DOI: 10.58895/ksp/1000128686-16 erschienen in:
OCM 2021 - 5th International Conference on Optical Characterization of Materials, March 17th – 18th, 2021, Karlsruhe, Germany : Conference Proceedings
DOI: 10.58895/ksp/1000128686 | https://www.ksp.kit.edu/site/books/m/10.58895/ksp/1000128686/

Improvement of Roughness Measurement in Sub-micron Ranges Using Contrast-based Depolarization Field Components

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Abstract The characterization of a surface, especially the roughness, is of great importance for industrial applications. There are already various optical methods for roughness measurement, which usually do not consider the depolarization effects of the scattered beam caused by the sample. This work aims out improving the roughness measurement method described in [1] by taking into account depolarization effects, due to the rough sample. For validation, other instruments are employed to compare the results in the measurement interval for which this technique is applied.

Keywords Roughness measurement, optical method, speckle, depolarization, contrast

1 Introduction

Surface roughness characterization is essential in many industrial applications: for monitoring manufacturing processes in the optical industry [2], for determining the roughness of pharmaceutical pills to ensure their effectiveness [3], and for analyzing fatigue in materials [4]. Due to the production of novel structured materials and the need to ensure their functionality without damaging them, the demand for purely optical characterization of roughness in industry is also increasing. Several methods have been provided for determining the surface roughness. Often profile-based methods, such as the stylus method, are used because they provide reliable results [5]. The diamond tip of the stylus instrument, however, may not be useful for soft surfaces like rubbers and some plastics because it destroys the surface under test. Moreover, these techniques are very time-consuming.

There are also optical techniques, such as the white light interferometer [6] or the confocal microscope [7]. One advantage of these optical methods is their accuracy, but they are associated with high acquisition and maintenance costs. This motivates research of alternative optical measuring techniques for roughness determination, which are fast, accurate, and cost-effective. At the same time, non-destructive properties must not be neglected. Most of the different optical procedures for roughness measurements do not take into account depolarization effects in the light-matter interaction process [1], which limits the applicability range of these methods. Other techniques based on light scattered by the rough surface, however, take into consideration changes in polarization, extending their possibilities in application [8, 9]. Another way to determine the roughness is to consider the depolarization processes in interferometric fringe speckle patterns by analyzing two different contrasts in two interferograms corresponding to the respective polarization field components. For this purpose, the interferogram is spatially evaluated in regions. This has already been the subject of previous investigations [10]. The method promises a higher accuracy compared with [1] of the estimated surface roughness and is valid for small roughness values ($15\ \text{nm} < Rq < 40\ \text{nm}$), where different industrial applications may be found. To verify the presented method, measurements are carried out for different rough samples and compared with measurement results from a stylus instrument, a white light interferometer, and a laser confocal microscope to verify the roughness values measured with the interferometer. The results are also evaluated concerning the objectives used in the confocal microscope and the white light interferometer. To investigate the current applicability of the method in industry, the suitability of the commercial measuring instruments for the presented technique is also evaluated. The roughness of the samples is measured in each case, and the accuracy and applicability of those methods are analyzed.

2 Methodology

The theory of the method is explained below, before further detailing the operation principle of the roughness measurement by contrast-based depolarization field components.

2.1 Theory

The presented method is based on two-beam interference of two waves. This superposition results in the typical speckle pattern with the interference fringes. The two averaged intensities in the interferogram, $\langle I_{\mathrm{A}} \rangle$ and $\langle I_{\mathrm{B}} \rangle$, visible on the camera can be expressed as follows [10]:

$$\begin{aligned}\langle I_{\mathrm{A}} \rangle &= I_{\mathrm{ys}} + I_{\mathrm{ym}} + I_{\mathrm{xs}} \\ &+ 2\sqrt{I_{\mathrm{ys}} I_{\mathrm{ym}}} \cdot \exp\left(-\frac{\left(2ku_{\mathrm{geom}}\sigma\right)^2}{2} \right) \cdot \cos\left(u_{\mathrm{geom}} k f\left(x, y\right)\right), \end{aligned} \quad (2.1)$$

$$\begin{aligned}\langle I_{\mathrm{B}} \rangle &= I_{\mathrm{xs}} + I_{\mathrm{xm}} + I_{\mathrm{ys}} \\ &+ 2\sqrt{I_{\mathrm{xs}} I_{\mathrm{xm}}} \cdot \exp\left(-\frac{\left(2ku_{\mathrm{geom}}\sigma\right)^2}{2} \right) \cdot \cos\left(u_{\mathrm{geom}} k f\left(x, y\right)\right), \end{aligned} \quad (2.2)$$

