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CALIBRATION OF A WHITE-LIGHT INTERFEROMETER WITH A USE OF MATERIAL MEASURES RECOMMENDED BY ISO 25178 SERIES: RELIABILITY AND UNCERTAINTY

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Abstract − There is a discrepancy between rapid pace of introducing more and more sophisticated white-light interferometers and a tardy tempo of developing proper calibration procedures applicable to these machines. Therefore, the authors evaluated both repeatability and credibility of calibration results obtained with a use of *PGR* and *PPT* calibration standards recommended by ISO 25178 series. The outcomes of the research, as well as limitations of the calibration artefacts usefulness, are presented in the paper.

Keywords: areal surface metrology, calibration, white-light interferometer

1. INTRODUCTION

White-light interferometers, which are also called coherence scanning microscopes (CSI), dedicated to areal surface texture measurements combine extremely high vertical (up to hundredths of nanometres) and horizontal resolutions with short measurement time, which does not exceed a few minutes. Due to these unique features, such metrological equipment, in spite of its relatively high price, becomes more and more common. However, this growth of popularity is not reflected by the development of widely accepted and used procedures ensuring sufficient reliability and reproducibility of measurement results obtained with white-light interferometers. Despite coherence scanning microscopes had run into the market in the late '80s, the first ISO standards referring to metrological characteristics and calibration of these measuring machines were published more than two decades later – in 2013 and 2014 respectively [1,2] as parts of ISO 25178 series. However, as the normative documents include only general recommendations, information concerning applicability of particular material measures to determine instruments' vertical response curve *F* [1] and, therefore, amplification coefficient *α* [1] is still severely limited.

In effect, the authors found it necessary to evaluate both repeatability and credibility of calibration results obtained with a use of the material measures applicable to white-light interferometers calibration and recommended by ISO 25178 series. These standards are periodic triangular shapes (*PPT*) and grooves, rectangular (*PGR*) [2]. The white-light interferometer used in research was CCI SunStar by Taylor Hobson. Its main metrological properties are specified in Table 1.

Table 1. CCI SunStar characteristics [3].

Type of interferometric objective	Mirau interferometer
Magnification power of the objective lens	10x
Working distance, distance between sample and lens	7.4 mm
Vertical resolution [max]	0.01 nm
Spatial sampling interval	1.65 µm

2. MATERIAL STANDARDS AND CALIBRATION PROCEDURES

Standards used in the research differed in their nominal characteristics and material they were made of, but, as mentioned, they could have been divided into two main groups: *PPT* and *PGR* material measures. Detailed information concerning metrological properties of these material measures was presented in the chapter.

2.1. Periodic triangular shape (PPT)

Two periodic triangular shape (*PPT*) calibration artefacts, called *PRN-10* and *PGN-10* were used in the research. Their characteristics according to material measures certificates are presented in Table 2.

Such standard artefacts reproduce triangular shape, which is characterised by its depth d_t and period p_t [2], as it is shown in Fig. 1. However, parameters which are the measurands in the calibration process are not the ones mentioned above, but standardised areal surface texture parameters: *Sa* and *Sz* [4]. It is worth mentioning that applying only the first one is recommended by ISO standard [2], whereas using another one is suggested by measuring equipment manufacturers [5].

In order to determine repeatability of obtained *Sa* and *Sz* values, the calibration procedure was repeated ten times.

Firstly, some introductory steps, presented in [6], had to be made. Then, surface data was collected. However, as area that can be assessed in a single measurement with a use of CCI SunStar 10x objective lens is limited to (1.65 x 1.65) mm and minimum measurement area essential for proper performance of Gaussian linear filter (λ_c = 0.8 mm) equals to (5 x 5) mm, it was necessary to apply the image stitching procedure implemented in TalyMap Platinum software. Therefore, the output surface measurement result consisted of 16 single surface images recorded as 4 x 4 matrix with overlaps of 0.53 mm. Finally, the Gaussian filter mentioned above was applied and areal surface texture parameters (*Sa*, *Sz*) were calculated. These values provide the basis for determining the amplification coefficients *α(Sa)* and *α(Sz)* respectively as in (1) and (2):

$$\alpha(Sa) = \frac{Sa}{Sa_{nom}}, \tag{1}$$

$$\alpha(Sz) = \frac{Sz}{Sz_{nom}}. \tag{2}$$

Sa_{nom} and Sz_{nom} are nominal values of *Sa* and *Sz* parameters, as stated in Table 2.

Table 2. Properties of *PRN-10* and *PGN-10* standards.

