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EVALUATION OF CNC ROUTED SURFACE QUALITY OF BEECH (*FAGUS SYLVATICA* L.) WITH DIFFERENT MILLING ANGLES AS FUNCTION OF GRAIN ORIENTATION

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Abstract: *The paper presents an experimental investigation of the quality of CNC routed surfaces with a V-Grooving router bit (90°) on various milling angles as a function of wood grain direction on beech (Fagus sylvatica L.) wood. The quality of the machined surface was first visually assessed for the presence of raised fibre and other processing defects on the routed circles with a diameter of 180 mm using feed speeds of 3 m/min and 6 m/min respectively, and spindle speeds of 12,000, 15,000, and 18,000 rpm. The quality of the processed surfaces on the circle indicated the most unfavourable CNC routing regime accompanied by the conclusions regarding the most unfavourable angles related to the grain. Further research considered the assessment of the surface quality on straight CNC routing with angles of 0, 15, 30, 45, 60, 75, and 90° related to the wood grain direction at feed speeds of 3 and 6 m/min and spindle speed of 15,000 rpm. In this case, the characterisation of the wood surface quality was made by measuring the roughness parameters. The highest values of the roughness parameters, showing the presence of the fibres detached from the surface, were recorded for the cutting angle of 60°, followed closely by 75°, then 45°, and 90° at a feed speed of 3 m/min. No significant difference was found between the Rk of the cutting angles from 0° to 45°, but it increased significantly for 60, 75, and 90°, showing frequent deeper anatomical voids on the surface.*

Key words: *CNC router, surface roughness, milling angles, beech wood.*

1. Introduction

Since ancient times, furniture craftsmen have employed various methods of embellishing furniture to give it an appealing appearance. These methods have been enriched with techniques and technologies tailored to the requirements of mass-produced furniture. Thus, profiling and carving can be done both

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manually and mechanically, through milling.

Computer Numerical Control (CNC) machining centres in the furniture industry provide an opportunity to perform milling operations for the decoration of wooden surfaces. This action is accomplished by importing a previously created vector file into graphic software, containing the detailed design of the original model. Alternatively, the process can be carried out by transforming 2D digital images into three-dimensional (3D) representations using specialised applications, such as Visual C++ software [9].

The carving operation carried out through CNC technology is based on optimising milling parameters, selecting an appropriate processing tool, and choosing a suitable processing method.

The rotation speed of 14,500 rpm and the feed rate of 2 m/min for CNC milling of birch and beech wood resulted in low values (around 1μm) of the Ra roughness parameter (the average surface roughness measured as the arithmetic mean of the absolute values of all irregularities) for a conventional cutting mode [7].

In another study [2], a feed rate of 2 m/min and a rotation speed of 18,000 rpm were found to be the optimal parameters for achieving superior surface quality in beech wood processing.

The Ra parameter measured on a Yin-Yang ornament milled on CNC on walnut, chestnut, and beech wood panels [10] indicated that the effect of the heterogeneous wood structure on surface quality is inevitable, depending on the anatomical structure, density, fibre direction, and wood cutting direction, all of them resulting in significant variations among the measurements.

Zhu et al. [11] conducted an assessment of surface roughness during the milling of beech wood, employing a combination of Response Surface Methodology (RSM) and Adaptive Network-Based Fuzzy Inference System (ANFIS). Their findings highlighted that the ideal parameters for rake angle, spindle speed, and depth of cut were determined to be 15°, 3,400 rpm, and 0.6 mm, respectively.

Rabiei and Yaghoubi [8] focused on investigating the impact of various machining parameters on both the quality and economic aspects of beech wood samples. The Group Method of Data Handling (GMDH) was employed to train a neural network and uncover the underlying relationships governing the machining process. Optimisation of the machining parameters was achieved using the Bees Algorithm (BA). In the optimised experimental test, the value of surface roughness was reduced to 4.4 μm and processing time was 93 s.

Due to the current lack of extensive information in the specialised literature regarding the behaviour of beech wood on CNC routing, the influence of the milling direction relative to the longitudinal grain of the wood is studied herein. This involves evaluating the quality of the milled surface at angles of 0, 15, 30, 45, 60, 75, and 90° relative to the grain direction, both at the macroscopic level for curved contours and by measuring the roughness parameters for straight-line machining. The aim of this study is to find the routing parameters that affect the quality of the processed surface less, in order to be used for the CNC routing various ornaments on the wood surface.

2. Materials and Methods
2.1. Contour Milling

In the case of CNC routing ornaments on a wood surface, both curved and straight lines are parts of the patterns. In both cases, the quality of the processed surface is affected by the position of the tool in relation to the inclination of the wood grains. The purpose of the next investigations is to determine the inclination angles of the wood grains where processing defects occur during CNC milling curved contours and straight lines. A round contour was selected to perform the first investigation. For this purpose, 300 × 200 × 18 mm beech wood panels with an average moisture content of 7.8% were used as the base support for CNC milling of a circle with a radius of 90 mm using the tool from Figure 1, which was made from high-strength Fatigue Proof® steel with tungsten carbide-tipped cutting edges [1].

The 3-axis CNC machine, ISEL GFV model, from Eiterfeld, Germany, was used to mill the circles on the wood surface under the following conditions: engraving milling; variable spindle speeds of 12,000, 15,000, and 18,000 rpm; two feed rates, namely 3 and 6 m/min; cutting depth of 3 mm.

Engraving is a processing method with a constant cutting depth (2 or 3 mm) for contours and can be applied to both closed and open design contours.

Before the milling of the circles onto the wooden surface, the panels underwent calibration using a 60-grit size abrasive to guarantee the surface flatness within a tolerance range of ± 0.15 mm.

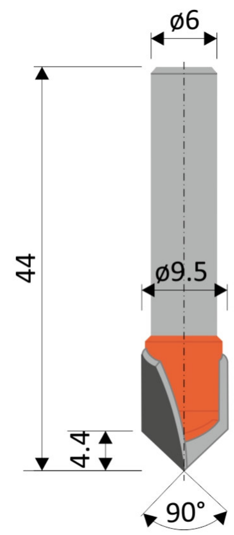


Fig. 1. *The CMT Orange V-groove router bit with a 90° angle used in milling on solid wood panels*

The study involved the visual examination of the quality of the routed surface based on the tool's position relative to the wood grain direction, calculated as an angular value related to the central angle of the circle (Figure 2). Thus, for a central angle (α), the machining angle in relation to the wood grain direction is (90° - α) for angles above the horizontal axis, to the right of the vertical axis (quadrant Q_1) (Figure 2a), (α - 270°) for angles above the horizontal axis, to the left of the vertical axis (quadrant Q_2) (Figure 2b), (270° - α) for angles below the horizontal axis, to the left of the vertical axis (quadrant Q_3) (Figure 2c), and (α - 90°) for angles below the horizontal axis, to the right of the vertical axis (quadrant Q_4) (Figure 2d) [5].

