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The effect of the type of stylus on the results of surface roughness of pine wood (*Pinus sylvestris* L.) after milling

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Abstract: *The effect of the type of stylus on the results of surface roughness of pine wood (Pinus sylvestris L.) after milling.* The article presents results of the surface roughness of pine wood and it shows a problem of comparison of results obtained using profilometers with different measuring gauges**.** Moreover, the effect of feeding speed and rotational speed of a spindle on the surface quality was investigated. Large dispersion of the results was observed, depending on applied measuring gauge. The differences between the results were variable and depended on technological parameters of milling process. During increasing the rotational speed (cutting speed), difference between the results for each gauge also increased. Moreover it was stated that rotational speed of the spindle, and feeding speed have a considerable effect on the surface roughness of pine wood. Multiple regression equations were designated for both measuring gauges and both analyzed roughness parameters.

Keywords: surface roughness, type of stylus, feeding speed, rotational speed, pine wood, milling

INTRODUCTION

Wood is a material which is used to made a plenty object of everyday use, such as furniture, constructions and many others. However, in order to use wood for a particular purpose, it is necessary to carry out a special treatment, which allows getting a proper shape, dimensions and geometrical structure of surface. One of the most important types of treatment is wood machining. Commonly used type of machining of wood and wood-based materials is milling process. To define the propriety of milling process, analyzing of the surface roughness is often done, as the indicator of machining quality. Measurements of the surface roughness may be completed with the use of direct or indirect methods. Poon and Bhushan (1995) investigated differences between different types of roughness measurement, including contact (stylus), optical and AFM (atomic force microscope) methods, showing that the results are different and depend on applied method. In case of measurement of the surface roughness, contact methods are the most used because of their commonness, uncomplicated measuring process and availability of the equipment.

The Surface roughness of wood and wood-based materials depends on many factors, among others wood species, density, moisture content, hardness, anisotropy and anatomical structure etc. Pine wood (*Pinus sylvestris* L.) is characterized by big differentiation of early and late wood in aspect of anatomical structure and mechanical properties. Some authors carried out research on the surface roughness separately for both these areas, presenting large dispersion of the results (Magoss 2008, Pinkowski et al. 2016).

Measurement of the surface roughness with the use of contact method can be done with modification of parameters of the measuring process. Some of them may have a considerable effect on the experiment results. These parameters are measurement pressure (especially when it comes to wood with low hardness), length of the measuring section, the cut-off length, type of the filtering method (Tomasik and Rudziński 2005, Łętocha 2017), feeding speed of the measuring gauge, apex angle and radius of the tip (Radharkrishnan 1977, Magoss 2008).

Many authors conduct research using measuring devices, which are equipped with different measuring gauges, mainly differing in geometry but also in material. For these reasons there have been complications with a comparison of research results obtained using different measuring devices. Therefore, researchers commonly use control samples to define references for their experiments. However, in rare cases comparisons between results from other studies have been done.

The aim of this study was to define differences occurring during measurements of the surface roughness with the use of two measuring gauges with different geometry (tip radius and apex angle). The additional aim of the research was to confirm the well-known dependence between the surface roughness of pine wood and feeding and rotational speed during machining on the bottom-spindle milling machine and to designate regression equations for this dependence.

RESEARCH METHODOLOGY

For the experiments, samples made of pine wood (*Pinus sylvestris* L.) were prepared, with a mean density of 480 kg/m^3 and a moisture content of 12%. The grain direction was parallel to the sample axis. Samples were cut out from bigger elements in order to eliminate defects which can affect the results, such as knots, cracks, rottenness, spiral grains, resin bladders etc.

Machining process of the samples was carried out with the use of Felder F900 bottom-spindle milling machine equipped with Felder F-38 feeding device, which allowed conduction machining with 8 levels of a feeding speed. Five rotational speeds of the spindle were used, thus 40 variants of machining process were conducted in total. The cutting tool was a four-edge cutterhead, with four knifes made of HSS SW18 by GOPOL company. Dimensions of the knifes were 50 x 30 x 3 mm. A sharpness angle was 45°, a rake angle was 25°, and a cutting circle diameter was 120 mm. A depth of cut (working engagement) was 1 mm.

Two types of a profilometer were used in the experiments: Mitutoyo SJ-201P and Carl Zeiss Jena ME-10, with an attempt to get the same measuring conditions. A main difference between both profilometers was geometry of a measuring gauge, whose scheme is presented in Fig. 1.

