Validation of optical surface texture measurements on a milled technical surface using a stylus profilometer

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ABSTRACT

In the recently completed EU project TracOptic, a Good Practice Guide (GPG) has been developed to aid in the selection of instrumentation for optical surface texture measurements using confocal microscopy, coherence scanning interferometry, and focus variation instruments. This guide outlines several criteria and steps for selecting the appropriate instrument and objective, where validation of optical surface texture measurements by comparison with reference measurements using AFM or a stylus profilometer remains crucial. AFM reference measurements are needed for surfaces with high-frequency structures, whereas stylus reference measurements are sufficient for classical technical surfaces with relatively low-frequency structures and limited surface slopes. In this paper, we focus on the validation of optical measurements with stylus profilometers on technical surfaces with moderate local slopes. Marks have been applied to the test surface to ensure that both optical and stylus-based methods measure at exactly the same surface location. Two comparison methods were developed: 1) Profile Matching: Aligning and matching the measured stylus profiles with the corresponding optical measurements; 2) Statistical Comparison: Evaluating the statistical consistency between results from stylus profilometry and optical measurement. For the second method, simulations were carried out to determine the minimum number of evenly distributed profiles required to obtain optical surface texture height parameters (e.g. Sa and Sq) within a ±2.5% tolerance. Experimental investigations were then carried out based on these simulation results. A milled technical surface with marked areas corresponding to the field of view (FOV) of different microscope objectives (i.e., 20x, 50x, and 100x) has been measured using a confocal laser scanning microscope and a stylus instrument. The comparison results for both methods are presented in this paper. The methodology developed for stylus instruments can also be applied to AFM as a reference instrument for validating optical surface texture measurements.

Keywords: surface texture, optical surface texture measuring instruments, technical surfaces, local slopes, stylus profilometer, validation measurements

1. INTRODUCTION

Three-dimensional (3D) optical microscopy, including coherence scanning interferometry (CSI) [1], confocal microscopy (CM) [2], and focus variation instruments (FV) [3], has become an essential tool for rapid, non-contact and non-destructive surface topography measurement across various scientific and industrial applications. Its ability to capture areal surface features efficiently offers significant advantages over traditional stylus profilometry. However, the traceability of optical surface topography measurements remains a major metrological challenge. To ensure measurement reliability and comparability, optical techniques need to be validated against well-established and standardized contact-based methods, which are widely accepted as reference techniques due to their maturity and metrological traceability [4-5].

A fundamental difficulty arises from the intrinsic differences between the two measurement modalities: optical methods typically provide areal (surface) measurements, whereas contact-based techniques yield profile (line) measurements. As a result, comparing the outcomes of these two fundamentally different approaches is non-trivial. The lack of standardized comparison procedures and reference artifacts further complicates the validation process [6-8]. Therefore, developing robust methods for the comparison of optical and stylus measurements is crucial and urgently needed to establish traceability for optical surface topography measurements.

In the recently completed EU project TracOptic, a Good Practice Guide (GPG) [9] was developed to support the selection of instrumentation for optical surface texture measurements using confocal microscopy, coherence scanning interferometry, and focus variation. The guide provides a set of criteria and procedural steps for choosing suitable instru-

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ments and objectives. A key aspect emphasized in the GPG is the validation of optical surface texture measurements through comparison with reference measurements using either atomic force microscopy (AFM) or stylus profilometry.

