

# NOISE AND STEP HEIGHT PERFORMANCE OF SELECTED OPTICAL SURFACE MEASURING INSTRUMENTS

MATEJ HARCARIK, ROBERT JANKOVYCH

Brno University of Technology  
Faculty of Mechanical Engineering  
Institute of Production Machines, Systems and Robotics  
Brno, Czech Republic

DOI: 10.17973/MMSJ.2017\_12\_201781

e-mail: [matej.harcarik@vutbr.cz](mailto:matej.harcarik@vutbr.cz)

[jankovyach@fme.vutbr.cz](mailto:jankovyach@fme.vutbr.cz)

Increasing demands for manufacturing quality and new standards in surface metrology foreshadow a widespread adoption of 3D surface topography measurement in manufacturing quality control. This raises the question of instrument selection. Coherence scanning interferometry and laser scanning confocal microscopy are some of the most common technologies in optical measurement of surface topography. These methods differ significantly in their suitability for different types of measurement. This article provides a comparison of the measurement noise and step height measurement performance two measuring instruments based on these two principles in relation to objectives used for measurement. Such data can be used to inform instrument selection in an industrial environment.

## KEYWORDS

surface texture, confocal microscopy, coherence scanning interferometry, comparison of instruments, topography measurement noise, step height repeatability

## 1 INTRODUCTION

With introduction of the [ISO 25178-1:2016] standard, which defines the mode of specification of areal surface texture parameters, 3D surface topography measurement and areal evaluation are becoming ready for wide industrial deployment. This raises many practical questions, including one of selection of the most useful measuring instruments for industrial use.

Coherence scanning interferometry and laser scanning confocal microscopy are among of the most common technologies in optical measurement of surface topography, as evidenced by available guide publications [Giusca 2012, Giusca 2013], as well as research articles such as [Cai 2017, Jancar 2011, Mohammadi 2016, Mouralova 2016] and others. Each of these methods is suited for different types of measurement under different conditions.

The authors had already compared these two methods using samples from a partner in automotive manufacturing [Harcarik 2016]. However, the unexpectedly underwhelming result of the confocal microscope used in said study led the authors to re-examine the abilities of the instruments with more focus on the instruments themselves while eliminating the influence of sample choice.

This article attempts to provide an overview of the capabilities of these two technologies in order to facilitate matching of instruments and applications. For this purpose, measurement noise and step height measurement capabilities of the instruments are evaluated for each objective of the instruments

available to the authors. To the extent of the author's knowledge, no similar studies have been published so far.

## 2 INSTRUMENTS

Coherence scanning interferometry (CSI) is a surface topography measuring technique, which uses height-dependent interference of non-coherent light for mapping 3D surface topography [Leach 2011].

The samples are illuminated with non-coherent light sources with a continuous spectrum. Such light produces visible interference, when two paths from the source have a very small length difference. In order to achieve this effect, suitable interference objectives must be used. Such objectives, illustrated in Fig. 1, must focus at the distance of zero optical path difference and be balanced for wavelength-dependent refractive index [Leach 2011].

Coherence scanning microscopes are often built as conventional microscopes aside from the interference objectives [Leach 2011].

To obtain a topography measurement, the objective is scanned vertically over the range, in which interference fringes appear. These are recorded throughout the range using a CCD camera. Based on peak intensity of the fringes, Z coordinates are assigned to each point in the CCD matrix, yielding a 3D point cloud of the measured topography [Leach 2011].

