Aspheric Finishing of Glass and SiC Optics

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Abstract: Aperture Optical Sciences Inc. was founded in 2010 to develop and produce advanced aspheric optics in silicon carbide and other materials. This paper explores Zeeko robotic polishing as an effective technology for aspheric finishing.

Introduction

Aperture Optical Sciences Inc. was founded in 2010 to develop and produce advanced aspheric optics in silicon carbide (SiC) and other materials. This paper explores Zeeko robotic polishing as an effective technology for aspheric finishing as well as continuing efforts to combat the prevalence of periodic surface features, which often result from the use of deterministic finishing processes.

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, remote sensing and many other applications. AOS has and continues to develop analysis and manufacturing processes, which optimize corrective finishing of such extreme optics – particularly to mitigate the impact of mid-spatial surface errors on image performance. This paper will discuss robotic polishing, the benefits it provides and some of the remaining challenges. Our recent experience with finishing SiC is demonstrated by some examples that illustrate what we and our industrial peers can now produce with this technology.

Robotic Polishing

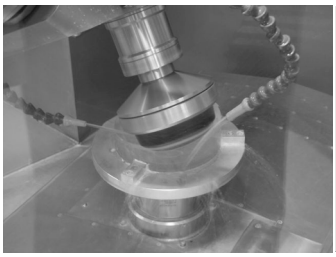
Robotic polishing addresses the fundamental problem in aspheric fabrication of surfaces by controlling both the tool contact geometry and the polishing tool motion over the aspheric surface to precisely correct for errors in surface form. This process is dependent on accurate measurement of the surface prior to polishing. Interferometric maps of the surface form are translated into machine instructions, which guide the corrective polishing process. However, 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, and tool path strategies.

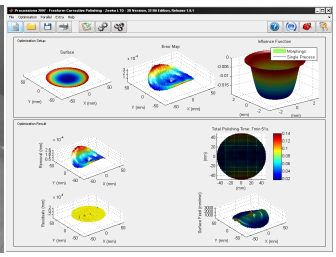
The Zeeko solution employs a seven-axis robotic platform, which traverses the surface of the workpiece with a user defined polishing tool and abrasive. The tool contact geometry, dwell time, and pressure may all be varied and serve as degrees of freedom to achieve a corrective solution to a user input error map obtained with mechanical or optical metrology. Calculation of a corrective solution also depends on the input of an accurate characterization of the "influence function", or volumetric removal function over a defined geometry. This is achieved by having the polishing tool dwell over a fixed spot on a calibration sample and then interferometrically measuring the geometry of the removed material. As a result of process instabilities, and possible errors in the inputs to the correction plan, 100% predictability of actual material volume is never fully achieved - requiring an iterative process of sequential measurements, calculations, and polishing runs. Keys to managing an acceptable convergence rate include accurate input metrology, calibration of the influence function and maintaining stability of the process parameters.

A large element of the success or failure of robotic polishing (as well as any form of deterministic finishing) is the accuracy of the measurements made to the surface to be polished. Some of the major sources of error in collecting and processing such data include:

- Ambiguity in magnification and orientation of interferometer data
- Geometric distortion in the XY plane of the interferometer data
- Difficulties locating fiducials on the wavefront image
- Large slopes in the optic surface making measurements irresolvable in some areas of the optic surface

Zeeko Robotic Polishing at Aperture Optical Sciences Inc.





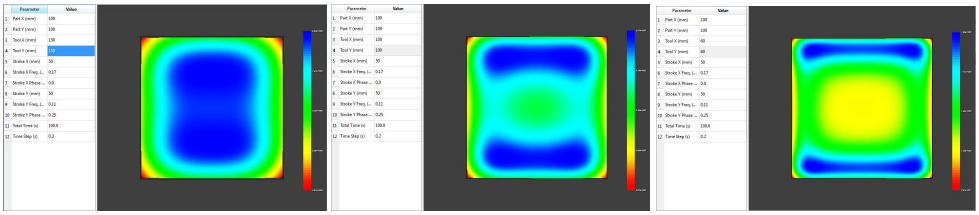
Control of Mid-Spatial Frequency Features & Silicon Carbide

There are many origins of Mid-spatial and High-spatial frequency surface errors, not the least of which are created by the use of small area tools and tool indexing during the generating of an optical form. These 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[1]. By comparison, large tools are well suited to the shaping and finishing of 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.

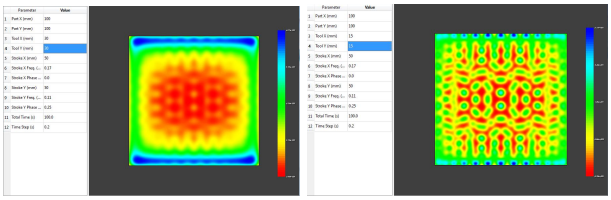
Causes of Mid-Spatial Errors in Optical Polishing

- Overlap in rastered or spiraled sub-aperture tool paths over large surfaces
- Machine (tool) motion control instability
- Machine vibration
- Tool-wear instability
- Periodic patterning in work tool surface geometry
- Tool deformation
- Work-piece deformation

To illustrate this point we developed analysis software to be used in conjunction with corrective finishing algorithms (such as those used in the Zeeko software suite) 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, allowed us to better control, and in some cases, prevent the build of mid-spatial content in the polished surface.