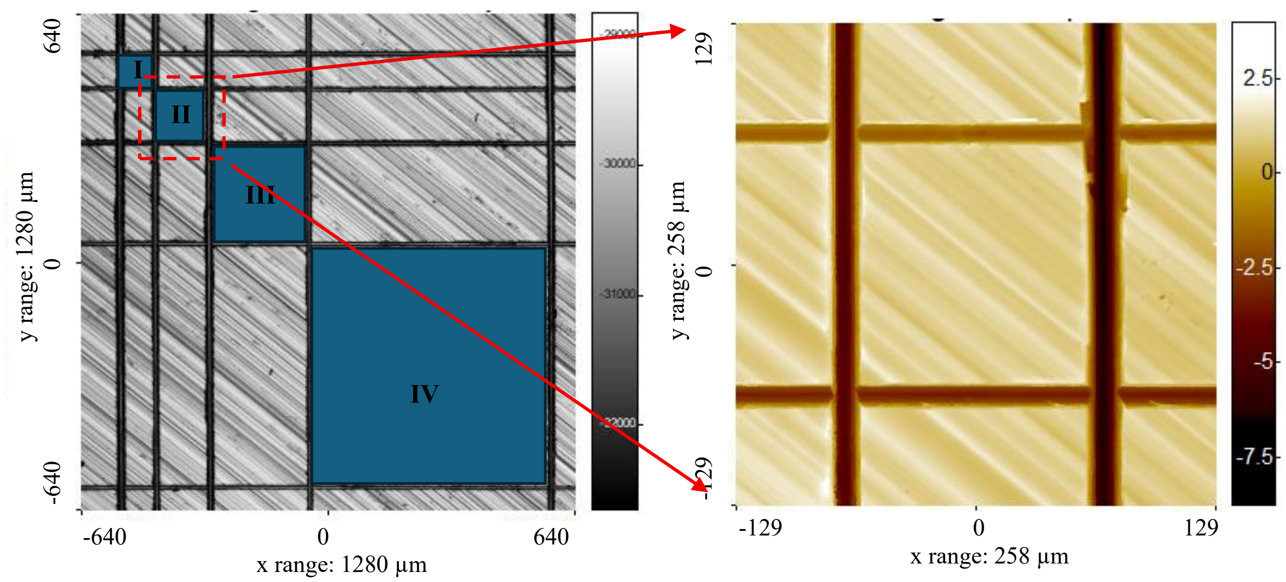
In this context, prior knowledge of the surface characteristics -- such as the slope threshold θ(95%), i.e., the 95th percentile of the slope distribution of the surface to be measured [9], and the autocorrelation length (Sal) [10] -- is essential for selecting a suitable objective when utilizing the confocal laser scanning microscope (CLSM) available in our laboratory for surface texture measurements.. This information helps determine whether AFM or stylus reference measurements are necessary for validation as well. Specifically, AFM reference measurements are recommended for surfaces with small Sal values or steep local slopes, while stylus profilometry is generally sufficient for classical technical surfaces with relatively low-frequency features and moderate slopes.

As a first step in our study, we focus on validating optical measurements using stylus profilometers on technical surfaces with moderate local slopes. In this paper, Section 2 describes the technical surface under investigation and the marked areas designated for both optical and stylus measurements; Section 3 outlines the selection of suitable objectives and scanning parameters for both measurement techniques, with the aim of minimizing optical measurement artefacts and avoiding surface damage during stylus measurements; Section 4 presents and compares two methods for aligning and comparing the results obtained from optical and stylus measurements.

2. EXAMPLE TECHNICAL SURFACE AND DESIGNATED MARKED AREAS FOR VALADATION OF OPTICAL SURFACE TEXTURE MEASUREMENTS

A milled aluminum surface, as shown in Figure 1, was selected for the validation measurements. The typical surface parameters -- Sa, Sal, and θ(95%) -- are 150 nm, 4.1 µm, and 11°, respectively.

Since the surface is not ideally homogeneous, the results for roughness or surface texture parameters are highly dependent on the measurement location. To enable an accurate comparison between optical and stylus measurement methods, specific areas on the surface were marked. As shown in Figure 1(a), four square measurement areas with side lengths of 60 µm, 120 µm, 240 µm, and 600 µm were defined. The latter three areas correspond to the fields of view (FOV) of the CLSM objectives, namely 100x, 50x, and 20x, respectively. Figure 1(b) presents a topography image of the 120 µm square area, acquired using the 50x objective, which provides a FOV of 258 µm × 258 µm.



(a) Marked square areas on the milled surface

(b) Topography image of Area II measured with a 50x objective (NA 0.95) using a CLSM

Figure 1. Milled technical surface with designated marked areas for measurement. The sizes of the marked square areas are as follows: Area I – 60 µm × 60 µm, Area II – 120 µm × 120 µm, Area III – 240 µm × 240 µm, and Area IV – 600 µm × 600 µm.