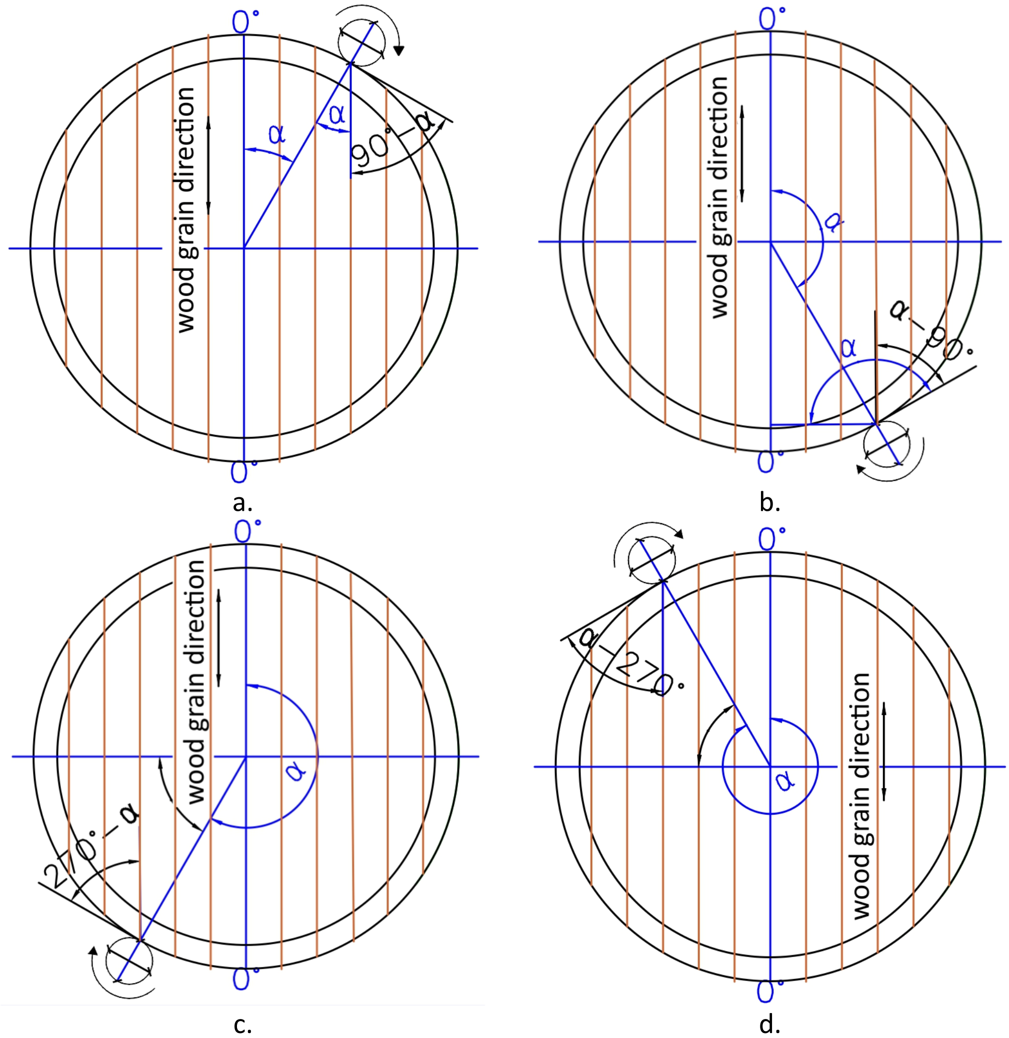


Fig. 2. *Calculation of milling angle relative to grain direction, based on the central angle of the circle, α: a - for quadrant 1 (Q_1); b - for quadrant 2 (Q_2); c - for quadrant 3 (Q_3); d - for quadrant 4 (Q_4)*

The purpose of the study was to visualise defects such as torn fibres and rough surfaces on the 180 mm diameter circles milled on the CNC machine during the machining process. These qualitatively defective areas are marked on the circle based on the angle at the centre of the circle, and the respective arc segments of the circle are indicated by the starting and ending angles of the regions where machining defects are visible. Blue was used for the negative angles and red for the positive angles (Figure 3).

Figure 3 presents an example where the circular pattern was machined by CNC with a speed of 15,000 rpm and a feed rate of 3 m/min in a clockwise direction. Machining defects are visible starting at an angle of 98° and end at 148° in interval 1 (red) and between 278° and 342° in interval 2 (blue). The vertical axis of the circle corresponds to the direction of the wood fibres.

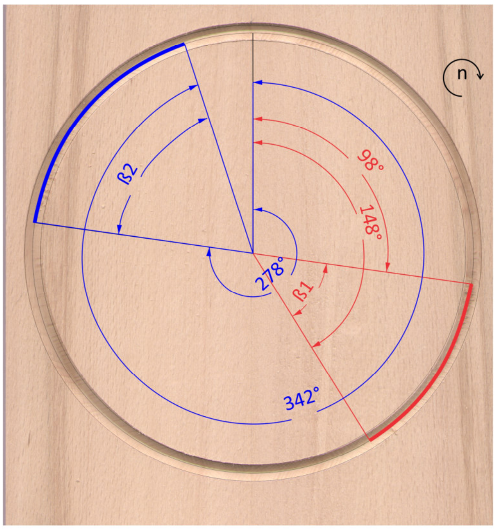


Fig. 3. *Scanned image of one beech panel and the circle machined by CNC on the wood surface with highlighting of the visible areas where machining defects occur*

The size of the qualitatively affected area by the tool position is equal to the length of the arc (*L*), in mm, calculated by multiplying the radius of the circle (*r*), in mm, by the angle at the centre of the circle (*ß*), in degrees, as presented in Equation (1):

$$L[mm] = \frac{\beta \cdot \pi \cdot r}{180} \qquad (1)$$

2.2. Straight-Line Milling

The same CNC machine used in the experimental research for contour milling was employed to obtain the samples needed for assessing the quality of the surfaces obtained by straight-line wood processing. Three samples were marked for each cutting angle relative to the fibre direction, and the same feed rates of 3 and 6 m/min were used in the routing process, as in the case of circular contouring. The spindle speed used in the experiment was 15,000 rpm, and the cutting depth of 3 mm.

The milling angles relative to the wood grain direction were 0, 15, 30, 45, 60, 75, and 90°. Samples with sizes of 40 x 10 x 18 mm were cut from the panels, as illustrated in Figure 4. Consequently, a total of 42 samples were available for measurement (Figure 5a). The visible defects observed on the processed surface are detailed in Figures 5c and 5d.

