Evaluation of CNC Routed Surface Quality of Maple (*Acer pseudoplatanus*) and Oak (*Quercus robur* L.) with Different Milling Angles as Function of Grain Orientation

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The study assessed CNC routing quality on maple and oak samples, using 90º V-Grooving router bits at various milling angles as function of grain orientation: 0°, 15°, 30°, 45°, 60°, 75°, 90°, and feed speeds of 3 and 6 m/min at spindle speed of 15,000 rpm. The routing quality was evaluated by roughness parameters for the V flank surfaces and by visual examination for the flanks' edges. The change in the feed speed had no significant effect for the flanks surface quality of both species, but roughness values were considerable higher for maple samples at 90º and u=3 m/min (R_k = 23.7 µm compared to along the grain, R_k=9.83 µm for u=6 m/min) due to possible processing vibrations. The milling angle as function of grain orientation was significant in the case of oak, as the processing roughness increased with the cutting angle from 0° (R_k=11 to 13 µm) to 60°(R_k =28 to 30 µm). Fuzziness around the earlywood pores of oak was higher for the 6 m/min feed speed. A substantial increase in waviness coinciding with the annual growth areas was measured for crosscut oak samples (W_a = 34.0 µm, compared with W_a =7 .39 µm along the grain). The surface waviness of maple was not sensitive to the variation in the cutting angle or feed speed (W_a was around 3 to 4 µm). For the flank edges, the best visual option was found for cutting along the wood grain and the worst was for 60º, which caused biggest ruptures and especially for the 3 m/min feed speed, for both species.

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INTRODUCTION

Computerized numerical control (CNC) routing is a widely used method for the manufacture of wood-based furniture ornaments (Lungu *et al*. 2021a). This technique can be employed to revive traditional motifs from cultural heritage (Lungu *et al*. 2021b) and wood-carved ornaments embedded in the historical objects (Namicev and Namiceva 2018). In order to follow the shape of complex ornaments, the processing tools can encounter a large range of angles related to the wood grain direction, which makes it important to understand the outcome of tool-wood interaction and implications on surface quality when processing at different angles. Establishing a good correlation among the processing parameters for the selected species is important for the surface quality of CNC milled members (Thoma *et al.* 2015; Hazir and Koc 2016; Kazlauskas *et al.* 2017; Hazir and Koc 2019). Therefore, the overall assessment of the surface quality is not only very important for the finishing process but also determining the quality of the final product. The surface roughness after any processing has an impact on the surface quality of next processing. For example, a milled surface which was rough may not get smoothed by sanding unless several sanding passes are used. A very bad surface often cannot be corrected by the next processing. Therefore, it is important to find a combination of processing parameters suitable for a minimum surface roughness. In this respect, different roughness parameters represent the main indicators of the surface quality of the unit (Koc *et al.* 2017; Sedlecký *et al.* 2018; Starikov *et al.* 2020; Gürgen *et al.* 2022), and they are measured by contact and contactless roughness-measuring equipment. The arithmetic mean deviation of the roughness profile (R_a), the highest peak-to-valley height (R_z), and the root mean square deviation (R_q) are most widely used parameters for the evaluation of the processed surface quality (Sütçü 2013; Sütçü and Karagöz 2013; Sedlecký 2017). The measured R_a parameter on a CNC routed Yin-Yang ornament in walnut, chestnut, and beech wood panels (Sütçü and Karagöz 2013) showed that the effect of the heterogeneous structure of wood on the surface quality is inevitable as a function of the anatomic structure, density, grain direction and cutting section of wood; these factors result in substantial variation among measurements. For porous species such as chestnut with low density, the measurements showed high variability.

Oak (*Quercus robur* L.) that was CNC routed at different grain angles showed homogeneous behavior due to the narrow density variation within the annual rings (Goli *et al.* 2002). Analyzing the arithmetic mean deviation of the primary profile (P_a) and the total height of the primary profile (P_t), there was a rapid increase of P_a for grain angles between -30º and -80º. The surface quality of the samples was high for grain angles of -10º and -20º.

The side surfaces of the patterns processed with straight router bits by CNC on spruce, pine, and beech samples edge-glued panels indicated that up-milling occurs on one side, while down-milling takes place on the other, which can be related to having torn fibers only on one side of the samples (Sütçü 2013).

Another study (Mitchell and Lamaster 2002) on the maple specimen machining concluded that down-milling produced a significantly higher surface quality than up-milling on the flat grain surfaces.

The more detailed roughness analysis is recommended to have a better understanding of the surface quality of wood as function of their processing defects. A previous study carried out on larch (*Larix decidua* Mill.) samples cut through by CNC routing measured roughness parameters including R_a, R_p, R_v, R_{sk}, W_a, W_t, P_a, and P_t, indicating the rough surfaces, fuzziness, waviness, and material pull-out for different cutting angles of the wood grains (Gurau *et al.* 2021). Cutting angles of 15° and 60° relative to the wood grains resulted in rougher surfaces and occasionally pull-out of the material. Surface quality of European black pine (*Pinus nigra* Arnold) with a density of 730 kg/m^3, which is close to that of oak, was also evaluated by using the arithmetic mean deviation of the roughness profile (R_a), showing the optimal routing parameters, as feed rate 2 m/min, spindle speed of 18,000 rpm and depth of cut of 2.646 mm for R_a = 5.564 μm (Hazir and Koc 2016). The same optimal processing parameters were also found for beech samples (Işleyen and Karamanoglu 2019), and feed rate of 3 m/min and spindle speed of 17,900 rpm were determined for the lowest R_a value of 3.83 μm for CNC routed pine (*Pinus sylvestris*) samples (Gürgen *et al.* 2022).

Çakiroğlu *et al.* (2019) investigated CNC milling surfaces of spruce, chestnut, larch and iroko samples using R_z. The lowest R_z value of 70 μm was found when the milling parameters were set to low spindle speed and low feed rate of 10,000 rpm and 5 m/min, respectively, for species with low density and high spindle speed and relatively low feed rate of 18,000 rpm and 7 m/min for species with high density. The R_z values of the samples increased with increasing feed rate and decreased with increasing spindle speed.

Currently there is limited information on the surface quality of maple and oak processed by CNC as a function of different milling angles and grain orientation. Therefore, the objective of this study was to determine the surface topography of such species processed by CNC milling with V-Grooving router bit of 90° at a cutting depth of 3 mm using two different feed speed levels and fixed spindle speed at various grain orientations. A visual assessment of the edges of the V-flanks was carried in addition to roughness measurement employing a stylus type equipment considering various roughness parameters to have a better understanding of surface quality of such samples so that the ornaments machined on the surface of the furniture manufactured from both species can be used with a better efficiency during their service life.

