BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 65, No. 1, 2017
DOI: 10.1515/bpasts-2017-0007

Influence of temperature gradient on surface texture measurements with the use of profilometry

T. MILLER[1]*, S. ADAMCZAK[2], J. ŚWIDERSKI[2], M. WIECZOROWSKI[3], A. ŁĘTOCHA[1], and B. GAPIŃSKI[3]

[1]Institute of Advanced Manufacturing Technology, 37a Wrocławska St., 30-011 Kraków, Poland
[2]Kielce University of Technology, 7 Tysiąclecia Państwa Polskiego Ave., 25-314 Kielce, Poland
[3]Poznań University of Technology, 3 Piotrowo St., 60-965 Poznań, Poland

Abstract. The paper presents an analysis of influence of ambient temperature changes on the values of parameters in topography measurements with the use of different profilometry techniques. In order to check this, a series of measurements was performed. Two multiprofilometry instruments were used – a contact profilometer, further equipped with an interferometric transducer, and an optical one with a confocal probe. Measurements were performed on first-class flat interferometric glass and on an A-type roughness standard – under different conditions, with simultaneous registration of differences in ambient temperature values. These values were either intentionally changed or the temperature variations were the result of air conditioning control. The performed research showed that – despite the asperities on the surface being really small – there is a relationship between changes of temperature and the results obtained from the measured surface, which in some cases can be seriously distorted.

Key words: profilometry, surface topography, temperature influence on measurements, credibility.

1. Introduction

The subject of the research described in this paper is the analysis of influence of temperature changes on measurement results during topography measurements of surface texture with the use of profilometry methods.

In industrial reality, more and more often areal analysis is used for surface texture description, and it is because of the fact that measurement of a single profile does not give complete information about surface texture of the researched object. One of the methods used in areal measurements of surface texture are the ones coming from profilometry, based on measurement data acquisition by scanning the surface in two perpendicular directions.

The main drawback of profilometry in general is the lengthy measurement, which depends on the measurement area, measurement speed in X axis (this axis should be perpendicular to traces of machining) and sampling interval in Y axis (resulting from the number of measured profiles and the area to cover). Dimensions of the area to measure come from the surface roughness of the inspected object. Surfaces with greater roughness usually require performing measurements on a bigger area. Typical probe movement speed in profilometry varies from 0.1 to 2 mm/s, although for some optical probes it can be higher if the converter is good enough. In contact profilometers the use of measurement speed above 0.5 mm/s is risky, because of the possibility of the flight phenomenon, i.e. a loss of contact between tip and surface.

Furthermore, measurement with too little profiles in Y direction (low density or small width) may result in loss of information about the measured surface.

Requirements and restrictions resulting from the presented factors influence the fact that a measurement lasts from tens of minutes to even more than few hours. Therefore, particularly for measurements lasting very long, during the calculation of the uncertainty budget, an operator should pay special attention to ambient temperature gradient and changes.

During the research performed under the project "Research and evaluation of reliability of modern methods of surface topography measurements in micro and nano scale" [1, 2], it was observed that with air conditioning working, small temperature changes that affect the measured values occur. And those issues are the subject of the research and analysis presented below.

Quite often we assume that the influence of thermal conditions on surface topography measurement results is negligible. The order of magnitude of changes is even 10 million times smaller than that of dimensions, and since when measuring asperities, we're talking about micrometers, changes within single picometers will not be observed. Still, changes of temperature also influence the structure of measurement devices, and here the dimensions are already in milimeters (even more than 100 mm sometimes), so the thermal conditions start to play a role. Particularly when the measurement takes a couple of hours and the laboratory is equipped with air conditioning that works between the upper and lower limits (respectively switching cooling on and off). This causes expansion drift of profilometer assembly parts that can significantly change measurement results. To prove this, we did some tests changing the temperature accordingly.

---

*e-mail: tatiana.miller@ios.krakow.pl

2. The research program

Measurements were made using the following profilometers:

- Form Talysurf 1200 PGI contact profilometer equipped with an interferometric transducer: cone-shaped mapping tip with $\alpha = 90°$ angle and $r_{tip} = 2$ μm radius,
- Altisurf 520 optical profilometer with a CL1 confocal probe.

The measurements were performed on material standards surfaces:

- flat plane type AFL – first-class accuracy [4],
- grooves: rectangular type A/PGR [3, 4],
- static measurement on glass – flat plane type AFL,
- bearing raceway surface,
- ZERODUR® sample.

For clarity of presentation, the following abbreviations were used:
X axis – measuring direction axis,
Y axis – axis perpendicular to the X measurement direction,
Z axis – vertical axis,
dY – the distance between the cross sections in Y axis
Δt – range of temperature (Max–Min),
R – Pearson correlation coefficient,
λ – dominant wavelength.

The measurements were performed in different environmental conditions, both maintaining quasi-constant temperature and with the temperature changing, provided that these changes did not exceed ±0.5°C. The duration of a single measurement (digitization of an area) was at least three hours (but much more in some cases), due to the fact that scanning a surface with satisfactory density using profilometry can last that long, particularly for larger measurement areas.

All the measurements were made along the X axis. Still, since temperature changes influenced the results, they were visible in the Y axis. Because of that, our analysis takes place along the Y axis, perpendicular to the measurement direction, on mean profiles, re-scaled onto a time axis in minutes. Some of the results were compared with these measured at a constant temperature, to show that just temperature changes are a reason of errors, visible as waves, non-existent on real surfaces.

Temperature registrations were performed using thermo-hygrometers type LB 520, with 0.01°C reading resolution and discretization of 30 s and 60 s.

3. Measurement results of areal material standards – flat plane type AFL

Below there are examples of measurements on an AFL-type material standard – first accuracy class flat interferometric glass, for which the nominal flatness deviation is ≤ 0.03 μm.

