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Aspheric optics: smoothing the ripples with semi-flexible tools

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Abstract. A well-known fabrication problem with aspheric optical surfaces lies in high-frequency surface irregularities inherent in the figuring process. Optical grinding and polishing tools can smooth these ripples, yet retain the flexibility required to fit the aspheric surface. An *f*/0.52, paraboloidal, 17-in. convex surface is produced with conventional rigid tools. A transmission ronchigram is obtained showing high-spatial-frequency errors of large magnitude. After four hours of grinding with a semi-flexible multiple-segment ring tool, almost all high-frequency error is removed. This shows good potential for smoothing finished aspheric optics. Flexible tools can also be involved in the figuring process itself.

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1 Introduction

The production of aspheric optical surfaces has traditionally employed small rigid tools to grind and polish the aspheric surface. Good results can be achieved in obtaining the desired overall shape, however, high-spatial-frequency ripples are often evident in the finished surface.

These surface ripples come about because the rigid tools do not fit the aspheric surface well, which causes areas of high polishing pressure at the edge of the tool to develop. This high pressure, combined with low stroke velocity at the endpoints of the stroke, cause high wear rates at the stroke maxima. Variation of the stroke position and length to remove the desired volume of glass can cause multiple radial grooves to develop. These grooves may be closely spaced or randomly distributed, but in either case, they are areas of high slope error, thus containing high-spatial-frequency components. By polishing over these ripples, one can smooth them out, but new grooves tend to develop simultaneously, so the process may not converge, and the finished surface may not improve significantly. Historically, these high-frequency ripples have been a common feature in aspheric optical surfaces.

2 Tool Design

One technique to remove these ripples is to employ semi-flexible tools, which bend to conform to the aspheric surface.[1] A properly designed tool will have adequate compliance over large scales to fit the low-frequency regime well (defined by the aspheric departure), and will not affect the overall shape of the surface. This same tool can have much higher polishing pressure for the high-frequency regime (surface ripples and steep slope errors).

The required flexibility is defined by tool geometry, position, and aspheric parameters. It can be shown that the required bending of a circular tool is an infinite series of circular polynomials, which can be expressed as the Zernike set. The strains induced by bending thin plates to fit an asphere influence the polishing pressure across the tool. Kirchhoff's thin plate equations are modified to include the effect of transverse shear strain. By modeling the surface as a Fourier series we can show that polishing pressure is a function of spatial frequency. For the one-dimensional case, we can derive Eq. (1) based on the theory of elasticity[2]:

$$p=q_0+\sum_{\xi}\frac{1}{\dfrac{1}{D(2\pi\xi)^4}+\dfrac{1}{D_s(2\pi\xi)^2}+\dfrac{1}{k_c}}s(\xi), \tag{1}$$

$$D=\frac{Eh^3}{12(1-\nu^2)}$$

and

$$D_s=\frac{Eh}{2(1+\nu)}.$$

In Eq. (1), p is the polishing pressure, q_0 is the applied pressure, D is the flexural rigidity, D_s is the transverse shear stiffness, k_c is the compressive stiffness of the pitch, ξ is the spatial frequency of the component in question, $s(\xi)$ is the amplitude of the surface error at spatial frequency ξ, and the plate parameters are: E is Young's modulus, ν is Poisson's ratio, and h is the thickness.

There are three domains with which to concern ourselves: low frequencies dominated by plate bending, middle frequencies dominated by shear stress, and high frequencies dominated by pitch compression. For good results, we want to be in the bending domain. In the bending domain, the pressure is proportional to the fourth power of the spatial frequency, ξ, preferentially polishing higher frequencies. This regime reduces surface ripples with less effect on low frequencies (bending due to aspheric misfit). In the shear domain, the pressure is proportional to the square of the spatial frequency and the polishing pressure is 180 deg out-of-phase with the surface, meaning that the surface gets worse with polishing. In this situation, the polishing cycle (feedback loop) is unstable. In compression, there is no dependence upon spatial frequency and the "filter" is again in-phase, but all frequencies are attenuated equally, which reduces the lower-frequency surface error as well as high-frequency ripples.

