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Shape Optimization of High Performance X-Ray Optics

F. Siewert, H. Lammert, T. Zeschke, T. Hänsel, A. Nickel, and A. Schindler

Abstract. A research project, involving both metrologists and manufacturers has made it possible to manufacture optical components beyond the former limit of 0.5 µrad in the root mean square (rms) slope error. To enable the surface finishing, by polishing and finally by ion beam figuring, of optical components characterized by a rms slope error in the range of 0.2 µrad, it is essential that the optical surface be mapped and the resulting data used as input for the ion beam figuring. In this chapter the results of metrology supported surface optimization by ion beam figuring will be discussed in detail. The improvement of beam line performance by the use of such high quality optical elements is demonstrated by the first results of beam line commissioning.

12.1 Introduction

To benefit from the improved brilliance of third generation synchrotron radiation sources and sources such as energy recovery linacs (ERL) or free electron lasers (FEL), optical elements of excellent precision characterized by slope errors clearly beyond the state of the art limit of 0.5 µrad rms for plane and spherical shapes are needed [1, 2]. The challenging specifications for such beam-guiding elements can be fulfilled by deterministic technology of surface finishing, for example, by ion beam finishing (IBF) or computer controlled polishing (CCP) [3, 4]. It is essential that the surface finishing be supported by metrology instruments of accuracy 3–5 times superior to that of the desired end product.

12.2 High Accuracy Metrology and Shape Optimization

Here a short description of the optimization of the surface of optical components based on ion beam technology is given. To demonstrate the capability of IBF supported by advanced metrology, three demonstration components have been shape-optimized after classical and chemical–mechanical polishing

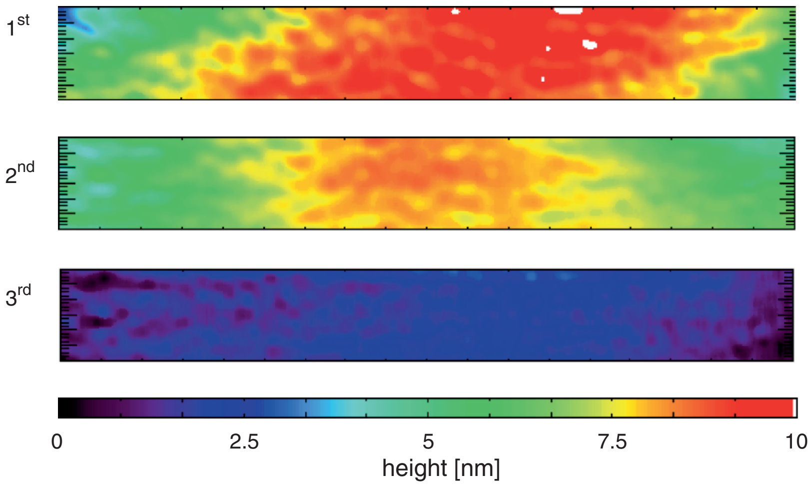

Fig. 12.1. Three iterations of ion beam finishing on a 100 × 20 mm grating blank (substrate material: Si). NOM measurement, spatial resolution: 2 mm
First iteration: 11.8 nm pv
Second iteration: 5.1 nm pv
Final state: 3.3 nm pv
Residual slope error: 0.1 µrad rms
measured at the center line

by IBF technology. The demonstration components are one plane mirror of 310 mm in length, one grating blank of 100 mm in length, and a refocusing mirror of plane–elliptical shape, 190 mm in length [3]. To obtain an optimal result of the surface finishing, the initial state of the substrate had to have a microroughness essentially of that required at the end: 0.2–0.3 nm rms for the plane elements and <0.8 nm rms for the plane–ellipse. To finish the plane grating blank, the substrate was measured by interferometry and on the BESSY-NOM. To define the macroscopic shape of the surface, the NOM 3D-data were used. In addition, to have an optimized spatial resolution in the range of 80–100 µm, required for the IBF, the interferometric data have been fitted into this matrix. The progress in the shape optimization and the final state of the blank of 0.1 µrad rms for the residual slope error is illustrated in Fig. 12.1. In the case of this grating blank, the residual height deviation of 0.38 nm rms and the microroughness of 0.2 nm rms, which were finally achieved, are of the same order of magnitude. For the 310 mm plane mirror this procedure was in use for the first two iterations of ion beam treatment. The last three steps were done based on interferometer data. In a completing step the final state of about 0.2 µrad rms for the slope error was determined by NOM measurements (Fig. 12.2)