3.1. Measurement performed with a contact profilometer with interferometric transducer. The contact stylus instrument used to obtain measurement data presented in this paper was an instrument equipped with a 1 mm and 2 mm radius conical stylus tip arranged in a PX o CY – S configuration (EN ISO 25178–601), where S means it is with arcuate error corrected.

In order to research how the change of temperature influences the obtained results during measurements, a first-class interferometric glass measurement was performed. The air conditioning system was on during the measurement. The change of temperature during the measurements was equal to ±0.5°C. The temperature registration was performed with a 30 s interval. The measurement conditions (speed and measurement area) were selected in such a way, that the duration of the measurement reached 180 min. The number of profiles in Y axis was correlated with the number of temperature registration points. The obtained results are presented below.

In order to compare the changes of mean profile in Y direction with the changes of temperature, the data was normalised to avoid any problems with different units and features. This was realized basing on the following equation:

$$a_i' = \frac{a_i - a_{i\_min}}{a_{i\_max} - a_{i\_min}}, \tag{1}$$

where:
a'_i – i-th value after normalisation,
a_{i_min} – minimum value in data set,
a_{i_max} – maximum value in data set.

As a result of such a normalisation (Fig. 1c), values of both features (profile ordinate in Y axis and temperature) are contained in a <0,1> interval.

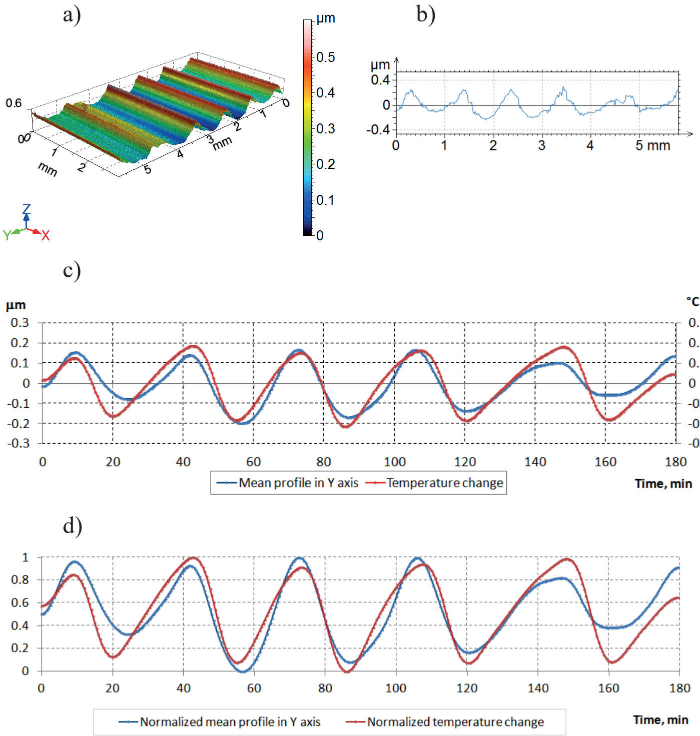


Fig. 1. Measurement results of areal material standard – flat plane type AFL, a) Isometric view: Sz = 0.631 μm, b) mean profile in Y axis: Pt = 0.533 μm, c) comparison of profile and temperature changes: Δt = 0.8°C, d) normalised changes of temperature and profile

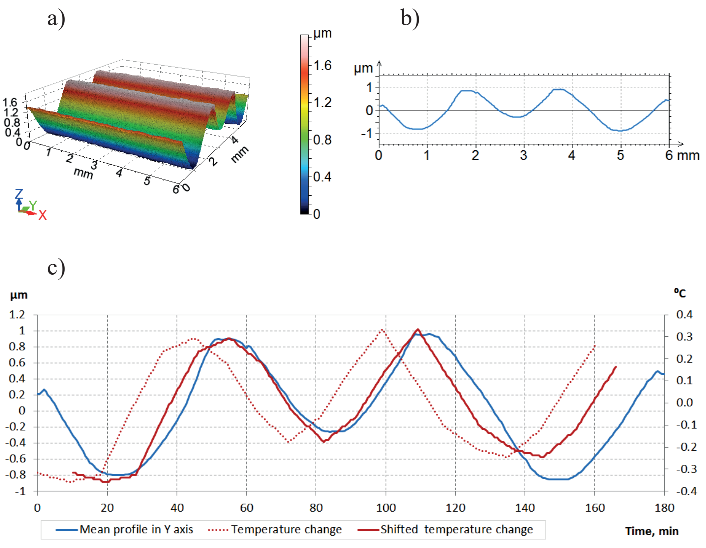


Fig. 2. Measurement results of areal material standard – flat plane type AFL, a) Isometric view: Sz = 1.93 µm, b) mean profile in Y axis: Pt = 1.82 µm, c) relationship between the mean profile in Y axis and temperature changes: Δt = 0.69°C

The results of the performed analysis showed a close relationship of profile waviness in Y axis with the temperature changes. The calculated Pearson correlation coefficient for profile data in Y axis and temperature changes is equal to R = 0.89.

3.2. Measurements performed with an optical profilometer with confocal probe. Below there are the results of a measurement on first-class accuracy flat interferometric glass with intentionally changed temperature.

Temperature changes were chosen to be smaller than 1°C, because such temperature variations often occur in laboratories as a result of air conditioning.

Figure 2 shows an isometric view of the measured surface, mean profile in the Y axis, and the relationship between the mean profile in Y axis and graph of temperature changes during measurement.

Table 1 presents the results of calculated Pearson's correlation coefficients designated without moving the data series and the temperature data, and after moving data in order to fit series in the time axis (there was a delay in ordinate changes versus temperature changes, so the data were shifted to show correlation).