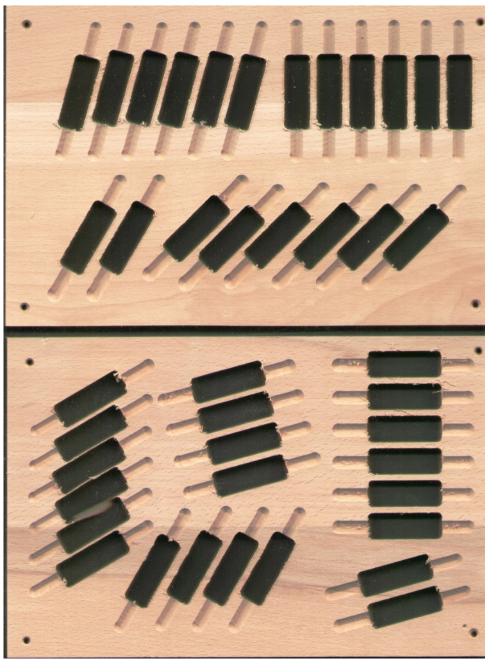


Fig. 4. *The panels from which the samples for roughness measurement were cut*

The equipment used to assess the surface quality of the samples was the MarSurf XT20 profile-meter (Figure 6) manufactured by MAHR Gottingen GMBH, Göttingen, Germany.

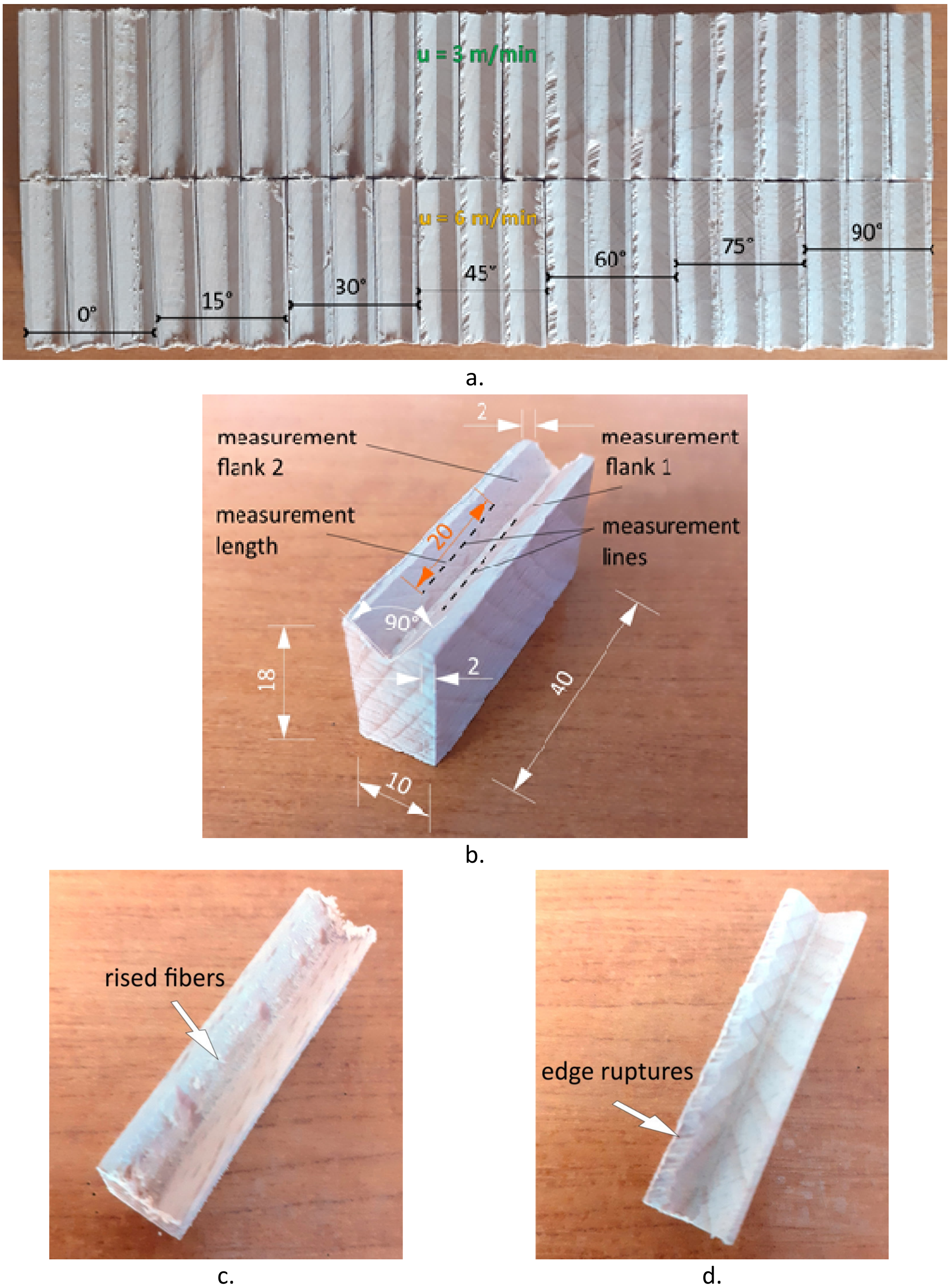
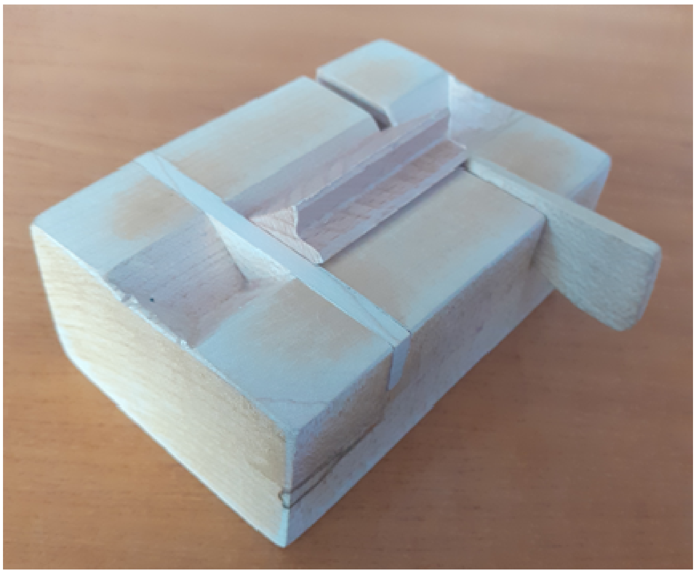


Fig. 5. *Samples for roughness measurement*

a.



b.

Fig. 6. *MarSurf XT20 profilometer used to measure the roughness (a.) and the holder used to position the measured surface perpendicular to the stylus direction (b.)*

The equipment features an MFW 250 scanning head, a tracking range of ±750 µm, and a BFW A10-135-2/90 0016 probe for direct contact measurement with the wood surface. Because the measured flanks of the processing samples are inclined at 45° degrees as related to the face of the part, due to the V-Grooving router bit (90°) used in the experiment, as can be observed in Figure 6a, a special designed device for fixing the sample during the roughness measurement process was necessary (Figure 6b). The samples were measured along the milling direction at the speed of 0.5 mm/s, with a scanning force of 0.7 mN, and lateral resolution (distance between two consecutive measured points) of 5 µm. Both sides of the traced model were measured, with a profile length of 20 mm, as depicted in Figure 5b, resulting in a total of six measurements for each milling combination, for a total of 84 profiles.