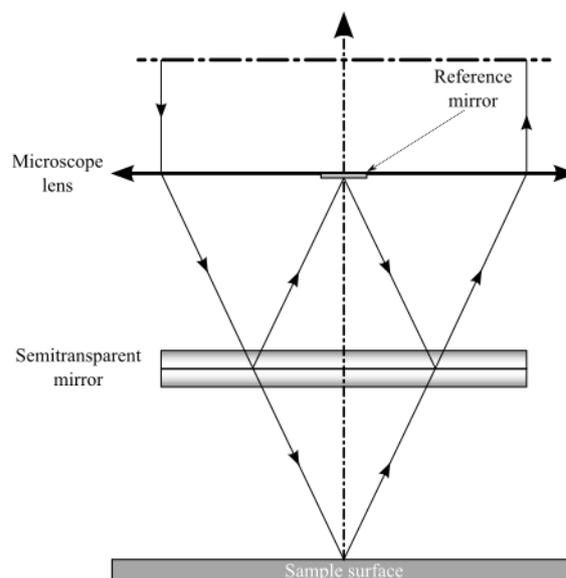


Figure 1. Mirau Interferometer as used in a CSI instrument

The instrument used in this study is a Taylor Hobson Talysurf CCI Lite (CCI), Fig. 2, an optical profiler based on the principle of Coherence correlation interferometry, which is a variant of coherence scanning interferometry. The device is equipped with three objectives with 10×, 20× and 50× magnification, which provide fields of view of 1.65×1.65 mm, 0.83×0.83 mm and 0.33×0.33 mm respectively. The image is captured via a CCD sensor with a resolution of 1024×1024 pixels. Vertical resolution may reach 0.01 nm, depending on measurement conditions. The stated step height repeatability of the instrument is <0.1 % of the measured step height.



Figure 2. Taylor Hobson Talysurf CCI Lite

Laser scanning confocal microscopy is a topography measurement method using patterned illumination [Leach 2011].

Configuration of such a microscope is shown in Fig. 3. A laser illuminates the sample through a pinhole. The narrow laser beam is deflected using a scanner, and is scanned across the measured surface along one of the horizontal axes. The reflected light must pass through a pinhole identical to the one obstructing the laser, before being detected by a photomultiplier or a similar sensor. This only happens when the sample surface is located in the focal plane of the objective [Leach 2011].

Thus, topography measurement involves scanning the surface with the laser at several different heights, corresponding to the height of the surface. Z coordinates are assigned to each point based on peak intensity of reflected light [Leach 2011].

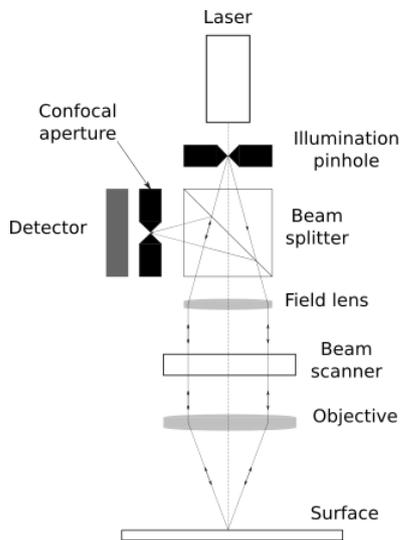


Figure 3. Laser scanning confocal microscope workings

Olympus LEXT OLS4100 SAF (LEXT), pictured in Fig.4, is a laser scanning confocal microscope. The microscope used in this study was equipped with objectives with 2.5×, 5×, 10×, 20×, 50× and 100× magnification, which provide fields of view of 2.56×2.56 mm, 1.28×1.28 mm, 0.64×0.64 mm, 0.256×0.256 mm and 0.128×0.128 mm respectively. Its vertical resolution is 0.01 μm. Its stated height measurement repeatability is 12 nm for the 50× objective, with stated accuracy of less than  $(0.2+L/100)$  μm.

Besides measuring surface topography, the LEXT can also be used as a digital imaging microscope with a color camera, which improves its visualization capabilities.



Figure 4. Olympus LEXT OLS4100 [Olympus 2013]

### 3 METHODOLOGY

Measurement noise and step height precision and repeatability were chosen as initial characteristics for comparison of the available instruments.

Comparison of measurement noise was carried out by subtraction, as described in [Giusca 2012, Giusca 2013]. Using each objective of each instrument, ten measurements were made in the same location on the surface of a glass flat. The resulting topographies were then subtracted from each other, yielding 9 residual surfaces.

These residual surfaces were then thresholded to remove spurious data resulting from glass artifact imperfections or contamination. These spurious data can be identified as the tails of the Abbot-Firestone curve of every measured surface, as demonstrated in Fig. 5. Thresholds at material ratios 0.1-99.9% were used for residual surfaces of the CCI's 10× and 20× objectives. For all the other configurations, thresholds were set at 0.5-99.5% material ratios.

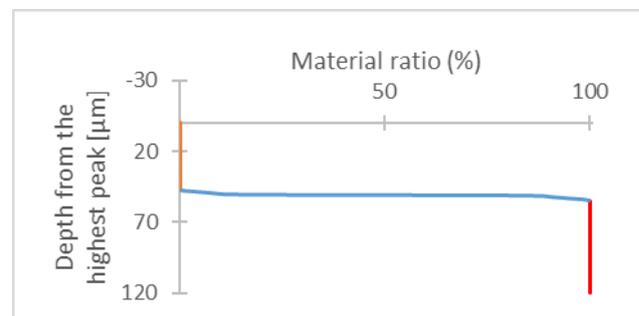


Figure 5. Abbot-Firestone curve of measurement noise residual surface. Tails which were removed were highlighted.

