Accuracy Optimization of High-speed AFM Measurements Using Design of Experiments

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Abstract

Atomic Force Microscopy (AFM) is being increasingly employed in industrial micro/nano manufacturing applications and integrated into production lines. In order to achieve reliable process and product control at high measuring speed, instrument optimization is needed.

Quantitative AFM measurement results are influenced by a number of scan settings parameters, defining topography sampling and measurement time: resolution (number of profiles and points per profile), scan range and direction, scanning force and speed. Such parameters are influencing lateral and vertical accuracy and, eventually, the estimated dimensions of measured features. The definition of scan settings is based on a comprehensive optimization that targets maximization of information from collected data and minimization of measurement uncertainty and scan time. The Design of Experiments (DOE) technique is proposed and applied to perform the optimization of AFM measurements on calibrated one-dimensional silicon grating featuring a triangular periodical profile (slopes of 54.7 degrees, period of 3 μm).

1 Introduction

Scan interaction force and speed play a key role on AFM performance, differently influencing extraction of quantitative information on the horizontal and vertical plane, as well as in cross-coupled directions (as in the case of slope angle estimation). Optimized instrument setting will result eventually in a trade off between uncertainty targets and scan parameters (i.e. scanning time). For the present study a compact stand-alone instrument, which can be easily implemented in an industrial manufacturing environment (Figure 1-left), was employed for the optimization using a calibrated grating (slope angle 54.7° and pitch 3µm, Figure 1-right). The AFM is an open loop instrument, actuated by a piezoelectric tube scanner, with a measuring volume of 200×200×10 µm. Experiments were performed to achieve the optimal instrument set up; the metrological performance was evaluated in particular considering scan speed and interaction force.

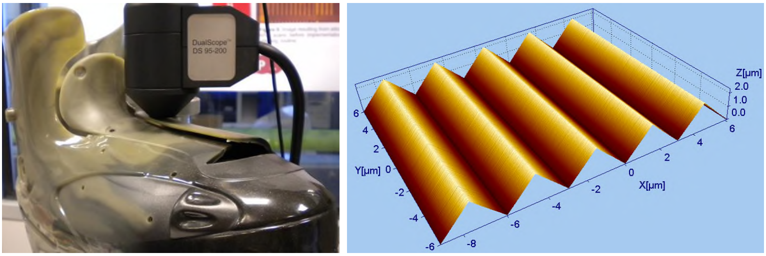

Figure 1: Compact AFM employed in an industrial environment (left) and measurement of the calibrated silicon grating with triangular shape (right).

2 Experimental tests: force and speed effect on pitch measurement

To determine the influence of different forces and scanning speeds on the measurement process, three different levels for the force (respectively 8, 15 and 20 nN) and three levels for the speed (respectively 3, 10 and 20 µm/s) were chosen. The experiments were statistically planned by using the DOE technique in a 3-factor/3-level full factorial design, resulting in a total of 9 different scan settings. For each scan setting, 5 measurements were carried out on a range of 50×10 µm (6 profiles, 2048 points per profile), with a scan direction perpendicular to the grating ridges.

The estimated average pitch was found to be linearly dependent on scan speed, with a maximum at the highest scan speed (20 µm/s). Horizontal characterization is more sensitive to speed than to force (see Figure 2-left); in fact, for open loop piezoelectric scanners, scaling and linearity in the horizontal plane are largely influenced by scanning speed [1]. At low scan speed, measurements gave evidence of minimum average pitch, associated to a maximum in standard deviation. This latter effect can be reasonably explained taking time related artefacts into account. With decreased scanning speed, total scan time increases proportionally and consequently time-depending artefacts such as noise and thermal drift are introduced, producing relevant distortions between subsequent measured profiles and also within single measured profiles. Usually, for open loops AFMs, quantitative results are corrected using a calibration factor obtained with measurements on calibrated gratings; hence, the effect of scanning speed can be compensated by performing the AFM calibration with the same setting as for the actual measurements. AFM uncertainty associated with such measurements is affected mainly by probe velocity rather than its interaction force because measuring repeatability is mainly depending on speed (Figure 2-right). Uncertainty budget for a horizontal AFM measurement can be defined as follows [2]: $U = k \cdot \sqrt{u_{res}^2 + u_{cal}^2 + u_{rep}^2 + u_{noise}^2}$, where: U=expanded combined uncertainty; k=2 for a confidence level of 95%; u_{res}=standard uncertainty related to the instrument resolution depending on the number of pixels and the scanning length along the fast scanning direction; u_{cal}=grating standard calibration uncertainty; u_{rep}=standard deviation of pitch measurements; u_{noise}=instrument background noise. Other uncertainty contributions have only a minor influence on final U computation.