Table 1
Correlation coefficients between mean profile in Y axis of flat plane glass measurement and temperature changes

Analysed series	Correlation coefficient
Mean profile of measured surface in Y axis versus temperature changes	0.17
Mean profile of measured surface in Y axis versus shifted temperature changes	0.91

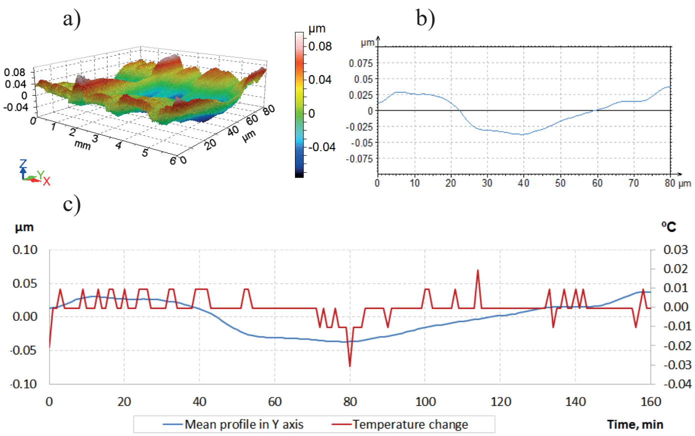


Fig. 3. Measurement results of areal material standard – flat plane type AFL, a) Isometric view: Sz = 0.173 µm, b) mean profile in Y axis: Pt = 0.075 µm, c) relationship between the mean profile in Y axis and temperature changes, T ≅ const., Δt ≅ 0.05°C

One can see a significant time-shift between the temperature change series and mean profile in Y axis series in the graph. It was not observed in the static measurements presented in chapter 4. It is clearly visible, both in Fig. 2c and from the designated values of correlation coefficients (Table 1), that after shifting the data series in the time axis to fit their waveforms in time, there is a high degree of correlation between the series in the graph.

Figure 3 presents the results of a measurement on the same flat plane, but on a very small distance in the Y axis (0.08 mm) to minimize stage errors, as it was not possible to perform the measurements on our device without any movement of the table. During the measurement, the temperature was quasi-constant (within the uncertainty).

When the temperature was quasi-constant (did not change by more than 0.05°C) during the measurements which took three hours, no significant amplitude changes (in Z axis) were observed along the mean profile in Y axis and in the isometric view in the amplitude.

3.3. Static measurement results performed with an optical profilometer with confocal probe. Static measurements were performed on one point on a flat glass standard without the movement of table and head.

Figure 4 presents the correlation between the sensor indications and temperature changes for the static measurement.

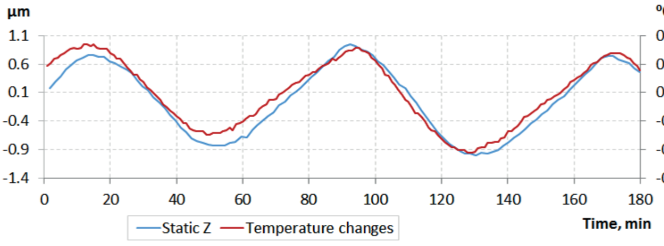


Fig. 4. Static measurement with intentionally changed temperature: Δt = 0.76°C, Pt = 1.91 µm

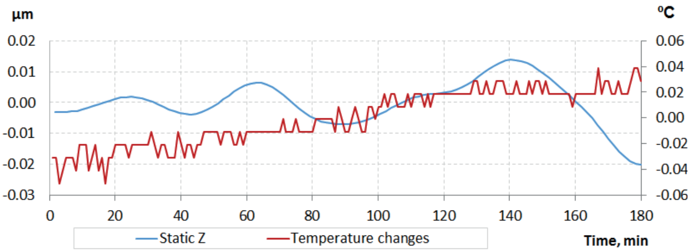


Fig. 5. Static measurement with quasi-constant temperature: Δt = 0.09°C, Pt = 0.034 µm

The temperature was intentionally changed within the range of Δt = 0.76°C.

For the static measurement on the glass, there is a noticeable correlation between the temperature and the value of the vertical axis – without moving data between the chart series on the time axis (Fig. 4).

For the static measurement on interferometric glass, performed when the temperature was almost constant with a very small upward trend, there is no characteristic dependence visible between data series presented in Fig. 5 as it was in Fig. 4. Changes in the value of the signal from the confocal sensors are very small.

4. Measurement results of profile standards – groove: rectangular type A/PGR

In the following paragraph, there are examples of two different A/PGR type standards measured in different conditions and with the use of different instruments.

4.1. Measurements performed with a contact profilometer with interferometric transducer. In order to investigate whether the change of temperature during measurements influences the measured value of depth of groove, inspection on a standard with 2.7 µm depth was performed. Air conditioning was on during the measurement. The change of temperature during measurements was equal to ±0.5°C. Duration of measurement reached 300 min.

Figure 6 presents the isometric view of the measured standard, mean profile of the groove, mean profile of upper surface of standard along the Y axis, mean profile of bottom surface of standard along the Y axis, and subtraction of the last two profiles. The profiles of upper and bottom surfaces of the standard are very close to each other. The subtraction of ordinates of those two profiles has a random character.

Figure 7 presents normalised changes of temperature and groove depth according to the normalisation described above. The changes of temperature are periodical, while the registered changes of groove depth are random. The calculated Pearson correlation coefficient of profile data along the Y axis and temperature changes is equal to R = -0.06. A comparison of changes in temperature and depth of groove is presented, Δt = 1°C.