EXPERIMENTAL

Materials

Maple (*Acer pseudoplatanus* L.) and oak (*Quercus robur* L.) wood panels with sizes of 300 mm × 200 mm × 18 mm, with an average density of 660 kg/m^3 and 700 kg/m^3 and the moisture content values of 7.3% and 11.2%, respectively, were cut for the experiments, after material storage in a climatic chamber at 20 °C and 65% air humidity. For each species, two panels were used, as in Fig.1. Before cutting the samples, the panels were calibrated with 60 grit to ensure their overall flatness in the range ± 0.15 mm. Then CMT Orange Tools 715.095.11, V-Grooving router bit (90°) with a diameter of 9.5 mm, (C.M.T. UTENSILI S.p.A., Pesaro, Italia) was employed for routing the panels' surface. This tool is recommended for wood engraving and bas-relief with low depth, which are methods applied for wood surface ornamentation in conditions of high spindle speeds and feed rates. The 3-axis CNC router, model ISEL GFV type (Eiterfeld, Germany) was used for milling the surface. The panels were processed on their surfaces at two feed speeds (3 and 6 m/min) and at various angles in relation to the wood fiber direction: 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The tool spindle speed was 15,000 rpm, and three replicates were produced for each combination cutting angle and feed speed. The marks left by the tool had a V shape, as can be seen in Fig. 1. In order to make the measurements possible, samples with sizes of 40 mm x 10 mm x 18 mm were cut out from the panels as illustrated in Fig. 1, where the black areas represent the voids left in the panels after subtracting the samples for study. For two feed speeds, seven cutting angles and three replicates for each combination, 42 samples resulted for surface quality measurements. The samples for measurements had the shape and dimensions as in Fig. 2b, where the processed flanks are shown.

Roughness Measurement

The surface quality of the samples was measured employing a MarSurf XT20 profilometer manufactured by MAHR Gottingen GMBH, Göttingen, Germany. The equipment has an MFW 250 scanning head, tracing arm in the range of ±750 µm, and a stylus BFW A10-135-2/90 0016, as shown Fig. 2a. The surface measurements were made on both processed flanks of the 42 specimens, one measured profile for each flank, making for three replicates a total of 6 measurements per routing feed speed and angle combination resulting in a total of 168 profiles for both species. The flanks were inclined at 45 angle each side from a normal plane. Therefore, in order to have a measurement perpendicular to the flank, a special maple holder was used (Fig. 2c), in which the specimens were fixed so that the measured flank would stay in horizontal position. After measuring one flank, each specimen was turned to have the other flank in horizontal position. The specimens were measured along the routing direction with a speed of 0.5 mm/s, scanning force of 0.7 mN, and resolution of 5 µm. The two flanks of the routed pattern were measured, with a profile length of 20 mm, as illustrated in Fig. 2b. MARWIN XR20 equipment software has been used to process the scanned profiles. According to ISO/TS 16610-31 (2010), the measured data were separated by filtering the wavelengths of irregularities in waviness profiles and roughness profiles, corresponding to W parameters for the longest wavelengths, while R parameters evaluated the shortest wavelengths. A robust Gaussian regression filter with 2.5 mm cut-off length was used. This filter and cut-off value were recommended for a wood surface (Gurau *et al*. 2006; Tan *et al.* 2012).

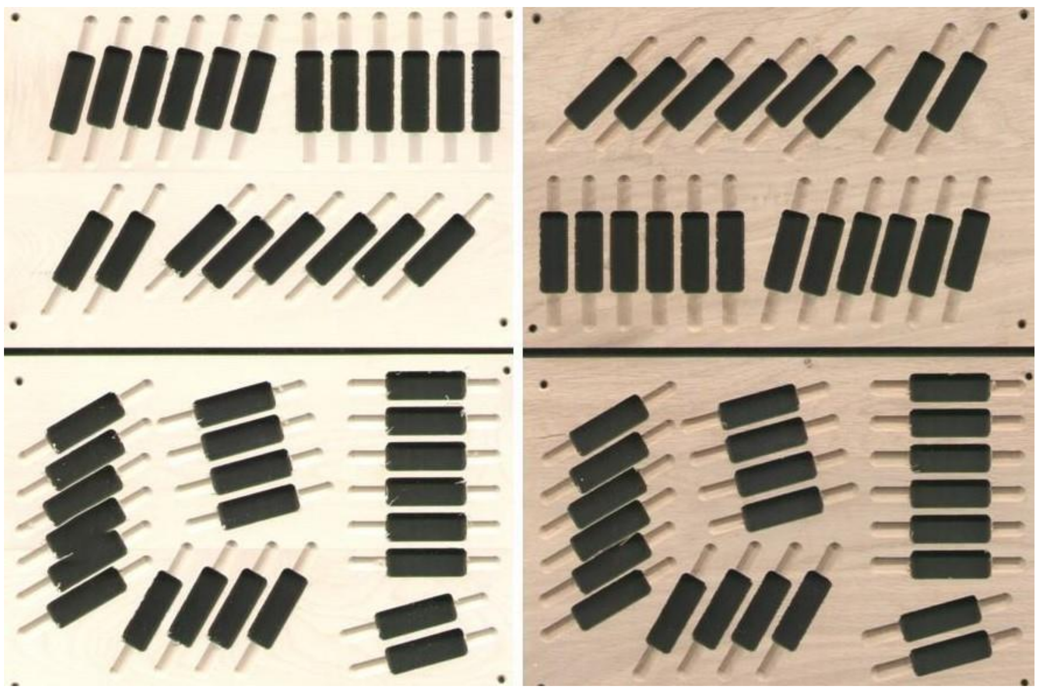

Fig. 1. Maple (a) and oak (b) panels used for measuring the roughness measurements

The following roughness parameters were used for the assessment of the routed surfaces of the samples: R_a (arithmetic mean deviation of the roughness profile), R_v (the largest absolute profile valley depth), R_{sk} (skewness of the profile), W_a (arithmetic mean deviation of the waviness profile) according to ISO 4287 (2009). In addition, R_k (the core roughness depth), R_{pk} (the reduced peak height), and R_{vk} (the reduced valley depth) were employed according to ISO 13565-2 (1998).

Compared with other parameters, R_k depends the least on the wood anatomical structure and measures the height of the core roughness, the region defined by the highest concentration of data points in a measured profile, which excludes isolated peaks and valleys. Instead, R_{pk} is defined by the isolated peaks, which for a wood species, according to Westkämper and Riegel (1993), can be considered an evaluation of wood raised grain and fuzziness of the surface. The fuzziness is caused by groups of fibers that are attached to the surface at only one end. R_{vk} is defined by isolated valleys, which in case of wood can be caused by accidental material pull-out during processing and/or deep anatomical cell lumens.

