EVALUATION OF THE MACHINED SURFACE QUALITY OF SCOTS PINE (*PINUS SYLVESTRIS* L.) WOOD SPECIMENS, DEPENDING ON THE CUTTING MODE OF A CNC MACHINE

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ABSTRACT

In this paper, the surface quality of scots pine *(Pinus sylvestris L.)* wood specimens, processed with a CNC woodworking drilling and milling machine with a negative face mill helix, has been investigated. The changes in the surface roughness, depending on the changes in main factors determining the cutting process, such as cutting tool rotation speed (n); feed speed (V_f) and radial depth of cut (h), have been evaluated. The quality of the processed surfaces was evaluated by the roughness parameter R_z, measured with a portable roughness tester, model *Surftest SJ-210* (Mitutoyo, Japan).

Based on the experiments performed, graphical dependencies, presenting the influence of the individual factors on the quality of the processed surface, were derived. A regression model was derived that could be used for quantitative prediction of the surface roughness of Scots pine wood specimens when processed with a CNC machine, depending on the changes of the variable factors (n, V_f, h).

Key words: surface quality, CNC machines, cutting mode, milling, Scots pine, rotational speed, radial depth of cut, feed speed.

INTRODUCTION

Milling is one of the most frequent technological operations used to process wood and wood-based materials, ensuring a certain shape and quality (roughness) of the processed surfaces. In this respect, the CNC (*Computer Numerical Control*) woodworking machines have proved their worth, and they are widely used in modern furniture production. The main reason for this is a number of advantages they have when compared to the traditional woodworking machines, among others, better quality and accuracy at the workplace, greater productivity, simple modification and reparation of given tasks etc.

Wood, as a material, is characterised by its anisotropic, layered-fibrous and hygroscopic structure, and it has a number of disadvantages, including plugs, the inclination of the fibres, resin channels, etc. (Bardarov, 2019). These characteristics and disadvantages of wood are responsible for the large range of values of the measured roughness parameter R_z.

A number of scientific papers have evaluated the influence of various factors affecting the quality of the processed surfaces under milling. Among those factors that are shown to have a great impact on the processed surface quality are the characteristics of the cutting tool and its wear, the type and structure of the processed material, the cutting mode etc. (Aguilera *et al.* 2000; Ohuchi & Murase 2006; Ohuchi *et al.* 2008; Koç *et al.* 2015; Vitchev 2019).

Some authors indicated factors, such as the cutting and feed speeds, cutting forces, vibrations generated during milling, etc. as the most impactful on the quality of milled surfaces (Ohuchi & Murase 2001; Davim *et al.* 2009; Sofuoglu 2017; Curti *et al.* 2017; Sedlecký 2017; Sedlecký *et al.* 2018; Hazir & Koc 2019; Starikov *et al.* 2020; Pelit *et al.*2021; Gürgen *et al.* 2022; Gochev & Vitchev, 2023; Ergin & Sofuoglu 2023). Other authors emphasised on the properties of the processed material, wood type (Malkoçoğlu & Özdemir 2006), the type of cut (tangential or radial) (Kılıç 2015; Gochev & Vichev 2023), the density of the wood (Zhong *et al.* 2013).

It has been demonstrated that the surface roughness increases with an increase in the diameter of the cutting tool. This relationship is explained by the friction occurring in the zone of contact between the cutting tool and the processed material. The influence of factors, such as rotation speed of the cutting tool (n), feed speed (V_f), tool wear rate etc., have also been investigated (Ohuchi & Murase 2001; Ohuchi & Murase 2006; Ohuchi *et al.* 2008; Davim *et al.* 2009; Hazir & Koc 2016). showed, for example, that the surface roughness increases at higher rotation speed of the cutting tool and lower feed speed (Davim *et al.* 2009; Sütçü 2013; Sütçü & Karagöz 2013; Sofuoglu 2015).