3. Statistical Analysis

The mean and standard deviation values were calculated for all the roughness parameters and waviness profile (W_a). The core roughness profile (R_k) was analysed with the statistical t-test for hypothesis testing to determine whether the feed speed had an effect on the R_k parameter, by taking the data from all cutting angles together. The parametric test One-Factor ANOVA was done to determine whether there is statistical evidence to show that the influence of the cutting angle is significant. Finally, in order to analyse the effect of the cutting angles, a Tukey's HSD (Honestly Significant Difference) multiple comparison test was done.

3. Results
3.1. Contour Milling

The model shown in Figure 3 was applied for the visual assessment of the routed surface, applying the three rotation speeds and the two feed rates, at a constant cutting depth of 3 mm. The data from this experimental phase are presented in Table 1.

Experimental data for CNC routing the circled contour Table 1

Spindle speed, n [rpm]	Feed speed [m/min]	The angle α within interval 1, red [°]		The angle α within interval 2, blue [°]		The centre angle, *ß* [°]		*L* [mm]
		Start	End	Start	End	1	2	
12,000	3	83	151	282	359	68	77	228
12,000	6	88	116	279	356	28	77	165
15,000	3	98	148	278	342	50	64	179
15,000	6	82	163	276	357	81	81	**254**
18,000	3	112	175	281	339	63	58	190
18,000	6	107	186	278	354	79	76	**243**

3.2. Straight-Line Milling

The evaluation of the CNC-milled surface quality employed the following roughness parameters: R_a (arithmetic mean deviation of the roughness profile), R_v (maximum depth of the roughness profile), R_{sk} (skewness of the profile, representing its asymmetry about the mean line), W_a (arithmetic mean deviation of the waviness profile) according to standard ISO 4287 [4], as well as R_k (core roughness profile), R_{pk} (reduced peak height of the roughness profile), and R_{vk} (reduced valley depth of the roughness profile) in accordance with standard ISO 13565-2 [3].

An analysis of the R_k parameter by comparing the effect of the cutting angle related to the grain was done by taking the data from both feed speeds together (3 and 6 m/min). In this way, there were seven groups to compare, each containing the results of 12 measurements (3 samples x 2 profiles/sample x 2 feed speeds=12). The mean and standard deviation values are contained in Table 2.

Analysis of the R_k parameter was done with a t-test to observe the effect of the feed speed on the R_k parameter, by taking the data from all cutting angles together. In this way, there were two groups to compare, each containing the results of 42 measurements (7 cutting angles x 3 samples x 2 profiles/sample =42). The mean and standard deviation values are contained in Table 3.

Table 2

Descriptive statistics of R_k, as function of the cutting angle as related to the grain

Angle relative to the grain	Mean	Standard Deviation	N
0	15.1117	6.95750	12
15	13.3867	4.15011	12
30	13.7300	2.89994	12
45	17.0275	4.05532	12
60	24.2892	4.79542	12
75	28.3658	6.20955	12
90	30.3600	3.75107	12
Total	20.3244	8.18190	84

Descriptive statistics of R_k, as function of the feed speed Table 3

	Feed_speed	N	Mean	Std. Deviation	Std. Error Mean
Rk	3	42	22.0721	8.61342	1.32908
	6	42	18.5767	7.42095	1.14508

4. Discussion

4.1. Contour Milling

According to the results in Table 1, the most advantageous CNC processing parameters for achieving a better quality surface are a spindle speed of 12,000 rpm and a feed rate of 6 m/min, for the length of the arc L_{min} =165 mm.

The results in Table 1 highlight that for the beech panels, the longest arc affected by machining the surface belongs to the model processed with a tool rotation speed of 15,000 rpm and a feed rate of 6 m/min. This value is followed by the result of the model processed with 18,000 rpm and 6 m/min.

The graphical representation in Figure 7 depicts the distribution of areas where rough and raised fibres are observed, correlated with the boundaries and average values of the angles at the centre of the circular model.

Analysing the degree of dispersion of these data, a preliminary observation is that the areas with visible machining defects are small, but the average values of the central angles are spread across wide intervals, ranging from 100 to 150° and 310 to 325° for all applied CNC milling parameters. The machining angles relative to the wood grain direction where the machining defects occurred fall within the range of 10 to 60° (angles for processing in interval 1) and 40 to 55° (angles for processing in interval 2).

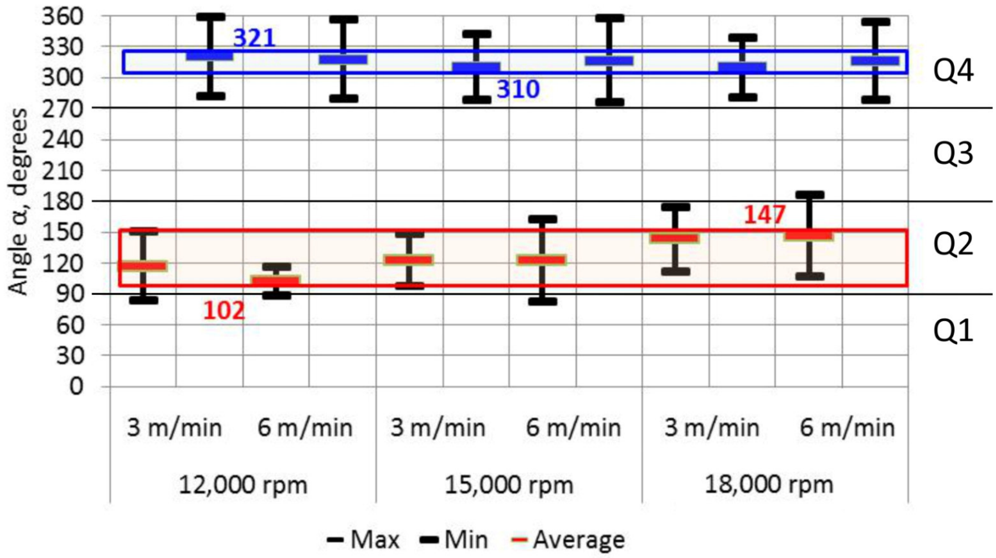


Fig. 7. *Graphic representation of the limits and mean values of the central angles for which defective surfaces affected by machining have been observed*

4.2. Straight-Line Milling

4.2.1. Analysis of the R_k Parameter Comparing the Effect of the Cutting Angle Relative to the Grain

From Table 4 it can be assumed that the smoothest processing roughness was produced in the case of the angles 15 and 30° and the worst for 90°. However, a more in-depth analysis was done in order to see if the differences between the mean values of R_k were significant or not. Therefore, an ANOVA test (one way) was done which showed that the influence of the cutting angle is significant (Table 4).