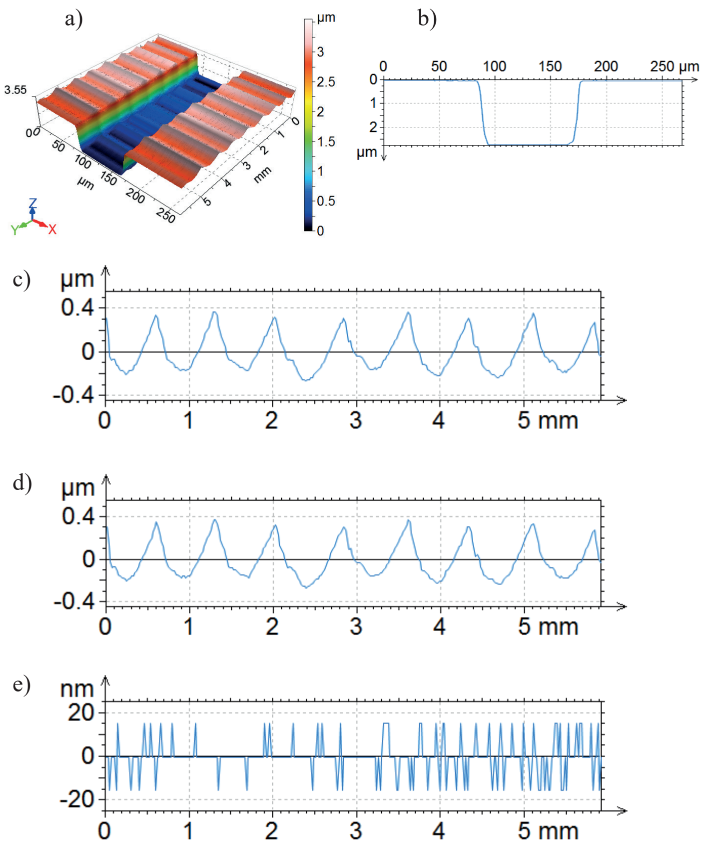


Fig. 6. Groove height of about 2.7 µm, a) isometric view, b) mean profile in X axis: Pt = 0.64 µm, c) mean profile of upper surface along Y axis: Pt = 0.64 µm, d) mean profile of bottom surface along Y axis: Pt = 31.31 µm, e) subtraction of two profiles: upper and bottom

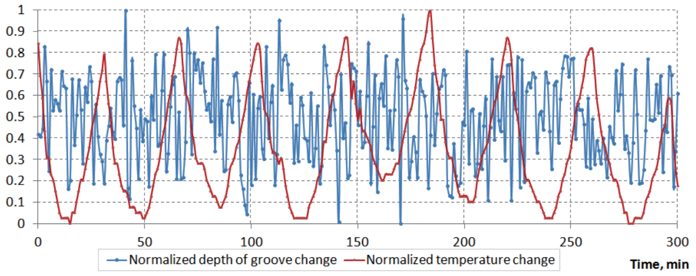


Fig. 7. Normalised changes of temperature and groove depth

Figure 8 presents spectrum analysis of mean profile of upper and bottom standard surface along the Y axis, and the profile of changes of depth groove. Mean profiles of upper and bottom surface (Fig. 6 c, d) are characterised by the same dominant wavelength λ ≅ 0.74 mm correlating with the character of temperature changes. The profile of groove depth changes does not have a single dominant wavelength. The amplitude of harmonic with wavelength λ ≅ 0.74 mm is ten times smaller than the amplitudes of harmonic for mean profiles of upper and bottom standard surface.

Based on the performed analysis, it must be said that for 2.7 µm groove depth and the used instrument, there are no bases

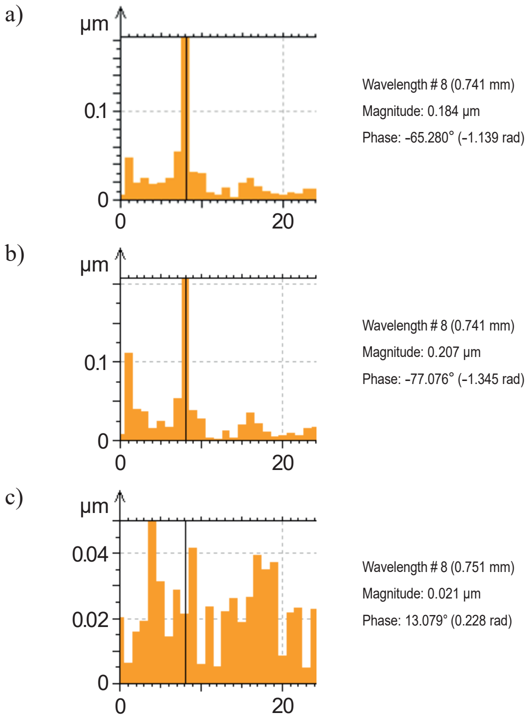


Fig. 8. Frequency spectrum: a) upper surface b) bottom surface c) depth of groove

to conclude that a correlation between periodical changes of ambient temperature and values of groove depth exists. The differences of groove depth have a random character and are a sum of random errors and groove depth changes on the standard surface.

4.2. Measurement performed with an optical profilometer with confocal probe. Below, the results of profile standard measurements (rectangular groove type A/PGR) are shown. The authors chose the smallest groove of the Rubert 513 standard with about 30 µm of depth. Fig. 9 presents the results of a measurement performed with temperature intentionally changed within the range of $\Delta t = 0.83$°C.

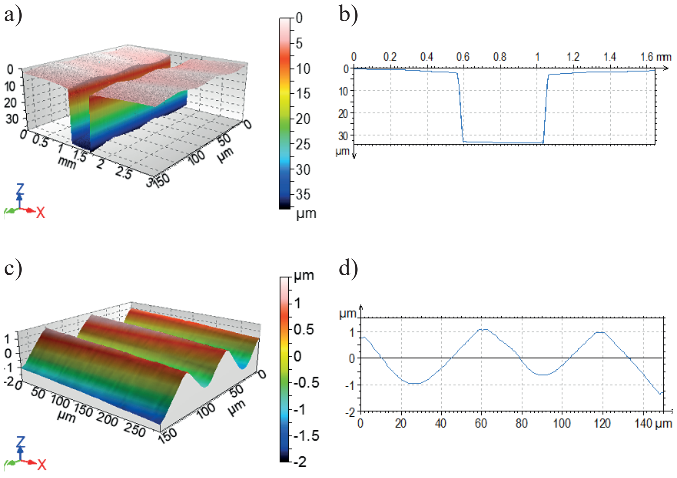


Fig. 9. A groove chosen from Rubert 513 standard: a) isometric view, b) mean profile in X axis, c) a part of upper surface: $Sz \cong 30$ µm, d) mean profile of upper surface along Y axis: $Pt \cong 2.46$ µm

The bottom surface of the groove shows almost the same form as the upper surface, and both display waving, which means that there is a correlation between the profiles (bottom and upper) along Y axis and the changes of temperature.