Most of the factors affecting the milling process can be controlled and managed. Therefore, their influence on the surface roughness should be studied to apply optimal milling modes.

The objective of this study was to investigate the degree of influence of the following controlled factors: rotation speed (n), feed speed (V_f) and radial depth of cut (h) on the surface quality of workpieces of Scots pine wood (*Pinus sylvestris* L.)., processed with CNC-machining centre.

MATERIALS AND METHODS

The experimental research was performed with a CNC-machining centre, model Rover A 3.30 (Biesse, Italy) (Figure 1). The machine has three interpolated control axes (X, Y and Z), with operational steps of X = 3060 mm; Y = 1260; mm; Z = 150 mm, respectively. The machine software provides the opportunity for stepless regulation of feed rate (V_f) and change of cutting speed via changing the rotation speed (n).

Figure 4: General appearance of CNC-machining centre, model A 3.30 (Biesse, Italy).

In the current experiment, a new CNC finishing spiral router cutter, with a negative spiral with sharpening radius ρ_0 = 6 µm, made from solid tungsten carbide (CMT, Italy, Figure 2), was used. The technical characteristics of the cutting instrument are presented in Table 1, where: D

is the cutting circle diameter, *I* – cutting length, *L* – total length, *s* – diameter of the shank, *z* – number of spirals (number of teeth), *n* – maximum RPS.

Figure 2: CNC shank spiral finishing cutter – CMT (Italy).

Table 1: Technical characteristics of the instrument used

D mm	*I* mm	*L* mm	*d* mm	*Z* count	*n* s^{-1}	Material of the teeth	Geometry
12	35	83	12	3	18000	Solid Carbide	Negative spiral

For the current experiment, wedge-shaped boards of Scots pine (*Pinus sylvestris* L.) were processed. The test specimens were processed across the grain of the wood. The density profile (P_{12} = 483 kg.m^{-3}) of the boards was determined according to BDS ISO 13061 – 2:2014 and the moisture content (*W* = 10.3%) was determined according to BDS ISO 13061:2019. The measurements were performed in the laboratory of the University of Forestry, Sofia. The test specimens were with the following dimensions: length (*L*) = 600 mm; width (*B*) = 200 mm; thickness (*T*) = 22 mm.

To evaluate the influence of the factors: rotation speed of shank cutter (*n*), feed rate (V_f) and radial depth of cut (*h*), the methodology of multifactorial planning (Vuchkov 1986) was implemented. The levels of variation in the variable factors are presented clearly and in coded mode in Table 2.

Table 2: Level of change of the variables n, V_f and h

Variable factors	Minimum value		Average value		Maximum value	
	Expl.	Coded	Expl.	Coded	Expl.	Coded
Rotation speed $n = X_1$, [min^{-1}]	12000	-1	15000	0	18000	1
Feed speed $V_f = X_2$, [m.min^{-1}]	2	-1	3,5	0	5	1
Radial depth of cut $h = X_3$, [mm]	1	-1	2	0	3	1

The roughness of the processed Scots pine wood surfaces was evaluated by the roughness parameter R_z.

The roughness parameter R_z was calculated for each sampling length of the studied surface area using the following equation:

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

where:

y_{pi} – the hight of the five tallest peaks of a profile within the sampling lenght, μm;

y_{vi} – the depth of the five deepest valleys of a profile within the sampling lenght, μm.

The methodology used to determine the surface roughness is in accordance with the BDS EN ISO 4287, as described by Gochev (2005).

The values of the roughness parameters were measured with a portable roughness tester, model *Surftest SJ-210* (Mitutoyo, Japan) (fig. 3) according to BDS EN ISO 3274:2002, with the following settings:

- profile – *R*, profile filter – Gauss;
- number of base lengths $n_1 = 5$;
- evaluation length ln =12.5 mm;
- upper limit of filter λc = 2.5 mm;
- lower filter limit λs = 8 μm;
- measuring speed 0.25 mm.s^{-1}.