Further, a Tukey multiple comparison test was done in order to understand the effect of the cutting angle in more detail (Table 5).

Tests of Between-Subjects Effects- the cutting angle. Dependent Variable: R_k Table 4

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3729.092[a]	6	621.515	26.191	.000
Intercept	34698.840	1	34698.840	1462.231	.000
Angle	3729.092	6	621.515	26.191	.000
Error	1827.216	77	23.730		
Total	40255.148	84			
Corrected Total	5556.308	83			
a. R Squared = .671 (Adjusted R Squared = .646)					

Multiple comparisons of the effect of the cutting angle, by using the Tukey HSD test for the R_k parameter

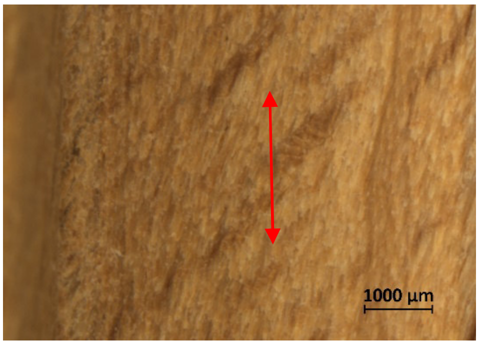
Table 5

(I) Angle relative to grain	(J) Angle relative to grain	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
0	15	1.7250	1.98872	.976	-4.2962	7.7462
	30	1.3817	1.98872	.993	-4.6395	7.4028
	45	-1.9158	1.98872	.960	-7.9370	4.1053
	60	-9.1775*	1.98872	.000	-15.1987	-3.1563
	75	-13.2542*	1.98872	.000	-19.2753	-7.2330
	90	-15.2483*	1.98872	.000	-21.2695	-9.2272
15	0	-1.7250	1.98872	.976	-7.7462	4.2962
	30	-.3433	1.98872	1.000	-6.3645	5.6778
	45	-3.6408	1.98872	.532	-9.6620	2.3803
	60	-10.9025*	1.98872	.000	-16.9237	-4.8813
	75	-14.9792*	1.98872	.000	-21.0003	-8.9580
	90	-16.9733*	1.98872	.000	-22.9945	-10.9522
30	0	-1.3817	1.98872	.993	-7.4028	4.6395
	15	.3433	1.98872	1.000	-5.6778	6.3645
	45	-3.2975	1.98872	.645	-9.3187	2.7237
	60	-10.5592*	1.98872	.000	-16.5803	-4.5380
	75	-14.6358*	1.98872	.000	-20.6570	-8.6147
	90	-16.6300*	1.98872	.000	-22.6512	-10.6088
45	0	1.9158	1.98872	.960	-4.1053	7.9370
	15	3.6408	1.98872	.532	-2.3803	9.6620
	30	3.2975	1.98872	.645	-2.7237	9.3187
	60	-7.2617*	1.98872	.008	-13.2828	-1.2405
	75	-11.3383*	1.98872	.000	-17.3595	-5.3172
	90	-13.3325*	1.98872	.000	-19.3537	-7.3113
60	0	9.1775*	1.98872	.000	3.1563	15.1987
	15	10.9025*	1.98872	.000	4.8813	16.9237
	30	10.5592*	1.98872	.000	4.5380	16.5803
	45	7.2617*	1.98872	.008	1.2405	13.2828
	75	-4.0767	1.98872	.393	-10.0978	1.9445
	90	-6.0708*	1.98872	.047	-12.0920	-.0497
75	0	13.2542*	1.98872	.000	7.2330	19.2753
	15	14.9792*	1.98872	.000	8.9580	21.0003
	30	14.6358*	1.98872	.000	8.6147	20.6570
	45	11.3383*	1.98872	.000	5.3172	17.3595
	60	4.0767	1.98872	.393	-1.9445	10.0978
	90	-1.9942	1.98872	.952	-8.0153	4.0270
90	0	15.2483*	1.98872	.000	9.2272	21.2695
	15	16.9733*	1.98872	.000	10.9522	22.9945
	30	16.6300*	1.98872	.000	10.6088	22.6512
	45	13.3325*	1.98872	.000	7.3113	19.3537
	60	6.0708*	1.98872	.047	.0497	12.0920
	75	1.9942	1.98872	.952	-4.0270	8.0153

Based on the observed means, the error term is Mean Square(Error) = 23.730.

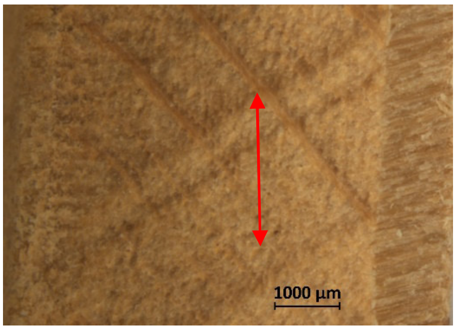
*. The mean difference is significant at the .05 level.

From Table 5, it can be concluded that there was no significant difference between the R_k of the cutting angles from 0-45°, but R_k increased significantly when the angle changed to 60, 75, and 90°. Among the latter angles, the differences were not significant. The higher cutting angles exposed deeper anatomical voids, but also increased their frequency. Furthermore, as the processing changed direction from longitudinal to transversal, zones of earlywood-latewood alternated with a higher frequency. Their different density influence R_k inversely proportional, the less dense wood of earlywood being processed rougher.

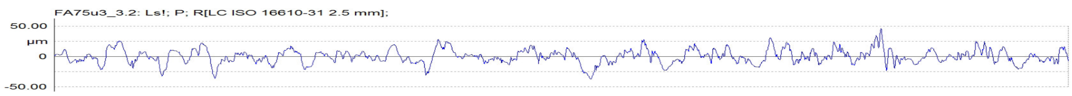


a.

b.



c.



d.

Fig. 8. *Microscopic images of the processed flank- u=3 m/min- (30x magnification) and roughness profile measured from the same surface (red arrow indicates the measuring line); a. and b. 15° cutting angle; c. and d. 75° angle*

These observations are further exemplified by comparing the surfaces processed with the 15° and the 75° cutting angle in Figure 8.

The microscopic images as well as the roughness profiles measured in those zones have shown an increase in roughness for the higher cutting angle. The variation of R_k with the cutting angle in Figure 9 confirms an increase for the high angles of 60, 75, and 90° in comparison with the previous ones.