As a compilation of various relations, the following were found out: mean profiles in the Y axis – in upper and lower surfaces, the difference between them, changes of the groove height, and changes of temperature.

Figures 10 and 11 present the correlation of mean profiles in Y axis of upper and bottom surfaces of the groove, and also the temperature changes. In Fig. 11 the relationship between the mean profile in Y axis of the upper surface and the temperature changes, after normalisation according to the formula (1), is shown. In Fig. 12, the following dependencies between series are shown: deviations from the average high of the groove, difference between mean profile of upper and bottom surfaces in Y axis, and temperature changes.

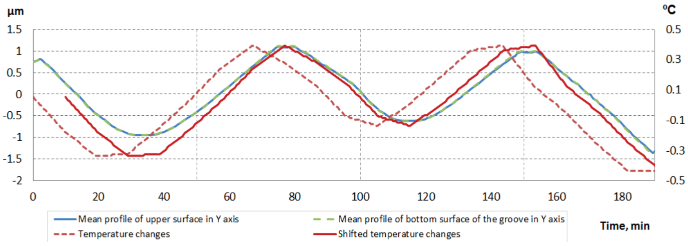


Fig. 10. Mean profiles in Y axis and temperature changes: $\Delta t = 0.83$°C, $Pt = 0.064$ µm

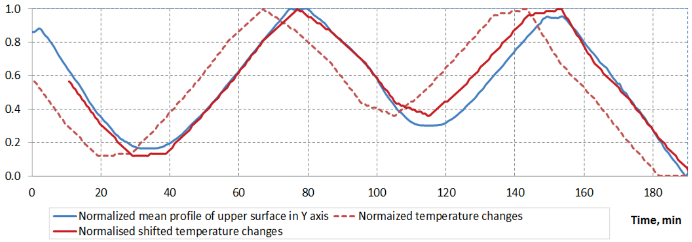


Fig. 11. Mean profile in Y axis of the upper surface and temperature changes after normalisation

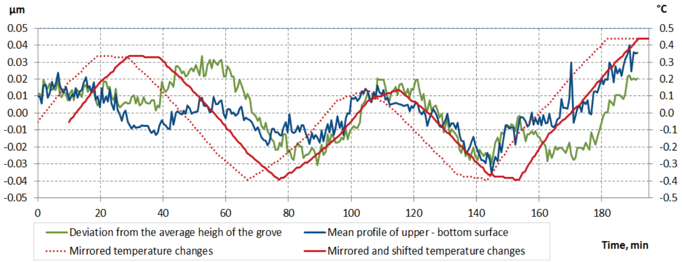


Fig. 12. Relations between series: the deviations from the average height of the groove, difference between mean profile of upper and bottom surfaces in Y axis, and the changes in temperature

In the analysis presented above, both the data and temperature graphs were shifted to fit the waveforms in time axis and finding relations and correlations between the data sets.

The upper and bottom surfaces show high correlation with temperature series after a time shift, which is about R ≅ 0.97.

Changes of the groove height show a slightly smaller, but still a significant correlation the with changes in temperature, which was shifted in the time axis, and mirrored in the vertical axis.

Data for some of the results of the temperature measurement were shifted by approx. 10 minutes. It was noticed that when the data is moved, there is a very strong correlation, and the shift results from a delayed reaction of the measurement system to changes in temperature.

Table 2 presents the results of correlation coefficients calculations for different configurations regarding the measured groove and the registered temperature.

Table 2
Correlation coefficients of measurement groove

Analysed series	Correlation coefficient
Mean profile in Y axis of upper surface versus bottom surface of the groove	0.99
Mean profile in Y axis of upper surface versus temperature changes	0.67
Mean profile in Y axis of bottom surface of the groove versus temperature changes	0.68
Mean profile in Y axis of upper surface versus temperature changes shifted	0.97
Mean profile in Y axis of bottom surface of the groove versus temperature changes shifted	0.97
Deviation from the average height of the groove versus difference between mean profiles of upper and bottom surfaces	0.57
Deviation from the average height of the groove versus temperature changes	–0.22
Difference between mean profiles of upper and bottom surfaces versus temperature changes	–0.66
Deviation from the average height of the groove versus temperature changes mirrored and shifted	0.69
Difference between mean profiles of upper and bottom surfaces versus mirrored and shifted temperature changes	0.57

In Fig. 13, graphs of the frequency spectrum are shown, designated for mean profiles of upper and bottom surface in Y axis of measurement of the groove and of their difference. The spectral representation is obtained by the fast Fourier transform. The graph represents frequencies, but the values are given in wavelengths so that they are easier to read.