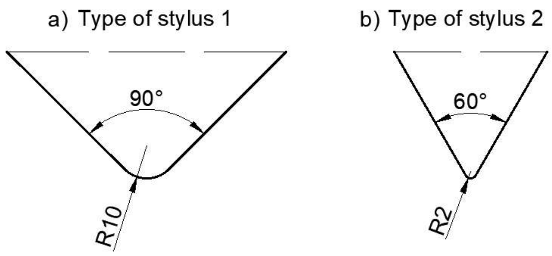

Figure 1. Schemes of the measuring gauges applied in the experiments, linear dimensions in μm; a) Carl Zeiss b) Mitutoyo

Parameters used for measurements of the surface roughness are presented in table 1. Measurements were conducted in accordance with ISO 4287 (1997). For each variant of machining process 5 measurements were completed, thus in total 200 measurements were done for each profilometer.

Table 1. Parameters of measurements of the Surface roughness of the samples

Parameter	Stylus 1	Stylus 2
Manufacturer / type of profilometer	Carl Zeiss Jena ME-10	Mitutoyo SJ-201
Feeding speed [mm/s]	0.5	0.5
Detector measuring force [mN]	0.70	0.75
Stylus Tip angle (apex angle) [°]	90	60
Stylus Tip radius [μm]	10	2
Evaluation length [mm]	12.5	12.5
The cut-off length [mm]	2.5	2.5

Two the most used parameters were calculated: the arithmetic mean surface roughness (R_a) and the maximum height of the profile (R_z).

Statistical analysis of the results was conducted with the use of Statistica 13 software. Regression analysis was done at assumed significance level of P=0,05.

RESULTS AND DISCUSSION

After the registration of primary profile on the samples, 400 values of each parameter were calculated, which then were the basis for regression analysis. Graphical presentation of the obtained results is shown in Fig. 2.

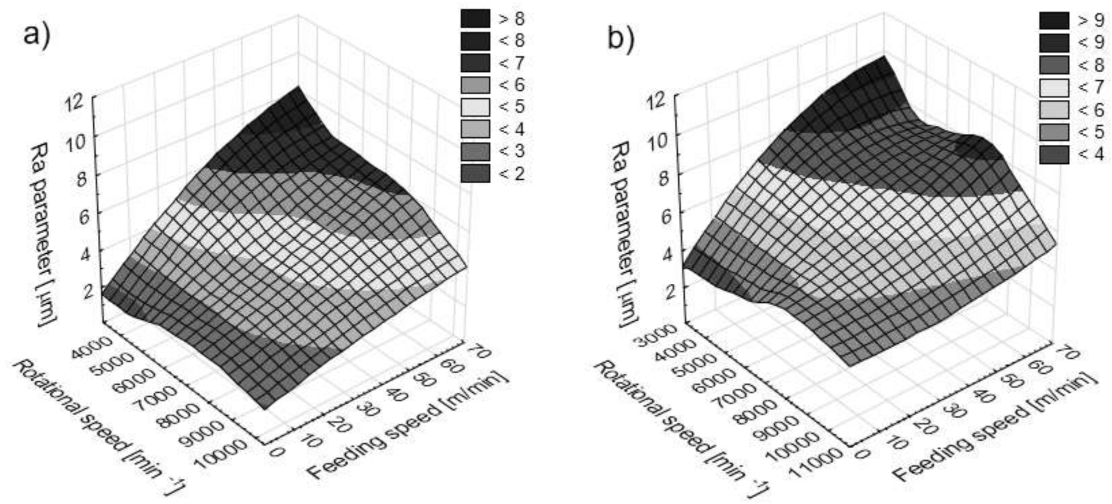

Figure 2. Results of roughness parameter *Ra* for analyzed variants of machining process: a) stylus 1 b) stylus 2

The presented graphs show that during increasing the feeding speed values of roughness parameter R_a also increased. In case of rotational speed, an increase in this parameter causes a decrease in surface roughness, what has been confirmed by many authors in previous research (Aguilera and Martin, 2001, Sogutlu 2010, Kvietková et al. 2015a, 2015b). However, comparison of the graphs shows that results obtained using stylus 2 are higher. In Fig. 3. an average values and dispersion of the results of R_a parameter are presented, together for all samples and for the lowest and the highest rotational speeds, which amounted 3500 min^{-1} and 10 000 min^{-1}. It is visible that values of R_a parameter obtained using stylus 1 are lower than for stylus 2.