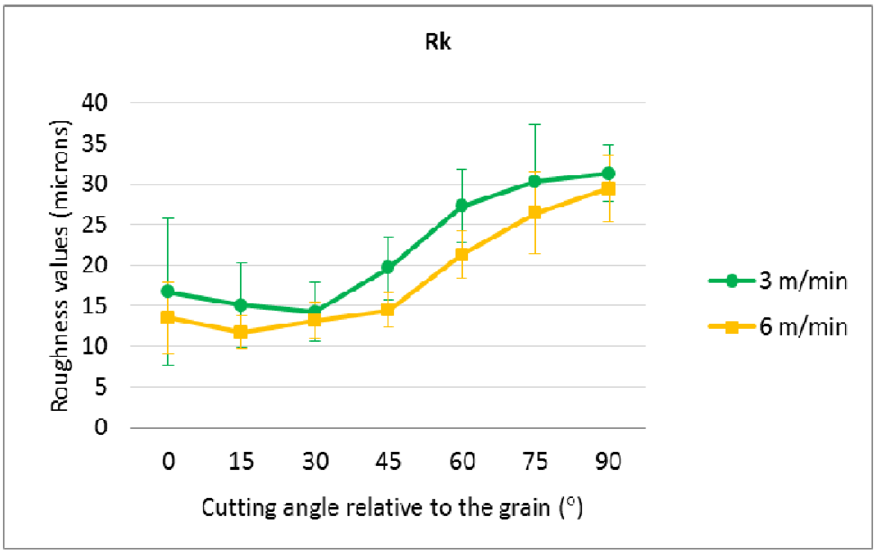


Fig. 9. *The variation of the processing roughness R_k with cutting angle and feed speed*

Similarly, in a recent study on maple wood [6], there were no significant differences between the R_k values of the samples processed with milling angles from 0 to 60°, regardless of the cutting speed. Only angles of 75 and 90° caused increased roughness of the samples.

4.2.2. Analysis of the R_k Parameter Comparing the Effect of the Feed Speed

The result of the t-test is presented in Table 6.

The t-test in Table 6 has shown that the higher mean value R_k for the feed speed 3 m/min in comparison with 6 m/min, seen also in Figure 9, was statistically significant. Apparently, the lower feed speed produced deeper tool marks on the beech wood surfaces. However, the tool marks are not the only ones affecting the wood surface. The wood anatomical structure revealed by various cutting angles has an effect regarding the raising of fibre, which consists of bundles of fibres detached at one end from the surface.

Figure 10 shows, with the exception of 0° cutting angle, a slight increase of R_{pk} with the increase in the cutting angle. However, the Tukey test indicated that R_{pk} was significantly higher for the 0° angle, in comparison with 15, 30, and 45°, but only for the 3 m/min feed speed.

The result of the t-test. Independent Samples Test Table 6

R_k	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std.Error Difference	95% Confidence Interval of the Difference Lower	Upper
Equal variances assumed	1.188	.279	1.992	82	.050	3.49548	1.75432	.00557	6.98539
Equal variances not assumed			1.992	80.244	.050	3.49548	1.75432	.00442	6.98653

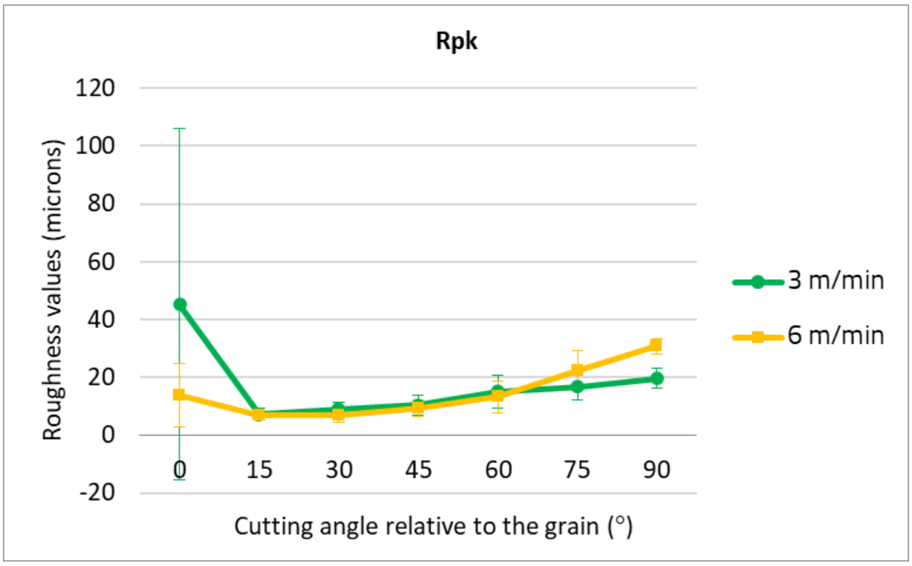
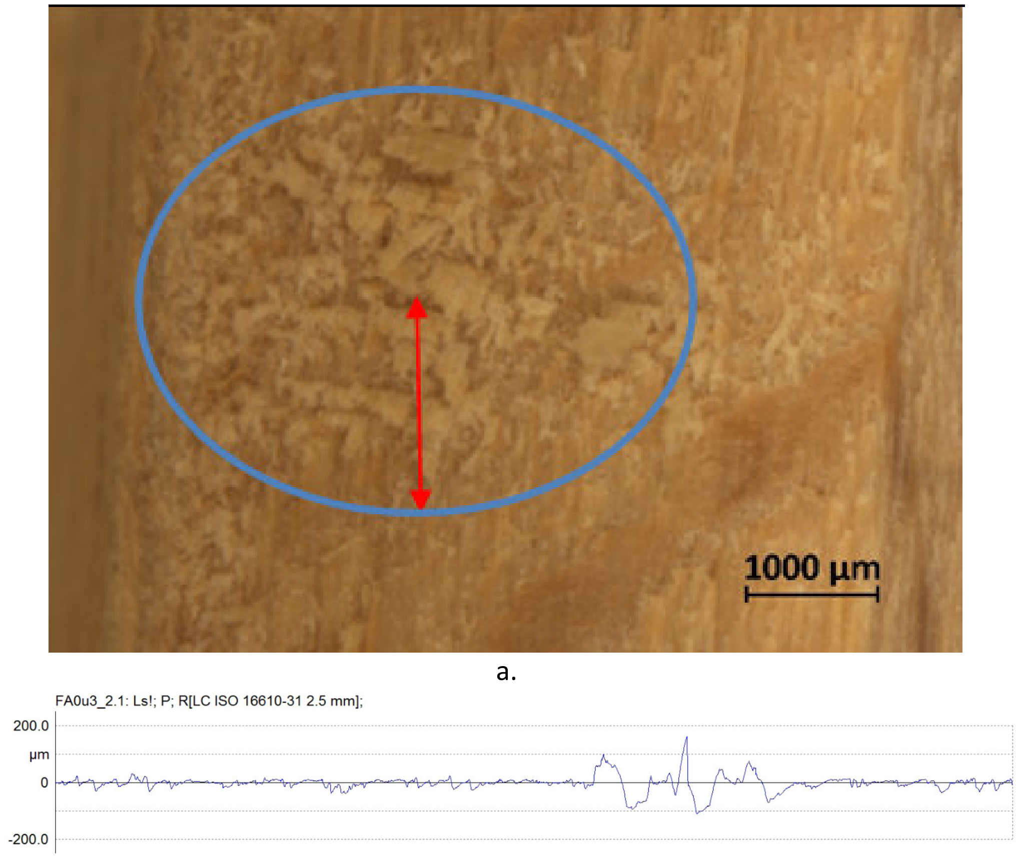


Fig. 10. *The variation R_{pk} with cutting angle and feed speed*

The microscopic investigation of the samples processed along the grain has confirmed the presence of fibres detached from the surface in the case of 3 m/min feed speed (Figure 11).

