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EVALUATION OF WOOD SURFACE ROUGHNESS BY CONFOCAL MICROSCOPY

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ABSTRACT

The main aim of this study is to define the usability of the confocal scanning optical microscope (CSOM) to evaluate the wood surface roughness. Therefore, systematic investigation was carried out to define the influences of CSOM on the acquisition of 2D surface roughness parameters. Mahr Perthometer was applied to get reference data to estimate the applicability of the CSOM. Because wood roughness parameters measured with stylus and optical methods are not always comparable a calibration method was conducted on a metal calibration etalon. After the calibration process, the roughness profiles taken with the optical and stylus units were much closer to each other and only the optical R_{pk} parameter was definitely higher due to artificial peaks generated by the optical system. In order to eliminate this measuring failure, the morphological filter option of the optical apparatus may be activated. The surface roughness parameters were measured on planed Scotch pine samples. The planed surface plains were produced with 0.2 mm parallel offset to investigate the structural influence of the single cutting plains.

The obtained results show that the average values for R_a, R_q, R_z, R_k, *and* R_{vk} are close to each other for both measuring systems, only the optically measured R_{pk} values must be corrected. The standard deviations, however, are systematically slightly higher for optical system. This may be explained by the higher resolution of the optical system giving more fine profile details. The earlier developed and introduced dimensionless quantities, such as Abbott ratio, are also fully comparable for both systems provided that the optically measured R_{pk} values are also correct.

KEYWORDS: Surface roughness, CSOM, 2D roughness parameters, Abbott ratio, relative value of standard deviation.

INTRODUCTION

The accuracy and surface-finish requirements for machined parts in modern industry have been becoming ever more stringent (Udupa et al. 2000). At the same time, the global forest area is shrinking, limiting the supply of industrially usable raw resources. Therefore, there are new innovation toward increasing environmental and economic sustainability of timber production to reduce the volume of wood residues for example by minimizing the sawing kerf (Orlowski et al. 2022). Furthermore, the quality requirements of the wood processing is even more difficult task. The surface of orthogonal anisotropic wood material is always containing valleys and some unstable peaks. One of the main difficulties is the fact that the wood is not a true solid material having caves inside (vessels, cell lumens) and, furthermore, the wood as a brittle material is inclined to brittle fracture. Consequently, the cutting mechanism is always associated with local fracture of the material giving uneven surface. The caves cut during the machining give also uneven surface. In this latter case, the surface irregularities depend on the local position of the cavities relatively to the surface. The roughness of specimens due to the anatomical structure is the ultimately attainable minimum surface roughness for a given anatomical structure (Magoss 2008). Usually, the aim of the wood processing to achieve smooth surface. Having rougher surfaces of the samples revealed that their higher bonding strength values can be achieved (Hiziroglu et al. 2014).

The outer cell layers of a machined solid wood surface usually collapse and compact during processing due to the cutting forces. This layer is called deformation zone. The deformation zone is excessively instable, varies with temperature and moister content variation of the environment (Molnár et al. 2018).

The evaluation of the wood surface roughness is difficult measuring task (Gurau and Irle 2017, Thoma et al. 2015, Laina et al. 2017, Magoss 2017). The visual examination of the wood surface roughness based on the human perception are strongly limited (Sandak and Tanaka 2002, Sinn et al. 2008). The usability of different surface roughness measuring methods to estimate the wood surface roughness also limited. The light sectioning (Peters and Cumming 1970, Yang et al. 2006) and the image analysis (Faust 1987) methods are capable only in certain cases to give reliable results to characterize the wood surface roughness. The porosity and the reflectance of the wood surfaces are the main problems using the optical measuring methods (Lundberg and Porankiewicz 1995, Goli and Sandak 2016). Therefore, more researchers recommend the stylus surface roughness measuring method to evaluate wood surface roughness (Gurau and Irle 2017). The next difficulty is to distinguish the waviness from roughness by using electric filters. Two main filters have been standardised, 2RC and the digital phase-correction filter (GS). These filter usability to measure reliable surface roughness parameters on wood surfaces are strongly limited. Special filter methods are developed to prevent the influence of the anatomical structure (Fujiwara et al. 2003). The choice of the suitable standardized surface roughness parameters is also an important task. It is a proven fact that a single roughness parameter does not provide a comprehensive description for three-dimensional analysis of processed surfaces, even in the case of homogeneous metal surfaces (Dong et al. 1994). To characterize the internal relationships between roughness parameters of wood the summarized Abbott parameters (R_{pk}+R_k+R_{vk} and