(a) 150% tool (b) 100% tool (c) 60% tool



(d) 30% tool (e) 15% tool

In the illustration above, we modeled the polishing of a SiC convex cylinder with a rectangular outer geometry. The

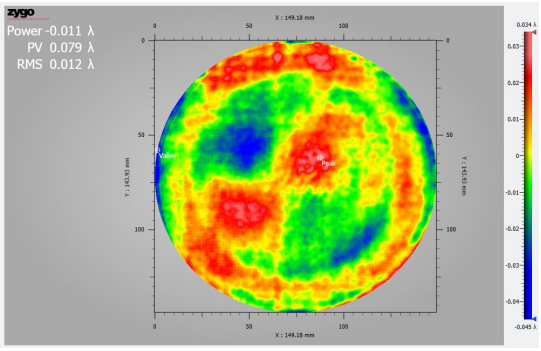
figures show the wear over the full surface of the workpiece with different ratios of tool to workpiece dimension. Figure (a) shows a nearly uniform wear pattern over the surface when the tool measures 150% the dimension of the work-piece. When the tool size is reduced to 100% of the work-piece dimension and the motion sequence is unchanged we observe the emergence of some low frequency lobes (b). As we reduce the tool size to 60% in Figure (c) and 30% in Figure (d), 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 (e).

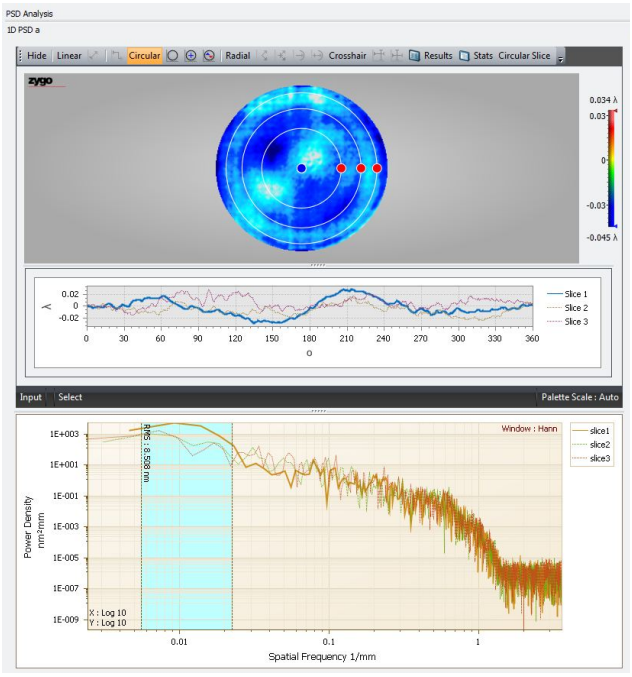
There are many variables at work in the optimization of computer controlled polishing. This illustration merely addresses the impact of tool size in isolation of the other factors. However it provides a glimpse into the algorithmic control system we've begun to employ to tune a process design optimized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

These effects can have a lesser or greater impact as a function of the substrate materials' mechanical properties such as hardness, fracture toughness, chemical durability etc. implying that the control and smoothing of mid-spatial errors is not only process specific but also material specific. Therefore, reliable and cost competitive manufacturing processes of hard ceramics requires an engineered process strategy that may or may not bear similarity to those employed on traditional glasses.

Recent Results

An example of recent results we've obtained using this combined approach of mid-spatial error prediction & process control plus Zeeko robotic polishing is shown in the following figures. The substrate is a 150-mm off-axis SiC parabolic mirror with an aspheric departure from a sphere of over 500 microns. This mirror was polished to a Peak to Valley form error of 0.079λ and RMS form error of 0.012λ for spatial scale lengths greater than 2-mm. RMS Gradient of the surface was < 2.6 μradians.





Overview of AOS

Aperture Optical Sciences Inc. develops and employs advanced technology for making aspheric mirrors and lenses, SiC optics, optics for high energy lasers and engages in developmental processes of advanced materials. AOS optics are deployed in aircraft vision systems, research facilities using advanced lasers, and remote sensing applications.

AOS was formed in 2010 by Flemming Tinker and Kai Xin PhD. Our principal products are Silicon Carbide optics, Aspheric mirrors and lenses, laser optics, and precision optronics. Our customers are located in the United States, Europe and Japan. AOS established and maintains an advanced optics manufacturing facility in Central Connecticut.

[i] [i] D. Anderson and J. Burge, "Optical Fabrication," Chapter 26 in *Handbook of Optical Engineering*, D. Malacara and B. J. Thompson, eds.,(Marcel Dekker, New York, 2001).