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EVALUATION OF THE SURFACE QUALITY OF THE PROCESSED WOOD MATERIAL DEPENDING ON THE CONSTRUCTION OF THE WOOD MILLING TOOL

Pavlin Vitchev

ABSTRACT

The aim of the current study is to investigate the changes in the surface quality of specimens from Scots pine (*Pinus Sylvestris* L.) wood during longitudinal milling. Further, the influence of the cutter head construction of three different cutting tools (CH-1, CH-2, CH-3) on the surface quality was evaluated at different rotational frequencies n (from 4000 min^{-1} to 8000 min^{-1}) and feed speed v_f (from 3.5 m·min^{-1} to 10.5 m·min^{-1}). The surface roughness was measured with a digital profilometer, model „Surf test SJ-210" (Mitutoyo, Japan). Based on the experimental results, three regression equations are derived and the changes in the roughness parameter R_z in relation to the evaluated factors are graphically presented. Our results show that the values of the roughness parameter range from 25.7 μm to 39.6 μm. The highest surface quality is achieved when the surface is processed with the cutting tool CH-3, which cutting teeth edges are located at a certain angle (30°) to the axis of cutting rotation. The optimal values of the evaluated variables, at which the height quality of the processed surfaces is achieved, are as follows: rotational frequency n = 6500 min^{-1}, at which the reached cutting speed is v_c = 42 m·s^{-1}, and feed speed is v_f = 7 m·min^{-1}.

Key words: wood milling, surface roughness, cuter head construction, cutting mode.

INTRODUCTION

Milling is one of the main technological processes involved in the processing of solid wood and wood-based materials. It is well-known that this technological procedure aims to give a certain shape of the processed material as well as to ensure the highest possible class of surface roughness, i.e. a better surface quality. The quality of the milling surface is influenced by a number of factors, among others: the characteristics of the material to be processed (SANDAC *et al*. 2004), the characteristics of the cutting tool and the cutting mode (KETURAKIS *et al*. 2007, MOLITOR *et al.* 2011, GOCHEV 2014b, SIKLIENKA *et al.* 2016, GOCHEV 2018, KORCOK *et al.* 2018, VANCO *et al.* 2017, VITCHEV *et al*. 2018c). Due to the anisotropic structure of the wood, the roughness of the surface depends on the direction of the wood fibers (SANDAC *et al*. 2004). Therefore, this is another important factor in evaluating the surface roughness. Some of the above mentioned factors can be monitored during the milling process. Therefore, they are a subject of wider investigation in order to be managed in a more precise and adequate way.

A number of scientific studies investigate the changes in the processed surface quality during longitudinal, transversal and vertical (profile) milling. Their main objectives are to provide a higher surface quality by investigating and evaluating the optimal parameters, processing conditions and characteristics of the cutting tool (COSTES *et al*. 2002, PRAKASVUDHISARN *et al*. 2009, ROUSEK *et al*. 2010, GONZALEZ-ADRADOS *et al*. 2012, GOCHEV 2014a, KAVALOV *et al*. 2015, PANAYOTOV *et al*. 2015, KMINIAK *et al*. 2016, KMINIAK *et al*. 2017, KUBS *et al*. 2017, ANGELSKI *et al*. 2018, SEDLECKY *et al*. 2018, VITCHEV *et al*. 2018a, VITCHEV *et al*. 2018b, DOBRZVNSKI *et al.* 2019).

The aim of the current study is to investigate the changes in the surface quality during longitudinal milling of specimens from Scots pine (*Pinus Sylvestris* L.) wood depending on the cutter head construction of the three cutting tools, measured at different rotational frequency (n) and feed speed (v_f).

MATERIALS AND METHODS

The experiments were carried out using woodworking spindle moulder machine, type T1002S (ZMM "Stomana" GmbH, Bulgaria) (Fig. 1). The machine was equipped with a two-speed three-phase electric motor with power 3.2/4.0 kW, which through a belt drive provides the following rotating frequency of the working shaft: 3000, 4000, 5000, 6000, 8000 and 10000 min^{-1}.

Fig. 1 Woodworking spindle moulder machine, type T1002S – general view.

Three cutting tools with different cutter head construction (Metal World, Italy), named CH-1, CH-2 and CH-3, are used in the current study. The technical characteristics are given in Table 1, where D is the diameter of the cutter head; d – diameter of the threaded hole; L – longitude of the main cutting edge; γ – hook angle; z – number of teeth; f_z – feed per tooth.