	PRN-10	PGN-10
Manufacturer	Mahr	Mahr
Material	steel	glass
Sa_{nom} - *Sa* nominal value (Gaussian linear filter applied, λ_c =0.8 mm)	2.39 µm	3.10 µm
Sz_{nom} - *Sz* nominal value (Gaussian linear filter applied, λ_c =0.8 mm)	9.56 µm	10.52 µm
Uncertainty of determining nominal measurands values (level of confidence 95%)	5%	4%

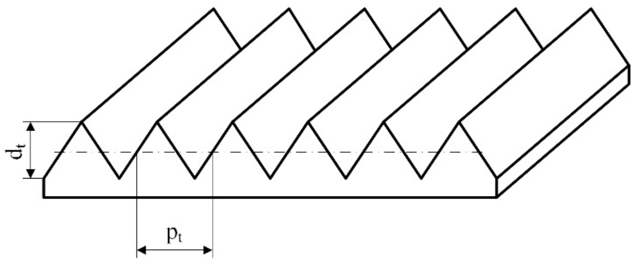

Fig. 1. Periodic triangular shape material measure.

2.2. Grooves, rectangular (PGR)

These calibration standards have a wide groove with a flat bottom. Such grooves are characterised by their depth *d* and width *w* [2], as shown in Fig. 2. However, only the first of these parameters is a measurand in calibration procedure.

In order to evaluate repeatability and credibility of calibration results three *PGR* material measures, differing in their nominal depth d_{nom}, were chosen. The groove standards properties are specified in Table 3.

The same preliminary steps were made, as when *PPT* measures were used. Then, surface data was collected. It has to be mentioned that introducing stitching procedure was not needed in this case because a single surface image provided sufficient number of data points. Surface used for assessment purposes was even limited to the one equal in size to three times the nominal width of groove (Table 3) both in X and Y direction.

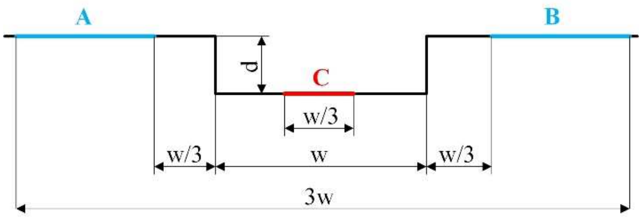

Fig. 2. A cross-cut of *PGR* material measure [2].

Table 3. Characteristics of *PGR* standards.

	PGR-0.35	PGR-2.55	PGR-9.40
Manufacturer	Taylor Hobson	Taylor Hobson	Mahr
Material	glass	glass	glass
d_{nom} – nominal depth	0.35 µm	2.55 µm	9.40 µm
w_{nom} – nominal width	0.55 mm	0.55 mm	0.6 mm
Uncertainty of determining nominal measurands values (level of confidence 95%)	5%	5%	5%

The groove depth *d* obtained in the calibration process equals to the distance between two parallel planes fitted by the method of least squares [7] to the portion of surface image: A, B and C respectively (see Fig. 2). Then, the amplification coefficients *α(d)* were calculated as in (3).

$$\alpha(d) = \frac{d}{d_{nom}} \tag{3}$$

3. RESULTS AND DISCUSSION

3.1. Repeatability of Sa and Sz values (PPT standards)

The *Sa* parameter values obtained when *PPT* standards were used to calibrate CCI SunStar are presented in Fig. 3. The thin dotted and solid lines refer to the nominal *Sa* values and associated uncertainty intervals obtained from material measures certificates. What is more, these lines are in the same colour as measurement results referring to them. Similar chart for *Sz* parameters is shown in Fig. 4.

Both figures indicate that *Sa* parameters are slightly underestimated when white-light interferometer is used, whereas *Sz* values for *PRN-10* standard obtained with this instrument are seriously overestimated.

Also, the repeatability of calculated Sz values is significantly worse than the one of *Sa* parameter. In neither case standard deviation of results exceeds tenths of a micrometre, however, the range of *Sz* measurement results exceeds 10% of nominal value when *PRN-10* standard is applied. In the same time, a range of obtained *Sa* values is no larger than 3% of the nominal measurand value.

The reason for worse repeatability of calibration results for *Sz* parameter may be the fact that it is much more vulnerable to single outliers than *Sa*, as it is a maximum height of the scale-limited surface, whereas *Sa* is just an arithmetical mean height of the surface. Impact of the outliers is the more visible, the more non-homogenous surface of material measure is.