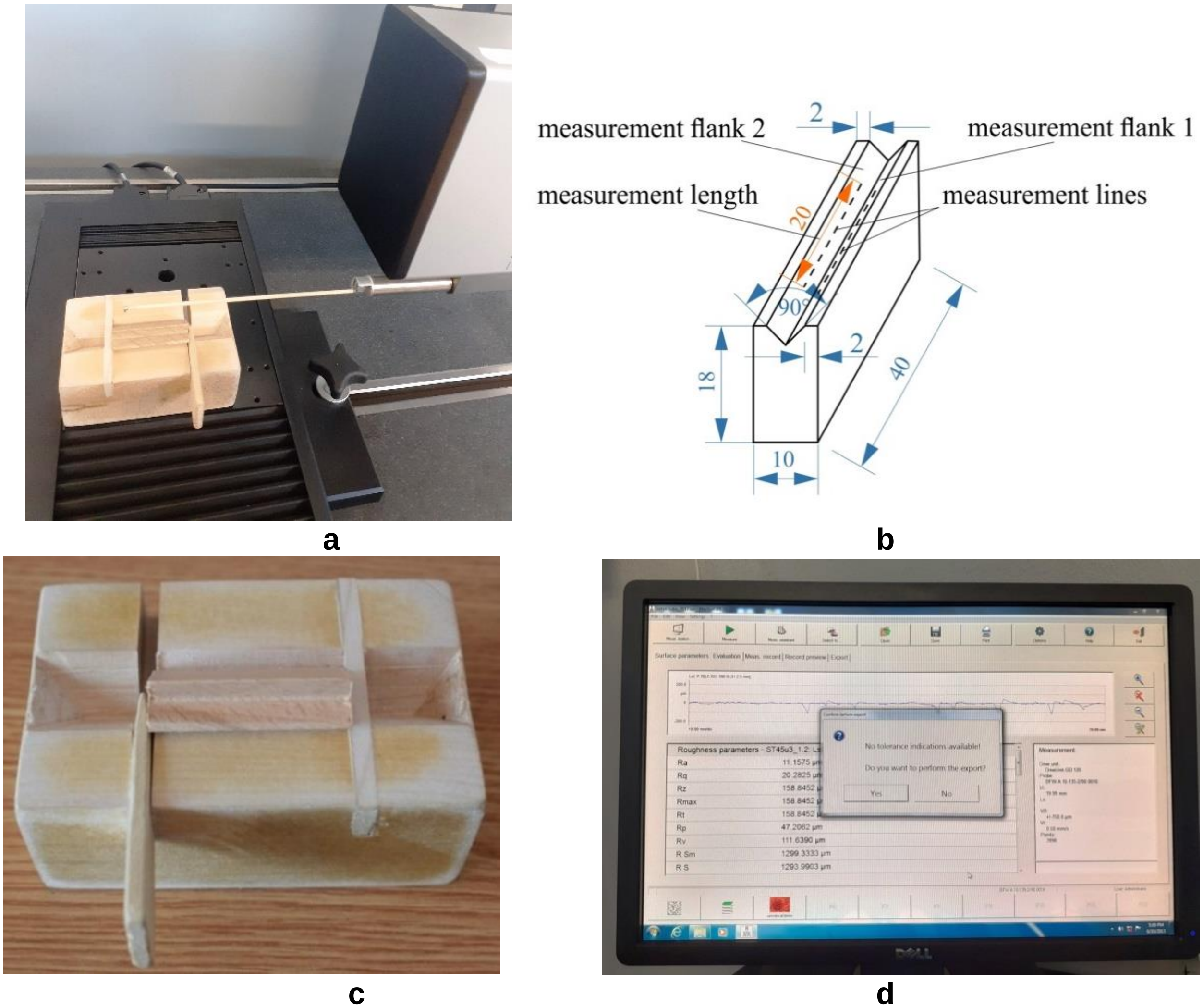

Fig. 2. MarSurf XT20 profilometer used to measure the roughness and the holder used to position the measured surface perpendicular to the stylus direction: (a) stylus scanning the sample; (b) the sample with measurements; (c) the specimen holder with the sample fixed on top; (d) screen displaying the measured parameters

As can be seen in Fig. 2c, and Fig. 3, the measured flanks of the processing samples are inclined at 45° degrees as related to the face of the part, because of the V-Grooving router bit (90°) used in the experiment, which is different than in a previous study, where maple wood was cut perpendicular to the top surface (Gurau *et al*. 2022).

The tested samples are shown in Figs. 3a and 3b for maple and oak samples, respectively. Surface defects visible with the naked eye were detailed in Fig. 3c for maple and Fig. 3d for oak.