The three cutting tools differ in their construction. In particular, the CH-1 has a monolith construction; the CH-2 has an assembled construction with cutting elements parallel to the axis of cutting rotation and the CH-3 has an assembled construction with cutting teeth edges allocated at 30° to the axis of cutting rotation.

In the current study, specimens from Scots pine (*Pinus Sylvestris* L.) wood with the following characteristics: density $\rho = 490\ \text{kg}\cdot\text{m}^{-3}$ and moisture content $W = 12.7$ % were used. The wood characteristics are determined according to BDS ISO 3131 and BDS ISO 3130. The processed samples had the following dimensions: longitude (l) 1000 mm and milling width (b) 40 mm. The details were fed automatically by a roller feeder.

Tab. 1 Technical characteristics of the used cutting tools.

General look of the milling cutters	*D* mm	*d* mm	*L* mm	β °	γ °	*z* No	f_z mm	*Cutting tool material*
 **CH-1**	125	30	50	43	18	4	2.5	Metal-ceramic hard alloy
 **CH-2**	125	30	50	47	16	4	1.8	Metal-ceramic hard alloy
 **CH-3**	125	30	50	46	16	4	1.9	Metal-ceramic hard alloy

In order to evaluate the complex influence of the three assessed variables: rotation frequency (*n*) of the milling tool, feed rate (v_f) and thickness of the cut-out layer (*h*) (milling height) on the quality of the processed surfaces, the methodology of multifactorial planning and subsequent regression analysis were used (VUCHKOV *et al*. 1986). The measurements were performed in accordance with a preliminary designed matrix for three factorial experiment plan of G. Box (BOX *et al*. 1951, BOX *et al*. 1999). In Table 2 the levels of the input variables in explicit and coded form are presented. The values are in line with the most frequently used in practice.

Tab. 2 Values of the variables *n*, v_f and *h*.

Variables	Minimum value		Average value		Maximum value	
	expl.	**coded**	**expl.**	**coded**	**expl.**	**coded**
Rotation frequency $n = X_1$, min^{-1}	4000	-1	6000	0	8000	1
Feed rate $v_f = X_2$, m·min^{-1}	3.5	-1	7	0	10.5	1
Thickness of the cut-out layer $h = X_3$, mm	1	-1	2	0	3	1

The roughness parameter R_z, μm was used to assess the quality of the treated surfaces, depending on the variables. It was determined separately for five base lengths in the longitudinal direction of the wood fibers of each part. For each base length the parameter R_z was determined by the mathematical equation:

$$R_z = \frac{\sum_{i=1}^{5}\left|y_{p_i}\right| + \sum_{i=1}^{5}\left|y_{v_i}\right|}{5}, \mu m \qquad (1)$$

y_{pi} – the height of the biggest roughness of the profile, μm;
y_{vi} – the depth of the greatest slot of the profile, μm.

The surface roughness of each workspace was determined using the mean average value from the five measurement. The applied methodology is in accordance with the Bulgarian standard BDS EN ISO 4287 and is described in details (GOCHEV 2005). The measurements were performed with the digital profilomer, model “Surftest SJ-210“

(Mitutoyo, Japan) (Fig. 2). For the mathematical and statistical analysis of the results, a specialized software Q Stat Lab 5 was used.

Fig. 2 Profilometer, model Surftest SJ-210 – general view.

RESULTS AND DISCUSSION

Based on the performed experiments and after statistical analysis of the data, the following regression equation (2), (3) and (4) were used for the cutting tools CH-1, CH-2 and CH-3, respectively:

$$y_{CH-1} = 32{,}138 - 2{,}895X_1 - 1{,}4X_2 + 1{,}323X_3 + 4{,}604X_1^2 - 2{,}351X_2^2 - 2{,}206X_3^2 - 1{,}353X_1X_2 - 1{,}288X_2X_3 + 0{,}005X_1X_3 \quad (2)$$

$$y_{CH-2} = 28{,}568 + 2{,}574X_1 + 1{,}243X_2 + 1{,}177X_3 + 4{,}093X_1^2 - 2.092X_2^2 - 1{,}962X_3^2 - 1{,}202X_1X_2 - 1{,}145X_2X_3 + 0{,}005X_1X_2 \quad (3)$$

$$y_{CH-3} = 26{,}090 - 2{,}351X_1 - 1{,}134X_2 + 1{,}076X_3 + 3{,}735X_1^2 - 1{,}91X_2^2 - 1{,}79X_3^2 - 1{,}099X_1X_2 - 1{,}046X_2X_3 + 0{,}006X_1X_3 \quad (4)$$

where:
y – the expected surface quality of the processed detail, defined by the roughness parameter R_z in coded form;
X_1 – rotation frequency of the cutting tool (n) in coded form;
X_2 – feed speed (v_f) in coded form;
X_3 – thickness of the cut-out layer (h) in coded form.