3. SELECTION OF APPROPRIATE MICROSCOPE OBJECTIVE AND STYLUS SCANNING PARAMETERS

3.1 Selection of microscope objective for optical surface texture measurements on the milled technical surface

According to the Good Practice Guide (GPG) for instrument selection [9], two key criteria must be considered when selecting a microscope objective for this milled surface:

(1) $\theta_{Objective} > \theta(95\%)$, where $\theta_{Objective}$ denotes the calibrated maximum measurable slope of the microscope objective.

(2) $W_R <$ Sal, where W_R is the topographic spatial resolution of the microscope objective.

Two objectives of the confocal laser scanning microscope (CLSM) were considered for the optical measurements: a 20× objective with a numerical aperture (NA) of 0.6, and a 50× objective with NA = 0.95. The calibrated maximum measurable slopes of the 20× and 50× objectives are approximately 35° and 70°, respectively [11]. Both values exceed the θ(95%) = 11° of the milled surface, thus fulfilling criterion (1).

The topographic spatial resolution of the two objectives was characterized using a resolution standard RS-N [12], which consists of one-dimensional (1D) gratings with a nominal height of 0.19 µm -- comparable to the height of the milled surface -- and pitches of 0.3 µm, 0.4 µm, 0.6 µm, 0.8 µm, 1.2 µm, 2.0 µm, 3.0 µm, 4.0 µm, and 6.0 µm. Characterization results indicate that the 50× objective can reliably resolve 2 µm pitches within a 10% tolerance [13], while the 20× objective fails to resolve even the 6 µm pitch [14].

Given that the autocorrelation length (Sal) of the milled surface is 4.1 µm, the 20× objective does not meet criterion (2). Consequently, the 50× objective with NA = 0.95 was selected for the validation and comparison measurements.

3.2 Selection of scanning parameters for stylus Profilometry on the milled aluminium surface

When measuring surface topography with a stylus profilometer, the selection of measurement parameters, particularly the stylus force, scanning speed and sampling rate, is critical to avoid artefacts such as stylus flight or specimen damage [6, 15-16]. To establish safe and reliable scanning parameters for the stylus profilometry, four experiments using various combinations of scanning parameters were carried out at four different positions on the milled aluminium surface using a stylus profilometer. Three experimental sets were designed as follows:

(1) Force and sampling rate fixed, speed varied: With a constant stylus force, several scans were performed at the same measurement position using increasing scanning speeds. The resulting surface profiles and roughness parameters were compared to assess whether any stylus flight occurred at higher speeds.

(2) Speed and sampling rate fixed, force varied: With a constant scanning speed, the stylus force was gradually increased while scanning the surface at the same position. The resulting surface data and microscopic inspection were used to evaluate the potential for surface damage at higher forces.

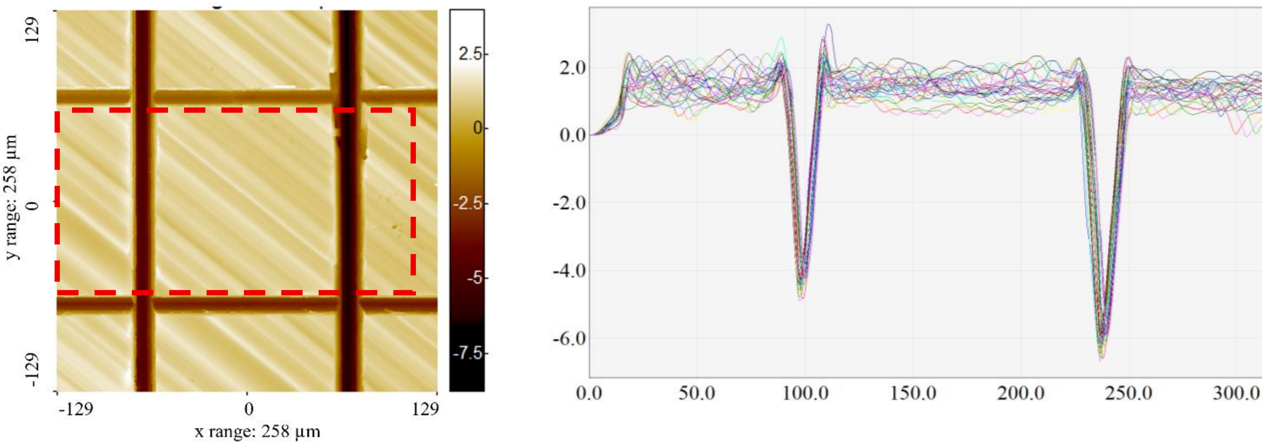
(3) Force and speed fixed, sampling rate varied: With constant stylus force and scanning speed, the sampling rate was gradually increased while scanning the surface at the same position. The resulting surface profiles and roughness parameters were compared to evaluate whether a higher sampling rate introduces any effects, such as increased noise.