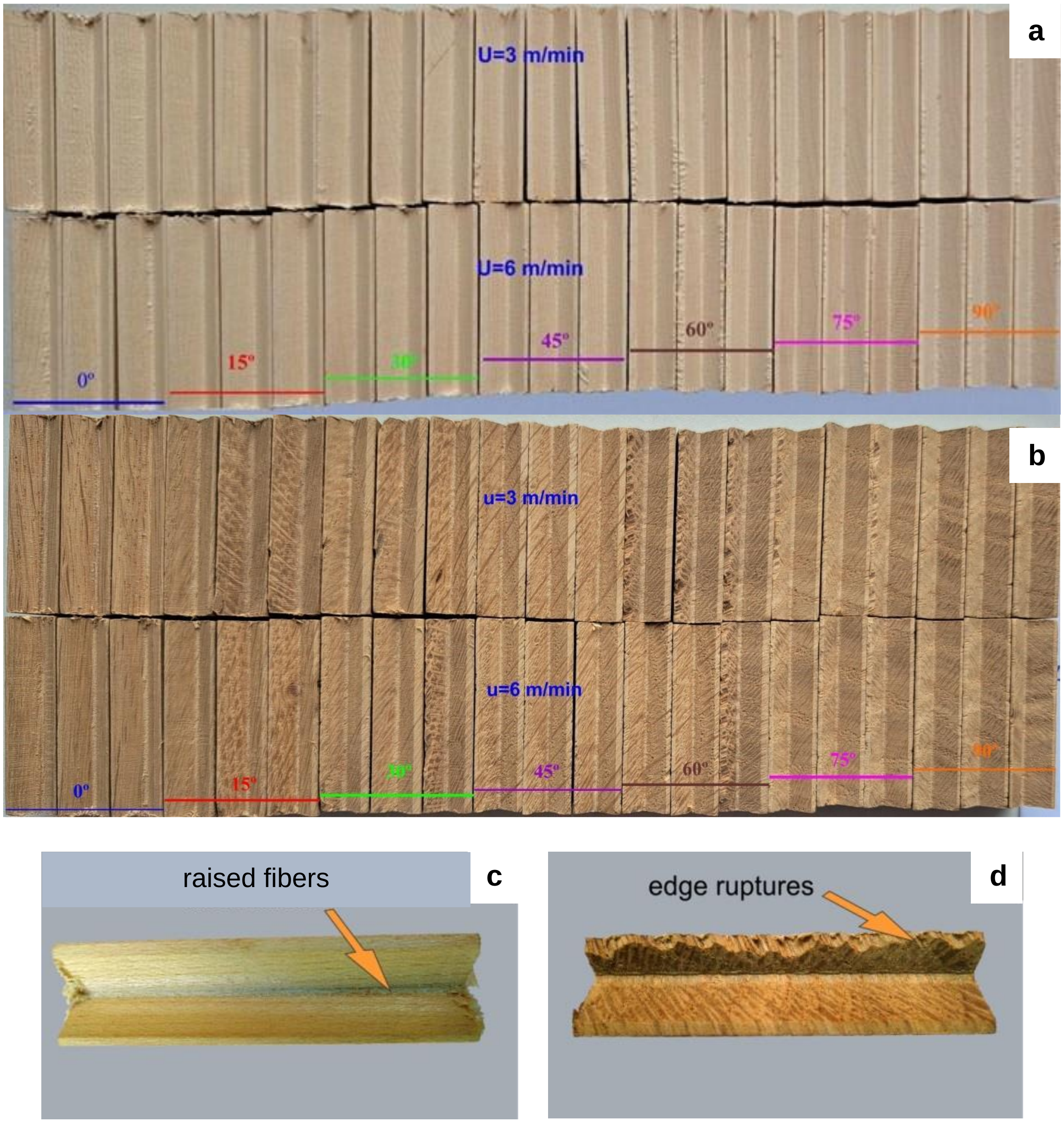

Fig. 3. Roughness measurements of maple (a, c) and oak (b, d) samples

RESULTS AND DISCUSSION

Visualization of the defects such as raised grain and fuzziness, which occur during the routing process, is important. The objective of the investigation was to measure the roughness parameters of the straight pattern lines routed by CNC on oak and maple wood surfaces with V-Grooving router bit (90°) tool on different inclination angles in relation with the wood grain direction, ranging from 0º to 90º with an increment of 15º and applying spindle speed of 15,000 rpm at the two feed rates of 3 m/min and 6 m/min.

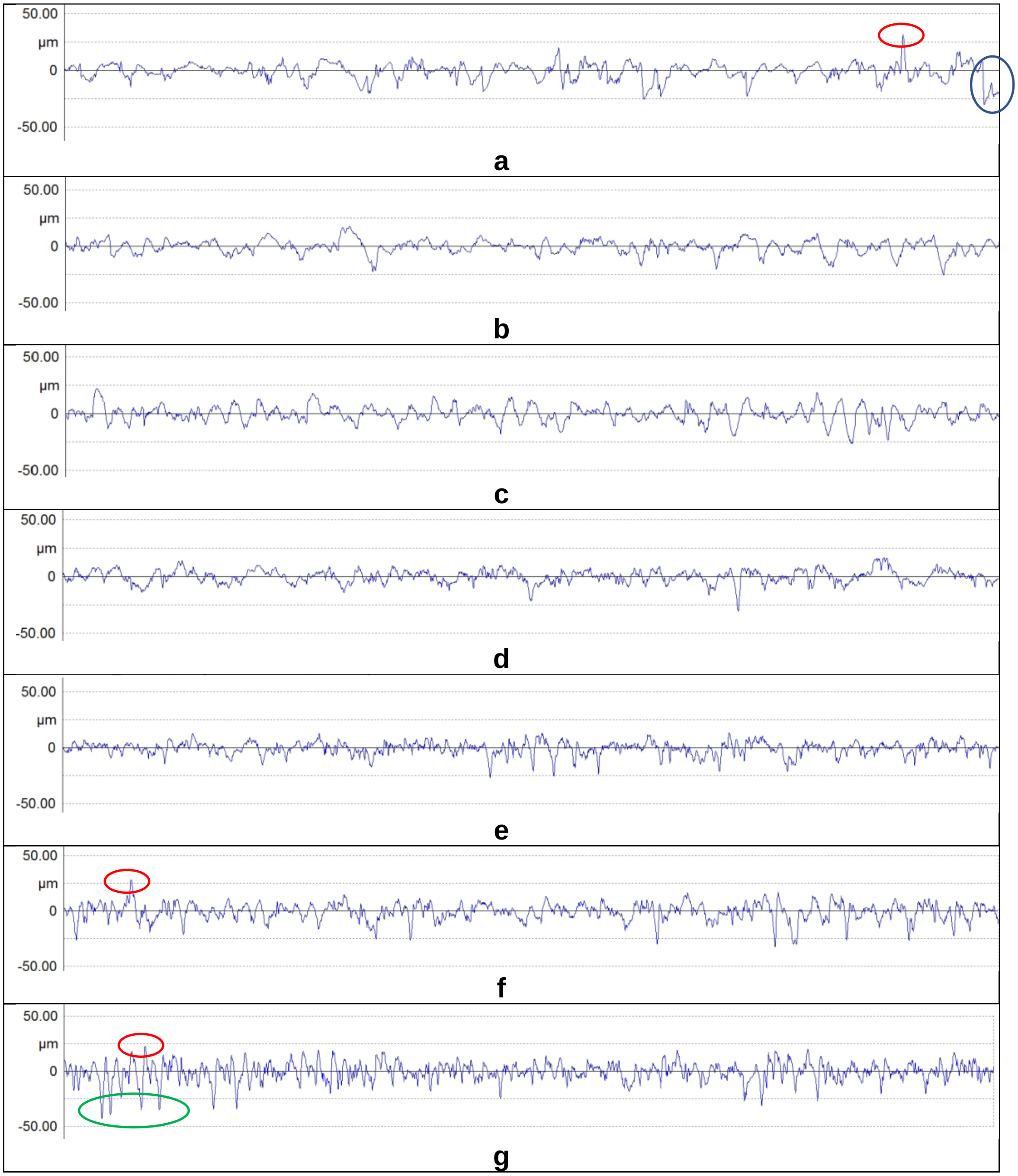

Fig. 4. Roughness profiles of maple, for u=3 m/min for various cutting angles as related to the grain: (a) 0°; (b)15°; (c) 30°; (d) 45°; (e) 60°; (f) 75°; (g) 90°. Example of raised fiber is encircled with red, wood pores are encircled with green, and blue represents longitudinally cut pore.

Roughness Measurement

Figure 4 shows examples of roughness profiles measured on the processed flanks of maple, for the feed speed *u*=3 m/min and for all seven cutting angles as function of the grain orientation.