Another aspect to be noted is the integrity of the edges of the samples. The sample edges seem to have deteriorated when the samples were cut out from the original panels after milling. Similarly to a previous study on maple and oak [6], certain grain orientations are more likely to cause ruptures. As in the above mentioned study, the worst case was the cutting angle of 60° followed closely by 75°, then 45°, and 90° and it was more accentuated for the 3 m/min feed speed. In comparison with the flanks investigated in this paper, which were cut under an angle of 45° with relation to the panel surface, the edges were obtained from a tool cutting perpendicular to the panel surface.



a.

b.

Fig. 11. *Microscopic images of the processed flank-a- (30x magnification) and roughness profile measured from the same surface-b- (red arrow indicates the measuring line) processed at 0° angle. Raised fibres area (blue ellipse)*

4.2.3. Roughness Parameters R_a, R_k, R_v, R_{vk}, R_{pk}, R_{sk}, and Waviness Parameter W_a

In Figure 12 it can be observed that the differences between the Ra values for the two feed rates are small. The feed rate of 6 m/min appears to be more favourable in terms of surface quality, but higher Ra values were recorded for both feed rates at angles of 60, 75, and 90°, as well as for milling along the grain.

The variations in R_{sk} values (Figure 13) are more significant at a feed rate of 3 m/min, with negative values for angles of 15, 60, and 75°, indicating the presence of anatomical valleys.

A feed rate of 3 m/min resulted in nearly constant values for the R_v parameter, with slight increases at 0 and 90° (Figure 14). However, at a feed rate of 6 m/min, the maximum depths of the roughness profile were observed at angles of 60 and 75°.

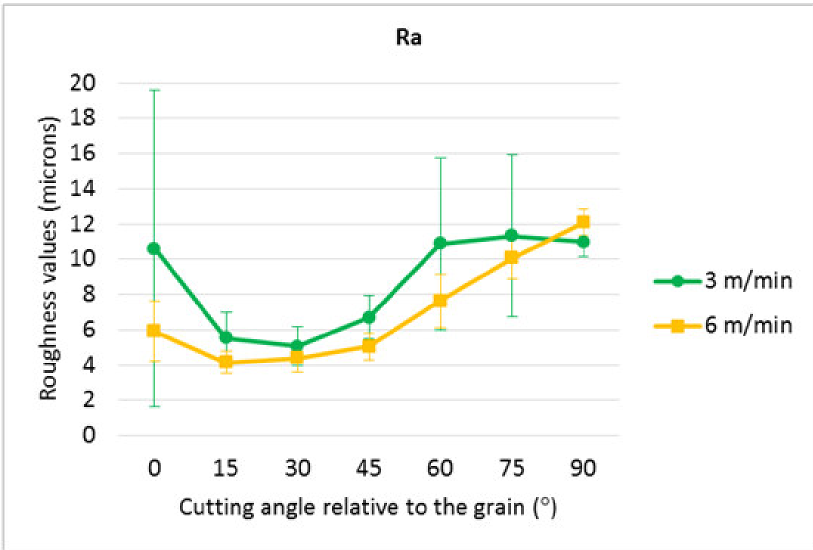


Fig. 12. *The mean values of the R_a parameter, CNC routed with two feed speeds and seven cutting angles relative to the grain orientation evaluated for beech surface*

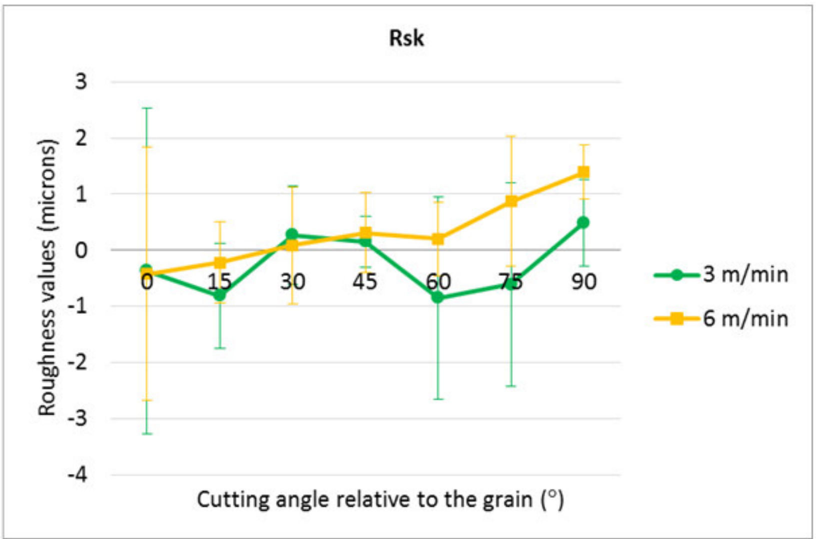


Fig. 13. *The mean values of the R_{sk} parameter, CNC routed with two feed speeds and seven cutting angles relative to the grain evaluated for beech surface*

The reduced depth of the valleys in the roughness profile (R_{vk}) followed the same trend as the R_v parameter (Figure 15). R_v, which measures the deepest valley in a profile, appears to show an increase with the cutting angle, which could be an effect of cross-cutting the anatomical elements, allowing the stylus to penetrate deeper into their cavities.

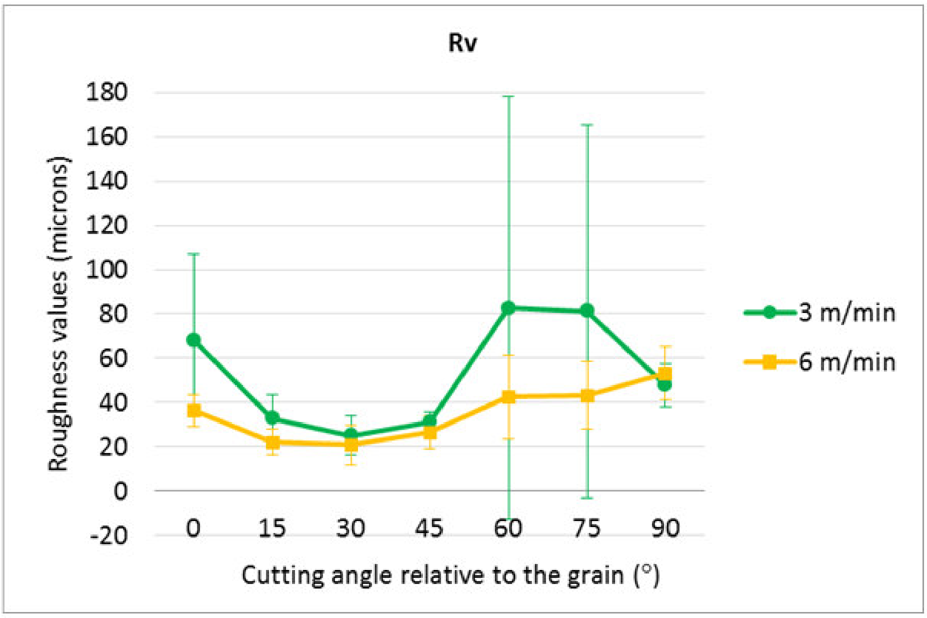


Fig. 14. *The mean values of the R_v parameter, CNC routed with two feed speeds and seven cutting angles relative to the grain evaluated for beech surface*