Figure 3: Portable roughness tester, model Surftest SJ-210 (Mitutoyo, Japan) during the measurement

The data was statistically analysed using Q-StatLab specialised software.

RESULTS AND DISCUSSION

Based on the experiments performed in accordance with the developed methodology and on the mathematical analysis of the results, the following regression equation was derived (2):

$$y = 46.51 + 0{,}3X_1 + 5.26X_2 - 0.16X_3 - 0.3X_1^2 + 5.26X_2^2 - 0.16X_3^2 - 14.2X_1X_2 + 6.72X_2X_3 - 2{,}19X_1X_3 \tag{2}$$

where:

y – predicted roughness value of the processed surface, defined by the roughness parameter *Rz* in coded form;

X_1 – rotation speed of the cutting tool (n) in coded form;

X_2 – feed speed (V_f) in coded form;

X_3 – radial depth of cut (h) in coded form.

Using the derived regression equation (2), the variation of the roughness parameter R_z can be numerically predicted, depending on the values of the variable factors: rotation speed of the cutting tool ($n = X_1$); feed speed ($V_f = X_2$); radial depth of cut ($h = X_3$).

The experimental matrix, based on which the combinations of the studied parameters and their levels of variation were established and the experimental study was carried out, is presented in Table 3. The arithmetic mean average values of the roughness parameter $\overline{R_z}$ (µm), calculated in the course of the experiment are also presented in Table 3. After performing the statistical and mathematical analysis, the regression coefficients were derived and presented in Table 4.

Table 3: Planning matrix for three-factorial experiment and mean average values of the roughness parameter $\overline{R_z}$ (µm).

№	$X_1 = n$ min^{-1}		$X_2 = V_f$ m.min^{-1}		$X_3 = h$ mm		$\overline{R_z}$ µm	№	$X_1 = n$ min^{-1}		$X_2 = V_f$ m.min^{-1}		$X_3 = h$ mm		$\overline{R_z}$ µm
1	-1	12000	-1	2	-1	1	40.18	9	-1	12000	0	3.5	0	2	50.11
2	-1	12000	-1	2	1	3	38.9	10	1	18000	0	3.5	0	2	42.74
3	-1	12000	1	5	-1	1	74.94	11	0	15000	-1	2	0	2	41.92
4	-1	12000	1	5	1	3	82.55	12	0	15000	1	5	0	2	51.43
5	1	18000	-1	2	-1	1	84.56	13	0	15000	0	3.5	-1	1	55.29
6	1	18000	-1	2	1	3	56.56	14	0	15000	0	3.5	1	3	58.51
7	1	18000	1	5	-1	1	44.49	15	0	15000	0	3.5	0	2	46.6
8	1	18000	1	5	1	3	61.34								

Table 4: Regression coefficients

Coefficient	Coded value	Coefficient	Coded value	Coefficient	Coded value
b_1	0.3	b_{11}	0.98	b_{12}	-14.2
b_2	5.26	b_{22}	1.23	b_{23}	6.72
b_3	-0.16	b_{33}	11.45	b_{13}	-2.19

The changes in the quality of the processed surfaces, depending on the rotation speed of the cutting tool (n) at different feed speeds (V_f), are presented in Figure 4. From the graph, it is visible that the lowest value of the roughness parameter R_z is obtained at the lowest values of the rotation speed (n = 12000 min^{-1}) and the feed speed (V_f = 2 m.min^{-1}); as the rotation speed of the cutting tool increases, the values of the roughness parameters increase as well. Our results confirm the observations by other authors, showing that the roughness of the processed surface increases with an increase in the rotation speed of the spindle and a decrease in the feed speed (Davim *et al.* 2009; Sütçü 2013; Sütçü & Karagöz 2013; Sofuoglu 2015).