After thresholding, root mean square height of the scale-limited surface  $S_q$  and maximum height of the scale-limited surface  $S_z$  were evaluated on each residual surface, in contrast with [Giusca 2012, Giusca 2013], who only evaluated  $S_q$  for purposes of calibration. This was done in order to assess the height range of noise given by the  $S_z$ .

Finally, the results were analyzed using one-factor ANOVA, with the purpose of identifying statistically significant differences between the noise of different objectives and instruments.

Step height measurement trueness and repeatability were evaluated using an artifact consisting of three parallel grooves 4.875 μm deep engraved on the surface of a glass flat, pictured in Fig. 6. Using each objective of each instrument, ten measurements were made in various locations along the grooves on the surface of the step height artifact. The 3D topographies were used to generate a mean profile of each measurement. The resulting profiles were compiled into a series and levelled. Afterwards, step height on each of the

profiles was evaluated in accordance with [ISO 5436-1:2000]. As with the measurement noise, the results of step height measurement were analyzed using one-factor ANOVA. The measurements were carried out using default settings of the respective instruments. Measurement range was set manually according to appearance of interference in case of the CCI or appearance of signal in case of the LEXT. The Z measurement step was left as default. All measured data were analyzed using TalyMap Gold software, which was provided with the Talysurf CCI Lite instrument. Data obtained with the LEXT OLS 3000 confocal microscope had to be converted into a suitable format using a free topography processing software Gwyddion [Necas 2011]. Statistical analysis was performed in Minitab.



Figure 6. Step height artifact used in the study

## 4 RESULTS

In the end, values of measurement noise  $S_q$ ,  $S_z$  and of step height were obtained for each available objective of both instruments. These data were analyzed in three separate analyses of variance. Their results are presented in the subsections below.

### 4.1 Measurement noise $S_q$

First, equality of variances of measurement noise  $S_q$  was tested using Levene's test. As Fig. 7 shows, there is a statistically significant level of difference in variances of at least some of the tested subgroups. Notably, the 2.5 $\times$  objective of the LEXT confocal microscope shows extreme variations in the  $S_q$  value.

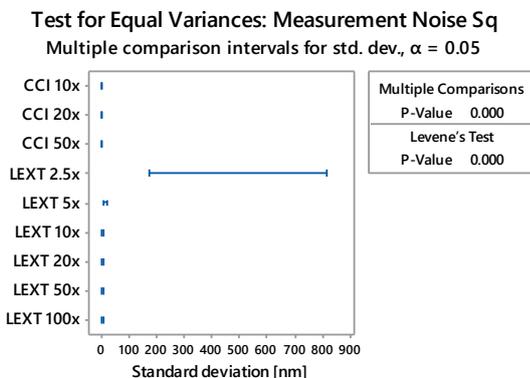


Figure 7. Variances of measurement noise  $S_q$  by instrument and objective

Afterwards, the data was analyzed using one-way ANOVA without assuming equal variances. Fig. 8 shows a boxplot of the data. Mean values of measurement noise  $S_q$  for LEXT's 2.5 $\times$  and 5 $\times$  objectives are obviously much higher, than values observed for the other objectives.

Pairwise comparison of the subgroups was performed using the Games-Howell procedure, as it does not require equality of variances. The results are shown in Fig. 9.

There are statistically significant differences between practically all the configurations of instrument and objective. The lowest noise  $S_q$ , in tenths of nm, was achieved by high magnification objectives of the CCI. Good performance with  $S_q$  in single units of nm was observed with CCI's 10 $\times$  objective and LEXT's objectives with magnification of 20 $\times$  and more. LEXT's low magnification objectives showed high levels of noise  $S_q$ , between hundreds and thousands of nm. Performance of LEXT's 50 $\times$  and 100 $\times$  objectives was statistically indistinguishable.