By treating the thin plate/pitch tool as a filter, we can model how each Fourier component is attenuated by polishing. Each polishing stroke is equivalent to one pass through the feedback loop. Since it is a feedback phenomenon, there is a possibility that the system can become unstable. It is stable when the phase of the transfer function is

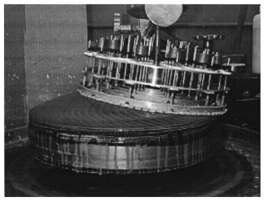

Fig. 1 Semi-flexible ring tool grinding a 17-in., *f*/0.52, paraboloidal convex surface at the University of Arizona's Optics Shop at the Optical Sciences Center (Courtesy Burge, Anderson, et al.[1]).

0 or 360 deg, and polishing pressure is in-phase with the surface. Shear-dominated frequencies are 180 deg out of phase and thus are inherently unstable. Optimal tool design should therefore take into consideration that any reasonable frequency range needs to be in the bending-dominated regime. It can be shown that the bending-dominated regime has a direct 360 deg transition to the compression-dominated regime if the thickness of the plate is less than

$$t=\frac{3E(1-\nu)}{k_c(1+\nu)}. \tag{2}$$

Under normal circumstances, the thickness of the plate will be well below this critical value. Equation (3) defines this transition frequency (double pole) in terms of compressive stiffness and flexural rigidity:

$$\xi_f=\frac{1}{2\pi}\sqrt[4]{\frac{k_c}{D}}. \tag{3}$$

A well-designed tool will be compliant to low-frequency bending, defined by the bending to fit the tool to the aspheric surface, as well as being rigid to high-frequency surface errors. Optimal tool design for a given task takes all factors into consideration and finds a balance between them. Two major classes of such tools have been developed. The first is a thin plate or shell with a compliant backing. The second is a series of cylindrical rings, which are free to flex (depending upon the material properties and ring geometry). A tool of this second type is shown in Fig. 1.

3 Experimental Results

At the University of Arizona, a 17-in.-diam, *f*/0.52, paraboloidal, convex surface was produced with conventional rigid tooling. A null ronchigram was obtained in transmission, through the ground surface, showing a reasonable surface figure with many high-frequency features in evidence. This ronchigram is shown in Fig. 2(a). After smoothing with the ring lap for four hours,[1] the ronchigram shown in Fig. 2(b) was obtained. The grinding process with the ring tool is shown in Fig. 1.

The same surface was then ground with a flexible-plate tool, further smoothing it, as well as figuring the surface. Spherical aberration was observed in Fig. 2(b), which was reduced in five hours of figuring with the flexible-plate tool.[1] This null ronchigram is shown in Fig. 2(c). We see that the lines are almost straight and smooth, with one tool performing both smoothing and figuring simultaneously.

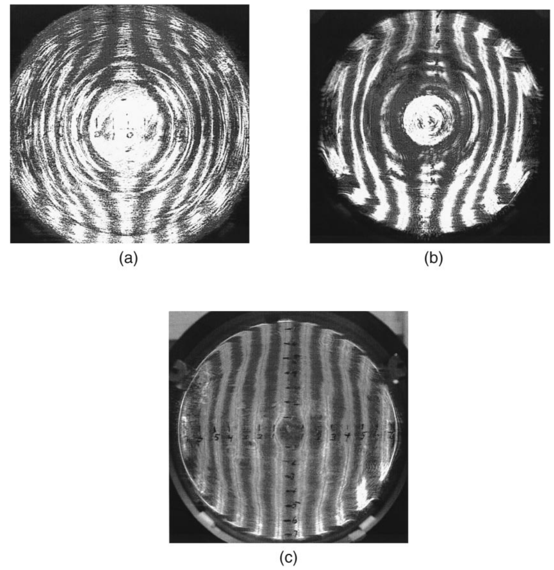

Fig. 2 Null ronchigrams in (single-pass) transmission of paraboloidal, *f*/0.52, 17-in. convex/plano lens while in grinding phase of fabrication. (a) After asphеrization with rigid tools, (b) after four hours of grinding with the five-segment ring lap shown in Fig. 1, and (c) after five hours of grinding with a flexible-plate tool. (Courtesy Burge, Anderson, et al.[1])

4 Conclusions

This dramatic improvement in high-frequency errors shows the enormous potential for flexible tools in the production of aspheric surfaces.[1–3] Furthermore, these same tool types can be used for initial figuring of the asphere as well as smoothing errors in the nearly finished surface.[1,4] High-frequency errors generally do not manifest in the surface with flexible tools because the fit is better and these trenches do not form as easily. Further research is continuing in connection with thin plates and shells for figuring and smoothing aspheric optical surfaces.

Acknowledgment

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