At the average values of the feed speed (V_f = 3,5 m.min^{-1}), no change in the quality of the processed surfaces was observed, regardless of the change in the rotation speed of the cutting tool. Also, other authors investigated the influence of the rotation speed of the spindle on the surface quality of specimens from Scots pine wood reported insignificant changes in the values of the roughness parameter R_z (Sütçü 2012; Starikov *et al.* 2020; Pelit *et al.* 2021; Gürgen *et al.* 2022).

The largest variation in the roughness parameter R_z was observed at the highest value of the feed rate (V_f = 5 m.min^{-1}). At this feed speed value and at the rotation speed value of the cutting tool (n = 12000 min^{-1}), the highest values of R_z were measured. The values of R_z decreased with an increase in the rotation speed of the cutting tool.

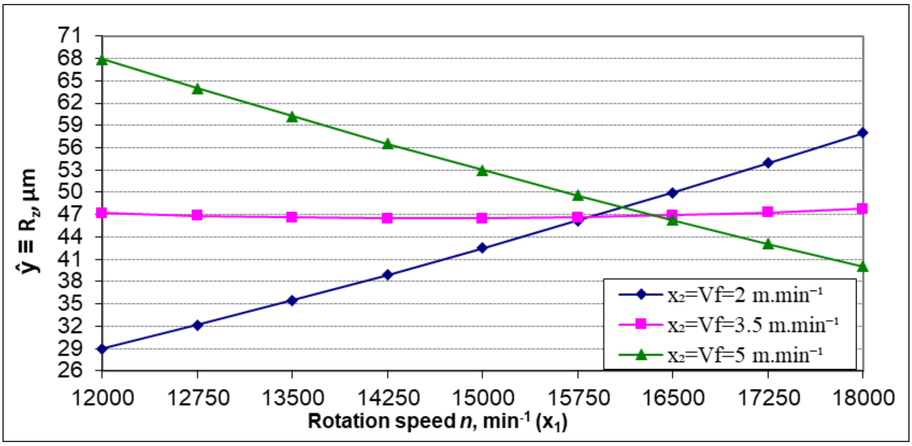

Figure 4: Changes in the roughness parameter R_z depending on the rotation speed of the cutting tool (n) and on the feed speed (V_f); radial depth of cut h = const = 2 mm

The relationship between the rotation speed of the cutting tool (n) and the radial depth of cut (h) is presented in Fig. 5. It is visible that for all measured radial depth of cuts, the rotation speed of the cutting tool (n) did not have a great influence on the quality of the processed surfaces. The lowest R_z values were measured at the radial depth of cut h = 2 mm. These results are in good correlation with the results of Sütçü (2013), who showed that the radial depth of cut does not impact the quality of the processed surface.

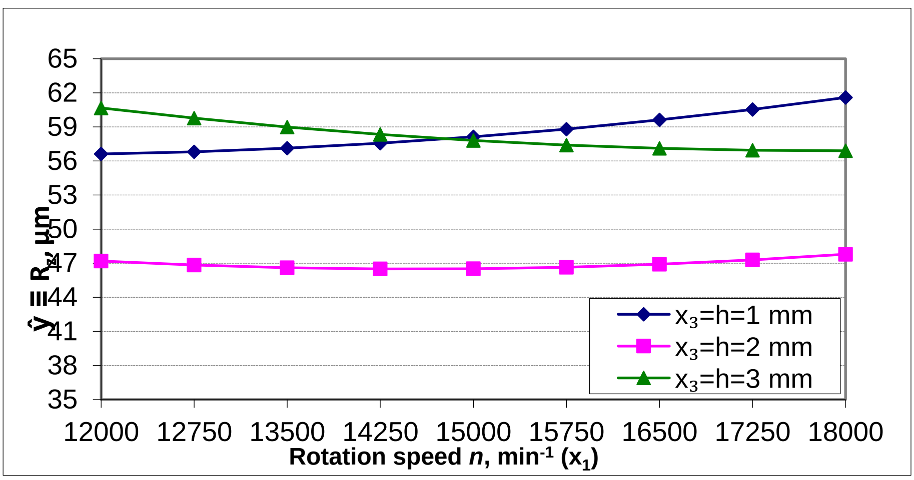

Figure. 5: Changes in the roughness parameter R_z depending on the rotation speed of the cutting tool (n) and on the radial depth of cut (h); feed speed V_f = const = 3.5 m.min^{-1}