The level of statistical significance (α = 0.05) of the results, derived from the regression equations is presented in Table 3.

Tab. 3. Characteristics of the derived regression equations

Regression equation	Intergroup dispersion	Intragroup dispersion	Fisher dispersion F	Tabulated coefficient (Fisher's criteria) F_T	Coefficient of determination R^2
(2) with tool CH-1	23.55513	9.23233	2.55137	3.02038	0.69662
(3) with tool CH-2	18.61965	7.29236	2.55331	3.02038	0.69678
(4) with tool CH-3	15.52592	6.09147	2.54880	3.02038	0.69641

From the values of the F-distribution and the tabulated coefficient F_T it is visible that for the three regression equations the Fisher criteria for the adequacy of the model, namely $F \leq F_T$ are fulfilled, Therefore, the results could be further analyzed.

The regression equations were used to predict the surface quality of the specimens from Scots pine wood, processed with different cutting tools during longitudinal milling and depending on the changes in the rotation frequency (*n*), feed speed (v_f) and the thickness of the cut-out layer (*h*).

The planning matrix for the three-factorial experiment and the mean average value of the roughness parameter R_z, for cutting tools: CH-1, CH-2 and CH-3 and determined for different combinations of variables, are presented in Table 4.

The changes in the surface roughness depending on the construction and the rotation frequency of the cutting tool (*n*), measured at the average changes of the variables $v_f = 7$ m·min^{-1}; $h = 2$ mm are presented in Fig. 3. It is visible that the highest value of the roughness parameter R_z is determined for the cutting tool CH-1, followed by CH-2 and CH-3. This can be explained by the higher feed per tooth (f_z) value, as a result of the monolith construction of CH-1. Another reason could be the cutting edges, located parallel to the axis of rotation, which made a simultaneous contact along the entire length of the work surface. The roughness parameter values for the cutting tool CH-1 range from 39.64 μm to 31.7 μm.

Tab. 4 Planning matrix for three-factorial experiments and mean average values of the roughness parameter $\overline{R_z}$ (μm)

No.	$X_1 = n$, min^{-1}		$X_2 = v_f$, m·min^{-1}		$X_3 = h$, mm		$\overline{R_z}$ μm		
							CH-1	CH-2	CH-3
1	-1	4000	-1	3.5	-1	1	29.77	26.47	24.17
2	-1	4000	-1	10	1	3	41.12	36.55	33.38
3	-1	4000	1	10	-1	1	36.11	32.10	29.31
4	-1	4000	1	3.5	1	3	32.25	28.66	26.18
5	1	8000	-1	3.5	-1	1	31.64	28.12	25.67
6	1	8000	-1	10	1	3	32.88	29.28	26.74
7	1	8000	1	10	-1	1	22.43	20.00	18.29
8	1	8000	1	3.5	1	3	28.82	25.52	23.32
9	-1	4000	0	0	0	2	41.03	36.18	33.04
10	1	8000	0	0	0	2	35.21	31.30	28.58
11	0	6000	-1	-1	0	2	29.96	26.70	24.39
12	0	6000	1	1	0	2	31.96	28.41	25.94
13	0	6000	0	0	-1	1	32.02	28.46	26.07
14	0	6000	0	0	1	3	30.27	26.91	24.57
15	0	6000	0	0	0	2	31.78	28.25	25.79

The assembled construction of the cutting tools CH-2 and CH-3 is responsible for the lower feed per tooth (f_z) value (Table 1), which assures better quality of the processed surface in comparison with CH-1. The values of the roughness parameter R_z for the cutting tool CH-2 range from 35.24 μm to 28.18 μm.

The values of the roughness parameter R_z for the cutting tool CH-3 range from 32.08 μm to 25.74 μm. The cutting edges of the cutting tool CH-3 located at an angle to the axis of rotation provide for a gradual contact between the tool and the processed material. This additionally improves the quality of the processed surface.

