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Novel hybrid interference and atomic force microscopy for *in-situ* reference areal surface metrology

Ziyang Jiao[1], Tianhang Deng[1], Xingyu Rao[1], Rainer Tutsch[2], Gaoliang Dai[1]*

[1] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[2] *Institute of Production Measurement Technology, Technical University of Braunschweig, Schleinitzstraße 20, 38106 Braunschweig, Germany*

Gaoliang.dai@ptb.de

Abstract
A novel concept of *in-situ* reference areal surface metrology is presented in this paper. It is realised by a hybrid microscope, which combines an interference microscopic (IM) and an AFM measurement mode. It provides two very promising application potentials: (i) the limited resolution capacity of the IM mode can be complemented by the high-resolution AFM mode; (ii)AFM measurements provide high-fidelity topography data applicable for characterizing and improving IM measurements. In this paper, its design concepts are highlighted, its traceable calibration is introduced and its application for *in-situ* reference metrology of an engineered surface is demonstrated.

Surface metrology, phase shifting interference (PSI), white light interference (WLI), atomic force microscopy (AFM), topography fidelity, calibration

1. Introduction

Various optical tools such as phase shifting interference (PSI), confocal, white light interference (WLI) and focus variation microscopes are widely applied for surface metrology owing to their advantages of fast and noncontact measurements. However, optical surface measurement techniques suffer from measurement errors, particularly when measuring surfaces and structures with large slope angles, complex geometries, diffusely reflecting surfaces. Their measurement results often include outliers, missing points, and other unexpected topographic features (e.g. batwings in WLI). Comparisons between measurement results of 3D optical microscopes and that of tactile tools frequently reveal significant discrepancies [1]. This issue is referred to as the topography fidelity issue of optical tools.

Many research have been carried out to understand and/or to improve the topography fidelity of optical tools on several aspects: (i) calibrations of geometrical properties of the tools in terms of magnification, linearity, squareness, flatness, and noise; (ii) studies of the interaction between light and surfaces, e.g. to simulate the formation of interference fringes in interference microscopes; (iii) characterisations of bandwidth characteristics of tools in terms of instrument transfer function (ITF).

However, there remains a challenge in addressing the measurement fidelity issue — reference areal surface metrology. A fundamental reason lies at the fact that, only if the reference value of a surface topography is available, it is possible to quantitatively characterise and to improve the measurement fidelity of optical tools. In past research, we proposed a concept to provide reference surface metrology using a metrological large-range atomic force microscopy (AFM). The concept worked well, however, suffered from great efforts needed to transport and relocate samples in different tools [2].

Recently, we developed a novel hybrid microscope (referred to as "hybrid IM+AFM") [3] which combines an interference microscopic (IM) and an AFM measurement mode. It provides two very promising application potentials: (i) the limited resolution capacity of the IM mode can be complemented by the high-resolution AFM mode; (ii)AFM measurements provide high-fidelity topography data applicable for characterizing and improving IM measurements.

The paper aims to introduce the further developments of the hybrid microscope, its traceable calibration and its application for *in-situ* reference areal surface metrology.

2. Hybrid IM+AFM

The principle of the hybrid microscope is illustrated in Fig. 1. It is realised by adding an AFM probe to an IM, where the AFM probe can be mechanically switched in or out of the beam path of the IM. When the AFM cantilever is out of the beam path as shown in Fig. 1(a), the system works in the IM measurement mode for noncontact and fast optical measurements. When the AFM cantilever is in the beam path as shown in Fig. 1(b), it works in the AFM measurement mode, where the AFM tip interacts with sample surfaces for measurements. The deformation of the AFM cantilever induced by the tip-sample interaction force is detected from interference fringes, which are formed by the interference of the light beam reflected from the backside of the AFM cantilever and a reference beam in the IM.

The probe switcher is motorised and can be operated conveniently by the measurement software. By using adapt rings, the same probe switcher can be applied for different objectives, for instance, Mirau type objectives with 10x, 20x and 100x optical magnifications. A photo of the probe switcher with a 100x Mirau objective is illustrated in Fig. 1(c).

One major target of the development of the hybrid microscope is to realise *in-situ* reference areal surface metrology, therefore, several design concepts were purposely conceived, for instance:

- Correlative microscopy. Owing to the high positioning stability (< 1 µm) of the probe switcher and the convenient calibration of the AFM-IM offset using e.g. a find marker, the AFM and IM measurements can be easily correlated without the sample being moved. It solves the problem of sample transportation and/or relocation encountered in our previous research [2].

- High synergy of IM and AFM techniques. Unlike classical muti-sensor design concept, e.g. [4], where the sensors work rather independently with each other, our hybrid design combines AFM and IM in a high synergic level.
- Reduced cost owning to two facts: (i) IM and AFM measurement modes share the fine and coarse motion stages; (ii) The omit of (additional) detection sensor for AFM.
- Interferometrical AFM detection. The displacement and bending of AFM cantilevers is detected interferometrically. Its results can be directly linked to the wavelength of its light source.
- Ease of use. The AFM probing signal can be conveniently evaluated from the interference fringe acquired in the field of view (FOV) of the IM. As the FOV can reach a size of hundreds of micrometres to a few millimetres, the AFM cantilever can be conveniently detected in the FOV (almost) without the need of tip and signal adjustments.

