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OPTIMIZATION OF THE CNC MILLING PROCESS VIA MODIFYING SOME PARAMETERS OF THE CUTTING MODE WHEN PROCESSING *QUERCUS ROBUR* L.

Alexander Doichinov

University of Forestry, Sofia, Bulgaria
E-mail: a_doichinov@ltu.bg

ABSTRACT

This article examines certain cutting regime parameters that influence the quality of milled surfaces of oak wood (*Quercus robur L.*) parts processed on a CNC woodworking milling-drilling center. The present study aims to determine the combined effect of key cutting parameters such as spindle speed (*n*), feed rate (V_f) and depth of cut (*h*). The evaluation of the milled surfaces was conducted based on the roughness parameter R_z, with measurements taken using an electronic profilometer model Surftest SJ-210 (Mitutoyo, Japan). As a result of the conducted experiments, graphical dependencies were derived, illustrating the degree of influence of the studied factors on the surface roughness of the machined parts.

Key words: Surface quality, oak, milling, CNC machines, spindle speed, feed rate, depth of cut.

INTRODUCTION

CNC machines and technologies are widely used in modern woodworking and furniture industries due to the numerous advantages they offer compared to conventional machines. Their main advantages include high productivity and precision, a high degree of automation of key production processes, rapid tool changes, flexible processing modes, and more. With the rapid advancement of CNC machines and the automation of manufacturing processes, expectations for improved quality of milled surfaces have significantly increased.

Wood, as a primary material used in the furniture and woodworking industries, is characterized by its layered-fibrous, hygroscopic, and anisotropic structure. Additionally, it has several natural defects such as knots, grain deviation, and cross grain (Bardarov, 2019).

These inherent characteristics of wood are the main reason for the wide range of roughness parameter values, which define the quality of machined surfaces.

The milling operation is one of the most commonly used technological processes in the machining of solid wood materials, aiming to achieve a specific shape and surface quality of the milled parts.

Numerous scientific publications emphasize the quality of milled surfaces depending on the influence of various factors. The type and structure of the machined material, cutting parameters, characteristics of the cutting tool and its wear during the machining process, as well as vibrations occurring during milling, have a significant impact on the quality of the processed surfaces (Aguilera *et al.*, 2000; Ohuchi & Murase, 2006; Ohuchi *et al.*, 2008; Davim *et al.*, 2009; Thoma *et al.*, 2013; Koç *et al.*, 2015; Curti *et al.*, 2017; Sedlecký *et al.*, 2018; İşleyen, 2019; Vitchev, 2019; Kminiak *et al.*, 2020; Pelit *et al.*, 2021).

In their publications, Ohuchi & Murase, (2001, 2006); Ohuchi *et al.*, (2008); Davim *et al.*, (2009) emphasize the influence of certain factors such as spindle speed (*n*), feed rate (V_f), tool wear, and others on the milling process.

According to Curti *et al.*, (2017); Sedlecký, (2017); Vitchev, (2019); Pelit *et al.*, (2021), the main factor significantly affecting the quality of machined surfaces lies in the design features of the cutting tools.

In their scientific studies, Davim *et al.*, (2009); Sütçü, (2013) found that increasing the diameter of the cutting tool leads to deterioration in surface quality, due to increased friction in the contact area between the tool and the workpiece.

Although there are numerous parameters that influence the surface quality, their proper adjustment is essential in improving the quality of surfaces machined from solid wood and wood-based materials (WBM) (Gochev & Vitchev, 2023[a]).

Surface roughness is a function of the manufacturing process, the type of material being processed, and the anatomical characteristics of the wood. The roughness of the wood surface can be measured using contact or non-contact methods (Aydin & Colakoglu, 2003).