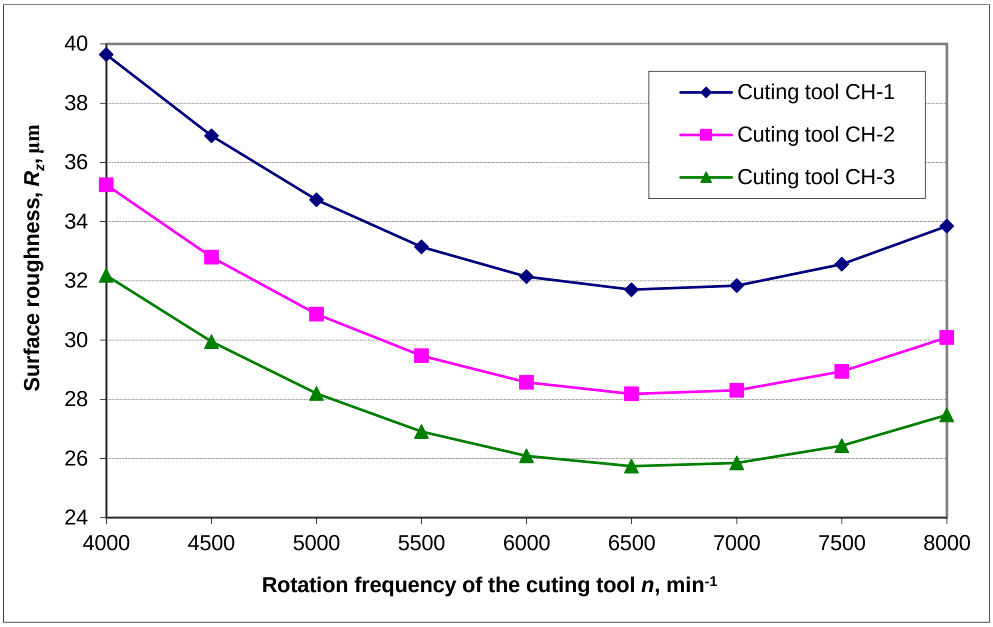

Fig. 3 Changes in the surface quality depending on the construction and the rotation frequency of the cutting tool, determined at feed speed v_f = 7 m·min^{-1} and thickness of the out-cut layer h = 2 mm.

The results from the current study clearly show that the rotational speed of the cutting tool (n) significantly influenced the quality of the processed surface (Fig. 3). The peak values of the roughness parameter R_z were detected at the highest rotational speed of the tool n = 4000 min^{-1}. An increase in the rotational frequency improved the surface quality of the processed material. The best quality for all three cutting tools was reached at rotational speed n = 6500 min^{-1}. Our results were in good correlation with the results obtained from other authors (GOCHEV 2014B, KUBS *et al.* 2017) which conclude that higher rotational speed results in better quality of the machined surface. In the current study, however, we also observed a deterioration of the surface quality at rotational frequency higher that n = 6500 min^{-1}. In particular, with an increase in rotational frequency of the cutting tool from 6500 min^{-1} to 8000 min^{-1}, the values of the roughness parameter R_z increased by 2 µm for the three cutting tools. The deterioration of the surface quality was probably due to the changes in the dynamic behavior of the machine and to the increased vibrations of the cutting tool resulting from the higher rotational speed.

Figure 4 presents the relationship between the changes in the roughness of the processed material (R_z) and the feed speed (v_f) for the three cutting tools, measured at rotational speed of the cutting tool n = 6000 min^{-1} and the thickness of the out-cut layer h = 2 mm. The roughness curves depicted in Fig. 4 were in good correlation with the results presented in Fig. 3, namely the highest surface quality was achieved with cutting tool CH-3, followed by CH-2. The highest value of the roughness parameter R_z was measured for the cutting tool CH-1.

It is well-known that the feed speed influences the surface quality. In the scientific literature, there is a large source of information, showing that independently of the wood type of the processed material, the surface roughness increases with the increase of the feed speed (BARCIK *et al.*, 2009, GOCHEV 2014b, SIKILIENKA *et al.* 2016, KUBS *et al.* 2017). Although not very pronounced, this trend is visible also from the results of the current study. The graphs in Fig. 4 show that the best surface quality is reached at the lowest feed speed v_f = 3.5 m·min^{-1}. An increase in the feed speed up to 7 m·min^{-1} results in the deterioration of the surface quality. Interestingly enough, an increase in the feed speed from 7 m·min^{-1} to 10.5 m·min^{-1} led to a slight decrease, by 05-0.8 µm, in the roughness parameter R_z. This decrease, however, is insignificant and it could be concluded that under the conditions of this study, an increase in the feed speed from 7 m·min^{-1} to 10.5 m·min^{-1} did not change the surface roughness of the processed material.