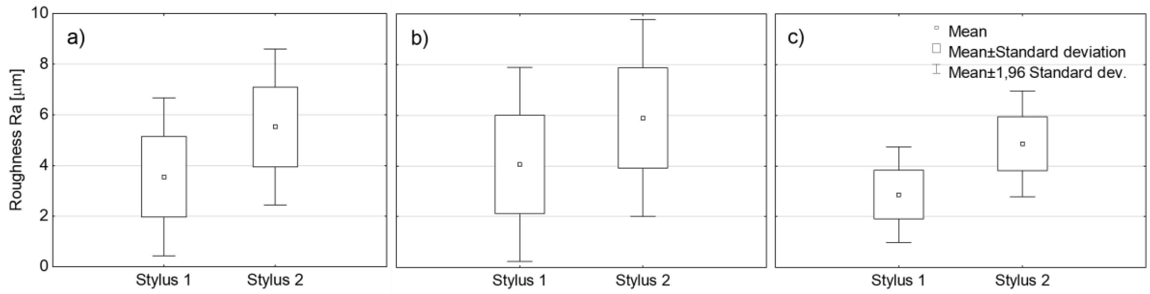

Figure 3. Mean values and standard deviation of *Ra* parameter for both measuring gauges a) all analyzed rotational speeds b) rotational speed of 3500 min^{-1} c) rotational speed of 10 000 min^{-1}

In the aspect of R_a parameter, obtained from the whole population of the results (Fig 3a), for the stylus 1 the mean value amounted 3.55 µm, while for the stylus 2 the result was 5.52 µm, thus 55% higher value. In Fig. 3b, results of R_a parameter are presented and it is visible, that the values of the R_a are the highest, but differences between each type of stylus are the lowest from the analyzed cases (45%). For the rotational speed of 10000 min^{-1} the lowest dispersion of the results was observed, but in this case the difference between each stylus was the largest. In this case, value of the R_a obtained using stylus 2 was higher by 70%

than the value obtained for stylus 1. It is clearly visible in Fig 4, where the differences for all analyzed cases for both R_a and R_z parameters are presented. In this figure rotational speed was replaced by cutting speed. Presented feature has a linear character with high coefficients of determination for both parameters, but for R_a the trend line is fitted slightly better (R^2=0,99) than for R_z (R^2=0,81).

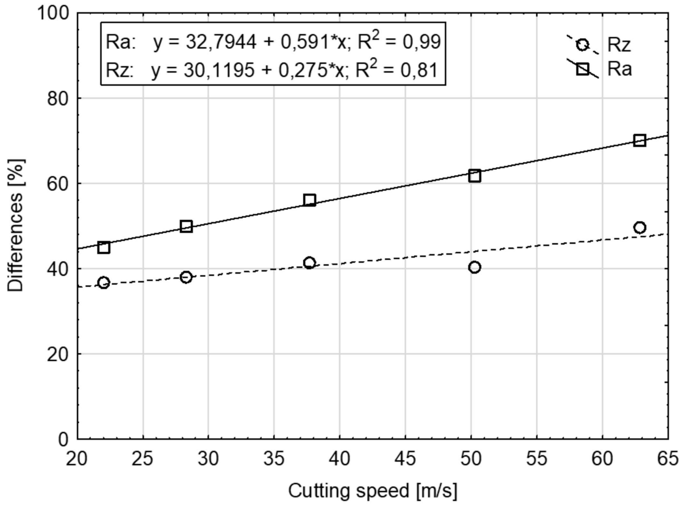

Figure 4. Differences in values of roughness parameters obtained for analyzed measuring gauges depending on the cutting speed

Figure 4 shows, that despite the constant difference between the radius and apex angle, differences between obtained results for both gauges are not constant and characterized by a directly proportional feature. During increasing the cutting speed the difference between the results for different measuring gauges also increase in range of 45% to 70% for R_a parameter and 35% to 50% for R_z parameter. The explanation of this differentiation is deeper penetration of the measuring gauge into the structure of wood surface. When rotational speed is high, the surface after machining is characterized by larger porosity, thus the differences in results between analyzed gauges are higher. Generally, it can be stated that the higher is radius of the stylus (measuring tip), the lower is penetration into a measured structure and the results are less accurate, so more deviated from the real profile and shape of analyzed surface. However, a decrease in the radius of the measuring tip results in higher production costs and some technical restrictions.

In table 2 results of multiple regression analysis are presented, for both analyzed roughness parameters and both measuring gauges. Multiple regression analysis with backward stepwise optimization was conducted, and based on the results regression models presented in table 3 were developed.

Data presented in table 3 shows, that equations designated for R_a parameter are the best fitted for stylus 1 and slightly worse fitted for stylus 2. In case of the R_z, coefficients of determination were lower, what can be explained by the method of calculation of this parameter. R_z is calculated as the difference between the highest peak and the deepest valley on the elementary section, thus it is sensitive for single interferences of the profile.

