (1b) (1c)

Figure 1: Example of Mid-Spatial Error in an unfinished F/2, 45 degree Off-Axis Parabola

1(a): raw interferogram; 1(b): phase map & 3D view of low spatial frequency content (> 10 mm scale lengths);

1(c): 3D view of mid-spatial error (1-10 mm scale lengths)

Mid-spatial errors are not caused entirely by the geometry of the grinding or polishing tools. Other causes include the geometry of the motion path of the tool, overlap in the programmed path, motion control instability, motion control overshoot (accelerations and decelerations), vibration in the finishing machine, tool chatter, tool wear instability, polishing tool deformation, cyclical tool wear, and workpiece deformation such as can be observed as face-sheet print-through from rib structures in light-weighted optics. When finishing hard materials like SiC, causes of mid-spatial errors relating to tool wear, tool deformation, and tool chatter / vibration can be more pronounced due to the increased hardness of the material.

Causes of Mid-Spatial Errors in Optical Polishing

- Overlap in the programmed path of the polishing tool
- Polishing machine motion control instability
- Polishing machine vibration
- Tool-wear (work function) instability
- Polishing tool deformation
- Work-piece surface deformation
- Print through in lightweight optics (face sheet)

1.3 Metrology of MSF Errors

The two fundamental interferometric sensor requirements for accurately characterizing mid-spatial errors are imaging system optical transfer function ("OTF") and the camera resolution. The imaging system optical OTF, must be capable of imaging features of the subject size without significant distortion and the camera detector must have sufficient pixel density to record the features. The first requirement can be empirically determined by calibrating the interferometer using a line-patterned calibration artifact. The second is based on the pixel density availability in the instrument. We generally require at least 5 pixels to define features of a certain wavelength. Therefore, to characterize 1 mm scale length features, we must have image resolution of at least 0.2 mm per pixel. Once data has been acquired, it can be processed in a number of ways to examine amplitudes and frequencies of mid-spatial errors. Which metrics are most useful is the subject of a companion paper by the authors entitled, "Correlation of mid-spatial features to image performance in aspheric mirrors"[9].

2 CONTROL OF MSF DURING FABRICATION

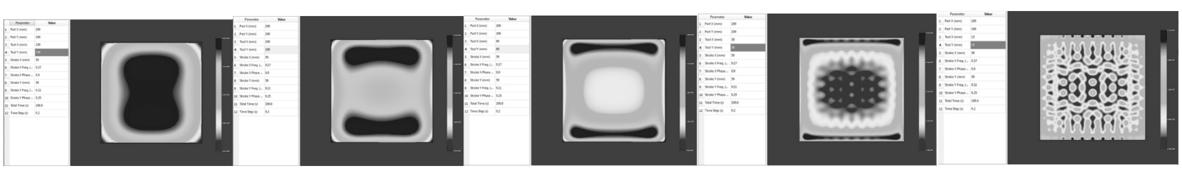
2.1 Small Tool Deterministic Finishing

When employing today's most common technologies for manufacturing fast aspheric optics we must recognize that along with the benefits of precise surface correction afforded by small tools running along a corrective path we must also deal with the equally precise and inescapable trail such tools leave behind. We may not be able to eliminate the use of small tools, but by designing controls into the process sequences during manufacturing, we can minimize the amplitudes of MSF, and then mitigate the residual MSF through surface "smoothing". This is the case with all sub-aperture finishing technologies such as computer Controlled Robotic Polishing ("CCP"), Magnetorheological Finishing ("MRF"), Ion Beam Figuring ("IBF") or Reactive Atom Plasma ("RAP") finishing. Control of mid and high-spatial frequency amplitudes in polished surfaces requires an engineered approach to process design that optimizes material selection, chemistry, tool design, software, and tool path strategies.

2.2 Integrated Process Design

As stated in section 1.2, many of the causes of MSF result from vibration, tool wear, and control system errors. These may be addressed in grinding by utilizing machines of appropriate stiffness, designing mechanically stable tools, selecting appropriate depths cut, and executing adequate dressing cycles. Control system errors can be both hardware and software related and trouble shooting often depends on both acquiring experimental data as well as careful modeling. In addition to these solutions however, AOS recently implemented an enhanced strategy that consists of tool size and path modeling, Controlled Force Grinding ("CFG"), and Conformal Surface Smoothing ("CSS").

