Specification of Optical Surfaces with Anisotropic Mid-Spatial Frequency Errors

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Abstract: Mid-spatial frequency (MSF) errors impact optical performance. Conventional surface specification methods assume isotropy, which gives misleading results for surfaces with anisotropic errors. We propose an alternate surface specification method. © 2019 The Author(s)

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1. Introduction

Bandlimited RMS of surface height data is widely used within the metrology, manufacturing, and optical design communities for specification of optical surfaces with mid-spatial frequency (MSF) errors [1-3]. Calculation of the RMS is not sensitive to the shape or distribution of the surface errors. However, oftentimes surfaces which pass the required RMS specification do not perform as expected within the optical system. This leads to confusion between designer and manufacturer and increases fabrication cycle times and costs. As a result, surfaces are often over-specified to overcome this challenge.

MSF errors are structured error types, caused by sub-aperture tools, and appear on the surface with different signatures (e.g. turned, milled, spiral) that comes from different fabrication techniques. These signatures have different anisotropy levels which are not sufficiently specified by surface RMS; *surfaces with the same RMS but different manufacturing signatures can have different optical performance* [4]. Therefore, it is crucial to take surface anisotropy into consideration for accurate specification of optical surfaces.

In this paper, we propose a new surface specification method for MSF errors which quantifies the surface RMS along all surface orientations through polar representation of RMS values. We demonstrate the connection of this approach to optical performance acceptance criteria through the modulation transfer function (MTF). For isotropic surfaces, results from the proposed method converge to results from statistical approaches for specification and tolerancing of MSF errors [2, 3].

2. Methods and Discussion

Anisotropy of MSF errors, in the form of different periodicities and signatures, is seen by the incident beam and impacts the optical performance. To be able to capture the RMS of all structured errors in different directions, we rotate a measured surface map at small angles (e.g. 1°), calculate the bandlimited RMS for each column of data, and then pick the maximum value between all columns at each rotation angle. This way, we are able to find the worst RMS value which translates to the most impact on the optical performance at a specific rotation angle. Plotting these RMS values with respect to the rotation angle in polar coordinate results an intuitive 'Polar RMS Plot' (PRP). Sample PRPs are shown in Figure 1 for both synthetic and experimental surface data. For the case of a surface with perfectly isotropic errors, the resulting PRP is a circle with a radius equal to the surface RMS.

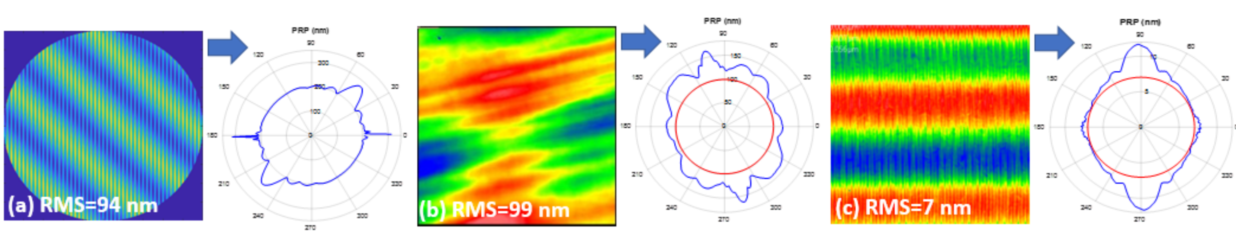

Fig. 1. PRP's for (a) An unrealistic synthetic MSF error with diamond cusp errors at 0° and sinusoidal errors at 45°; (b, c) Measured mid-spatial frequency errors from raster-ground SiC surfaces. The red circle in each plot corresponds to the equivalent isotropic PRP value.

For the purpose of illustration, Fig. 1(a) shows the PRP for an unrealistic synthetic MSF error with diamond cusp errors (of period 40 µm) oriented at 0° and a sinusoidal error (of period 0.5 mm) at 45°. We note that each error on the surface appears as a peak on PRP in the same direction, the peak width is wider for lower spatial frequency errors, and the peak amplitude is relative to the peak to valley (PV) of each error. Thus, a quick look at the PRP provides useful information about the surface errors. Figure 1 (b, c) shows the PRP calculation for experimental surface data.