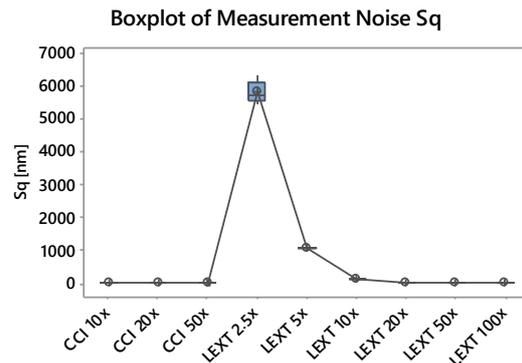


Figure 8. Boxplot of measurement noise  $S_q$  by instrument and objective

Grouping Information Using the Games-Howell Method and 95% Confidence

Factor	N	Mean	Grouping
LEXT 2.5x	9	5785	A
LEXT 5x	9	1067.34	B
LEXT 10x	9	137.868	C
LEXT 20x	9	9.547	D
LEXT 50x	9	3.688	E
LEXT 100x	9	3.167	E
CCI 50x	9	1.03592	F
CCI 20x	9	0.4225	G
CCI 10x	9	0.35479	H

Means that do not share a letter are significantly different.

Figure 9. Games-Howell grouping of measurement noise  $S_q$  by instrument and objective, means in nm

### 4.2 Measurement noise $S_z$

For measurement noise  $S_z$ , similar results were obtained. Test for equal variances shown in Fig. 10 again revealed statistically significant differences between subgroup variances. The 2.5 $\times$  objective of the LEXT again showed the highest level of variance.

The boxplot of measurement noise  $S_z$  in Fig. 11 is similar to the one for  $S_q$ , with values for LEXT's 2.5 $\times$  and 5 $\times$  objectives again being higher than values observed for the other objectives.

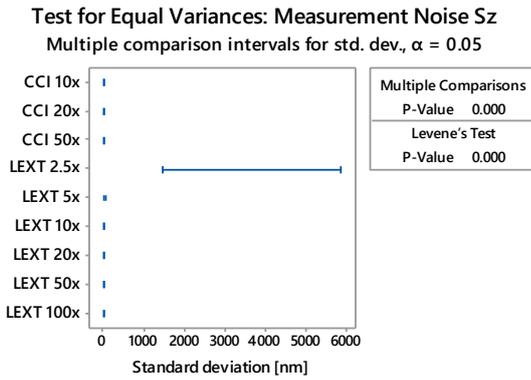


Figure 10. Variances of measurement noise Sz by instrument and objective

Games-Howell pairwise comparison of Sz, Fig. 12, once again showed statistically significant differences between nearly all the configurations. The 10x and 20x magnification objectives of the CCI jointly achieved the lowest values of noise Sz, between 2 and 3 nm. CCI's objectives had the best performance, with measurement noise in the single digits of nm. In LEXT's case, measurement noise Sz consistently fell with increasing magnification. For objectives with 10x or lower magnification, noise Sz approached or exceeded 1 μm, presenting potential problems for measurement of topography of common mechanical surfaces.

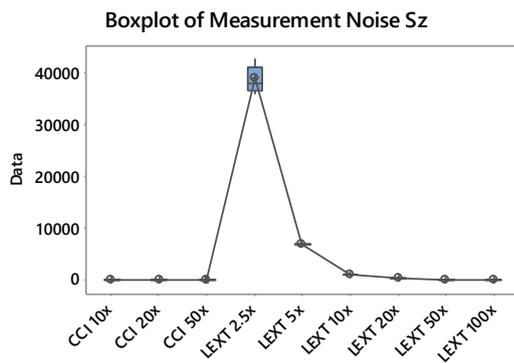


Figure 11. Boxplot of measurement noise Sz by instrument and objective

Factor	N	Mean	Grouping
LEXT 2.5x	9	38906	A
LEXT 5x	9	6781.86	B
LEXT 10x	9	913.14	C
LEXT 20x	9	60.91	D
LEXT 50x	9	19.644	E
LEXT 100x	9	14.898	F
CCI 50x	9	6.717	G
CCI 20x	9	2.7556	H
CCI 10x	9	2.6089	H

Means that do not share a letter are significantly different.

Figure 12. Games-Howell grouping of measurement noise Sz by instrument and objective, means in nm

### 4.3 Step height measurement trueness and repeatability

A similar procedure was used to assess the results of step height measurement. Once more, statistically significant differences between the variances of results were found, as Fig. 13 demonstrates. LEXT's 2.5x magnification objective had

shown the highest variance, with its 5x and 10x objectives following.

The boxplot of the step height results in Fig. 14 shows, that CCI's objectives and high-powered objectives of the LEXT obtained similar results, while results obtained by LEXT's 2.5x, 5x and 10x objectives clearly deviated from the others.