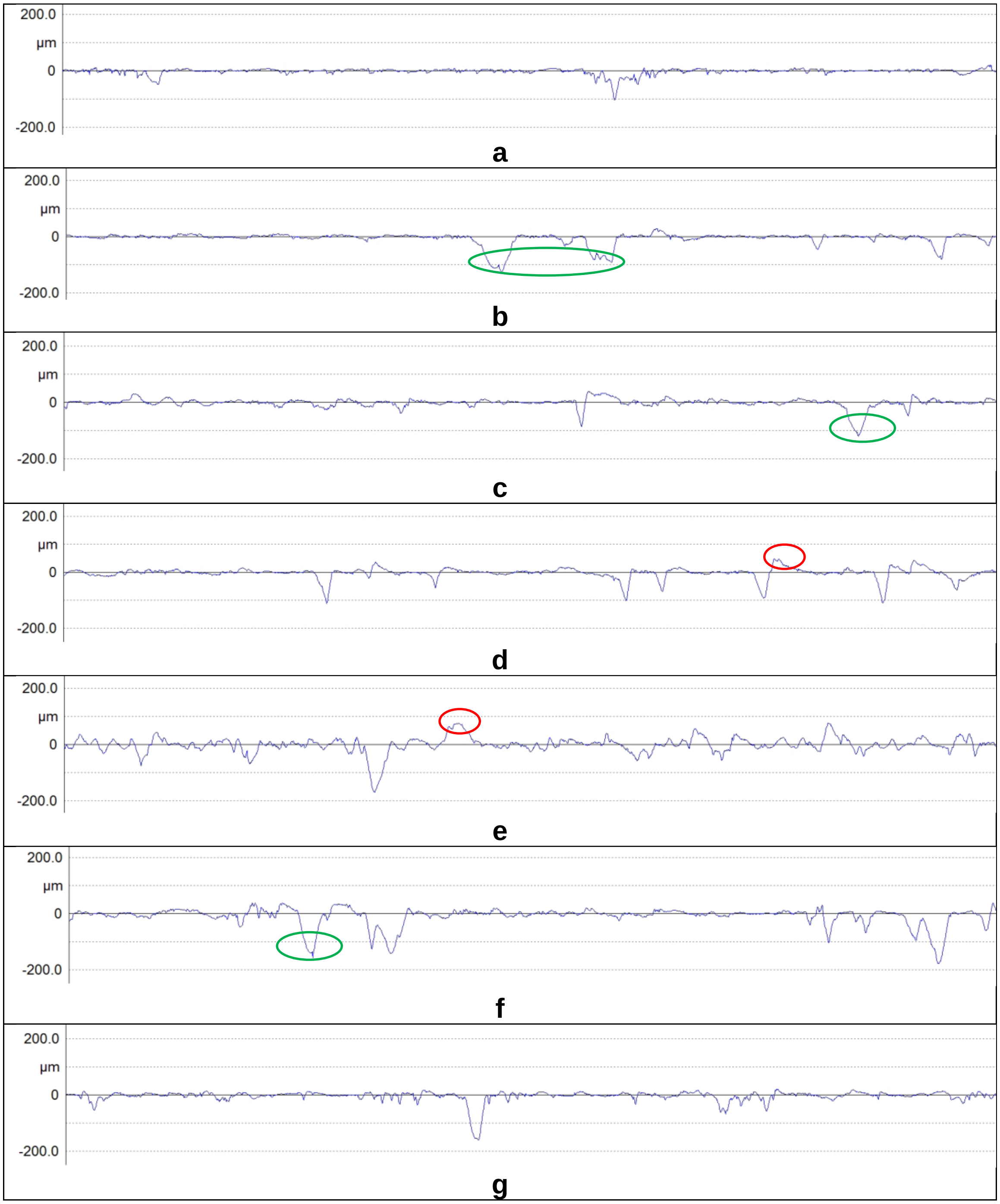

Fig. 5. Roughness profiles of oak, for u=3 m/min for various cutting angles as related to the grain: (a) 0°; (b)15°; (c) 30°; (d) 45°; (e) 60°; (f) 75°; (g) 90°. Examples of raised fiber are encircled with red and wood pores are encircled with green.

All of the roughness profiles represented a superposition of the cutting marks on the wood anatomical cavities, as illustrated in Fig. 4. Gradually changing the cutting angle from along the grain to across the grain resulted in the V-flanks having more anatomical cavities in the roughness profiles, so that the profiles became more detailed with more numerous features outlying from the zero/reference line, as can be seen in Fig. 4. The deep valleys in the 90º profiles were in the range of pores diameter for maple, ((25)30 – 50 -

70(110) µm) (Wagenführ 2000) and resembled those the 45º cut found in a previous study used for maple (Gurău *et al*. 2022). However, that study had used a cut through routing and with an Integral Helical CMS milling cutter. Therefore, the analysis of surface roughness should consider not only the cutting direction as function of the grain orientation but has to also consider the type of CNC tool, its tip geometry and the type of cutting, as well as whether the tool acts on the panel face or it cuts through it.

Roughness profiles measured for u=3 m/min and for each cutting angle with relation to the grain of oak samples are shown in Fig. 5. Deep isolated valleys visible in all profiles such as encircled with green color in Fig. 5 belong, most probably, to oak pores having a magnitude of 150-270-350 up to 500 µm in earlywood and 30-70-140 µm in latewood (Wagenführ 2000).

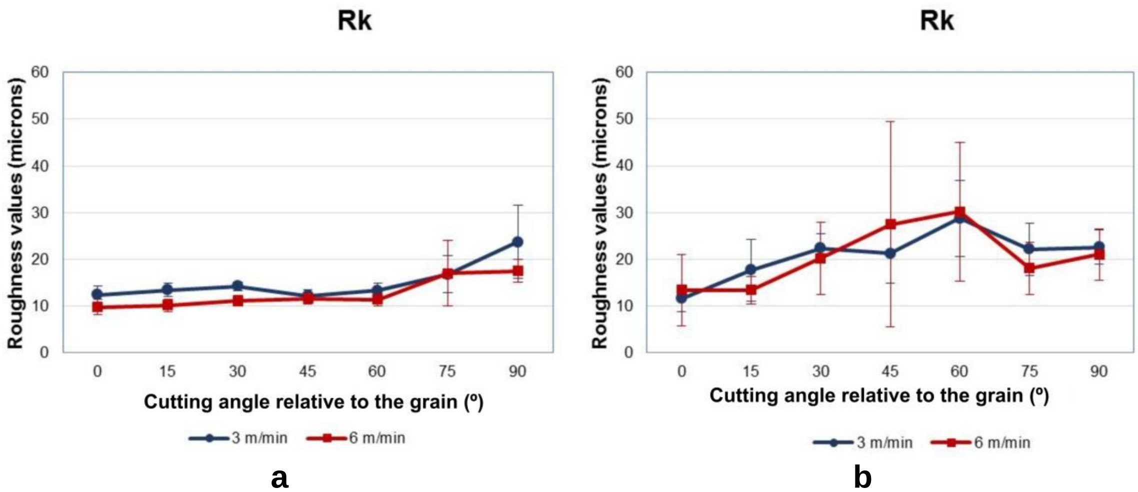

Fig. 6. The mean values of the core roughness, R_k, CNC routed with two feed speeds and seven cutting angles with relate to the grain: (a) evaluated for maple surface; (b) evaluated for oak surface

The oak pores, even those from latewood, exceeded in magnitude the maximum value of the processing roughness, R_k, depicted in Fig. 6b. The seven inclination angles of oak samples grain can be observed in Fig. 3b. The pores were cut longitudinally when processing along the grain, progressing towards a cross-obliquely trend. The stylus meets long lines of early pores for 45º angle and clustered groups of early wood pores for 90º. This only shows a high anatomical variability uncovered by the different cutting angles. Furthermore, the anatomical variability will also be given by the measurement location on the flank surface, comprising more or less percentage of earlywood or latewood in the measured profile. It is clear why two measured profiles of the same flank and milling angle will not be alike, as reported in a previous study because of the heterogeneous structure of wood (Sütçü and Karagöz 2013) and in this case, the inclination angle against the grain. Oak is known as a ring-porous species, making processing quality difficult to assess due to the anatomical cavities' depths, which are higher in magnitude than the processing marks.

Within the scope of this perspective, the R_k parameter should approximate the processing roughness with the least bias from wood anatomical features retained in the roughness profiles. Analyses of R_k for both for maple and oak samples are depicted in Figs. 6a and 6b, respectively. If the anatomical irregularities of the samples are not completely removed from the assessment of processing roughness, even R_k could be biased to a certain extent, as in the case there are many clustered pores in the measured profiles. Under this reserve, R_k remains the most reliable parameter when it is necessary to approximate the processing marks.