It is useful to consider connections between the PRP and the Modulation Transfer Function (MTF). From statistical approaches [2, 3], the MTF for an isotropic surface with RMS = σ can be calculated as:

$$MTF = \exp[-(\frac{2\pi}{\lambda})^2 \sum_{i=1}^{N} (n_i - n_i^{'})^2 \sigma_i^2] \times MTF_{diff\,\lim} \qquad (1)$$

where λ is wavelength of application, and n is the refractive index. Similar to tolerance methods for controlling form errors, this is the MTF value a designer expects to obtain from a surface with a given RMS. Therefore, we assign this as the MTF acceptance for a given bandlimited RMS value. As an example, Fig. 2 shows the PRP and MTF acceptance drawing for a f/25 PMMA lens at λ=532nm with RMS=70nm.

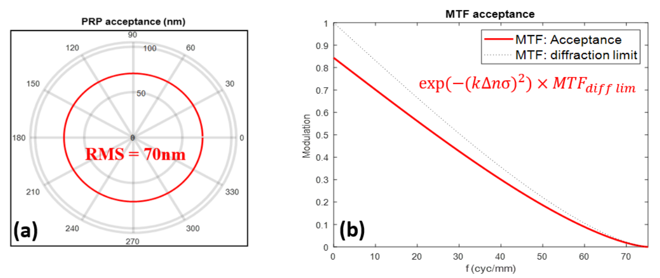

Fig. 2. (a) PRP acceptance for bandlimited RMS=70nm. (b) MTF for a f/25 PMMA lens at λ=532nm, with an isotropic surface with RMS=70nm.

3. Example

For a surface with anisotropic MSF errors, the MTF is expected to perform above the red acceptance line as long as the surface PRP is within the red circle. To illustrate this point, we consider the same lens as in Figure 2 but with a structured linear sinusoidal error (Fig. 3(a)). Figure 3(b) shows PRP and MTF simulations in blue for a 2mm sinusoidal surface with RMS=70nm and 8cycles/aperture periodicity. The PRP shows peaks outside of the red (acceptance) circle in the direction of the sine periodicity, and the MTF drops below the acceptance line for an isotropic surface with 70 nm RMS. This example indicates that overlooking the structured nature of MSF errors could lead to a specification failiure. In Fig. 3(c), reducing amplitude of the sinusoid such that RMS = 50nm while keeping everything else the same shrinks the PRP such that the peaks just touch the red acceptance circle and the resulting MTF is just above the red acceptance line. This result suggests that the proposed approach can provide a means to assign quantitative specification and acceptance criteria for optical surfaces with both isotropic and anisotropic MSF errors.

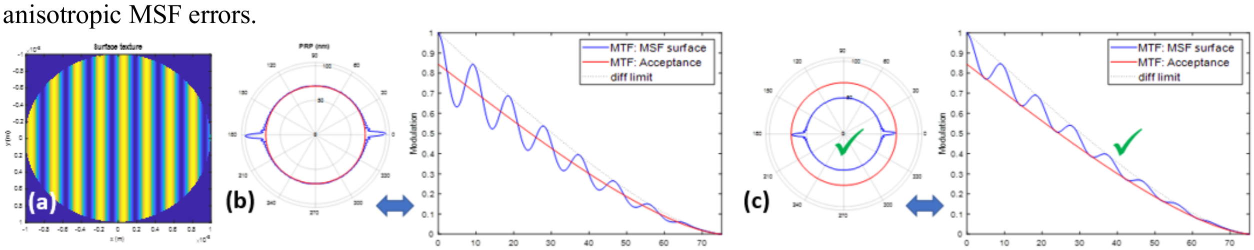

Fig. 3. (a) Surface with linear sinusoidal error. (b) RMS=70nm: PRP and MTF for the lens in blue and acceptance line in Red. (c) RMS=50nm: both PRP and MTF meet acceptance lines.

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5. References

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