Finally, scanning parameters consisting of a stylus force of 20 µN, a scanning speed of 20 µm/s, and a sampling rate of 50 Hz were selected for subsequent measurements on the milled aluminium surface. Measurements were performed using a stylus with a tip radius of 2 µm and a cone angle of 60°.

4. COMPARISON METHODS FOR OPTICAL AND STYLUS SURFACE MEASUREMENTS

Profiles with a spacing of 4 µm were measured using a stylus profilometer within the red-marked area shown in Figure 2(a). Figure 2(b) shows the measured profiles. It can be observed that the stylus profilometer defines the height of the starting point of each profile as zero, using it as the reference level for the entire profile. Therefore, it is not possible to obtain correct areal surface texture parameters by simply combining all the profiles scanned in the region of interest. A direct comparison with areal parameters (such as Sa and Sq), which can be easily obtained from optical topography measurements, is not feasible, since individual profiles lack a well-defined reference plane as provided in areal measurements.

Two methods are considered for comparing optical and stylus surface measurements by comparing the roughness parameters such as Ra and Rq. The first approach involves directly matching the profile measured by the stylus profilometer to the corresponding profile extracted from the optically measured topography. The second approach involves measuring multiple profiles within the region of interest (ROI) using the stylus instrument and comparing the statistical results (e.g., roughness parameters) with those obtained from the corresponding profiles extracted from the optical topography data.



(a) The scanning area for a stylus profilometer measurements

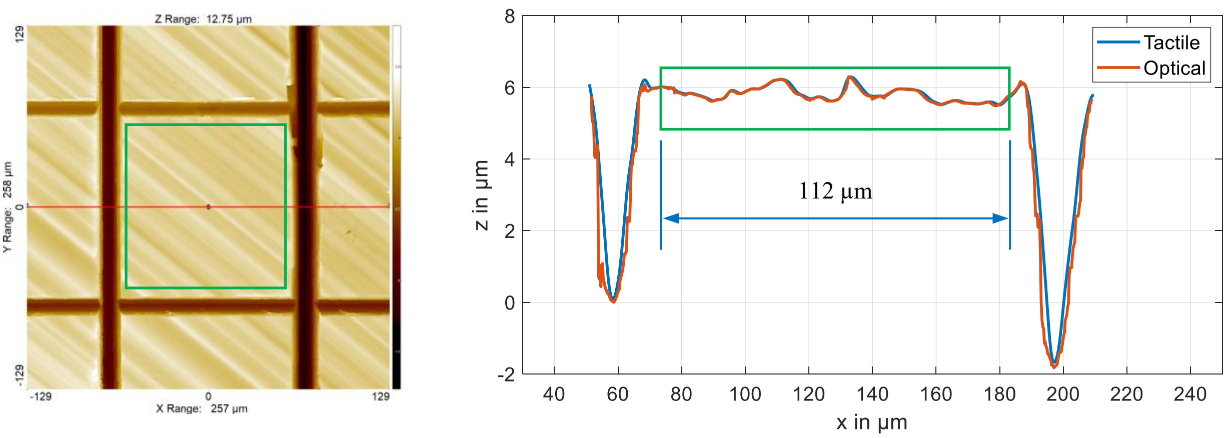
(b) The measured profiles (units: µm)

Figure 2. Profiles measured in the red line marked area using a stylus profilometer