S_{pk}+S_k+S_{vk}) are useful tools to complete the characterization of the wood surface roughness (Csanády and Magoss 2012, Csanády et al. 2015). The Abbott ratio introduced in 2015 is important parameter to characterize the surface roughness of the wood material independently of the wood species (Csanády et al. 2015).

Confocal scanning laser microscopy is a relatively new surface roughness measuring method in the wood science, but there are some research experiences concernig the characterization the surface roughness of more homogeneous materials (Klauer et al. 2018, Udupa et al. 2000, Hongru et al. 2017, Al-Shammery et al. 2007). The examination of metal etalons and samples the experimental results demonstrate that the stylus profilometer presents the most reliable measurement with the highest measurement speed and the least complex algorithms, while the image confocal method takes advantage of higher vertical and horizontal resolution when compared with the employed stylus profilometer (García et al. 2018). Furthermore, the confocal scanning optical microscope could produce sharp peaks and valleys which are not real.

The aim of this research work is to compare the new confocal optical system and a stylus type Perthometer using soft wood samples, to clear the reasons for occasional deviations and to give recommendations for their common use for better wood surface characterization. In order to exclude possible cross-effects between measuring systems and random wood structural properties, it was crucial to determine a reliable average value and its standard deviation for each roughness parameter and for both measuring systems. This required large number of measurements in several spatial plains.

MATERIALS AND METHODS

Experimental materials

Five defect free stepped samples in radial grain orientation were planed to have five parallel flat surfaces by CNC wood milling machine after they were cut from the same pine lumber. The wood cutting parameters were the followings: diameter of the spiral wood milling tool was 20 mm, the feed speed was 8 m·min^{-1}, and the rotation speed of the tool was 1600 rev per min. The perpendicular offset of the five surfaces is 0.2 mm, the horizontal offset is 60 mm on every sample (Fig. 1).

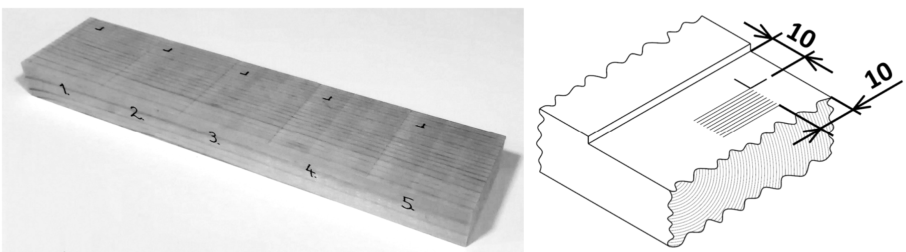

Fig. 1: Stepped test sample with reference point.

The samples were conditioned in a climate chamber with temperature of 20°C and a relative humidity of 65% until they reach equilibrium moisture content of 12%. The last step of the preparation work was the marking of the reference point for both surface roughness measuring methods. Fig. 1 shows the position of the reference point, which was the starting point of the surface roughness measuring process of both measuring system. This identification procedure ensured the comparability of the measuring data. To perform the calibration of the confocal microscope a type Mahr PRN-10 (R_a 2,4 μm) metal etalon is measured.