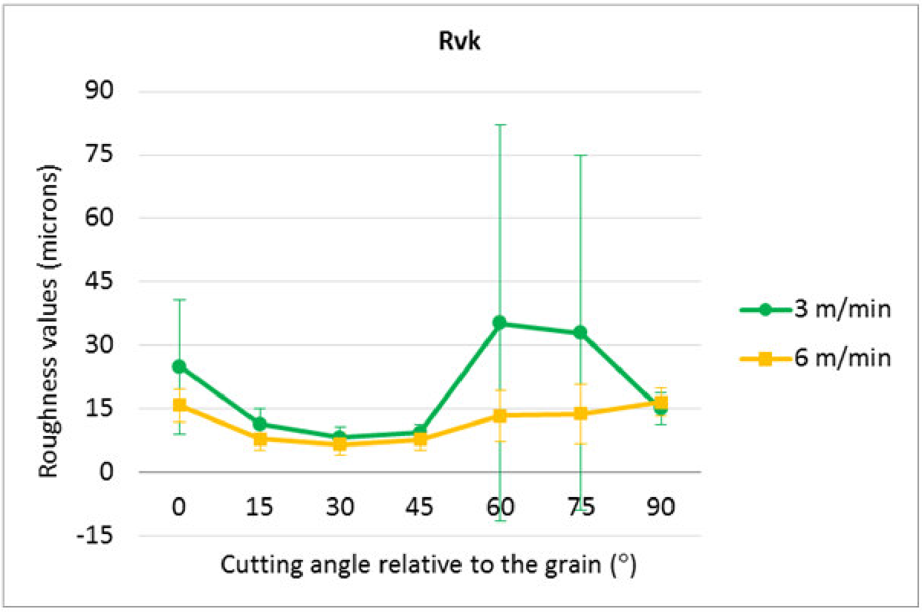


Fig. 15. *The mean values of the R_{vk} parameter, CNC routed with two feed speeds and seven cutting angles relative to the grain evaluated for beech surface*

As observed in Figure 16, it is not possible to establish a clear dependency rule for surface waviness (W_a), concerning the feed rate and the milling angle relative to the fibre direction.

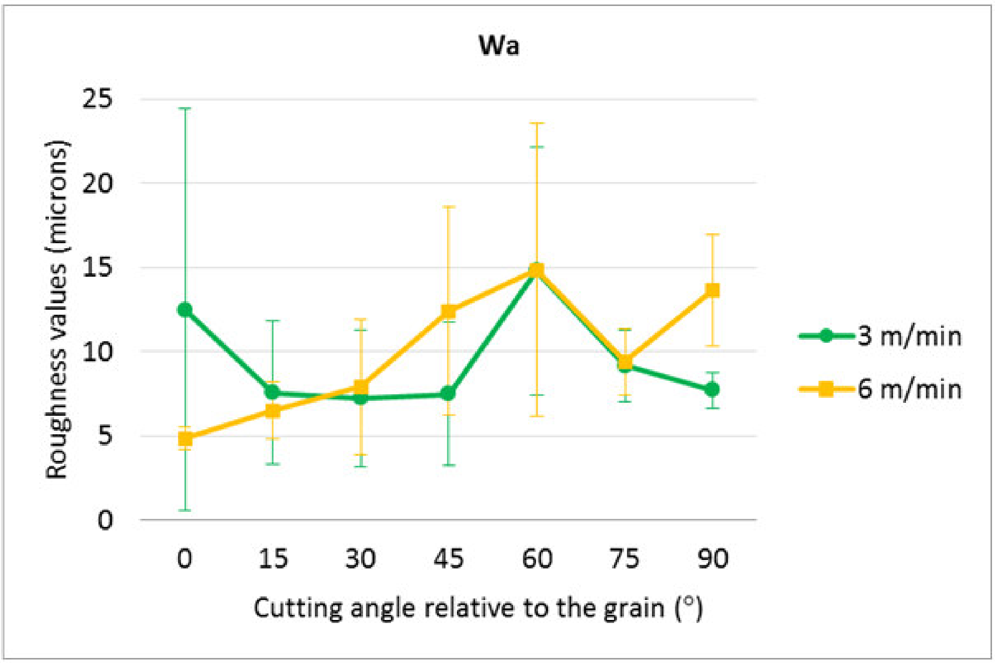


Fig. 16. *The mean values of the W_a parameter, CNC routed with two feed speeds and seven cutting angles relative to the grain evaluated for beech surface*

5. Conclusions

The results of the experimental research on the quality of the circle surfaces processed on CNC machines highlight that the favourable milling parameters for beech wood in this regard are as follows: the ideal spindle speed is 12,000 rpm and the recommended feed rate is 6 m/min. The machining defects occurred at an inclination angle of the fibres within the range of 10 to 60° when milling in the fibre direction, and 40 to 55° when milling against the fibre direction.

In the case of straight line milling, the measurement of the surface roughness parameters R_a, R_k, R_v, R_{vk}, R_{pk}, R_{sk}, and the waviness parameter W_a on the samples milled at different angles within the range of 0-90° (with a 15° increment) relative to the fibre direction indicated that beech wood exhibited increasing roughness variations at angles of 45, 60, 75, and 90°, as well as when milling in the fibre direction. The worst case was the cutting angle of 60° followed closely by 75°, then 45° and 90°, and was more accentuated for the 3 m/min feed speed.

The microscopic investigation of the samples processed along the grain confirmed the presence of fibres detached from the surface in the case of 3 m/min feed speed. The Tukey test indicated that R_{pk} was significantly higher for the angle

0°, in comparison with 15, 30, and 45°, but only for the 3 m/min feed speed. It was found that there was no significant difference between the R_k of the cutting angles from 0-45°, but it increased significantly for the higher angles of 60, 75, and 90°. The differences were not significant between the 60, 75, and 90° angles, but they exposed deeper anatomical voids with higher frequency than the other ones.

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