where $\langle I_{\mathrm{A}} \rangle$ is the intensity on camera part A and $\langle I_{\mathrm{B}} \rangle$ is assigned to camera part B, where the quarter-wave plate is inserted in front of the reference mirror. I_{ys} and I_{xs} are the y component and the x component of the total intensity I_{S} of the rough surface, where the same is assumed for the total intensity on the reference mirror I_{M}. u_{geom} is the geometrical factor that describes the scattering at the surface, defined here as $u_{\mathrm{geom}} = 2$, since the rough surface and the reference mirror are reflective. $k = \frac{2\pi}{\lambda}$ corresponds to the wave number with the laser wavelength λ, σ is the standard deviation of the heights on the surface of the target and $f\left(x, y\right)$ defines the shape of the reference, which here corresponds to an inclination around the x- or y-axis, resulting in parallel interference fringes. The Michelson contrast C_{M}, which describes the fringe visibility in the interferogram [1], is composed of the maximum intensity I_{max} and the minimum intensity I_{min} as follows:

$$C_{\mathrm{M}} = \frac{I_{\mathrm{max}} - I_{\mathrm{min}}}{I_{\mathrm{max}} + I_{\mathrm{min}}}. \tag{2.3}$$

The two different contrasts C_{A} and C_{B} in the interferogram of the two camera parts can be determined under the assumption for the total intensity on the reference mirror formula $I_{\mathrm{M}} = I_{x\mathrm{m}} \approx I_{y\mathrm{m}}$ [10]:

$$C_{\mathrm{A}} \approx \frac{2\sqrt{I_{\mathrm{ys}} I_{\mathrm{ym}}} \exp\left(-\frac{\left(2u_{\mathrm{geom}}k\sigma\right)^2}{2}\right)}{I_{\mathrm{xs}} + I_{\mathrm{ys}} + I_{\mathrm{M}}}, \tag{2.4}$$

$$C_{\mathrm{B}} \approx \frac{2\sqrt{I_{\mathrm{xs}} I_{\mathrm{xm}}} \exp\left(-\frac{\left(2u_{\mathrm{geom}}k\sigma\right)^2}{2}\right)}{I_{\mathrm{xs}} + I_{\mathrm{ys}} + I_{\mathrm{M}}}, \tag{2.5}$$

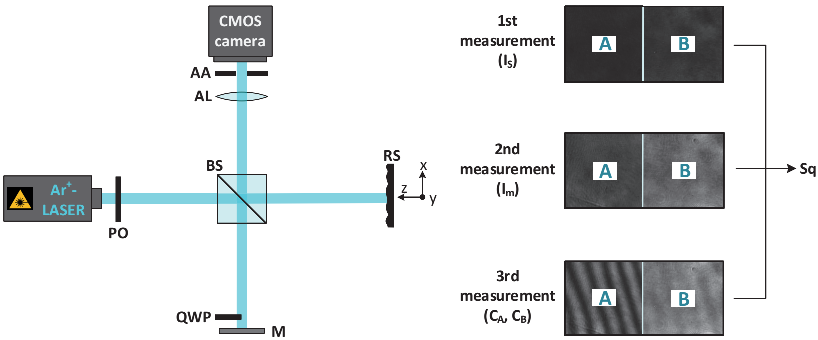
which result from only one experiment due to the quarter-wave plate being with one half inserted into the reference beam and provide the separated information on the camera. This divided information and the independent knowledge of the intensity components I_{xs} and I_{ys}, where $I_{\mathrm{S}} = I_{\mathrm{xs}} + I_{\mathrm{ys}}$ applies, is required for the roughness determination of the sample, since the sample depolarizes the light with $I_{\mathrm{xs}} \neq 0$. By rearranging the previous formulae the following expression for the standard deviation of the height the object surface σ results in [10]:

$$\sigma = \frac{\lambda}{4\pi} \sqrt{\ln\left(\frac{4 I_{\mathrm{M}} I_{\mathrm{S}}}{\left(I_{\mathrm{xs}} + I_{\mathrm{ys}} + I_{\mathrm{M}}\right)^2 \left(C_{\mathrm{A}}^2 + C_{\mathrm{B}}^2\right)}\right)}, \tag{2.6}$$

where σ can be equated with the root mean square (RMS) height $Sq = \sigma$ [11], which allows a comparison of the measurement results with the interferometer setup and the results of the measurements with the commercial measuring instruments. For the validity of the presented method, the standard deviation σ of the height must be Gaussian-distributed on the object surface, the surface itself must be a weak scatterer, i.e., $Rq < \lambda/4$ [12], so that we still find the necessary interference fringes and the speckles are not fully developed, and the rough object surface must be flat.