To illustrate tool size and path modeling we developed in-house analysis software to be used in conjunction with corrective finishing algorithms to predict the resulting wear patterns as a function of tool dimension. Using this as a tool for predicting the power spectrum of features resulting from a given correction solution, allows us to better control, and in some cases, prevent the build of mid-spatial content in the grinding and polishing processes.



(2a) 150% tool (2b) 100% tool (2c) 60% tool (2d) 30% tool (2e) 15% tool

Figure 2a-e: Graphic Output showing the modeled build up of periodic errors as a function of tool to workpiece ratio

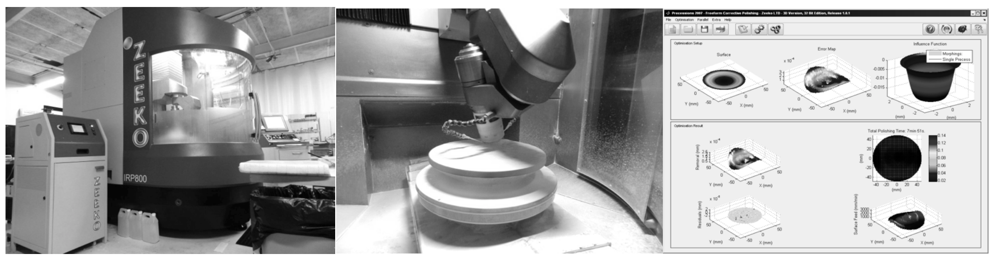
In the illustration above (figure 2a-e), we modeled the polishing of a SiC convex cylinder with a rectangular outer geometry. The figures show the wear over the full surface of the workpiece with different size tools. Each graphic shows the result of the same tool-path sequence but with tools representing a different ratio of tool size to work-piece size. Figure (2a) shows a nearly uniform wear pattern over the surface when the tool measures 150% the dimension of the work-piece. When the tool size is reduced to 100% of the work-piece dimension and the motion sequence is unchanged we observe the emergence of some low frequency lobes (2b). As we reduce the tool size to 60% in Figure (2c) and 30% in Figure (2d), we begin to see the introduction of mid-spatial frequency errors. Finally, when the tool is brought down to 15% of the work-piece dimension, we see the formation of even higher spatial frequencies (Figure (2e)). It should be noted that it is most often the case that corrective influence functions or tools contact "spots" are considerably smaller that 15% of the optics dimensions.

There are many variables at work in the optimization of computer controlled polishing. This illustration merely addresses the impact of tool size in isolation of the other factors. However, it provides a glimpse into the algorithmic control system we've begun to employ to tune a process design optimized for low mid-spatial content.

The process of controlled force grinding involves the control of tool wear during the grinding process. AOS implemented this process using a Zeeko robotic polishing machine – outfitted for a series of fine grinding tools. By measuring removals and wear rates of the grinding surface, we were able to achieve consistent removal rates and low periodic errors during grinding.

This process is incrementally graduated to polishing by replacing coolant for slurry, and grinding tools for polishing pads. Polishing rate, tool size, and contact geometry must be carefully calibrated and regulated to prevent the creation of unwanted surface texture. Correction of specific periodic defects must be targeted within the correction strategy / algorithm. This process is not unlike the traditional process of using progressively smaller polishing tools to knock down the amplitudes of surface waviness. Once amplitudes have been specifically reduced however, the power spectrum of the surface typically shifts toward frequencies proportional to the last tool size and path geometry employed. These frequencies can no longer be mitigated through corrective polishing (and are limited to the smallest contact spot allowed by the process). This tends to be on the millimeter scale for most technologies – which falls square into the MSF range. Correction of such frequencies must be done by "smoothing". The amount of smoothing required can be minimized by machine controls and removal strategies upstream in the process (including grinding). When mid-spatial features are generated during grinding, sometimes tool marks remain in the sub-surface and are not visible until polishing – so it is critically important to control the process throughout.

Figures 3a-c: Zeeko Robotic Polishing at Aperture Optical Sciences Inc.