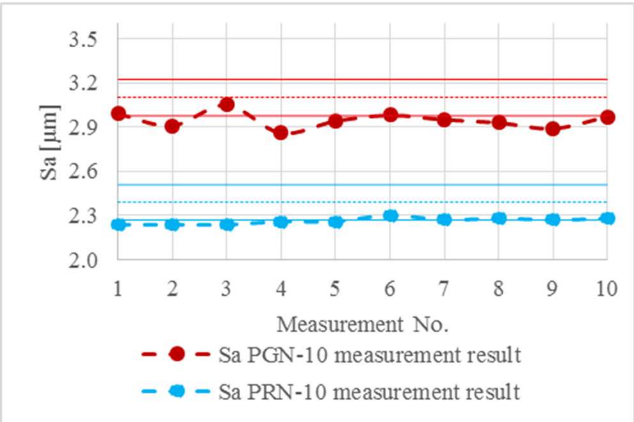

Fig. 3. Repeatability of *Sa* parameters (*PPT* standards used).

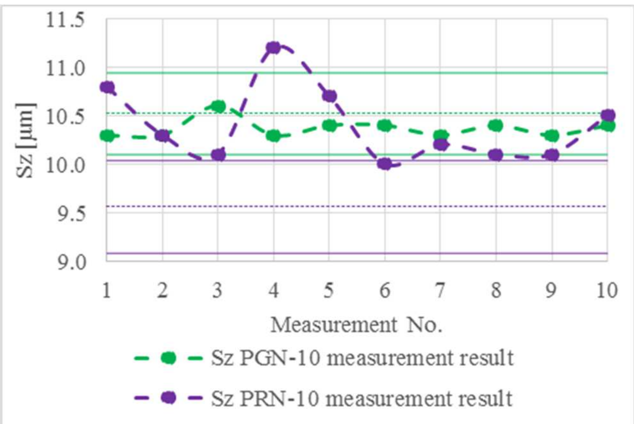

Fig. 4. Repeatability of *Sz* parameters (*PPT* standards used).

3.2. Repeatability of groove depth d (PGR standards)

Sample charts showing measurement results when *PGR* standards were applied are presented in Fig. 5 and Fig. 6. The measured and nominal groove depths with the uncertainty intervals referring to them are outlined similarly to the ones in Fig. 3 and Fig 4.

In spite of *PGR-9.40* standard measured depths seem to be slightly underestimated, the difference between nominal and measured values is within the uncertainty of nominal groove depth determination. Therefore, the groove depth measurement results are consistent with the nominal measurand values, whichever *PGR* material measure is used.

Also, the conducted research has shown that the deeper standard groove is, the higher absolute range of the results is observed. However, when the range of measured values is compared to the nominal groove depths, it turns out that the changeability of the calibration outcomes may be as low as a few per mils in relative values both for *PGR-2.55* and *PGR-9.40* standard. At the same time, the relative range of results for *PGR-0.35* material measure exceeds 10%. The worsened repeatability in this case is a result of the limitations of the measuring method itself, as a white-light interferometer's capability to measure steep surfaces may be inadequate. This is due to the numerical aperture of objective lens and the effects of multiple scattering, which are neglected by signal processing algorithms of the measuring equipment [8]. These factors may significantly affect measuring results when the steep gradient surface is measured and the height of the step is within or similar to the CSI light wavelengths, as it takes place when *PGR-0.35* material measure is applied.

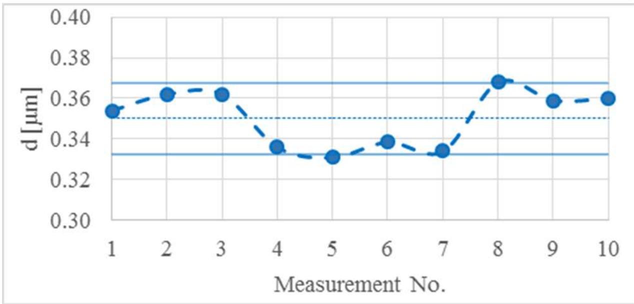

Fig. 5. Repeatability of groove depth measurement results for *PGR-0.35* standard.

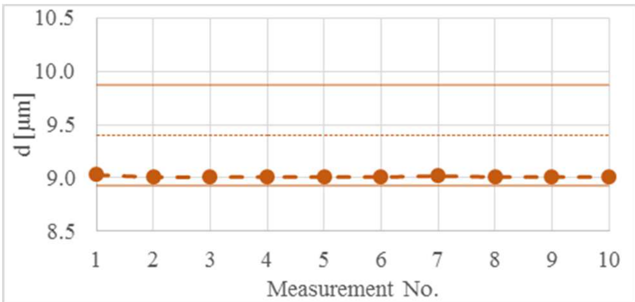

Fig. 6. Repeatability of groove depth measurement results for *PGR-9.40* standard.