2.2 Roughness Measurement by Contrast-based Depolarization Field Components

For the measurements, we use a modified Michelson interferometer with a quarter-wave plate (QWP) set with one half in the reference beam (figure 16.1(a)). For the Ar^+-laser, we choose the wavelength $\lambda = 488$ nm to verify the roughness measurement by contrast-based depolarization field components because it is in the middle of the spectrum of the laser and has a high intensity. To guarantee the initial polarization conditions, i.e., linear polarization of the laser light, a polarizer (PO) is placed in front of the Ar^+ laser. A 50:50 beam splitter (BS) divides the beam into an object and reference path. The laser beam, linearly polarized in the y-direction, is directed to the tilted plane mirror (M) in the reference path, where a QWP is placed in one of the two halves, called here part B, whose optical axis is set to 45°, which enables the required two different polarization states of the reference beam, providing the different information about part A and part B. The rough surface (RS) scatters the laser light, creating different interferometric fringe patterns on both camera parts A and B. The camera (Photonfocus) has a resolution of 1312×1082 pixels (12 bit) with a pixel size of 8 μm × 8 μm. The achromatic lens (AL) and the adjustable aperture (AA) produce a focused image of the object (RS) and the reference (M) on the camera. The magnification of the measuring system is 1.5. To determine the RMS height Sq of the rough surface, the roughness measurement by contrast-based depolarization field components consists of three measurements. In the first measurement, we determine the total intensity of the rough surface I_S, for which only the object path in figure 16.1(a) is considered. The light backscattered from the surface (RS) is recorded by the camera (see figure 16.1(b)) and we can calculate the intensity I_S reflected from the rough surface. In a second measurement, we measure the total intensity of the reference mirror (M) I_M, assuming approximately equal intensity on both parts of the plane mirror $I_M = I_{xm} \approx I_{ym}$. To ensure that the intensity of the reference mirror is the same, we place a glass in front of the mirror (in part A) for additional radiation absorption, since the QWP absorbs about 8 % of the radiation, in all directions of propagation. The glass must have the same absorption properties as the QWP. For the measurement, only the reference path in the Michelson interferometer is considered in figure 16.1(a) and the intensity reflected from the mirror (M) is recorded and shown in figure 16.1(b). In the third measurement, both paths of the Michelson setup in figure 16.1(a) are now considered, producing two interference patterns with different contrasts C_A and C_B generated on the camera image (see figure 16.1(b)). These two contrasts are calculated according to equation 2.3 by the Michelson contrast for part A and part B. If now the measured values for I_S, I_M, C_A, and C_B are inserted into equation 2.6, the RMS height Sq of the rough surface results.



(a) Measurement setup. **(b)** Interferograms.

Figure 2.1: Interferometer setup and measuring procedure of the roughness measurement by contrast-based depolarization field components for the surface under test with RMS roughness $Rq_{\text{stylus}} = 28$ nm at a wavelength of $\lambda = 488$ nm.

3 Experimental Results

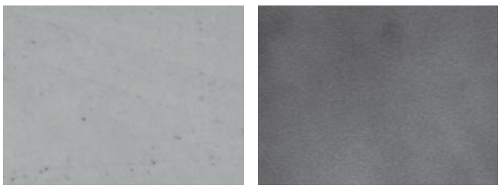
To verify the suitability of the measurement instruments, the roughness of five different samples is evaluated using the theory explained above. The measurements with the interferometer setup in figure 16.1(a) were performed with the wavelength $\lambda = 488.0$ nm. Since the Michelson interferometer results (according to equation 2.6) may vary slightly from one part of the surface to another, the $Sq_{\text{michelson}}$ values from nine different areas for each sample were calculated and averaged. Besides, in order to compare this new technique with the basic methodology shown in [1], a calculation of the roughness without considering the depolarization of the scattered light was performed (Sq_{MWODSL}). To validate the proposed procedure, measurements using other instruments were carried out. In addition, these measurements also serve to analyze the suitability of each technique for industrial applications. To this objective, a stylus instrument, a white light interferometer, and a laser confocal microscope were used.

We measured the samples twenty times in different directions using a stylus instrument (SURFCOM FLEX 50 A with a measuring force of 0.75 mN and a stylus tip radius of 2 μm) and then averaged them. The measurements with the white light interferometer (Wyko NT3300) have been performed in the VSI mode [13], i.e., by vertical scanning interferometry. To generate the magnification of a 40X objective, a 20X objective and an additional adjusted filter with a field of view (FOV) of 2 were used, and for the 10X objective, a 20X objective and an additional adjusted filter with a FOV of 0.5 were placed. With the confocal microscope (SENSOFAR PLμ 2300), two different microscope objectives were employed (50X and 100X).