(3a) Zeeko Machine *(3b) Polishing* *(3c) Zeeko Software Interface*

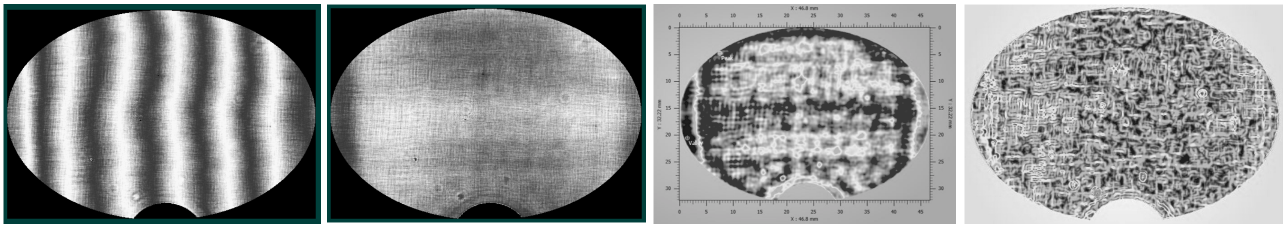
AOS has employed calibrated stock removal protocols and dressing cycles that minimize the depth of periodic structures. Smoothing is still "mostly" done by hand although some automated solutions have been demonstrated. The process of smoothing must exhibit a combination of path randomization and conformal tool fitting to the surface. Hand processing tends to be very effective and is difficult to replace. Unfortunately, it is time consuming and labor intensive. These characteristics make it costly and difficult to scale into production. The effectiveness of hand smoothing stems from the ability to "sense" tool fit and regulate pressure accordingly to optimize friction and fit, without causing damage to the surface. This varies by optic according to its steepness of curvature and slope. Unfortunately, the process of smoothing can also worsen figure error. Therefore, the process of corrective polishing and smoothing must be executed iteratively until both low frequency and mid-frequency errors have been resolved. As arduous a task as this can sometimes be, the rewards of diligent and relentless patience can be great. AOS has employed the process described above and yielded the following results in two very challenging optics. The first is an F/1.4 SiC concave off-axis parabola with 35 microns of aspheric departure. The second is a far more extreme case - an F/1.5 SiC off-axis parabola with over 500 microns of aspheric departure. We have since expanded this process in the finishing of several dozen aspheres since and are moving this process towards serial production readiness. Similar results have been obtained in glass / fused silica optics and mirrors up to 600 mm in size.

3 RECENT RESULTS

The F/1.4 off-axis parabola had an aspheric departure of 35 microns and was made to a PV surface form error of 42 nm and RMS error of 4.4 nm. We have found the gradient to be an effective visual indicator of MSF errors and patterns. This helps us to diagnose the cause of the feature. In figure 4d, we see a relatively uniform distribution of gradient artifacts and have driven such textures below the MSF threshold. The RMS gradient for spatial scale lengths between 1-10 mm was 5.9 micro-radians (1.2 arc-seconds). The distribution of spatial frequencies can be further explored by examining the power spectral density (figure 3e). In this plot we are looking for a combination of low amplitude of frequencies and even distribution. Similar results were obtained for a much steeper asphere having an aspheric departure of more than 500 microns.

The F/1.7 off-axis parabola shown in figures 4a-e had an aspheric departure of over 500 microns and was made to a PV surface form error of 68 nm and RMS error of 10 nm. The RMS gradient for spatial scale lengths between 1-10 mm was

1.8 micro-radians (0.37 arc-seconds). This mirror underwent a considerably more extensive smoothing process for the first, and although had more aspheric departure, resulting in a dramatically improved result. One of the keys to determining when smoothing is needed and when to stop, is knowing how the optic is being used[9] and what the ultimate resolution of the detector electronics is.



(4a) *(4b)* *(4c)* *(4d)*

Figure 4: Data for a finished SiC, F/1.4, Off-Axis Parabola; 4(a-b): raw intensity interferograms;

4(c): phase map (> 1 mm scale lengths); 4(d): Mid-spatial Gradient Analysis (1-10 mm scale lengths)

SiC Concave Off-Axis Parabola
Diameter = 58-mm
Aspheric Departure = 35 mm (approximately, actual design is restricted)
Maximum Aspheric Slope = 200mrad

PV Form Error = 42 nm, RMS Form Error = 4.4 nm
Lateral Resolution = 138 μm/pixel

RMS Gradient Magnitude Analyzed for Mid-Spatial Errors (1-10 mm scale lengths): 5.9 μrad

