Optical measurement of absolute flatness with the deflectometric measurement systems at PTB

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Abstract. Highly accurate flatness measurements are needed for synchrotron optics, optical flats, or optical mirrors. Recently, two new scanning deflectometric flatness measurement systems have been installed at the Physikalisch-Technische Bundesanstalt (PTB). The two systems (one system for horizontal and the other for vertical specimens) can measure specimens with sizes up to one metre with an expected uncertainty in the sub-nanometre range. In addition to the classical deflectometric procedure, also the ‘extended shear angle difference (ESAD)’ and the ‘exact autocollimation deflectometric scanning (EADS)’ procedures are implemented. The lateral resolution of scanning deflectometric techniques is limited by the aperture of the angle measurement system, usually an autocollimator with typical apertures of a few millimetres. With the EADS procedure, the specimen is scanned with an angular null instrument which has the potential to improve the lateral resolution down to the sub-millimetre region. A new concept and design of an appropriate angular null instrument are presented and discussed.

1. Introduction

Angle-based measurement systems such as the Nanometre Optical Component Measuring Machine (NOM) at the Institute for Nanometre Optics and Technology (INT) of the Helmholtz Zentrum Berlin (HZB) (formerly: Bessy) [1], the upgraded Long Trace Profiler-II (LTP-II) at the Advanced Light Source (ALS) Optical Metrology Laboratory (OML) [2], the upgraded LTP of the Japan Synchrotron Radiation Research Institute at SPring-8 [3], the Diamond-NOM [4] or the Deflectometric Flatness Reference (DFR) systems at PTB [5, 6] are used to characterize optical surfaces with nanometre or even down to sub-nanometre uncertainties. Especially the measurement of grazing incidence optics of synchrotrons requires highest accuracies.

Based on the ‘extended shear angle difference (ESAD)’ system at PTB [7] and the Nanometre Optical Metrology (NOM) system at HZB, two new deflectometric systems have recently been installed at PTB [5, 6]. The systems have different operating modes like the difference deflectometric procedures, also named ESAD [7], and the direct deflectometric mode used in the NOM.

Deflectometric scanning procedures are typically based on scanning a pentaprism or a corresponding double mirror unit (DMU) across the specimen, thereby measuring the surface slopes with an angle measuring system. These 90° beam deflectors eliminate – to a great extent – guidance errors of the scanning stages which are required to attain topography measurements with sub-nanometre uncertainty. The precise alignment of the optics as well as the mechanics is therefore necessary [8]. For the precise alignment of the pentaprism or the corresponding DMU to the optical
axis sophisticated procedures are available [9-11]. A drawing and a photo of the system which is mainly used for measurement of horizontally orientated specimens is shown in Figure 1.

![Drawing and photo of the system for horizontally aligned specimens](image)

Figure 1. Drawing and photo of the system for horizontally aligned specimens

A typical measurement of 7 scans with a length of 500 mm is shown in Figure 2. The measurements were performed with the direct deflectometric mode. The specimen was scanned step by step with a step size of 1 mm and a spot size of 10 mm.

![Graphs and plots](image)

Figure 2. A typical measurement of a 500 mm scan with the direct deflectometric mode and a spot size of 10 mm: (a) Measured slopes, (b) Slope differences between the scans, (c) Resulting topography, (d) Standard deviation of the 7 scans

The angle measurements are performed by commercially available autocollimators. The spot size of the autocollimator then determines the lateral resolution. The smallest spot size which can be achieved with a standard commercially available autocollimator is about 3 mm. Further reduction of the spot size to approx. 1.5 mm can be realized with an appropriate phase mask in the autocollimator [12]. Smaller spot sizes and thus higher lateral resolution have not been possible up to now. With the idea of the exact autocollimation deflectometric scanning (EADS), which is explained in the following paragraph, it is possible to further improve the lateral resolution.
2. The EADS principle and its possibility for a smaller scanning beam

The exact autocollimation deflectometric scanning (EADS) method is shown in Figure 3. The scanning beam of autocollimator AC1 only acts as a null instrument. The surface under test is kept perpendicular to the scanning beam by tilting the specimen with a piezoactuator. The EADS principle is implemented in the new scanning deflectometric reference systems. The procedure as well as the controller is described in more detail in [13]. The autocollimator AC1 provides 25 readings per second. As piezoactuator a low voltage piezoactuator with an integrated position sensor from Physik Instrumente (PI) GmbH & Co. KG is used. The control deviations are usually less than 0.01 arcseconds after 4 cycles of the control loop, but typically we use 7 cycles at each measurement point, which requires in total about 10 seconds. This corresponds to a measurement rate of 0.1 points per second. In the present setup the EADS is rather slow, but with an optimized control setup, this time could be improved and even a control mechanism ‘on the fly’ could be realized.

The main advantages of this method are that the optical path length of the angle measuring device (AC2) is constant, that this angle can be measured with better accuracy, since a greater measurement aperture can be used and that a smaller spot size can be realised for the null instrument.

3. Concept and design of an appropriate null angle instrument

We aim at a scanning beam diameter of less than 1 mm for a scan length of up to 1 m. Just using a Gaussian beam is not possible, because the Gaussian beam always has a certain divergence of \( \theta = 2\lambda/(\pi w_0) \) with the wavelength \( \lambda \) and the beam waist \( w_0 \). This means, the smaller the beam waist, the greater is the divergence of the beam. For example, a He-Ne laser with a beam waist of \( w_0 = 0.5 \) mm has a beam radius of 0.84 mm after one meter propagation. In comparison, a He-Ne laser with a beam waist of \( w_0 = 0.05 \) mm already has a beam radius of 4 mm after one meter propagation.

A new concept for realizing a small scanning beam is shown in Figure 4. The unit with the null
instrument is mounted directly at the carriage of the scanning stage. Due to the guidance errors of the scanning stage, the mirror is tilted. The autocollimator (AC) directly measures the difference between the guidance of the scanning stage and the tilting of the specimen, which represents the slope of the specimen. The null sensor has a fixed optical path length and, thus, a small scanning beam of less than 1 mm seems to be realistic.

4. Conclusion and outlook
Two new deflectometric scanning systems were set up at PTB. A typical measurement was shown, where sub-nanometre repeatability was demonstrated. The concept illustrated in Figure 4 will be realized now and it is expected that measurements with the deflectometric reference system down to a lateral resolution of less than 1 mm can be carried out.

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