Fabrication of freeform mirrors: Metrology and figuring

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Abstract: Application of mirror manufacturing and its appropriate metrology at Carl Zeiss Laser Optics shall be illustrated by recent examples. Specifications and achieved results of finalized mirrors with different geometries and sets of specifications are discussed.

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1. Introduction

Carl Zeiss has a long-lasting expertise in the field of optical manufacturing and material processing for reflecting and refracting optical systems. In particular at *Carl Zeiss Laser Optics* mirrors of various geometries ranging from small flats to large freeform mirrors are subject to our extensive research and development activities. Standard requirements are slope errors significantly below 1 arcsec for aspheric elements and below 0.1 arcsec for flats or spheres. Exceedingly stringent specifications are placed on the optical components used in newly designed systems.

In order to achieve the desired surface quality in terms of slope and height errors, a very close interaction between metrology and polishing is mandatory. Testing and manufacturing are complementary tools for fabrication of highly defined optical surfaces. Reaching the desired roughness quality requires sophisticated smoothing processes.

Besides "steering" of synchrotron light along a desired path within a beamline the task of synchrotron optics is to focus light from one point to another, or to focus a parallel or divergent beam to a well defined point. This can generally be achieved by the using conic sections, e.g. ellipsoidal or paraboloidal mirror surfaces, respectively. Depending on the desired imaging quality, substitution of conic sections by "fundamental geometries" such as flats, spheres, cylindrers or toroids come into play.

2. Fabrication

Fundamental geometries are usually easier to fabricate, since the appliance of full aperture tools for polishing and smoothing is possible. Results for nano-, micro and mid spatial frequency roughness are generally excellent (0.2 nm rms or below). In contrary conic sections or freeform geometries need the application of sub- aperture polishing and smoothing tools. In addition figuring is not as straight forward as in the case of fundamental geometries. In case of low departure (a few µm) of the desired conic sections from fundamental geometries a popular "work around" is to polish and smooth a base geometry akin to the desired surface. We account for the departure by final figuring. This process combines excellent slope (<0.05 arcsec) and height errors (< 1 nm rms) with smooth surfaces (see example 2).

At *Carl Zeiss Laser Optics* the entire set of tools relevant for mirror fabrication, ranging from large full aperture tools to tiny a few mm sub- aperture tools are available. Robot based computer controlled polishing (CCP) and ion beam figuring are contributing to the achievement of state of the art specifications. *Carl Zeiss* Cooperate Software ensures an unobstructed interplay between metrology results and CCP. Special purpose solutions can be easily included. Recently CAD support has been fully integrated into the fabrication process. CAD based premachining and CCP enable full freeform capabilities for the optical surface and the substrate alike.

3. Metrology

Carl Zeiss has available metrology devices to cover the entire spatial error range from several nm to above 1 m: Full aperture interferometry is best suited for plane and spherical surfaces with dimensions below 12". Thus stitching interferometry and 3D profilometry steps in when it comes to large or complex surfaces with high aspherical departure resp. For this purposes Carl Zeiss has available the 3D ultrahigh-resolution coordinate measuring machine M400. This device is able to measure surfaces up to 550 mm with a resolution < 10 nm where aspheric departure from base geometries is almost unlimited (see example 1). Interferometric metrology devices are not strictly limited to plane or spherical surfaces. Cylindrical or weak freeform aspheres can be well measured by interferometric setups. Measurements with a plane stitching interferometer in the sub-nm level have been successfully demonstrated (example 2). Metrology is completed by µ-interferometers and AFMs, covering the entire PSD from nm to m range.

4. Examples

1. Application of mirror manufacturing and its appropriate metrology at *Carl Zeiss Laser Optics* shall be illustrated by recent examples. Specifications and achieved results of finalized mirrors with different geometries and sets of specifications are discussed below.