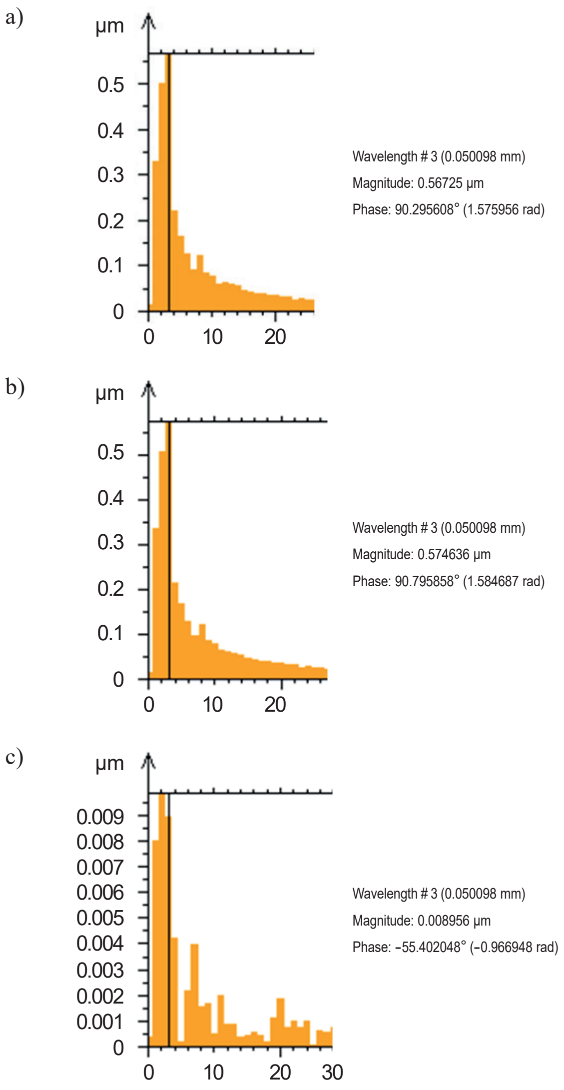


Fig. 13. Frequency spectrum of mean profiles of upper and bottom surface in Y axis: a) upper surface, b) bottom surface, c) upper surface – bottom surface

The dominant component of the frequency spectrum (λ ≅ 0.05 mm) is visible on all graphs in Fig. 13. This component is also present for the plot showing subtraction of the upper and bottom mean profiles, which looks very similar to the deviation of the average height of the groove [Fig. 11]. This confirms the earlier findings, which state that there is a correlation between temperature changes and the measured height of the groove.

5. Measurement results performed on a ZERODUR® sample using a contact profilometer

Measurements performed on a ZERODUR® sample, i.e. a material having a very small thermal expansion coefficient, were aimed at finding out whether generation of surface waviness

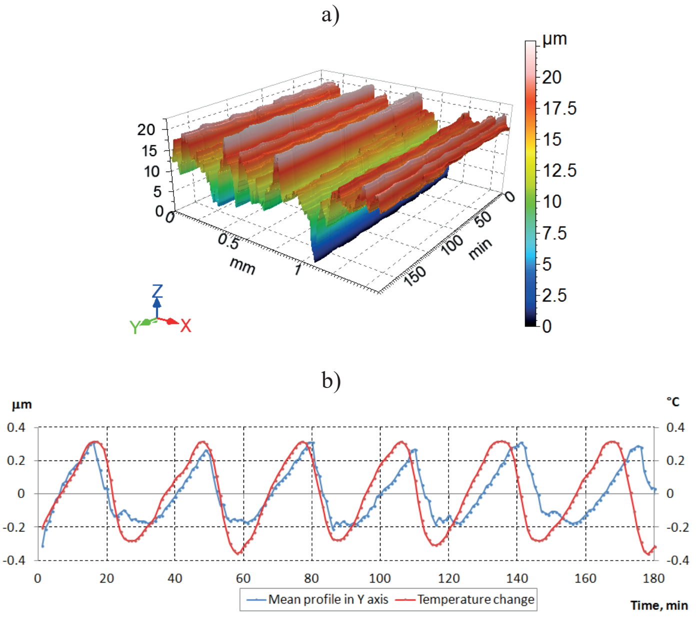


Fig. 14. Measurement results of ZERODUR® sample: a) isometric view, b) relationship between the profile in Y axis and temperature changes: Pt = 0,687 μm, Δt = 0.35°C

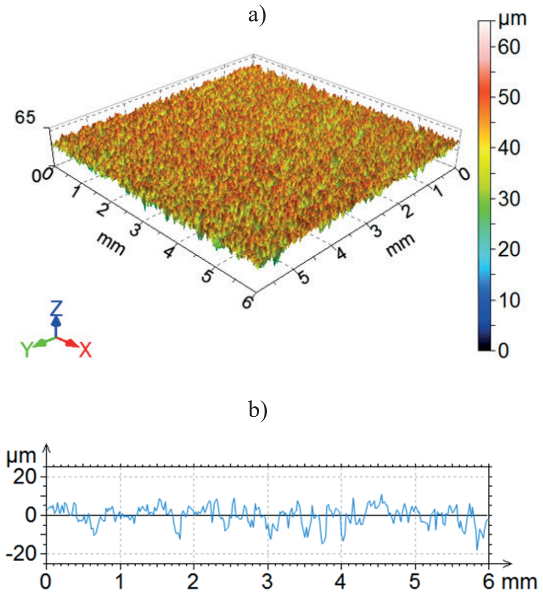


Fig. 15. Measurement results of ZERODUR® sample, a) isometric view: Sz = 65.07 μm, b) mean profile in Y axis: Pt = 28.88 μm, Δt = 0.35°C

while the temperature changes does not solely depend on thermal expansion coefficient of the sample material, but is rather a result of influence of ambient temperature changes in the measurement instrument loop. The second goal was to check how temperature changes influence roughness parameters in case of surfaces with very high asperities (e.g. about 50 micrometres).

Two ZERODUR® sample measurements were performed in the following conditions:

- range of temperature changes Δt = ±0.35°C, 300 measurements dY = 0 (in the same place), duration of measurement was 180 min,
- range of temperature changes: Δt = ±0.35°C, 300 measurements dY = 20 mm, duration of measurement was 180 min.

Figure 14 presents the results of measurements performed in conditions defined in Section 1. The Y axis is the axis of measuring time. On the profile along the Y axis, the influence of temperature changes on the measurement results is clearly visible, which indicates that surface waviness generation, as a result of temperature changes, does not solely depend on the coefficient of thermal expansion of the sample material, but is the result of influence of ambient temperature changes on the measurement instrument loop, so it comes from the device itself.