Authors in various publications have noted that properties of the processed material such as wood species (Malkoçoğlu & Özdemir, 2006), wood density (Zhong *et al.,* 2013), cutting direction (tangential or radial) (Kılıç, 2015; Gochev & Vitchev, 2023b), and whether cutting is performed along or across the grain (Mitchell & Lemaster, 2002; Iskra & Tanaka, 2005; Sütçü, 2013) affect the evaluation of surface quality. For wood species with higher density, lower values of surface roughness parameters are generally observed (Thoma *et al.,* 2015; Singer & Ozsahin, 2020). Oak is a ring-porous wood species, which further complicates the evaluation of surface quality due to its anatomical characteristics. The vessels of earlywood and latewood influence the roughness of the machined surfaces (Lungu *et al.,* 2023; Bardarov, 2018).

Pinkowski & Szymański, (2010) also found that roughness parameter values increase depending on the annual ring distribution and the location of the measurement point on the sample.

A number of scientific studies report that surface quality improves at high spindle speeds and low feed rates (Kminiak *et al.,* 2017; Davim *et al.*, 2009; Deus *et al.*, 2015; Vitchev & Gochev, 2018; Sedlecký *et al.,* 2018).

Ergin & Sofuoglu, (2023) emphasize chip formation as one of the most critical processes influencing the quality of milled surfaces and demonstrate that an increase in chip volume during milling leads to a decline in surface quality.

According to Sütçü, (2013), the depth of cut does not significantly affect the quality of the milled surfaces.

In their study, Yang *et al.*, (2023) noted that the surface roughness of machined wooden products has a significant impact on their productivity.

The main objective of this study is to optimize the milling process and to examine the extent to which controllable factors spindle speed (n), feed rate (V_f), and depth of cut (h) influence the milling process and the resulting surface quality of oak wood parts.

METHODOLOGY

In the present experimental study, the tests were conducted on a CNC woodworking milling-drilling center, model Rover A3.30 (Biesse, Italy). The machine is equipped with three interpolated control axes (X, Y, and Z) with working strokes of: X = 3060 mm; Y = 1260 mm; Z = 150 mm (Fig. 1). Using the machine's software, it is possible to infinitely adjust the feed rate (V_f) and to change the cutting speed by altering the spindle speed (n) of the cutting tool.

Figure 1: General view of the CNC woodworking milling-drilling center, model A3.30 (Biesse, Italy)

For the experimental tests, a new spiral shank cutter with a positive spiral (CMT, Italy) made of cemented carbide was used (Fig. 2). The technical specifications of the cutting tool are presented in Table 1, where: *D* – cutting diameter; *S* – shank diameter; *I* – cutting length; *L* – overall tool length; *d* – collet diameter (shank diameter); *z* – number of spirals; *n* – maximum spindle speed.

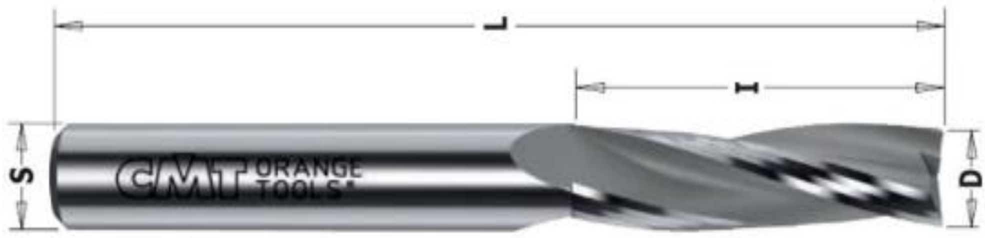

Figure 2: Face mill with positive spiral – general view

Table 1: Technical specifications of the milling tool used

D **mm**	***I*** **mm**	***L*** **mm**	***S*** **mm**	***Z*** **count**	***n*, min^{-1}**	**Material of the teeth**	**Geometry**
12	35	83	12	3	18000	metal-ceramic hard alloy	Positive spiral

During the experimental study, test specimens were machined from laminated oak wood panels (*Quercus robur* L.), and the density profile was analyzed according to BDS ISO 13061-2:2019, while moisture content was determined according to BDS ISO 13061-1:2019. in the laboratory of the University of Forestry. For the oak wood panels, an average density of P_{12} = 687 kg/m³ and a moisture content of *W* = 10.6% were recorded. The experimental specimens had the following dimensions: length (*L* = 600 mm); width (*B* = 200 mm); and thickness (*T* = 22 mm), and were machined across the wood grain.