Confocal scaning optical microscopy (CSOM)

Confocal microscope, brand Mahr (Göttingen, Germany), model Mahr Surf CM explorer was used with the software MahrSurf MfM Extented 7.4. A type 1600 S lens was used in the measurements with 10x magnification. Total measuring field of instrument was 1.62 x 18.2 mm, 1.3 μm and 0.04 μm were the horizontal and the vertical resolution respectively. Gauss filter was applied with cut-off length 0.8 mm and the average roughness R_a parameter was registered according to the ISO 4288 standard. The difference between the five times measured average R_z value and the reference value was 4.2%, the standard deviation of the five measuring value is $\sigma = 0{,}05$.

Surface roughness determination

Stylus Perthometer Mahr (Göttingen, Germany), model S2 with stylus tip radius of 5 μm/90°, measuring range of ± 250 μm was used in the comparison study to the confocal microscope. In order to have comparability, the measuring length was 17.5 mm; 2 μm and 0.008 μm were the horizontal and the vertical resolution respectively.

On a total of 25 planed surfaces on the five samples, measurements were made on 10 profiles each with a profile spacing of 50 μm perpendicular to the grain direction, considering the starting reference point. At the data processing unit of the Mahr S2 apparatus, the evaluation was performed on $N = 5$, $L_c = 2.5$ mm reference length.

For the optical measurement, the size of the scanned surface used by the stitching function was 1.62 x18.2 mm. Ten measurement lines were defined in the measuring rectangle, with similar pitch to the Perthometer measurement, and one of the vertices of the rectangle was fitted to the reference point.

The following 2D standardized surface roughness parameters were compared with the two measurement methods: five amplitude parameters: the average roughness (R_a), root-mean-square (R_q), maximum height of the profile (R_p), maximum depth of the profile (R_v) and maximum peak to valley height (R_z) and three Abbott parameters: reduced peak height (R_{pk}), core roughness depth (R_k) and reduced valley height (R_{vk}).

RESULTS AND DISCUSSION

In order to compare the two systems reliability, it is important to exclude cross-effects due to wood surface variability. The latter is not a simple task. It is difficult to perform measurements with the two systems accurately along the same path and trace length, quite small deviations can cause perceptible variations in the measurement results. Therefore, it seems to be a practical solution to use a more homogeneous wood species (such as conifers), a stepped sample with several measurement planes to average the structural effects and to make large number of measurement in order to obtain reliable average value and standard deviation for each roughness parameter. A visual observation of roughness profiles is also important to recognize artificial disturbances such as artificial peaks mentioned already in the literature (García et al. 2018).

The most important results taken all measurement points into account is given Tab. 1. For both systems, the average values, except R_{pk}, agree well and, therefore, the general comparability of measured values may be accepted. R_{pk} values for the optical system are definitely higher due to artificial peaks on the roughness profile which could have been observed visually. The CSOM has a filter option to remove these peaks but with some risk for profile modifications. To use a simple correction method seems to be a more reliable one. Furthermore, the relative value of standard deviation is systematically somewhat higher for all roughness parameters. A possible reason is for it that the CSOM detects more fine details of the roughness profile.

Tab. 1: Average deviation of main roughness parameters measured by the two systems

	R_a	R_q	R_z	R_{pk}	R_k	R_{vk}
Perthometer (μm)	5.230	6.760	38.590	5.030	14.300	10.540
CSOM (μm)	5.032	6.690	39.920	8.780	13.400	10.730
Average deviation (%)	3.92	1.04	2.80	54.30	6.50	1.80

CSOM – confocal scaning optical microscopy.

The Abbott ratio for the optical unit is slightly higher due to the higher R_{pk} value. If we correct the R_{pk} values, there is practically no difference in the Abbott ratios. The dimensionless number $R_a/\sqrt{R_k \cdot R_z}$ shows also no difference for the two methods. The R_q/R_a ratio is slightly higher for the optical system due to the more "spiked" profile detection.

Tab. 1 shows also the average deviation of the main roughness parameters measured by the Perthometer and the optical system. Except R_{pk}, all parameters are in an error bound acceptable for reliable comparison. From this results it may be concluded that the confocal optical system gives comparable results with those of the styles system. The optical R_{pk} value, however, require correction. Further measurements are needed with other wood species. It is worth to mention that earlier detailed experiments gave similar relative standard deviations for several wood species (Csanády and Magoss 2013).