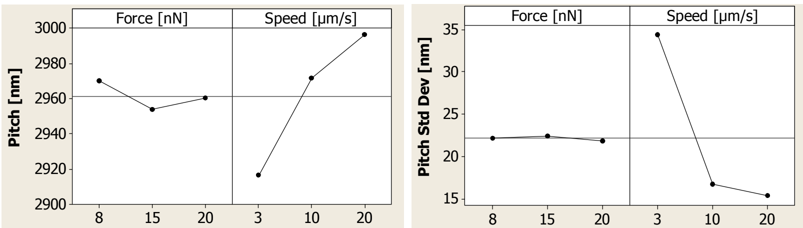

Figure 2: Influence of AFM scanning force and speed on pitch measurements (left) and repeatability (right).

Table1: Influence of scanning speed on the uncertainty of AFM pitch measurement.

Std. unc. contributors	u_{res}	u_{cal}	u_{noise}	u_{rep}		
				3µm/s	10µm/s	20µm/s
	7.0 nm	0.5 nm	0.3 nm	34 nm	16 nm	15 nm
Exp. comb. unc. (U) at 3 different scanning speeds				***69 nm***	***35 nm***	***33 nm***

3 Force and speed effect on slope measurement

Slope measurements were performed as previously described, including an additional set of measurements at 30 µm/s, and it was observed that the effect of scanning speed was higher than that of scanning force. Increasing scanning speeds lead to smaller measured slope angle, especially at the highest speed on descending slopes (Figure 3-left). Higher scan rates can produce a loss of interaction between the tip and the surface, producing an apparent height reduction (especially in the case of steep descending slopes) which will determine a lower measured angle (i.e. slope flattening artefact). Stiffer interaction between the tip and ascending slopes produced higher measurement standard deviation (i.e. less repeatable slope angle measurements) than on descending slopes (see Figure 3-right). This is most probably due to increased vibrations connected with stiffer interaction badly compensated by the feed-back control.

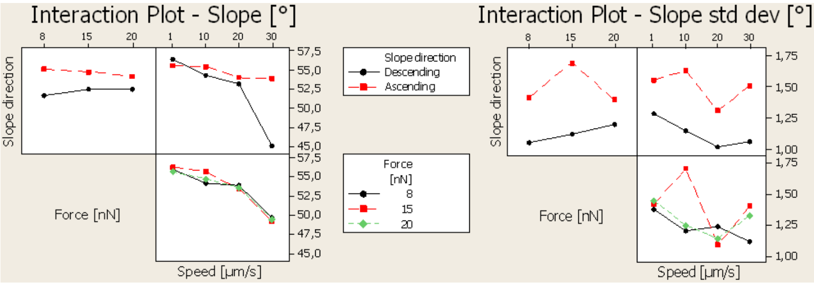

Figure 3: Influence of slope direction, AFM scanning force and speed on slope angle measurements (left) and repeatability (right).

4 Conclusion

The different influences of scan speed and force on pitch and slope angle AFM measurements, as well as the presence of slope flattening artefact were found. The dominant effect of scan speed when compared to scan force on horizontal measurements such as V-profile width measurements was also demonstrated and found to be in accordance with microscope's structure and specification. The use of DOE techniques on the optimization of measuring parameter settings have proved to be effective to investigate the effects of scan force and speed on repeatability (i.e. standard deviation of repeated measurements) and on finding the highest speed which allowed obtaining accurate results with low uncertainty.

References:

[1] Danzebrink H.U. et al., Advances in Scanning Force Microscopy for Dimensional Metrology, Annals of CIRP, Vol.55/2, pp.841-878, 2006.

[2] Joint Committee for Guides in Metrology (JCGM), 2008, JCGM 100:2008, Guide to the Expression of Uncertainty in Measurement (GUM), i-viii, pp.1-132.