3.3. Amplification coefficient α estimation

The amplification coefficient values acquired in the research with the uncertainty intervals (dashed lines) referring to their mean values are shown in Fig. 7. The α values were calculated according to (1-3).

The chart clearly outlines that there are some inconsistencies between the obtained amplification coefficients related to the calibration method and the measurand choice. However, most of the differences between the results are an effect of the uncertainty interval of the nominal measurand values. Other reasons for variability of the calibration results have already been mentioned in chapters 3.1 and 3.2.

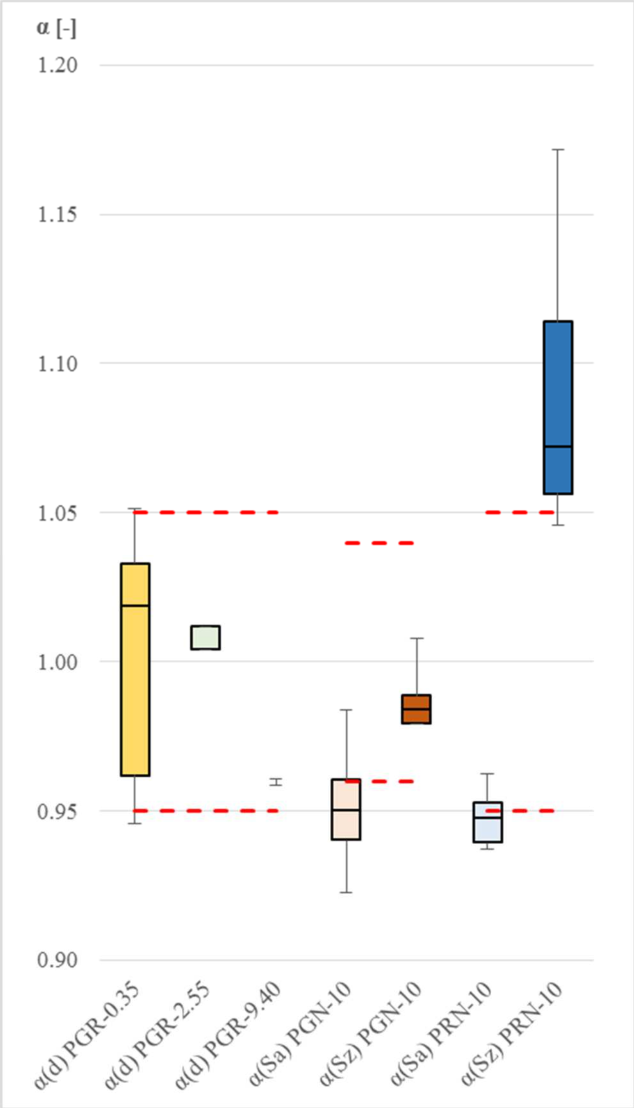

Fig. 7. Amplification coefficient α values acquired in the research.

4. CONCLUSIONS

The research has outlined that in spite of the variety of calibration methods and standards recommended by the ISO 25178 series, few of them can be used to determine CSI vertical response. The most popular and inexpensive among them are *PGR* and *PPT* calibration artefacts. However, even these materials measures have several serious drawbacks and their applicability is limited.

Firstly, due to its vulnerability to local deviations of material measures texture, *Sz* parameter should not be used as a measurand, in spite of the fact that it is recommended by manufacturers of commercially available white-light interferometers.

Furthermore, when groove standards are used, their nominal depth should be chosen carefully, as using an artefact with too low groove depth can result in introducing significant measurement errors. In result, amplification coefficient may not be estimated properly.

To make matters worse, the calibration standards proposed in ISO 25178 series let user determine instrument's response only at single, isolated points within the measuring range. Therefore, determining vertical response curve of the CSI and compensating its non-linearity demands using dozens of material measures differing in their nominal measurand values.

Finally, as the uncertainty of the estimated nominal values of groove depth and *Sa* parameter is relatively high (up to a few percent of the measurand), the calibration gives only general information concerning the measuring instruments performance.

All the difficulties mentioned above show how much is yet to be done in the field of areal surface texture metrology with a use of optical methods, such as white-light interferometry. The extra-ordinarily high resolution of the coherence scanning microscopes is not a guarantee of credibility and reliability of the measurement results, as the research proved. In order to ensure these, a completely new calibration standard or a set of them is to be devised.

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