By analyzing the experimental results shown in table 16.1 we find that the new method gives different values ($Sq_{\text{michelson}}$) than those obtained by the technique without considering depolarization effects Sq_{MWODSL} [1]. These series of values better confirm with some of the other methods employed. The stylus instrument and the confocal microscope (100X) seam to be adequate to compare the results. The Michelson interferometer working without depolarized scattered light (MWODSL) [1] provides values that do almost not change in the interval of the roughness values of samples 1 to 5. On the contrary, the $Sq_{\text{michelson}}$ varies approximately for S1 to S3 according to the stylus and the confocal microscope (100X). It shows that the method proposed may be a good estimate for small roughnesses up to 40 nm, which is an indicator for considering the depolarization effects of rough surfaces. It is interesting to note the discrepancies of the results among the techniques used. The results vary with the method and also with respect to the magnification of the objectives, then it is necessary to be careful when comparing experimental values. It is clear from table 16.1 that the confocal microscope with a 100X objective, and the stylus (radius of 2 μm), are suited to compare results within the investigated interval. The white light interferometer, even though has a very good resolution, it is not useful, in the context to validate the new technique. Exemplary captured images of sample 2 of the confocal microscope with a 50X objective and of the white light interferometer with a 40X objective are shown in figure 3.1.

Table 16.1: Experimental results for five samples (in nm) measured by the stylus profiler, the white light interferometer, the confocal microscope, the Michelson interferometer without considering depolarization of the scattered light (MWODSL), and the interferometer setup considering depolarization effects ($Sq_{\text{michelson}}$). The uncertainties of the results and the measuring instruments are also given.

	S 1	**S 2**	**S 3**	**S 4**	**S 5**
Rq_{stylus}	28 ± 2	31 ± 2	37 ± 2	45 ± 2	116 ± 4
$Sq_{\text{white light}}$ (10X)	9 ± 1	6 ± 1	52 ± 1	91 ± 1	260 ± 1
$Sq_{\text{white light}}$ (40X)	6 ± 1	4 ± 1	21 ± 1	43 ± 1	198 ± 1
Sq_{confocal} (50X)	15 ± 1	18 ± 1	29 ± 1	47 ± 1	106 ± 1
Sq_{confocal} (100X)	26 ± 1	28 ± 1	52 ± 1	49 ± 1	116 ± 1
Sq_{MWODSL}	40 ± 2	41 ± 2	44 ± 2	44 ± 2	49 ± 1
$Sq_{\text{michelson}}$	27 ± 1	31 ± 1	32 ± 2	28 ± 3	31 ± 4



(a) S 2: 50X **(b) S 2:** 40X

Figure 3.1: Captured images for sample 2 of the confocal microscope with the objective 50X ((a)) and of the white light interferometer with the objective 40X ((b)).

To determine the uncertainties of the experimental results, the expanded uncertainty is calculated [14]:

$$U\left(Sq_{\text{michelson}}\right) = k_{\text{cov}} u_c \left(Sq_{\text{michelson}}\right) \tag{3.1}$$

with the coverage factor $k_{\text{cov}} = 2$ [10] and the combined standard uncertainty $u_c^2\left(Sq_{\text{michelson}}\right)$ of the method [14]:

$$u_c^2\left(Sq_{\text{michelson}}\right) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2\left(x_i\right), \tag{3.2}$$

where f corresponds to the RMS height $Sq_{\text{michelson}}$ of the surface and $u\left(x_i\right)$ is the standard uncertainty for each input λ, I_{M}, I_{S}, C_{A}, and C_{B} (see equation 2.6). The uncertainties of the commercial measuring instruments, which are included in table 16.1, are given by the instrument and are determined according to the manufacturer's information.

From the investigation shown, we can conclude that the new technique, which includes depolarization effects, improves the results obtained with the usual Michelson interferometer. The confocal microscope may also be suitable for industrial applications due to its resolution in the same interval (15 nm $< Rq <$ 40 nm) but is associated with high acquisition costs of tens of thousands of euros. In the same way, the white light interferometer has great capabilities in a wide interval of roughnesses, but at significant costs. Thus, if only low roughness values of $<$ 40 nm are to be examined on materials, the modified Michelson interferometer may be preferable after a cost estimate.

4 Summary and Outlook

By the roughness measurement considering depolarization processes in interferometric fringe speckle patterns by analyzing two distinct contrasts in two patterns corresponding to the respective polarization field components, higher accuracy of the estimated surface roughness is possible for small roughnesses in the range of $Rq = 15$ nm to $Rq = 40$ nm. Commercially available measuring instruments, such as the confocal microscope, can be used for this method, and thus the technique can be currently applied in industry. Due to the short measurement time of a few seconds and the increased accuracy by considering the depolarization of the sample, the presented method is suitable for all reflective materials as a cost-effective method for optical characterization of surfaces in industry and as a supplement to (optical) measurement systems for roughness measurement.

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