To determine the combined influence of the controllable factors – spindle speed (*n*), feed rate (V_f), and depth of cut (*h*) – the method of multifactorial experimental design proposed by

Vuchkov & Stoianov, (1986) was applied. The values of these factors were varied at three levels, presented in both actual and coded form in Table 2.

Table 2: Levels of variation of the controllable factors *n*, V_f, and *h*

Variable factors	Minimum value		Average value		Maximum value	
	Expl.	Coded	Expl.	Coded	Expl.	Coded
Spindle speed $n = X_1$,(min^{-1})	12000	-1	15000	0	18000	1
Feed rate $V_f = X_2$, ($m.min^{-1}$)	2	-1	3,5	0	5	1
Depth of cut $h = X_3$,(mm)	1	-1	2	0	3	1

The roughness of the milled surfaces will be determined using the surface roughness parameter R_z.

The surface roughness parameter R_z is calculated for each sampling length using the following formula:

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

where:

– y_{pi} – the five highest peaks within one sampling length, in µm;

– y_{vi} – the five deepest valleys within one sampling length, in µm.

The method for determining surface roughness was applied in accordance with BDS EN ISO 21920-2:2022 and is described in detail by Gochev, (2005).

The measured values of the roughness parameter were obtained using a digital profilometer, model Surftest SJ-210 (Mitutoyo, Japan) (Fig. 3), in compliance with BDS EN ISO 3274:2002, under 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 $\lambda s = 8$ *µm*;
- measuring speed 0.25 $mm.s^{-1}$.

The specialized software product Qstat.Lab was used for processing mathematical and statistical data.

Figure 3: General view of the profilometer model Surftest SJ-210 during measurement (Mitutoyo, Japan)

RESULTS

Following the experimental study and the applied multifactorial design methodology, mathematical processing of the results, and regression analysis, the variation in the quality of the machined surfaces of oak wood parts using a cutting tool with a positive spiral can be described by the derived regression equation (2):

$$y = b_0 + b_1 X_1 + b_2 X_2 - b_3 X_3 - b_1 X_1^2 + b_2 X_2^2 - b_3 X_3^2 - b_{12} X_1 X_2 + b_{23} X_2 X_3 - b_{13} X_1 X_3 \quad (2)$$

$$\hat{y} = 28{,}81 - 0{,}450x_1 + 3{,}53x_2 - 1{,}52x_3 - 2{,}85x_1^2 - 1{,}14x_2^2 + 3{,}70x_3^2 - 1{,}81x_1x_2 - 1{,}40x_2x_3 + 0{,}99x_1x_3$$

where:

y – predicted value of the output value, defined by the roughness parameter R_z coded.

X_1 – rotation speed (n) coded.

X_2 – feed rate (V_f) coded.

X_3 – radial depth of cut (h) coded.

Using the regression equation (2), the change in the roughness parameter R_z can be numerically predicted based on the values of the controllable variables spindle speed ($n = X_1$), feed rate ($V_f = X_2$), and depth of cut ($h = X_3$).

Table 3 presents the experimental matrix, which forms the basis for the combinations of the studied controllable factors and their levels of variation. The obtained arithmetic mean values, calculated based on the conducted measurements, are also shown in Table 3.

Following the statistical and mathematical processing of the data, the regression coefficients were derived and are presented in Table 4.

