Control of Mid-spatial-frequency Errors for Large Steep Aspheric Surfaces

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Abstract: Control of mid-spatial-frequency errors on precision optical surfaces is very important for next-generation optical systems. We present results of smoothing experiments and of polishing runs utilizing figuring and smoothing for the 8.4m GMT off-axis segment.
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1. Introduction

Correcting mid-spatial-frequency errors on optical surfaces has become very important for the next generation of high precision optical systems such as E-ELT, LIFE, and the 24.5m Giant Magellan Telescope [1-3]. Since mid-spatial-frequency errors affect the sharpness of the point spread function (e.g. Airy disk diameter) control of these frequency components is essential to ensure the performance of the optical systems. For instance, most of the recent large precision optics including the 8.4m diameter GMT primary off-axis segment need to be polished until the surface satisfies a target structure function or power spectral density, which states the form accuracy as a function of spatial frequency [4].

Various computer-controlled optical surfacing (CCOS) processes provide efficient means to fabricate precision optics based on their deterministic removal processes. By spending more time on high areas, a well-calibrated computer-controlled polishing tool can figure the optical surface in a predictable manner. Many large aspheric optical surfaces and off-axis segments have been successfully fabricated using these CCOS techniques [5-8]. However, these 'figuring' processes based on dwell time are fundamentally limited to the correction of low-spatial-frequency errors (i.e. errors larger than the tool size). For instance, a 500mm diameter tool cannot spend more time only on a 20mm wide peak area without touching the surrounding areas.

The 'smoothing' process therefore becomes important because it is a convenient way to correct mid-spatial-frequency errors while still using large tools [9-10]. The smoothing effect can be easily described for an infinitely rigid tool as shown in Fig. 1. Such a rigid tool does not fit the surface irregularity under the tool, and the tool only rubs the highs on the surface. As the tool runs over the surface, it will wear down only the highs, and eventually the surface will be smoothed out.

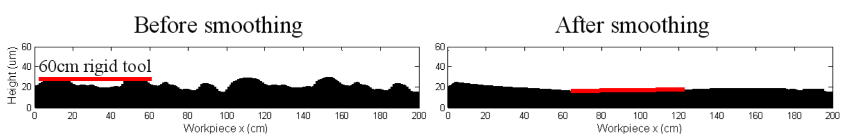

Fig. 1. Smoothing simulation for a infinitely rigid tool [10]

Mid-spatial-frequency errors can be corrected in both ways, figuring and smoothing. The figuring approach uses smaller and smaller tools to correct the relevant frequencies. However, smaller tools require higher tool positioning accuracy to avoid tool marks, which may add mid-spatial-frequency errors to the surface. Also, the total fabrication time will increase due to the small working area of the tools. The smoothing approach uses the smoothing effect from large stiff tools (e.g. stressed lap [8]). In this approach, understanding the smoothing effect quantitatively is crucial since the predictability determines the convergence rate.

This paper presents some experimental results showing the smoothing effect for different polishing tools, and provides actual CCOS results utilizing both figuring and smoothing methods to fabricate the 8.4m GMT segment.

2. Parametric smoothing model and measured smoothing factors

The parametric smoothing model to describe smoothing effects for various polishing tools was introduced in 2010 [10]. The smoothing factor *SF* was defined as the ratio of smoothing to bulk removal, or $\Delta\varepsilon$ / Δz, where ε is the p-v surface error at a particular spatial frequency and z is the average surface height. It depends on the initial surface error ε_{ini} and that dependence can be parameterized as

$$SF = k \cdot (\varepsilon_{ini} - \varepsilon_0) \qquad (1)$$

where k is the sensitivity to initial error and ε_0 is the minimum error for which smoothing occurs.

Using the parametric smoothing model in Eq. (1), a polishing tool's smoothing efficiency can be represented as a linear function of ε_{ini}. The two parameters can be easily determined by performing few sets of smoothing runs.

Series of smoothing experiments using various polishing tools were performed to investigate the smoothing effects as a function of polishing tool parameters such as pitch type. Three interesting cases are compared in Fig. 2. A complete set of the smoothing results will be presented in a separate paper [11].

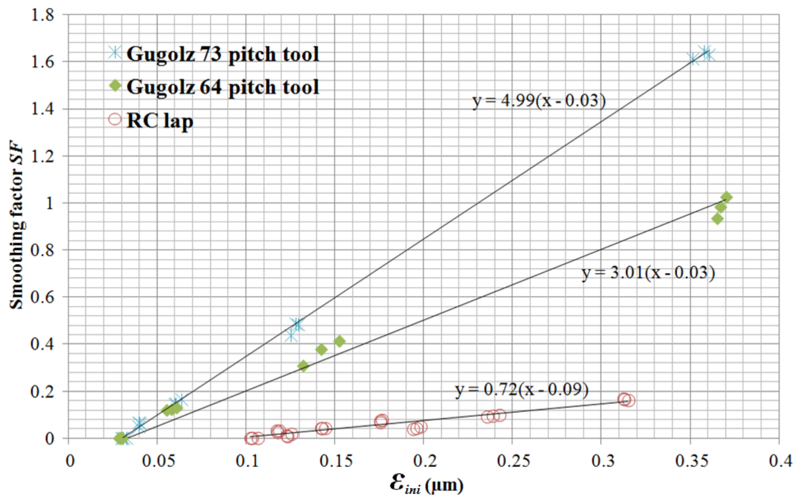

Fig. 2. Measured smoothing factor *SF* for two rigid tools using different pitch types and a Rigid Conformal lap with polyurethane polishing pad. [10]

The rigid pitch laps showed higher smoothing factors than the Rigid Conformal (RC) lap by 4-7 times steeper slope k. It is clear that the pitch tool is more effective than the RC lap with the polyurethane polishing pad. By comparing two common pitch types, Gugolz 73 (harder) and 64 (softer), Gugolz 73 showed ~1.7 times higher *SF* values, which verifies the empirical rule, "Harder pitch smoothes better," quantitatively.