The refocusing mirror was finished based on the data of NOM measurements only (Fig. 12.3). For this purpose a measuring point spacing of

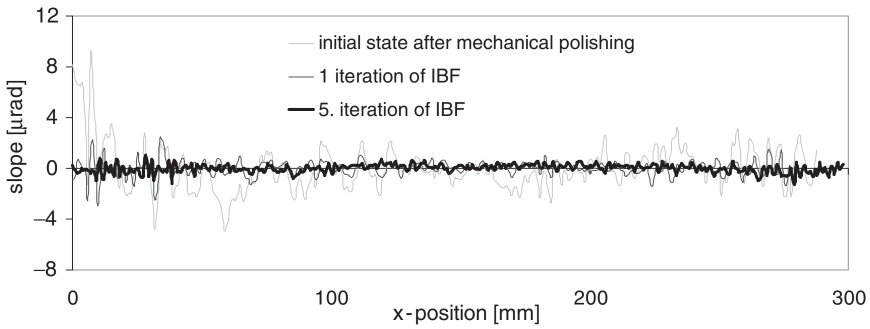

Fig. 12.2. NOM-measurements on a 310 mm plane mirror (spatial resolution: 2 mm, substrate material single crystal silicon, 5 iterations of IBF were used). The residual slope profile of the center line was the following: initial state, 1.69 µrad rms; after 1.IBF, 0.63 µrad rms; final state, 0.2 µrad rms

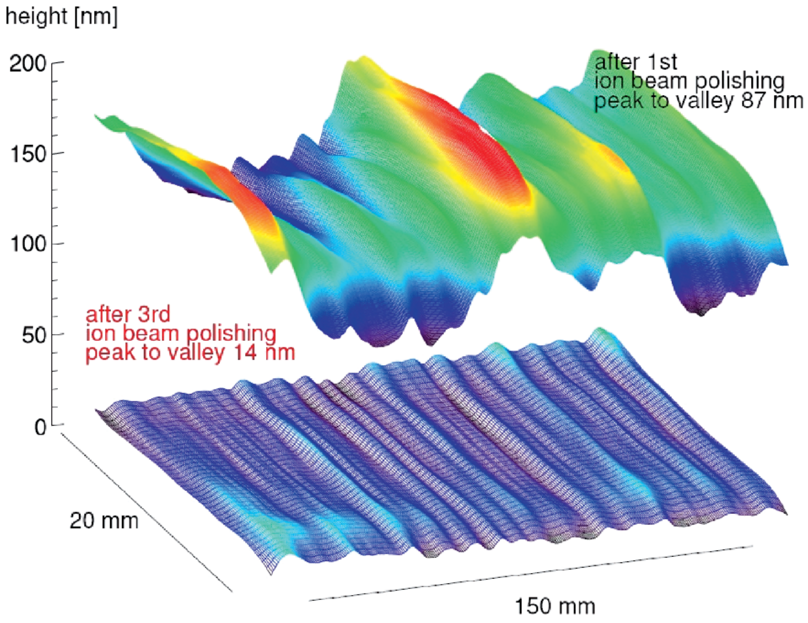

Fig. 12.3. Map of residual height of a plane–elliptical refocusing mirror after 1st iteration of ion beam polishing and final state. The residual slope error after three iterations of IBF is 0.67 µrad rms measured at center line

$0.2 \times 0.2\,\mathrm{mm}^2$ was chosen [6–9]. An interferometric measurement of this substrate would require a number of partial surface measurements to be stitched, a time consuming option of questionable reliability. The figuring process was realized by a computer controlled scanning of a small-sized ion beam with an ion beam of near-Gaussian profile across the surface. The linewidth and the dwell time have been varied in proportion to the amount of material

Table 12.1. Final results of surface finishing by IBF compared to the initial state after chemical–mechanical polishing