Table 2. Results of analysis of multiple regression for the surface roughness depending on tested technological parameters; v_f– feeding speed [m/min], n – rotational speed [min^{-1}]

Roughness parameter		Factor	Sum of squares	Degrees of freedom	Mean squares	Fisher's F-Test	*P*- value
The arithmetic mean surface roughness *Ra*	Stylus 1	Intercept	356,1373	1	356,1373	341,1201	0,000000
		v_f	267,3400	1	267,3400	256,0671	0,000000
		n^2	28,9145	1	28,9145	27,6953	0,000000
		Error	205,6726	197	1,0440		
	Stylus 2	Intercept	505,4173	1	505,4173	403,7506	0,000000
		v_f	42,6695	1	42,6695	34,0863	0,000000
		v_f^2	7,4702	1	7,4702	5,9675	0,015458
		n^2	18,6013	1	18,6013	14,8596	0,000157
		Error	245,3540	196	1,2518		
The maximum height of the profile *Rz*	Stylus 1	Intercept	18435,59	1	18435,59	391,7165	0,000000
		v_f	3495,51	1	3495,51	74,2721	0,000000
		n^2	363,40	1	363,40	7,7215	0,005985
		Error	9271,53	197	47,06		
	Stylus 2	Intercept	36286,72	1	36286,72	844,6178	0,000000
		v_f	4707,95	1	4707,95	109,5832	0,000000
		n^2	203,35	1	203,35	4,7333	0,030774
		Error	8463,57	197	42,96		

Table 3. Multiple regression equations for each roughness parameters and measuring gauges

The type of stylus	Regression equation	Coefficient of determination R^2
Stylus 1	$Ra = 2{,}793 + 0{,}0623 * v_f - 1{,}186e\text{-}008 * n^2$	0,59
	$Rz = 20{,}096 + 0{,}225 * v_f - 4{,}204e\text{-}008 * n^2$	0,29
Stylus 2	$Ra = 4{,}423 + 0{,}0950 * v_f - 0{,}000574 * v_f^2 - 9{,}511e\text{-}009 * n^2$	0,5
	$Rz = 28{,}194 + 0{,}262 * v_f - 3{,}145e\text{-}008 * n^2$	0,37

CONCLUSIONS

Based on the experiments results it can be stated that considerable differences exist between results of surface roughness parameters obtained during measurements with the use of gauges with different geometry. Despite the constant difference in radius and angle of the measuring tips, differences in roughness measurements have a variable character, depending on applied technological parameters of milling process. It was noted, that during increasing the rotational speed (cutting speed), the difference between results obtained using different gauges also increased in the range of 45-70% for R_a parameter and 35-50% for R_z parameter. This dependence has a linear character confirmed by high values of coefficients of determination of designated trend lines.

For measuring gauge with lower tip radius and apex angle, higher values of roughness parameters were obtained than for the second gauge. It is connected with deeper penetration of the stylus into the structure of wood.

The results of conducted experiments showed the differentiation in roughness parameters depending on technological parameters of milling process. It was observed, that the surface roughness increased during increasing the feeding speed and decreasing the rotational speed, what has been previously confirmed in the literature.

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Streszczenie: *Wpływ rodzaju końcówki pomiarowej na wyniki pomiarów chropowatości powierzchni drewna sosny (Pinus sylvestris L.) po frezowaniu.* Artykuł prezentuje wyniki badań chropowatości powierzchni drewna sosny i sygnalizuje problem porównywalności wyników uzyskanych na profilografometrach z różnymi końcówkami pomiarowymi. Ponadto badano wpływ prędkości posuwu i prędkości obrotowej wrzeciona na stan obrobionej powierzchni po obróbce na frezarce dolnowrzecionowej. Zaobserwowano duże zróżnicowanie otrzymanych wyników, w zależności od zastosowanej końcówki pomiarowej. Różnice między wynikami były zmienne, w zależności od rodzaju końcówki i wyznaczonego parametru chropowatości. Wraz ze wzrostem prędkości skrawania wzrastała różnica w otrzymanych wynikach chropowatości, pomiędzy zastosowanymi końcówkami pomiarowymi. Ponadto stwierdzono istotny wpływ prędkości posuwu i prędkości obrotowej wrzeciona na chropowatość powierzchni drewna sosny oraz wyznaczono równania regresji wielorakiej dla obu końcówek pomiarowych i analizowanych parametrów chropowatości.

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