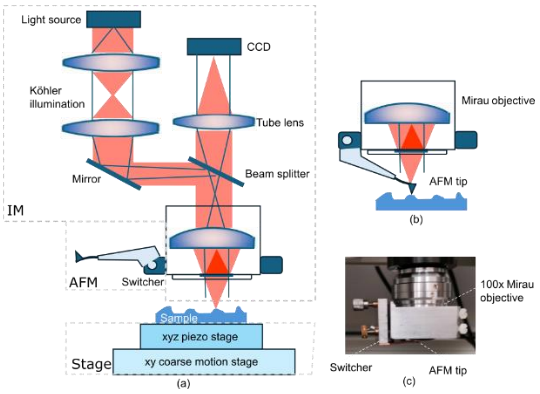

Figure 1. Principle of the hybrid AFM+IM, shown as (i) IM measurement mode; (ii) AFM measurement mode; (iii) photo of the mechanics with a 100x Mirau objective.

3. Traceable calibration

Unlike our previous solution [2] based on metrological AFM, this new solution applies "normal" AFM whose results are ultimately based on the outputs of displacement measuring sensors (capacitive or piezoresistive) embedded in the fine positioning stage. Although it is much more cost-effective and better applicable for industry than metrological AFMs, traceable calibration is needed *prior to* its usage for reference areal surface metrology.

Applying step height and lateral standards is a well-matured and standardised method for such traceable calibrations. As an example, an AFM image taken on a 2D10000 grating with a nominal pitch of 10 µm by the AFM measurement mode of the hybrid IM+AFM is shown in Fig.2(a). A cross-sectional profile at the marked position is illustrated in Fig.2(b), illustrating good quality. By comparing the evaluated height and pitch values with their reference values calibrated by the metrological AFM of the PTB, the scaling factors of the AFM are determined as 1.008 and 0.9978 for the z and y-axes, respectively.

4. *In-situ* reference areal surface metrology

The developed method has been applied for *in-situ* reference areal surface metrology on various surface made of different

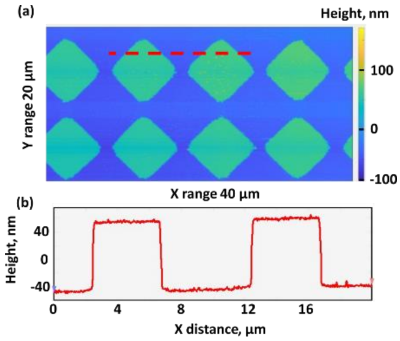

Figure 2. calibration of the AFM mode of hybrid microscope, shown as (a) an AFM image taken on a 2D10000 grating; and (b) a cross-sectional profile at the marked position in (a).

materials (aluminium, steel, glass, etc.) and engineering techniques (tunning, milling, polishing, etching, etc.), showing very promising result. Figure 3 illustrates a representative example, where a coated roughness sample (Fig.3a) is first measured by a 100x Mirau objective using five-step PSI algorithm over a FOV of 49.8 µm x 37.4 µm in the hybrid microscope. Then the hybrid microscope is switched to the AFM mode, and the marked area in Fig.3b is measured by an AFM probe type ContDLC (BudgetSensors) with a pixel distance of 20 nm at a scanning speed of 2 µm/s. After fine aligning the obtained AFM and PSI results, their images are compared in Fig. 3(c-d) and two cross-sectional profiles are compared in Fig.3e.

Using the example illustrated in Fig.3, several unique values of the concept of *in-situ* reference metrology are discussed below:

- Reference metrology directly enables quantitative characterisation of measurement limitations of optical tools. As an example, at the marked position A in Fig.3d, it can be seen that fine structures were not resolved in the optical measurements.
- Reference metrology can indicate scenarios where gross deviations (e.g. at marked positions B and C in Fig. 3e) occurred in optical measurements, offering important hints to understand measurements, and thus for improvements.

Furthermore, by combining the AFM and IM data, it is further potential to enhance measurement accuracy of the IM measurements, even for areas not measured by the AFM. This concept is under development.

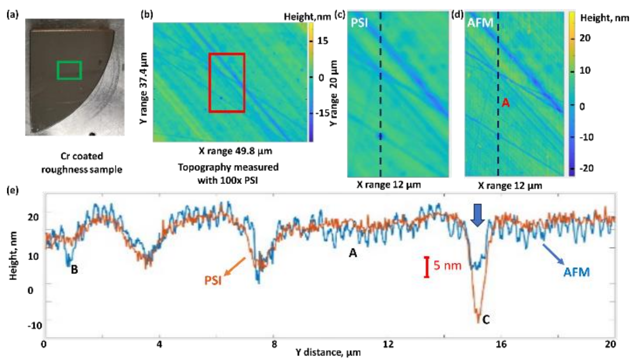

Figure 3. Illustration of *in-situ* reference areal surface metrology, shown as (a) photo of the applied sample; (b) measured topography by a IM with a 100x Mirau objective using PSI; (c)-(d) Correlated AFM and PSI measurement results; (e) Compare of cross-sectional profiles of AFM and PSI taken at the same marked position in (c)-(d).

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