Further comparisons may be done using measurement results for single plains randomly cut into the sample with less measurement data. They show the maximum range of variation on a given surface. Note that in this case each plain gives its own average value according to the random structural surface properties. The calculated relative standard deviations are less reliable, however, due to the smaller number of data.

The detailed analysis of measurement results for the five stepped surfaces has uniquely shown that they have definitely different average roughness components within the variability range of the given wood species. Therefore, the use of the stepped surfaces was a fortunate choice in order to obtain averaged roughness values for comparison. It was further important observation that the CSOM system has well followed the Perthometer readings, for example, both readings for R_a were either in the range from 4.5 to 5 (plain No.2) or in the range from 5.5 to 6 (plain No. 1). A further definite consistency may be recognized from the fact that plain No. 1

gave the highest average for all roughness parameters. Tab. 2 shows the calculated results for the 5 individual plains concerning R_a and R_z.

Tab. 2: R_a and R_z readings with Perthometer and optical method averaged for each plain.

		1	**2**	**3**	**4**	**5**	**Average**
$\bar{R}_a$ (µm)	Perthometer	6.034	4.900	5.330	4.460	5.440	5.233
	CSOM	5.720	4.480	5.440	4.094	5.424	5.032
$\frac{\sigma}{\bar{R}_a}$ (%)	Perthometer	6.800	8.250	2.930	7.200	3.790	11.600
	CSOM	6.500	9.170	2.830	7.700	3.530	13.900
	$\frac{\Delta \bar{R}_a}{\bar{R}_a^*}$ (%)	5.34	8.96	2.04	8.56	0.30	3.92
$\bar{R}_z$ (µm)	Perthometer	42.444	35.520	40.700	33.300	40.984	38.590
	CSOM	42.440	34.800	44.400	33.380	44.600	39.924
$\frac{\sigma}{\bar{R}_z}$ (%)	Perthometer	6.180	3.710	3.520	7.990	4.540	10.200
	CSOM	4.400	5.310	3.880	8.740	5.310	13.400
$\frac{\Delta \bar{R}_z}{\bar{R}_z^*}$ (%)		0.0094	2.05	8.70	0.24	8.45	2.80

Note: $\bar{R}_a = (\bar{R}_a(P) + \bar{R}_a(O))/2$.

The biggest difference for all roughness parameters was observed between the plains No. 1 and No. 4. The relative standard deviation for each plain is smaller than the overall value averaged for all plains. The overall averaged roughness values also show an interesting picture. R_a, R_q and R_k values measured by the perthometer are slightly higher than those measured by the optical system, R_{vk} averaged values are almost the same for both measuring systems. That means that the optical system does not see deeper into the tracheids than the needle is capable to scan them. The optical system measured slightly higher R_z values and considerably higher R_{pk} values due to the artificial peaks created by the optical system.

Evaluation of R_{pk} values measured on the five plains has shown (Tab. 3) that the deviation of the optical system is averaged to:

$$\frac{\bar{R}_{pk}(O)}{\bar{R}_{pk}(P)} = \frac{8.78}{5.03} = 1.74 \qquad (1)$$

$$\sigma = \pm 0.089 \qquad (2)$$

where: $R_{pk}(O)$ - reduced peak height parameters are measured by the optical system (µm),
$R_{pk}(P)$- reduced peak height parameters are measured by the perthometer (µm)
σ - deviation (µm).

Tab. 3: R_{pk} readings with Perthometer and optical method averaged for each plain.

		1	**2**	**3**	**4**	**5**	**Average**
$\bar{R}_{pk}$ (µm)	Perthometer	4.915	4.042	5.514	4.891	5.8	5.03
	CSOM	8.72	6.7	10.3	8.04	10.14	8.78

$\frac{\sigma}{\bar{R}_{pk}}$ (%)	Perthometer CSOM	7.41 11.71	9.03 7.61	11.96 7.95	9.67 15.35	9.58 10.82	15.2 18.5
$\frac{\Delta \bar{R}_{apk}}{\bar{R}^{*}_{pk}}$ (%)		77.4	65.7	86.8	64.4	74.8	74.5

Note: Deviation of averages are related to Perthometer averages.