Games-Howell pairwise comparison of the step-height results identified several groups of step height data, as Fig. 15 demonstrates. Overlapping groups A, B and C include all the CCI's objectives and LEXT objectives with magnification of 20x and more. These three groups can be interpreted as showing performance adequate for topography measurement. Groups D and E contain the low magnification objectives of the LEXT and present large deviations from the others as well as from the reference value of the measured step. This indicates they are not ideal for height and topography measurement.

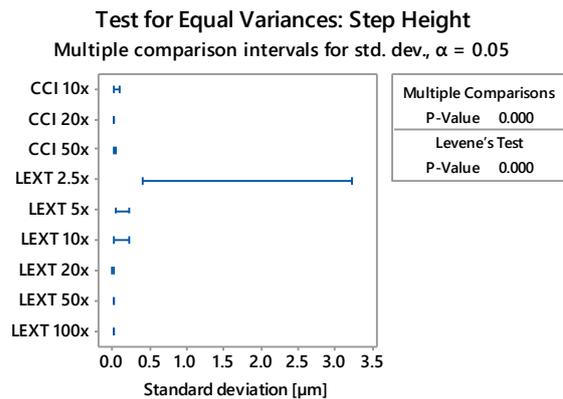


Figure 13. Variances of step height by instrument and objective

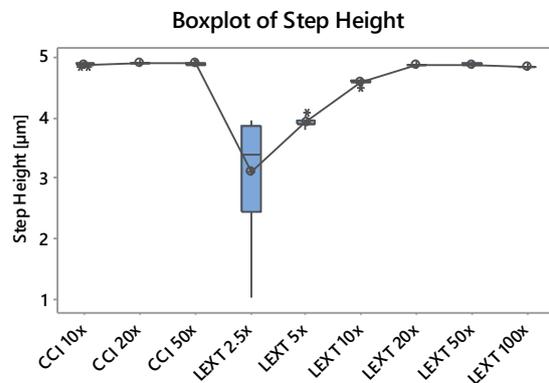


Figure 14. Boxplot of step height by instrument and objective

Factor	N	Mean	Grouping
CCI 20x	10	4.89338	A
CCI 50x	10	4.88281	A B
LEXT 20x	10	4.87658	B
LEXT 50x	10	4.87410	B
CCI 10x	10	4.86971	A B C
LEXT 100x	10	4.83387	C
LEXT 10x	10	4.5842	D
LEXT 5x	10	3.9145	E
LEXT 2.5x	10	3.112	E

Means that do not share a letter are significantly different.

Figure 15. Games-Howell grouping of step height by instrument and objective, means in nm

Deviations of average measured step height from the reference value of 4.875  $\mu\text{m}$  are shown in Tab. 1. The errors of objectives in groups A, B and C range from less than 1 nm to about 50 nm in case of LEXT's 100 $\times$  objective. This last measurement error may be inflated due to step height standard's inhomogeneity and the objective's small field of view. It is likely, that it would be reduced with larger number of measurements.

<b>Configuration</b>	<b>LEXT 50x</b>	<b>LEXT 20x</b>	<b>CCI 10x</b>
<b>Error [nm]</b>	-0.90	1.58	-5.29
<b>Configuration</b>	<b>CCI 50x</b>	<b>CCI 20x</b>	<b>LEXT 100x</b>
<b>Error [nm]</b>	7.81	18.38	-41.13
<b>Configuration</b>	<b>LEXT 10x</b>	<b>LEXT 5x</b>	<b>LEXT 2,5x</b>
<b>Error [nm]</b>	-290.83	-960.54	-1762.88

Table 1. Step height measurement errors of the various configurations

## 5 CONCLUSIONS

The coherence scanning interferometer Talysurf CCI Lite achieved the three lowest levels of measurement noise with each of its objectives. The lowest step height errors were achieved using the laser scanning confocal microscope LEXT OLS4100 using its 20 $\times$  and 50 $\times$  magnification lens. The relatively large measurement error in case of LEXT's 100 $\times$  magnification objective may be attributed to its small field of view and the resulting sensitivity to local height differences on the step height standard. The error would most likely converge closer to zero with added measurements in different locations on the standard.

Overall, the CCI appears to deliver consistent performance regardless of the choice of objective. In case of the LEXT, surface topography measuring performance expressed by noise and step height measurement improves with choice of high magnification objectives. Its low magnification objectives are better used for digital color imaging. The observed behavior is consistent with the observations in [Harcarik 2016], which were made based on measurements of more diverse samples.

In light of these findings, it is obvious that the underwhelming performance of the LEXT in [Harcarik 2016] was entirely caused by improper measurement using low magnification objectives, under the false impression that this would allow for comparison with similar powered lenses of the CCI.