Table 3: Planning matrix for three-factor experiment and mean values of the surface roughness parameter ($\bar{R}z$; µm)

№	$X_1 = n$ min^{-1}		$X_2 = V_f$ m.min^{-1}		X_3 = h mm		$\bar{R}_z$ µm	№	X_1 = n min^{-1}		$X_2 = V_f$ m.min^{-1}		$X_3 = h$ mm		$\bar{R}_z$ µm
1	-1	12000	-1	2	-1	1	22.717	9	-1	12000	0	3.5	0	2	26.255
2	-1	12000	-1	2	1	3	23.752	10	1	18000	0	3.5	0	2	26.426
3	-1	12000	1	5	-1	1	36.547	11	0	15000	-1	2	0	2	32.332
4	-1	12000	1	5	1	3	18.097	12	0	15000	1	5	0	2	19.758
5	1	18000	-1	2	-1	1	33.787	13	0	15000	0	3.5	-1	1	27.023
6	1	18000	-1	2	1	3	24.879	14	0	15000	0	3.5	1	3	38.736
7	1	18000	1	5	-1	1	24.204	15	0	15000	0	3.5	0	2	35.727
8	1	18000	1	5	1	3	23.601								

Table 4: Regression coefficients.

Coefficient	Coded value	Coefficient	Coded value	Coefficient	Coded value
b_1	-4.45	b_{11}	-2.85	b_{12}	-1.81
b_2	3.53	b_{22}	-1.14	b_{23}	-1.40
b_3	-1.52	b_{33}	3.70	b_{13}	0.99

Figure 4 shows the variation of the surface roughness parameter R_z depending on the spindle speed of the cutting tool at different feed rates. The figure indicates that as the spindle speed increases and the feed rate decreases, the values of R_z decrease. The best results were obtained at a feed rate of V_f = 2 m/min and a spindle speed of n = 18,000 min^{-1}, with a roughness parameter value of R_z = 18.658 µm. The least favorable results occur at low spindle speeds of n = 12,000 min^{-1} and high feed rates of V_f = 5 m/min. In their studies, Kminiak *et al.* (2017); Davim *et al.*, (2009); Deus *et al.*, (2015); Vitchev & Gochev, (2018); Sedlecký *et al.*, (2018) concluded that the lowest values of R_z are observed at high spindle speeds and low feed rates.

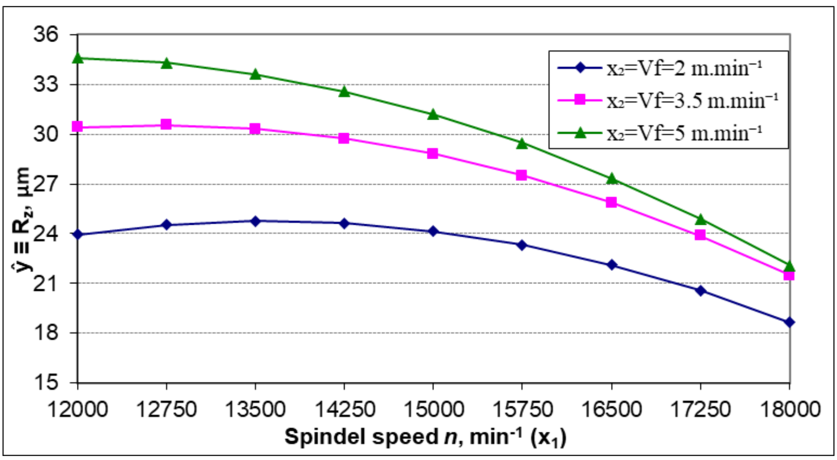

Figure 4: Variation of the surface roughness parameter R_z depending on the spindle speed (n) and feed rate (V_f)

The relationship between the spindle speed of the cutting tool and the depth of cut is graphically presented in Fig. 5. From the roughness curves, it can be seen that as the spindle speed increases, for each value of the depth of cut, the quality of the machined surfaces improves. The lowest values of the roughness parameter were observed at high spindle speeds of n = 18,000 min^{-1} and a depth of cut of h = 2 mm (R_z = 21.51 µm). In this case, the highest values of R_z were recorded at a spindle speed of n = 12,000 min^{-1}, ranging from 30.41 µm to 36.62 µm.