In Fig. 15, the results of measurements performed in conditions defined in Section 2 were shown. Due to very high asperities on the sample, the influence of temperature changes on the values of surface topography parameters is not visible.

6. Results of bearing raceway measurement performed using a contact profilometer

In order to check how temperature changes influence surface topography, measurements of an industrial workpiece (the bearing raceway) were performed. Fig. 16 presents the result of bearing raceway measurement performed in stable temperature conditions.

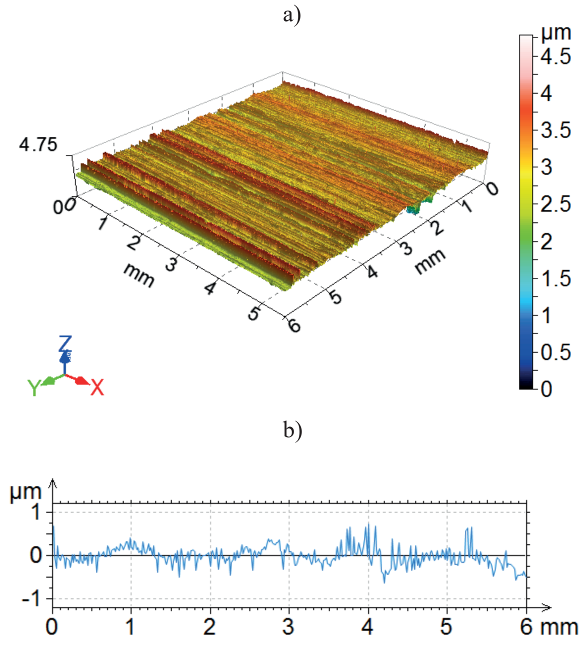


Fig. 16. Measurement results of bearing raceway, a) isometric view: Sz = 4.78 μm, b) mean profile in Y axis: Pt = 1.37 μm, temperature = const.

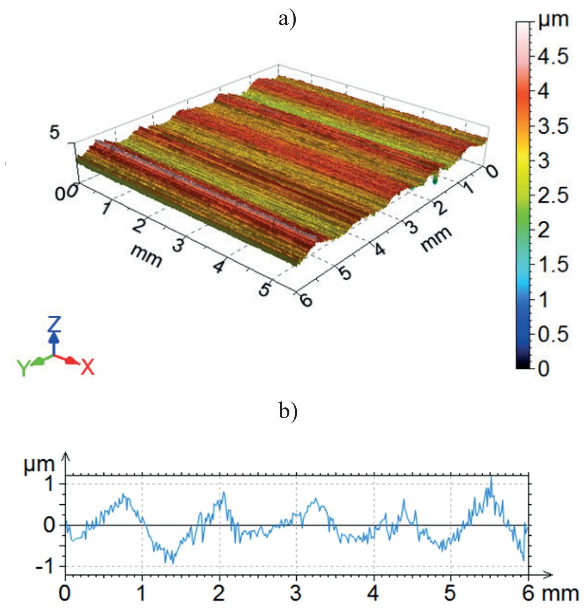


Fig. 17. Measurement results of bearing raceway, a) isometric view: Sz = 5.10 µm, b) mean profile in Y axis: Pt = 2.13 µm, Δt = 1°C

Figure 17 shows the results of surface texture measurement of bearing raceway, where the periodical changes of temperature were in the range of ±0.5°C.

Figure 18 presents the values of topography parameters calculated for the primary surface and filtered surface after using a Gaussian filter with a 0.8 mm cut-off, and on bearing raceway measurements for both in stable temperature conditions, and for periodical changes of temperature in the range of ±0.5°C took place. From this comparison, it is visible that the time gradient of temperature influences topography measurements of surfaces with low asperities.

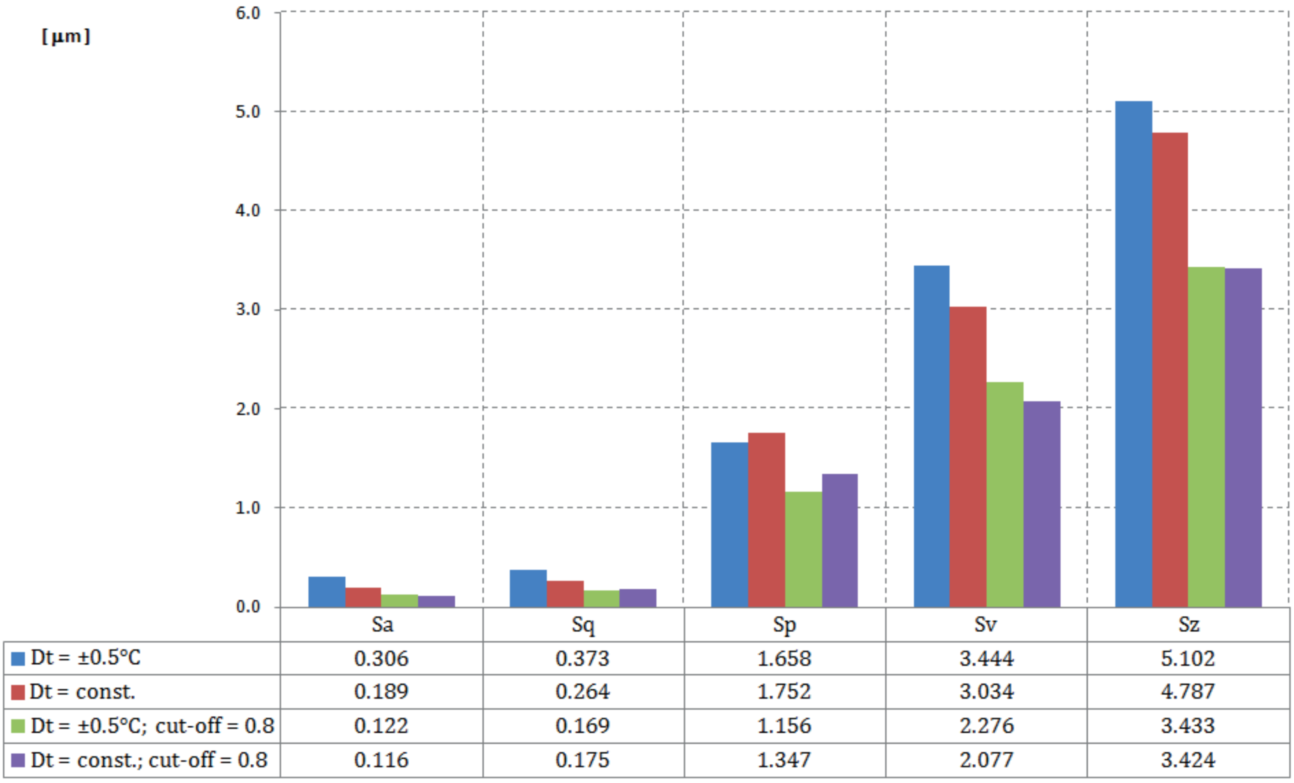
As it was expected, significantly bigger differences in parameter values exist for an unfiltered primary surface. Application of high-pass filter causes a reduction of differences of values for particular parameters.