R_k was statistically interpreted by means of the Duncan test as displayed in Table 1. A statistical analysis showed a parameter increase from the grain inclination angle 0º (R_k =11 to 13 µm) to a peak at 60º (R_k = 28 to 30 µm) for oak samples, which was significant without considering the cutting speed. This is also visible in the graph represented in Fig. 6b. As in the case of maple, milling along the grain had the lowest processing roughness, R_k (Fig. 6b). However, for the same routing angle, no significant differences in R_k values with the feed speed were noted, as displayed in Table 1. Maple samples having both cutting speeds resulted in the best core quality, R_k, when cutting was performed along the grain orientation, as depicted in Fig. 6a (R_k=9.83 µm for u=6 m/min). However, there were no significant differences between R_k values of the samples processed with milling angles from 0º to 60º, with no regard to the cutting speed, as can be seen in Table 1. Only angles of 75º and 90º caused increased roughness of the samples (Fig. 6a, Table 1). The roughness increase for these angles can also be observed by comparing the roughness profiles in Fig. 4. Such increase might partly be due to the tool vibration when crosscutting of the samples was performed, leaving some frequent regular patterns including surface undulations, remaining retained in the roughness profiles (Fig. 3a). R_k mean values for u=3m/min were slightly higher than those of u=6 m/min (Fig. 6a), but the differences between such speeds for cutting angles from 0º to 75º were not significant. An exception was observed at the angle of 90°, where the surface processed with u=3 m/min was significantly rougher (R_k= 23.7 µm) than for u = 6 m/min (R_k= 17.5 µm).

Table 1. Statistical Analysis of Rk Parameter (mean values in microns) - Duncan Test of Maple and Oak Wood, CNC Routed with Two Cutting Speeds and Seven Cutting Angles as Function of the Grain Orientation

Wood species		0º		15º		30º		45º		60º		75º		90º	
		u, m/min													
		3	6	3	6	3	6	3	6	3	6	3	6	3	6
Maple	Signif-icance	C	C	B,C	C	B,C	C	C	C	B,C	C	B	B	A	B
	Mean R_k	12.42	9.83	13.45	10.16	14.27	11.14	12.26	11.66	13.35	11.36	16.84	17.00	23.68	17.51
Oak	Signif-icance	C	C	B,C	C	A,B,C	A,B,C	A,B,C	A,B	A,B	A	A,B,C	B,C	A,B,C	A,B,C
	Mean R_k	11.64	13.41	17.69	13.43	22.36	20.20	21.31	27.51	28.75	30.17	22.15	18.13	22.62	21.02

As mentioned in the methodology section, the roughness measurements of the samples were carried out on the 45º inclined flanks, having a stylus perpendicular to the surface. It was observed that the cutting tool was causing defects on the edges of the V flanks, as ruptures and pull-out material for certain tool cutting directions, not necessarily reflecting in the quality of the processed flank surface. Such ruptures were observed with the highest magnitude for the cutting angle of 60º, and less for 75º and 90º, for both cutting speeds (Fig. 3a). This observation alone would render the value of 60º as the worst cutting option, without considering any feed speed levels. Raised bundles of fibers were also observed on the edge of V flanks cut with 30º and 45º and mostly for the 3 m/min feed speed.

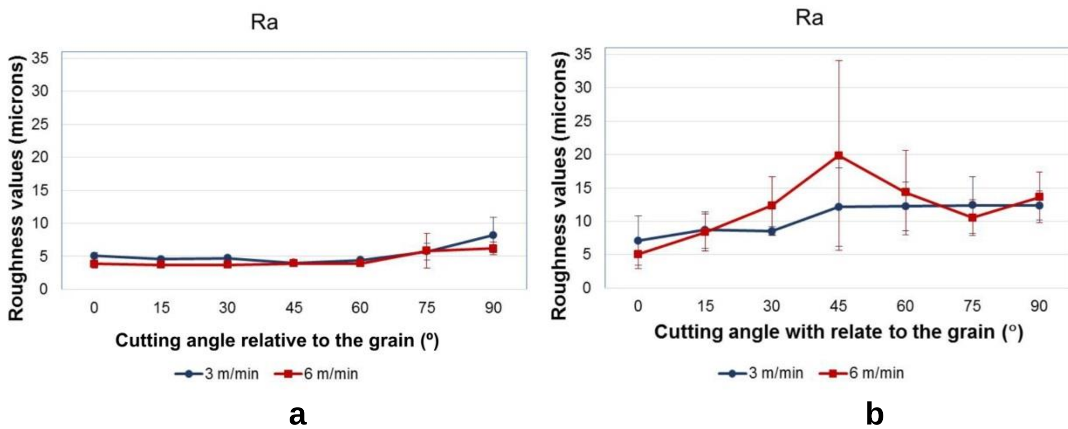

Fig. 7. The mean values of the R_a parameter, CNC routed with two feed speeds and seven cutting angles as function of the grain orientation: (a) evaluated for maple surface; (b) evaluated for oak surface

In maple, R_a values showed a similar trend as R_k, due to homogeneous anatomical structure of maple samples, as shown in Fig. 7a. It appears that R_a is not relevant when only the roughness caused by the processing marks is considered for the assessment of the surface. In oak, R_a, as an average parameter, includes in its calculation not only the processing marks, but also the valleys representing the wood pores and all irregularities in the positive and negative direction detaching from the zero line as illustrated in Fig. 7b. It is a fact that R_a can be biased by the presence of deep pores. In the case of maple samples, the crosscut directions of 75º and 90º increased R_{pk} (Fig. 8a), compared to the previous angles for both feed speeds, which may also be influence of an increased vibration, causing high frequency surface undulation. Fuzzy grain was remarked for the cutting angle of 0º and mostly for u=3 m/min, which in effect increased R_{pk} (Fig. 3a, Fig. 8a).

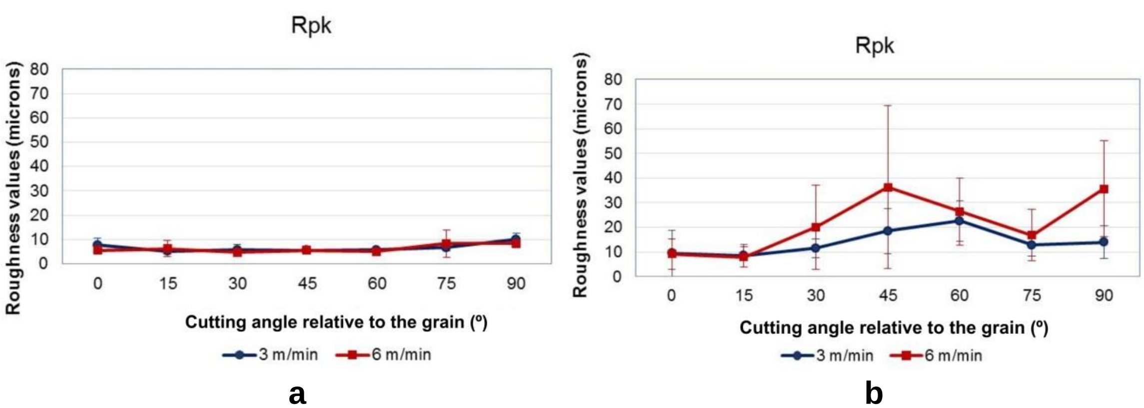

Fig. 8. The mean values of the R_{pk} parameter, CNC routed with two feed speeds and seven cutting angles as function of grain orientation: (a) maple surface; (b) oak surface

The negative skewness, R_{sk}, for all cutting angles as well as both feed speeds of routing maple samples indicated the prevalence of anatomical valleys against isolated peaks (fuzziness), as can be seen in Fig. 9a. This result reveals that the deepest features detected on the surface in Fig. 4 belong to anatomical cells, earlywood pores, rather than to processing marks quantified by R_k.