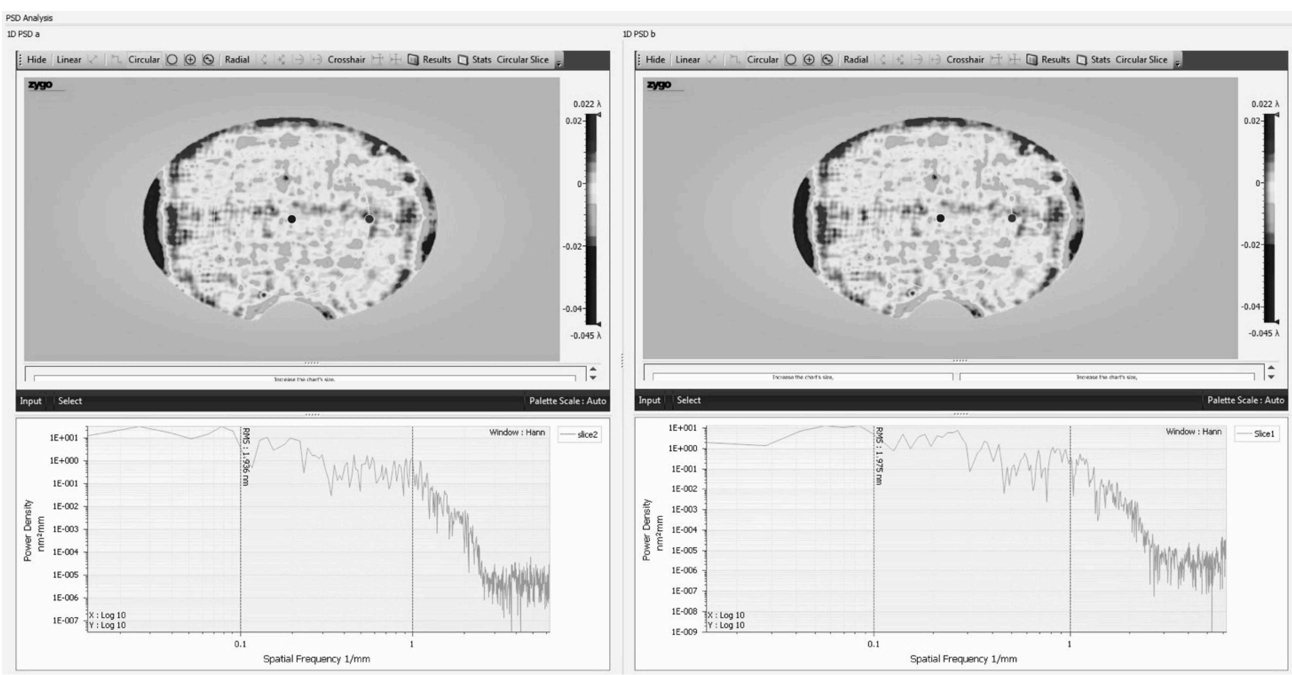
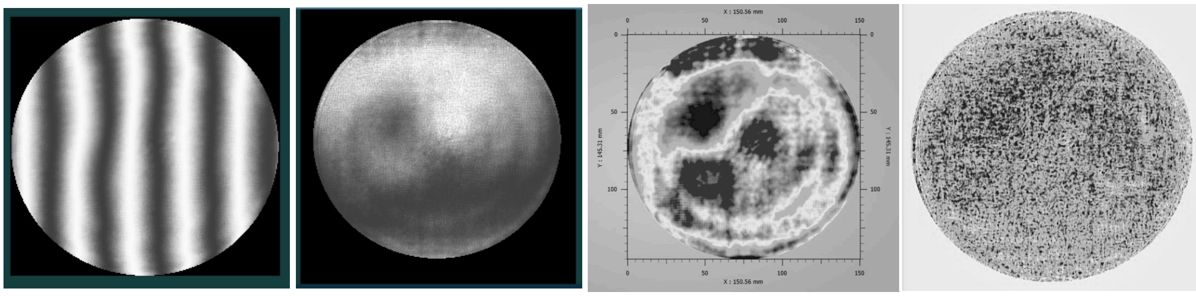


Figure 4e: PSD of finished Off-Axis Parabolic SiC Mirror, F/1.4



(5a) (5b) (5c) (5d)

Figure 5: Data for a finished SiC, F/1.7, Off-Axis Parabola;   5(a-b): raw interferograms;