The relationship between the feed speed (V_f) and the radial depth of cut (h) is depicted in Fig. 6. The results show that at the lowest value of the radial depth of cut (h = 1 mm), the increase in the feed speed (V_f) did not result in significant change in the roughness parameter R_z. At the medium and the highest value of the radial depth of cut (h = 2 mm and h = 3 mm, respectively), however, the increase in the feed speed (V_f) resulted in a significant increase in the values of the roughness parameter R_z. These results, taken together with those discussed in Fig. 4, correlate with those obtained by other authors in this field (Sedlecký 2017; Sedlecký *et al.* 2018).

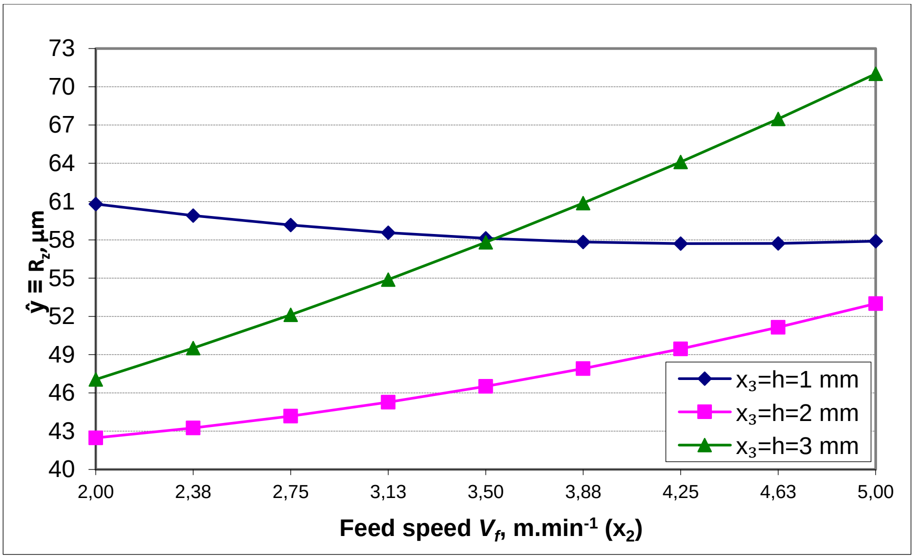

Figure 6: Changes in the roughness parameter R_z depending on the feed speed (V_f) and

on the radial depth of cut (h)

CONCLUSION

Based on the results obtained under the conditions of this study, the following conclusions can be drawn:

- The roughness of the processed surface, identified by the roughness parameter (R_z), is greatly influenced by the feed speed (V_f), the rotation speed of the cutting tool *(n)* and the radial depth of cut (*h*). These results are in good correlation with the results reported by other authors (Ohuchi&Murase 2006; Ohuchi *et al.* 2008; Sedlecký 2017; Sedlecký *et al.* 2018).
- Under the specific conditions of the current study, the values of the roughness parameter R_z varied in the range of 28.945 µm to 71.015 µm. The greatest influence on the quality of the processed surfaces is exerted by the feed speed (Vf), as in most cases, the feed speed increase resulted in an increase in the R_z. The radial depth of cut (*h*) has the least influence on the roughness parameter R_z.
- The increase in the rotation speed of the cutting tool (*n*) at low-speed feed (V_f) values leads to the deterioration of the processed surface quality (Fig. 4).

On the basis of the obtained results, it could be concluded that the best surface quality is obtained at rotation speed of the cutting tool $n = 12000$ min^{-1}, feed speed $V_f = 2$ m.min^{-1}and radial depth of cut $h = 2$ mm.

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