Beam guidance for soft x-ray applications to some extent involve geometries such as paraboloids (collimation) or ellipsoids (focusing). Here fixed type soft x-ray mirrors can become very challenging in terms of departure from base geometries and local curvature. A recent application for a soft x ray beamline is an off-axis rotational paraboloid (fig. 1a). The mirror cutout of 180 x 35 mm^2 is selected very close to the focal point making the sagittal radius changing dramatically from the mirror entry 61 mm to exit 49 mm and the tangential gradient exceeds 50 µm/mm. Fabrication of mirrors with strong curvatures require special measures for deterministic figuring. Here tool-orientation (better 0.1°) and positioning (better 0.3 mm) with respect to the mirror becomes essential for proper figure convergence. Mandatory usage of small sub aperture tools limit the mid spatial frequency roughness in reach. Slope errors of 1.2" and 1.89" (tang./sag.) and a surface roughness of 0.45 nm have been achieved.

2. FELs come with superior brightness to any other x-ray source. In order to transmit the full brightness of the XFEL radiation to an experiment, x-ray mirrors must have excellent reflection surface properties. Low divergence of an XFEL beam pushes the limits to advanced level specifications for figure (slope < 0.05", height < 2nm rms), mid (< 0.25 nm rms)- and high (< 0.4 nm rms) spatial frequency roughness. The advent of a new plane stitching interferometer enabled surfaces with figure errors below 1 nm and 0.02" resp. (fig 1b)

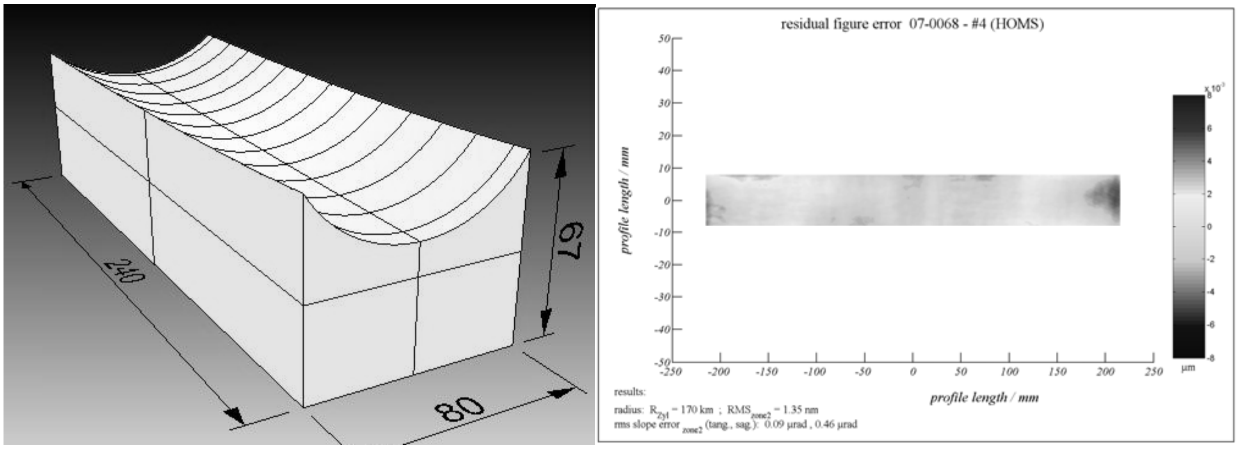

Fig. 1. (a) CAD layout of paraboloid. The changing of sagittal radii results in local curvatures above 1 µm/mm. (b) Interferometer map of the hard x-ray mirror resulting in height error 1.35 nm and tangential slope error 0.09 µrad

5. Outlook

Future applications such as FEL and 3rd generation diffraction limited synchrotron sources imply further improvement of the achievable quality. Here the level for the slope errors can be as small as 0.02". In addition beam quality preservation in the scattering process frequently demands height errors in the order of 0.5-1nm rms over the clear aperture combined with surface roughness about 0.1 nm rms. These new challenges are increasingly out of reach without proper profiling, interferometric and/or stitching methods.

However the process technology for the manufacturing of surfaces in given precision range cannot be achieved without close cooperation with our customers. Thus Zeiss is open for collaboration on topics such as figuring iterations with external surface data and metrology cross comparison.

6. Conclusion

Carl Zeiss Laser Optics is a reliable partner for the manufacturing of synchrotron mirrors. We have implemented powerful measuring and manufacturing techniques for the generation of highest-quality optical components for synchrotron radiation applications. Paraboloids with gradients that exceed 50 µm/mm have been fabricated successfully. The advent of a new plane stitching interferometer enabled the fabrication and metrology of surfaces with figure errors below 1 nm and 0.02" resp.