Optical element	Initial state residual slope (μrad rms)	Final state after IBF residual slope (μrad rms)
Plan grating blank (Si) $100 \times 20\,\mathrm{mm}^2$	0.6	0.1
Plane mirror (Si) $310 \times 30\,\mathrm{mm}^2$	1.7	0.2
Plane–elliptical mirror (Zerodur) $190 \times 37\,\mathrm{mm}^2$	5.9	0.67 (0.5 is possible)

to be removed [8]. The simulation of the figuring is based on a modification of van Citter deconvolution in the local coordinate space using the Fourier transformation and contains an optimal turn and smoothing of the output topology, a graphic output of the topologies and profiles as well as the generation of the dwell times. A 40 mm Kaufmann-type ion source with a focusing grid system was used [6]. The ion source parameters for the figuring using Ar as the etch gas were ion beam voltage, 800 eV; ion beam current, 20 mA. The positive charged ion beam was neutralized by a hot filament neutralizer. Because of the high requirements for X-ray optics these optical elements have to be finished by tools working at different optically relevant spatial frequency ranges. The size of the rotational symmetric Gaussian beam has been adjusted with the help of circular diaphragms of different hole diameters. The beam profiles and the etch rates have been determined by etching a “footprint” for a certain time into a test blank. The “footprint” was than measured by interferometry. The mirror substrate was figured in three IBF steps with the following ion current density profiles:

- For IBF steps 1 and 2 a beam size of 6 mm FWHM (diaphragm hole diameter: 4 mm) was used
- For the final IBF step a beam size of 2.1 mm (diaphragm hole diameter: 2 mm) was used

In the case of the three demonstration objects the substrates were moved relative to the fixed ion beam position. In Table 12.1 a general view on the capability of surface finishing by ion beam technology is shown.

12.3 High Accuracy Optical Elements and Beamline Performance

The performance of a SR-beamline is ultimately determined by the quality of the optical elements in use to guide the light from the source to the experiment at the focus. The shape-optimized plane–elliptical demonstration

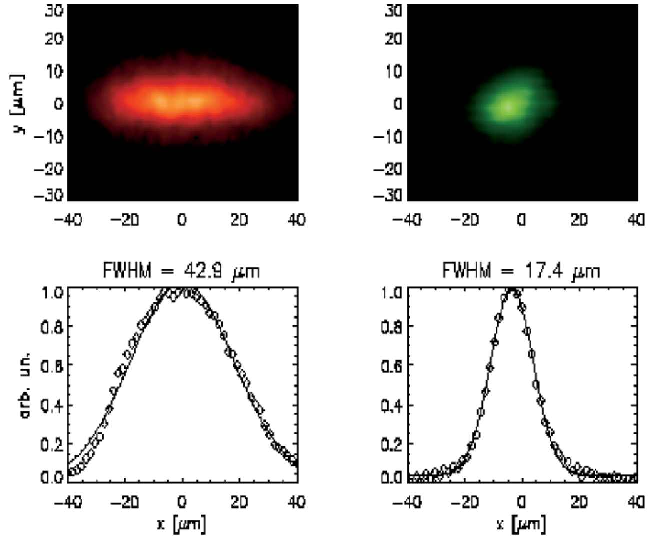

Fig. 12.4. Foci and horizontal energy distribution of two different refocusing mirrors characterised by a slope error of (*left*) 7.22 µrad rms and (*right*) 0.67 µrad rms

mirror described above serves as a refocusing mirror at the UE52-SGM1 beamline at the BESSY-II storage ring. By measurements of the focus size while commissioning the beamline the improvement achieved has been determined [8, 9]. Figure 12.4 shows the optimized focus and the horizontal energy distribution FWHM measured for the previous refocusing mirror and for the IBF improved mirror. A focus size of less than $20 \times 20\,\mu\text{m}^2$ for the energy range inspected (350–1,100 eV) at an exit slit width of 3–4 µm has now been achieved. Compared to the previously obtained horizontal focus size of about 43 µm (FWHM) the present value of about 17 µm (±10%) represents a more than twofold improvement. Because of the characteristics of the undulator source at this beamline, the potentially smallest dimension of the focus size has been reached. A further surface optimization of this refocusing element beyond the limit of 0.1 arcsec rms would not provide an improvement of beamline performance.

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