Due to the relatively narrow range of standard deviation, this correction may give reliable results also for the optically measured R_{pk} values. Note that the R_{pk} roughness parameter is not frequently used, but it is an input datum for calculating the Abbott ratio.

A further proof for the comparability of the optical measurement results is the representation of data for both systems in dimensionless form combining several roughness parameters, Fig. 2. The calculated similarity numbers are fallen onto a common curve describing a general relationship. Note that this curve covers only the range of conifers with large Abbott-ratios. Big vessel species supply smaller Abbott ratios down to 0.2.

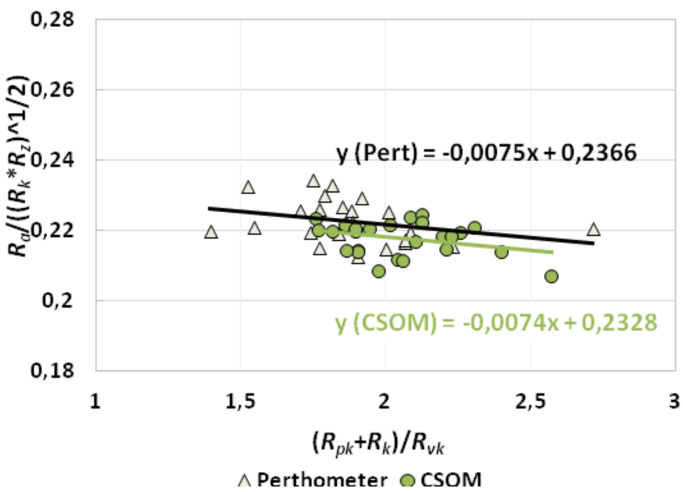

Fig. 2: Similarity relationship between Abbott-ratio and the related average roughness.

Fig. 2 shows the relationship between the Abbott ratio (*AR*) and the related average roughness of all cutting planes. The curves of the two measuring systems are almost the same. Therefore, the surface roughness parameters were produced by the optical measuring system are comparable with the parameters of the stylus measuring system. The optical system with the automatic focus function able to register the deep hollows more precisely than the stylus measuring system with the mechanical filtering effect of the needle, therefore the position of the measured profile is considerably influenced the surface roughness parameters by the tactile measuring system (Molnár et al. 2017).

CONCLUSIONS

Optical measurement methods for 3D roughness characterization can look back some three decades, with less success in the wood industry. The need for more complete characterization is fully obvious and some measuring tasks, such as measurement on curved surfaces, seems to be possible only with optical methods. Due to the varying reflection and colour properties of wood species, however, earlier optical methods were used with various success concerning their comparability with the well-established stylus method.

Present research work has examined a new confocal optical system in details, although using only one wood species. These experiments have convincingly shown that this optical method gave fully reliable and comparable results to those of stylus method. An exception is the reduced peak height R_{pk} which was measured systematically higher due to artificial peaks created on the roughness profile, $\overline{R_{pk}}(O)/\overline{R_{pk}}(P) = 1.74$. These artificial peaks can be removed by the given filter option or can simply be corrected. Further detailed experiments are needed to clear the possible consequences of the filtering in modifying the roughness profile. A correction seems to be fully acceptable due to the fact that R_{pk} values are rarely used for comparison. The used stepped samples gave reliable average roughness values corresponding to the structural variability of the given wood species. The equation of the Abbott-ratio (AR) and the related average roughness of all cutting planes are the followings: y(Pert) = -0,0075x + 0,2366 and y(CSOM) = -0,0074x + 0,2328. The correspondence also proves that the confocal scanning laser microscopy is adaptable surface roughness measuring method in the wood science.

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