4.1 Profile matching

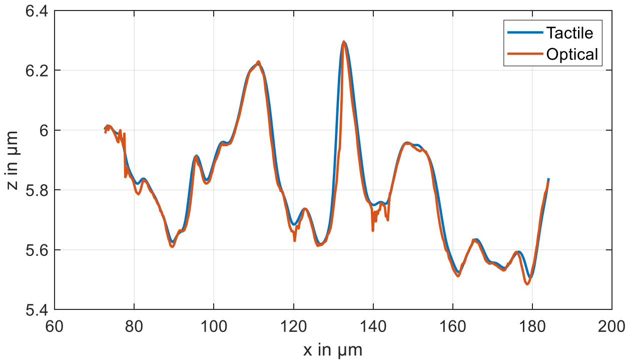
One profile measured by the stylus profilometer, positioned vertically at the center of the red-marked area in Fig. 3(a), is used for matching with a corresponding profile extracted from the optically measured topography. A cross-correlation method is employed to identify the best-matching profile from the optical data. Figure 3(a) shows the matched profile, identified as Line 511 in the topography image, while Figure 3(b) presents the aligned profiles: Line 511 from the optical measurement and the corresponding stylus-measured profile.

To calculate the roughness parameters, the regions affected by the marking trenches are cropped out, resulting in a comparison profile length of 112 µm, as indicated by the green-marked range in Fig. 3(b) and shown in Fig. 3(c).



(a) The surface topography measured by a confocal microscope (50x objective, NA 0.95)

(b) The matched profiles measured by a confocal microscope and a stylus instrument. The red profile was extracted from the 511th horizontal line in (a), while the blue profile was obtained using the stylus profilometer.



(c) Cropped profiles extracted from (b) for comparison of roughness parameters

Figure 3. Correlation between stylus-measured and confocally measured profiles

Calculated roughness parameters of the matched profiles and their relative deviations are listed in Table 1. It can be seen that the roughness values obtained from the stylus profilometer are slightly higher than those from the optical measurements, namely by 2% for Ra and 2.7% for Rq. This discrepancy is likely due to the fact that the stylus profile has not been deconvoluted, which can lead to overestimation of roughness height parameters. This effect is visible in Fig. 3(c). To improve accuracy, further investigation is required to characterize the stylus tip radius precisely, enabling proper profile deconvolution and correction. Additionally, the measurement uncertainty of the stylus profilometer, which is approximately 2% for profile measurements, should also be considered.

Table 1. Roughness parameters of matched profiles and corresponding deviations for measurements in Area II

Profile	**Ra in nm**	**Rq in nm**
stylus	140.0	172.2
optical	137.2 (-2%)	167.6 (-2.7%)

4.2 Statistical method

The profile matching method enables accurate comparison of individual profiles; however, it becomes time-consuming and impractical when applied to a large number of profiles. Therefore, a statistical approach was investigated to enable more efficient comparison of roughness parameters.

To determine the number of stylus profiles required for reliable statistical comparison, a simulation was conducted using topography data obtained from the confocal microscope. The topography was acquired with a 50× objective, providing a square field of view (FOV) of 258 µm and a resolution of 1024 × 1024 pixels, resulting in a pixel size of 250 nm.

The simulation was carried out in the following steps:

Step 1: The topography image was cropped to a region of 112 µm × 121 µm, as indicated by the green-marked area in Fig. 3(a), to exclude the influence of the marking trenches.