5(c): 4 phase map (> 1 mm scale lengths);   5(d): Mid-spatial Gradient Analysis (1-10 mm scale lengths)

SiC Concave Off-Axis Parabola
Diameter = 150-mm
Aspheric Departure = 500 mm (approximately, actual design is restricted)
Maximum Aspheric Slope = 400 mrad

PV Form Error = 68 nm,   RMS Form Error = 10 nm
Lateral Resolution = 138 µm/pixel

RMS Gradient (magnitude) Analyzed for Mid-Spatial Errors (1-10 mm scale lengths): 1.8 µrad

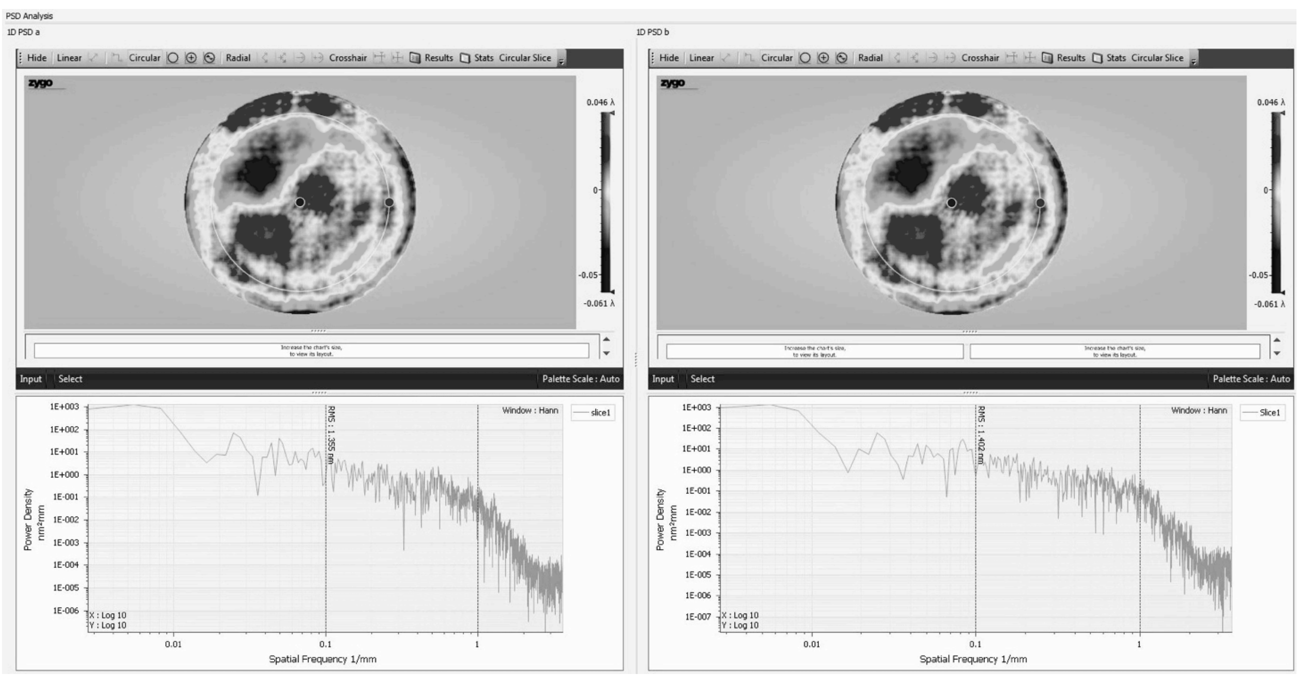


Figure 5e: PSD of finished SiC Mirror, F/1.7

4 CONCLUSIONS

Recent polishing results on SiC off-axis parabolas demonstrate the possibility of fabricating surfaces with minimal mid-spatial gradient error on the order of 2 micro-radians for spatial periods of 1-10mm. These examples do not necessarily represent process limits but are useful for showing characteristic data.

Optimized results required a combination of process design and technologies, which both minimize the introduction of mid-spatial texturing plus the mitigation of small tool polishing residues through surface smoothing techniques. Obtaining such results required interferometric metrology with both high image quality and data densities of less than 200 microns per pixel. Mid spatial content was evaluated using RMS gradient and Power Spectral Density metrics. This process has been repeated on a variety of aspheres in both glass and silicon carbide on surfaces as fast as F/1.4.

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