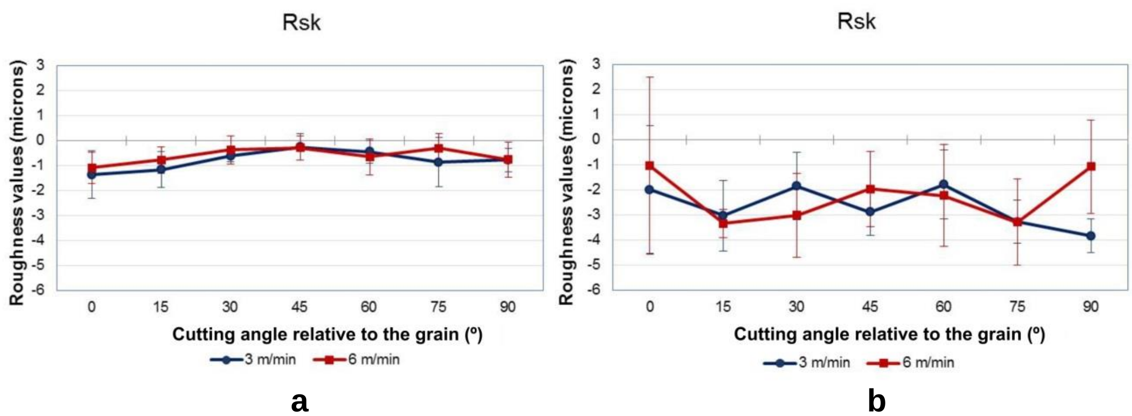

Fig. 9. The mean values of the R_{sk} parameter, CNC routed with two feed speeds and seven cutting angles as function of grain orientation: (a) maple surface; (b) oak surface

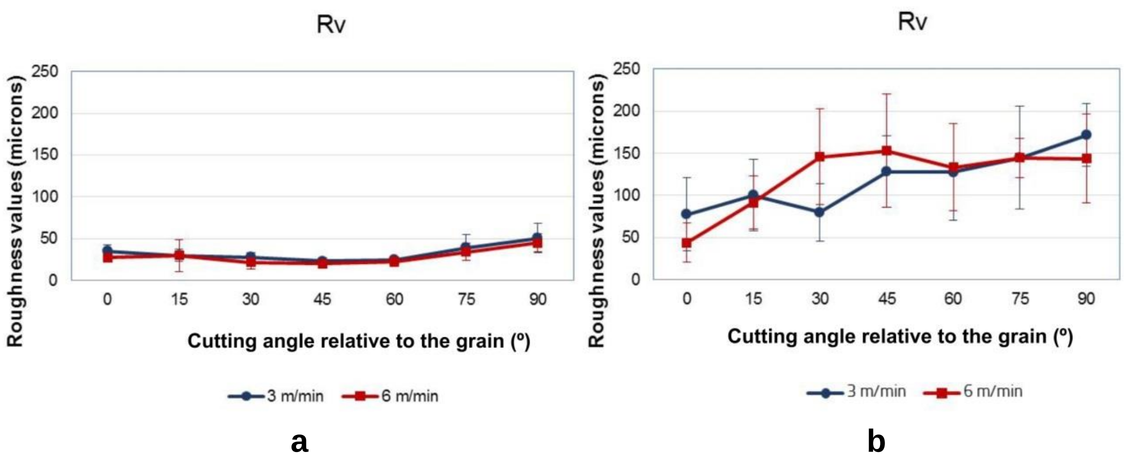

Fig. 10. The mean values of the R_v parameter, CNC routed with two feed speeds and seven cutting angles as function of grain orientation: (a) maple surface; (b) oak surface

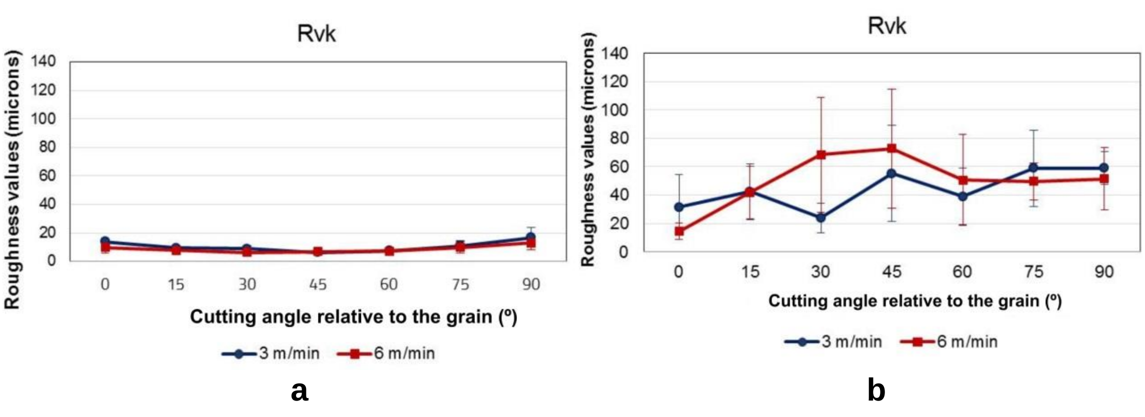

Fig. 11. The mean values of the R_{vk} parameter, CNC routed with two feed speeds and seven cutting angles as function of grain orientation: (a) maple surface; (b) oak surface

The anatomical valleys in maple samples that were observed for all cutting angles increased in magnitude and frequency when the cutting was performed nearly or quite perpendicular to the grain orientation with 75º and 90º levels, which can be observed having higher R_v and R_{vk} values, as illustrated in Figs.10a and 11a, respectively, as well as in the roughness profiles in Figs. 4f and 4g. When the cutting angle was 0º, the pores were scanned along their length and they appeared as wide features in the roughness profiles encircled with blue, for example in Fig. 4a. The surface waviness, W_a (Fig. 12a), was not sensitive to the variation in the cutting angle or feed speed, as can be noticed for maple samples (W_a was around 3 to 4 µm).