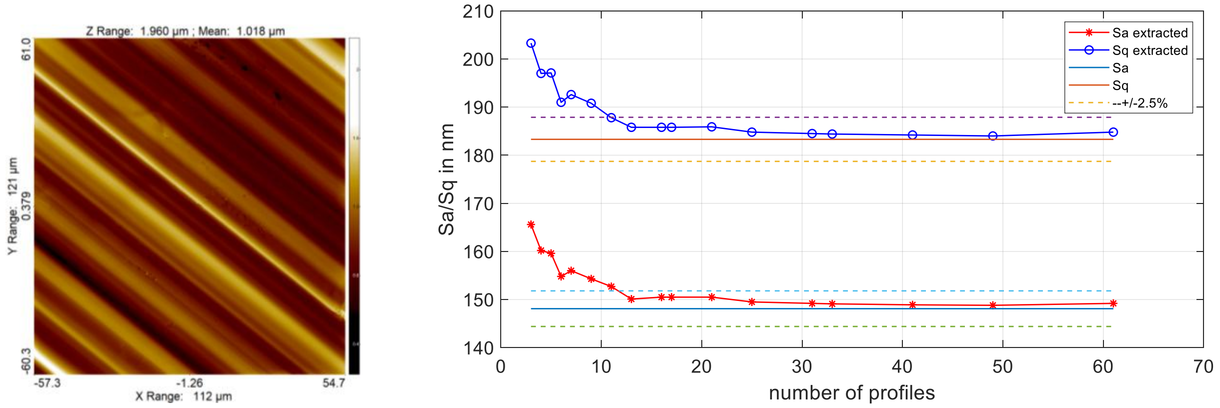
Step 2: A 2 µm S-filter was applied to approximate the smoothing effect caused by the stylus tip radius. The areal surface texture parameters of the cropped and filtered topography were evaluated, resulting in Sa = 142.5 nm and Sq = 173.2 nm.

Step 3: To simulate the stylus measurement resolution, every second pixel was extracted from the filtered topography data, achieving a lateral resolution of 0.5 µm, which closely matches the stylus resolution of 0.4 µm.

Step 4: Horizontal profiles were extracted symmetrically with respect to the vertical center line of the cropped topography image, which consists of 481 horizontal lines in total. The number of extracted profiles was varied as N = [3, 5, 7, 11, 13, 21, 23, 31, 34, 45, 56, 61].

Step 5: Reconstruct the extracted profiles to an areal topography image.

Step 6: The areal surface texture parameters (Sa and Sq) of the reconstructed images were calculated and compared to those obtained in Step 2 to evaluate the deviation due to limited sampling.



(a) The cropped topography image (b) The Sa/Sq values versus numbers of the extracted profiles

Figure 4. Simulation results using vertically evenly distributed profiles extracted from optical topography data

The simulation results indicate that, for this milled surface, using 13 evenly distributed profiles within the marked Area II yields surface texture parameters such as Sa and Sq with deviations of less than ±2.5%.

Profiles with spacing of 4 µm within Area II were measured using the stylus profilometer, resulting in a total of 31 scanned lines. The average Ra and Rq values of these profiles are 146.1 nm and 178.4 nm, respectively. For comparison, all 481 horizontal lines from the cropped and filtered optical topography image were extracted, yielding average Ra and Sq values of 142.5 nm and 173.2 nm, respectively. The measurement results are summarized in Table 2.

Table 2. Roughness parameters obtained using statistical method and corresponding deviations for measurements in Area II

Profile	**Ra in nm**	**Rq in nm**
Stylus, 31 profiles	146.1	178.4
Optical, 481 lines	144.6 (+0.3%)	176.6 (-1.0%)
Optical, 2 µm S-filter, 481 lines,	142.5 (-2.5%)	173.2 (-2.9%)

The roughness values obtained from the stylus profilometer are again slightly higher than those from the optical measurements. The possible reason for this discrepancy is discussed in Section 4.1.

5. CONCLUSIONS AND OUTLOOK

This paper developed a systematic approach to validate optical surface texture measurements on a milled aluminum surface with marked areas of different sizes. The 50× objective (NA 0.95) was selected which is suitable due to its adequate slope measurement range and spatial resolution. Stylus profilometry scanning parameters were tested and selected to avoid measurement artefacts such as stylus lift-off and specimen damage.

Two comparison methods, namely direct profile matching and statistical analysis method showed good agreement in roughness parameters (Ra, Rq), with deviations within a few percent. About 13 stylus profiles evenly spaced were sufficient for reliable statistical comparison. This result confirms that the chosen confocal laser scanning microscope can effectively characterize the milled technical surface texture and be cross-validated with stylus measurements.

Future work will improve accuracy by addressing stylus tip effects and extend validation to other surface types for broader applicability.

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