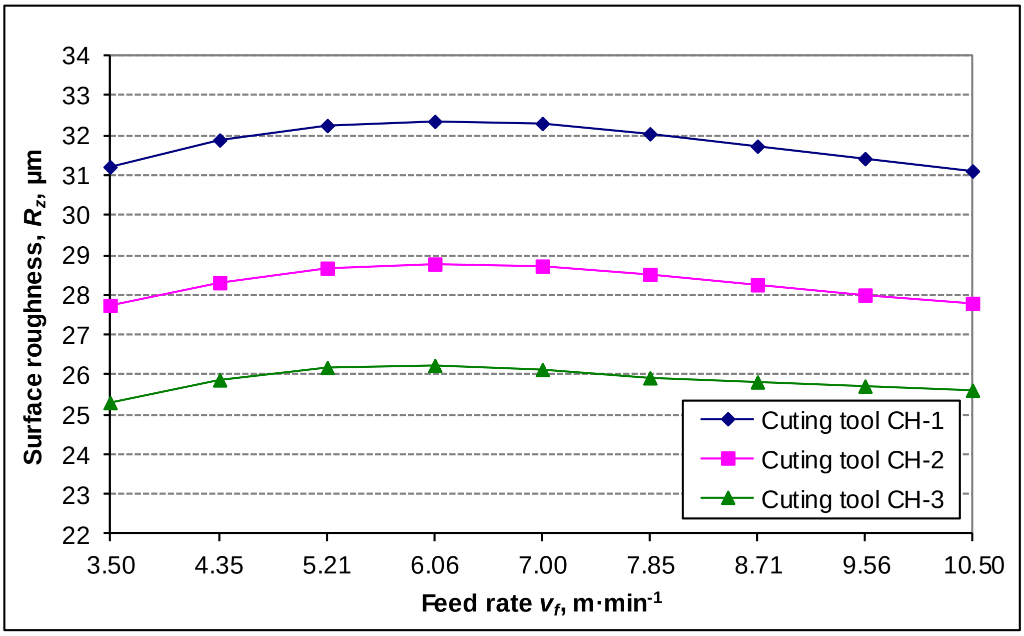

Fig. 4 Changes in the surface quality depending on the construction and feed speed, measured at rotational speed of the cutting tool *n* = 6000 min^{-1} and the thickness of the out-cut layer *h* = 2 mm.

Based on the obtained results, the roughness of surface processed with the three cutting tools – CH-1, CH-2 и CH-3, corresponds to a roughness class IX (GOCHEV, 2018). According to KAVALOV *et al.* (2014), surfaces of specimens from monolith wood with roughness R_z = 30 μm are qualified as "good quality surface". This surface quality is considered suitable for further processing, such as gluing and coating.

CONCLUSION

The experimental results of this study aimed at investigating the changes in the surface quality of the specimens from Scots pine (*Pinus Silvestryis* L.) wood, measured at different rotational speed (n) and feed speed (v_f) during longitudinal milling and in relation to the characteristics of the head cutter.

Based on the obtained results, the following conclusions were drawn:

- The surface quality is influenced by the construction of the cutting tool, which indirectly influences the cutting mode. Under the conditions of this study, the highest surface quality is achieved by using an assembled milling tool with cutting edges located at a certain angle to the axis of rotation (see Fig. 3).
- The influence of the rotational speed of the cutting tool, or the cutting speed, on the quality of the processed surface, assessed by the roughness parameter R_z is confirmed by the obtained results. An increase in the rotational frequency from 4000 min^{-1} to 6500 min^{-1} resulted in better surface quality, improved by 35% when compared to higher rotational frequency (from 6500 min^{-1} to 8000 min^{-1}). The observed

deterioration of the surface quality at higher rotational frequency values can be explained with the increased vibrations of the cutting tool (see Fig. 3).

- For a milling tool with cutting diameter D = 125 mm used for processing of Scots pine wood specimens, the optimal rotational speed range is from 6000 min^{-1} to 6500 min^{-1}. This range ensures a cutting speed (v_c) from 39 $m \cdot s^{-1}$ to 42 $m \cdot s^{-1}$.

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AUTHORS' ADDRESSES

Chief Assist. Prof. Pavlin Vitchev, PhD
University of Forestry
Faculty of Forest Industry
Department Woodworking machines
10 Kliment Ohridski Blvd.
1797 Sofia
Bulgaria
p_vitchev@ltu.bg