7. Conclusions

Summarizing the obtained results of the performed research and analysis, the influence of ambient temperature changes on the results of surface texture measurements is significant and cannot be neglected in the evaluation of the surface quality assessment.

There is a close relationship between the profile of the measured surface taken perpendicularly to the measurement direction and ambient temperature changes, which was depicted in the correlation coefficients of those two quantities.

Temperature changes in the range of ±0.5°C cause the appearance of surface waviness with a significant amplitude.



	Sa	Sq	Sp	Sv	Sz
🟦 Dt = ±0.5°C	0.306	0.373	1.658	3.444	5.102
🟥 Dt = const.	0.189	0.264	1.752	3.034	4.787
🟩 Dt = ±0.5°C; cut-off = 0.8	0.122	0.169	1.156	2.276	3.433
🟪 Dt = const.; cut-off = 0.8	0.116	0.175	1.347	2.077	3.424

Fig. 18. Values of topography parameters of the bearing raceway

The existence of profile changes perpendicular to the measurement direction is not solely an effect of thermal expansion of the sample material, which was proved by measurements performed on a ZERODUR® sample.

The research results showed a correlation between temperature changes and groove depths on an A/PGR type roughness standard with about 30 µm of amplitude, a similar correlation for an A/PGR type roughness standard with a 2.7 µm amplitude was not observed.

Periodical changes of the ambient temperature influence the calculated topography parameters of real technical surfaces, as it was presented when describing differences in the results of measurements taken on a bearing raceway, performed for both stable and changing temperature conditions.

The described phenomenon is one of the sources of measurement errors which appear in surface topography measurements. Some of the other sources are described in references [5–8], but so far, neither the results of research nor an explanation of how temperature changes influence surface topography parameters are published. There were only publications in which the authors considered thermal expansion of a device, its particular elements, and a workpiece as the factors influencing the measurements [9–11].

The changes can be different for each profilometer and depend on its construction. Still, when the cooling is switched on, one can see the table "move down", and then, when the temperature goes up, the whole structure of the table also goes up.

For future research, we started working on a thermomechanical simulation and correction of the output signal.

Acknowledgements. The study was possible thanks to a project contract with Polish National Centre of Research and Development no. PBS2/A6/20/2013/NCBiR/24/10 /2013: "Research and evaluation of reliability of modern methods of surface topography measurements in micro and nano scale".

REFERENCES

[1] S. Adamczak, T. Miller, J. Świderski, M. Wieczorowski, R. Majchrowski, and A. Łętocha, "A concept of the project: Research and evaluation of reliability of modern methods of surface topography measurements in micro and nano scale", *Proceedings of XIth International Scientific Conference on Coordinate Measuring Technique CMT 2014*, pp. 7–9, eds. K. Nikodem and S. Płonka, Bielsko-Biała, 2015.

[2] S. Adamczak, T. Miller, J. Świderski, M. Wieczorowski, R. Majchrowski, and A. Łętocha, "The assumptions to credibility assessment of surface topography measurements in various scales", *Mechanic* 3, 81–87 (2015), [in Polish].

[3] ISO 5436–2: Geometrical product specification (GPS) – Surface texture: Profile method; Measurement standards – Part 2: Software measurement standards, 2012.

[4] ISO 25178–70: Geometrical product specification (GPS) – Surface texture: Areal – Part 70: Physical measurement standards, 2014.

[5] P. Pawlus, M. Wieczorowski, and T. Mathia, *The Errors of Stylus Methods in Surface Topography Measurements*, ZAPOL, Szczecin, 2014.

[6] R.K. Leach, C.L. Giusca, H. Haitjema, C. Evans, X. Jiang, "Calibration and verification of areal surface texture measuring instruments", *CIRP Annals – Manufacturing Technology* 64 (2), 545–548 (2015).

[7] R. Leach, "The measurement of surface texture using stylus instruments", in *Measurement Good Practice Guide*, No. 37, Engineering Measurement Division National Physical Laboratory, 2014.

[8] D.J. Whitehouse, "A revised philosophy of surface measuring systems", *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 202 (3), 169–185 (1988).

[9] K.M. Baird, "Compensation for linear thermal expansion", *Metrologia* 4, 145–146 (1968).

[10] A.D. Khazan, *Transducers and Their Elements. Design and Application*, PTR Prentice Hall, Englewood Cliffs, NJ, 1994.

[11] N.K.P. Neubert, *Instrument Transducers: An Introduction to Their Performance and Design*, Oxford University Press, Oxford, 1963.