3. Mid-spatial-frequency error control for 8.4m GMT primary off-axis segment

As the target specification is given in terms of structure function, the 8.4m GMT primary off-axis segment requires good control of mid-spatial-frequency errors. Both figuring using small (50-300mm in diameter) tools and smoothing using a large stressed lap (1200mm diameter) with pitch have been used in balance as shown in Fig. 3-4 to control the mid-spatial-frequency errors on the segment at the Steward Observatory Mirror Lab, University of Arizona.

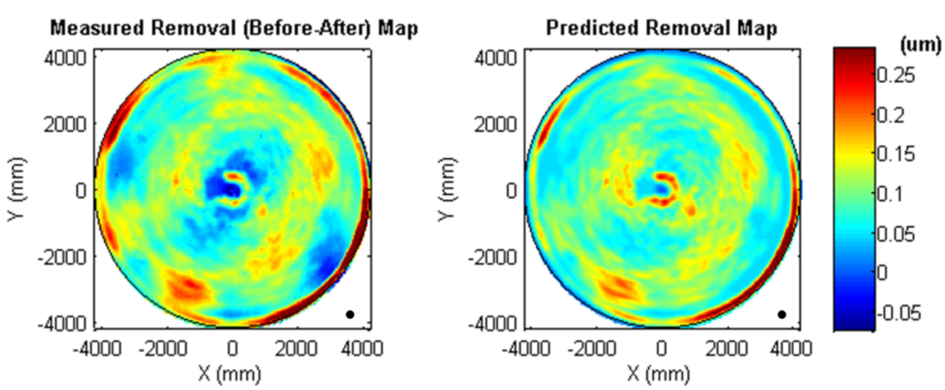

Fig. 3. Comparison between the measured and predicted removal map for a figuring run targeting mid-spatial frequency errors on the 8.4m GMT primary segment. The 250mm diameter RC lap used for the run is depicted in scale as a black disk at the bottom-right corner. (Note: Red areas (higher value) mean more removal.)

A result of a 44 hour figuring run using a 250mm RC lap is presented in Fig. 3. A filtered target removal map (i.e. surface error map) was used to optimize the dwell time distribution of the tool on the workpiece before the figuring run. As shown in the predicted removal map in Fig. 3 (right), the run is mainly targeting errors larger than the tool size (black disk at the bottom-right corner). After the run, the measured removal (i.e. difference between the before and after map) was calculated and compared with the predicted removal. The measured removal (left) matches very well with the predicted removal (right), which demonstrates the effectiveness of the figuring approach to correct those mid-spatial-frequency errors.

A smoothing run of 40 hours using the 1200mm stressed lap with pitch is presented in Fig. 4. This run was expected to smooth out features smaller than the 250mm RC lap. The before and after GMT segment surface map (high-pass filtered with 0.0067mm^{-1} cut-off frequency and zoomed in to ~1.7 x 1.7m area) is shown in Fig. 4 with the sizes of the 1200mm stressed lap (dotted circle) and the 250mm RC lap (black disk) indicated.

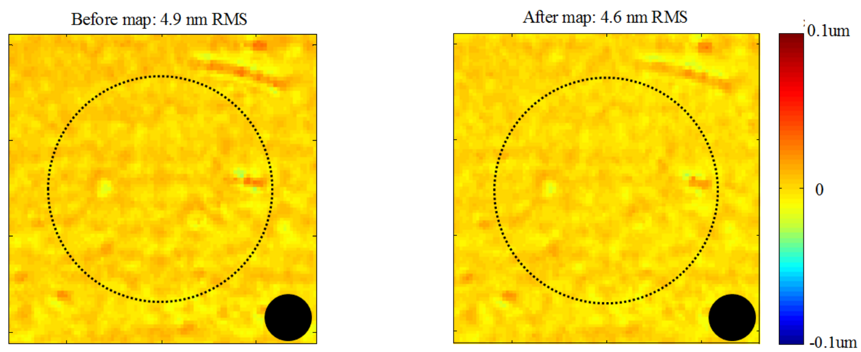

Fig. 4. Comparison between the before and after surface maps for a 40 hour smoothing run using a 1200mm stressed lap with pitch. The maps are high-pass filtered with 0.0067mm^{-1} cut-off frequency, and zoomed in to ~1.7 x 1.7m area on the 8.4m GMT primary segment.

Mid-spatial-frequency features smaller than the 250mm RC lap cannot be easily improved by figuring, since running a tiny (e.g. ~50mm) tool over the whole 8.4m GMT segment requires a high fidelity target removal map, very stable tool removal rate over hundreds of hours, and precise tool positioning accuracy. In this particular run with the 1200mm stressed lap, the surface RMS was reduced by ~6% (from 4.9nm RMS to 4.6nm RMS). A generalized parametric smoothing model to assess smoothing effects, not only for well defined sinusoidal ripples [10] but for realistic irregular surface maps (e.g. Fig. 4), has been developed and will be presented as a separate paper [12].

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