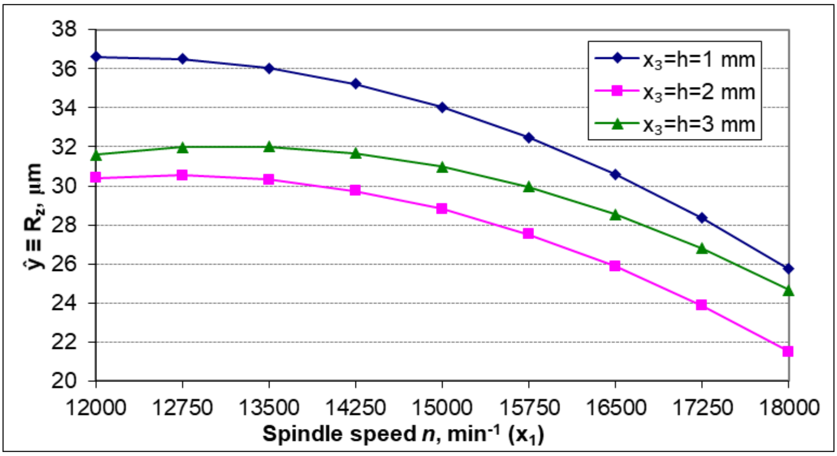

Figure 5: Variation of the surface roughness parameter R_z depending on the spindle speed (*n*) at different depths of cut (*h*)

Figure 6 presents the correlation of the surface roughness parameter R_z as a function of feed rate (V_f) and depth of cut (h). The figure shows that as the feed rate increases, the quality of the milled surfaces deteriorates. The lowest R_z values are observed at a low feed rate of V_f = 2 m/min, where the roughness parameter varies within a narrow range: R_z = 24.14 µm (h = 2 mm); R_z = 27.71 µm (h = 3 mm); R_z = 27.96 µm (h = 1 mm). In their scientific publications, Kminiak *et al.*, (2020); Sedlecký, (2017); Sedlecký *et al.*, (2018) also note the strong influence of feed rate on the quality of machined surfaces.

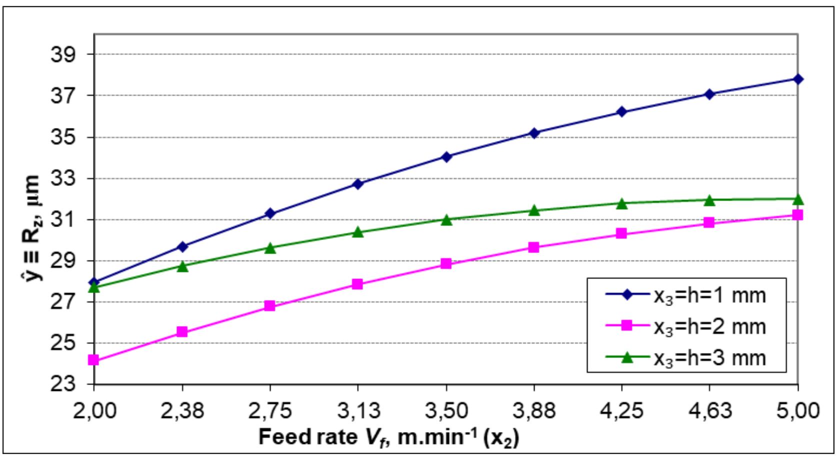

Figure 6: Variation in the surface roughness of machined oak parts depending on feed rate (V_f) at different depths of cut (*h*)

CONCLUSION

Based on the conducted experimental research and the presented results, the following key conclusions can be summarized:

The obtained results confirm the findings of other authors, who have concluded that the quality of milled surfaces is largely influenced by the feed rate (V_f) and spindle speed (n) (Deus *et al.*, 2015; İşleyen, 2019; Kminiak *et al.*, 2020; Sedlecký, 2017; Sedlecký *et al.*, 2018; Ohuchi & Murase, 2002; Ohuchi *et al.*, 2008), and that the depth of cut does not have a significant effect on the values of the surface roughness parameter (Sütçü, 2013).

Based on the obtained results, it can be concluded that the best surface quality in milling oak wood parts is achieved at the following values of the controllable factors: spindle speed n = 18,000 min^{-1}, feed rate V_f = 2 m/min, and depth of cut h = 2 mm.

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