The results of this study can be used to inform instrument selection for industrial quality control tasks in terms of instrument versatility.

## ACKNOWLEDGEMENTS

The authors would like to thank Ing. Radka Balkova, Ph.D. and CEITEC for access to the Olympus LEXT OLS4100, and Mesing, spol. s.r.o. for providing the glass flat used in measurement noise evaluation.

## REFERENCES

[Cai 2017] Cai, Y., Wang, X. and Yuan, S. Surface Roughening Behavior of 6063 Aluminum Alloy during Bulging by Spun Tubes. *Materials*, 2011, Vol. 10, No. 3, art.no.299. DOI: 10.3390/ma10030299. ISSN 1996-1944.

[Giusca 2012] Giusca, C. L. and Leach, R. K. Good Practice Guide No. 128. Calibration of the metrological characteristics of Imaging Confocal Microscopes (ICMs). Teddington: National Physical Laboratory, 2013. ISSN 1368-6550

[Harcarik 2016] Harcarik, M. and Jankovych, R. Measurement of Automotive Parts' Surface Texture Using Contact and Non-contact Methods. In: Dusan Maga et al, ed. 17<sup>th</sup> Mechatronika 2016, Prague, Czech Republic, 12/7-9/2016, Prague: Czech Technical University, 374-380, ISBN 978-80-01-05882-4

[Giusca 2013] Giusca, C. L. and Leach, R. K. Good Practice Guide No. 127. Calibration of the metrological characteristics of Coherence Scanning Interferometers (CSI) and Phase Shifting Interferometers (PSI). Teddington: National Physical Laboratory, 2013. ISSN 1368-6550

[ISO 5436-1:2000] Geometrical product specifications (GPS) - Surface texture: Profile method; Measurement standards - Part 1: Material measures. ISO 5436-1. Geneva: International Organization for Standardization, 2000.

[ISO 25178-1:2016] Geometrical product specifications (GPS) - Surface texture: Areal - Part 1: Indication of surface texture. ISO 25178-2. Geneva: International Organization for Standardization, 2016.

[Jancar 2011] Jancar, J., Kalfus, J., Balkova, R. On the differences in micro-deformation mechanism between isotactic polypropylene and b- nucleated iPP as revealed by the confocal laser scanning microscopy. *Polymer Engineering and Science*, 2011, Vol. 51, No. 9, pp. 2434-2438. ISSN: 0032- 3888.

[Leach 2011] Leach, R. K. Optical Measurement of Surface Topography. Berlin: Springer, 2011. ISBN 978-3-642-12011-4

[Mohammadi 2016] Mohammadi, H. and Patten, J. A. Anisotropy effect on cutting monocrystal sapphire by micro-laser assisted machining technique. In: ASME 2016 11th International Manufacturing Science and Engineering Conference, MSEC 2016, Volume 1, Blacksburg, USA, 27 June 2016 - 1 July 2016, Blacksburg: American Society of Mechanical Engineers, ISBN 978-079184989-7

[Mouralova 2016] Characterisation of 3D Topography of the Surface Machined by Finishing Technologies of WEDM and Grinding. Dusan Maga et al, ed. 17<sup>th</sup> Mechatronika 2016, Prague, Czech Republic, 12/7-9/2016, Prague: Czech Technical University, 374-380, ISBN 978-80-01-05882-4

[Necas 2011] Necas, D. and Klapetek, P. Gwyddion: an open-source software for SPM data analysis. *centr.eur.j.phys.*, 2012, 10, 1, 181-188, ISSN 1895-1082, <http://gwyddion.net/>

[Olympus 2013] Olympus Corporation. Olympus - Olympus LEXT OLS4100 3D laser scanning microscope. Olympus Europa, 2013, Hamburg [online]. 05/31/2013 [05/10/2017]. Available from: <http://goo.gl/API3pe>

## CONTACTS:

Ing. Matej Harcarik  
doc. Ing. Robert Jankovych, CSc.  
Brno University of Technology  
Faculty of Mechanical Engineering  
Institute of Production Machines, Systems and Robotics  
Technicka 2896/2. Brno, 616 69. Czech Republic  
Tel.: +420 774 115 410, e-mail: [matej.harcarik@vutbr.cz](mailto:matej.harcarik@vutbr.cz)  
Tel.: +420 605 440 420, e-mail [jankovych@fme.vutbr.cz](mailto:jankovych@fme.vutbr.cz)