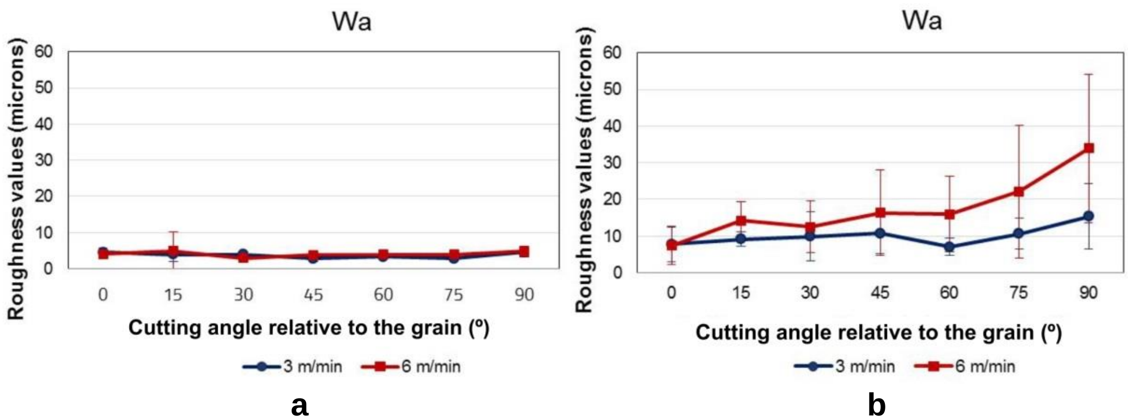

Fig. 12. The mean values of the W_a parameter, CNC routed with two feed speeds and seven cutting angles with relate to the grain; (a) evaluated for maple wood surface; (b) evaluated for oak wood surface

The values of R_v and R_{vk} illustrated in Figs. 10b and 11b, respectively, depended on the depth and percentage of pores on oak samples contained in the roughness profiles showing a great variation among the measurements, even when they were taken from the same flank. Therefore, the information provided by these parameters becomes less reliable for a particular cutting angle. However, R_v, measuring the deepest valley in a profile, seems to detect an increase with increasing cutting angle, which can be an effect of crosscutting the pores and allowing the stylus to go deeper into their cavities. R_{pk} is a measure of surface fuzziness, and in the case of oak fuzziness was apparent on all processed surfaces and for all cutting angles with relation to the grain. In general, fuzziness was found around the cut pores where the thin cell walls split and partly detached, as shown encircled with red in Fig. 5.

Considering the non-homogeneous structure of oak samples, the variation of R_{pk} with the cutting angle did not show a significant trend, but a higher magnitude of fuzziness was observed for the 6 m/min feed speed, as shown in Fig. 8b. The negative values of R_{sk} (Fig. 9b) for the oak samples indicated the strong influence of pores generating deep valleys going beyond the core data defined by R_k. Since R_{sk} is very sensitive to any outlying data, it was influenced by isolated valleys as well as raised fibers. Therefore, no specific trend with the variation in the cutting angle, nor with the feed speed was determined.

For routed oak samples, the surface waviness expressed by W_a increased with the cutting angle, for both feed speeds, but with a sharper trend for u=6 m/min, reaching a peak for 90º (W_a= 34.0 µm) and lowest values for cutting along the grain (W_a=7.39 µm), as depicted in Figs. 12b and 13.

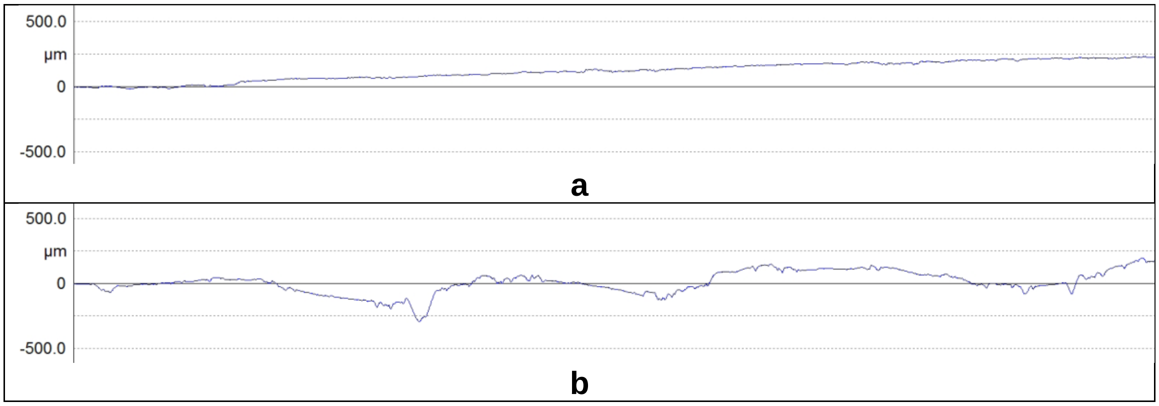

Fig. 13. Comparative surface profiles of oak sample, containing roughness and waviness together from surfaces processed with u=6 m/min: (a) cutting along the grain orientation; (b) cutting at 90° as related to the grain

The sharp increase for the angles 75º and 90º was significant for the oak samples, based on ANOVA test. When the cutting angle was 90º, the stylus followed the annual growth. The waviness observed in Fig. 13b overlapped with the sequence of earlywood and latewood, where the earlywood areas seemed to sink. This phenomenon may require further investigation to see whether the earlywood was processed deeper, or if it was wood elasticity resulting in a spring-back effect.

When the edges of the V models were examined, it was seen that the cutting angle of 60°, for both feed speeds, produced many oak material ruptures, rendering this cutting angle as the worst option. Big wood ruptures along the processed edges were noticed also for 30°, but to a lesser extent compared with 60°, which were followed by smaller edge pull-outs in 75° and then 90°.

It was interesting to observe that in a study on larch, although a helical cutter was used for milling, a cutting angle of 60° increased the occurrence of pull-out material (Gurau *et al.* 2021), as observed in the present study on the flanks'edges of both maple and oak.

Further studies will be conducted also on other species in order to understand which would be their behaviour when varying the cutting angle as related to the grain. It is espected that the routing outcome be influenced by species structure, but it is worth observing whether the angle of 60° would prove the worse scenario for other species as well.

CONCLUSIONS

1. The processing roughness evaluated by R_k on the routed V flanks seem to be best when cutting along the grain for maple sample (R_k=9.83 µm for u=6 m/min), although it presented some isolated fuzzy grain. However, there were no significant differences between the cutting angles from 0º to 60º, without considering the cutting speed. A roughness increase was particularly noted for 75º and 90º (R_k=23.7 µm for u=3 m/min), and it was most probably caused by a vibrational effect leaving high frequency undulations on the surface. The processing roughness, R_k, on the routed V flanks of oak showed a parameter increase from the cutting angle 0º (R_k = 11 to 13 µm) to a peak at 60º (R_k = 28 to 30 µm), but there were no significant differences in R_k with different

the feed speed levels. It appears that cutting along the grain orientation resulted in the best surface quality of the oak samples

2. The surface waviness, W_a, was not sensitive to the variation in the cutting angle or feed speed for maple samples (W_a was around 3 to 4 µm). The surface waviness expressed by W_a for oak samples increased with the cutting angle, but it was significant when crosscutting the samples at 75º and 90º using higher the feed speed (W_a= 34.0 µm, compared with W_a=7.39 µm along the grain).
3. The visually examined edges of the V flanks of the maple samples had ruptures and pull out, especially for *u*=3 m/min, with the highest magnitude at 60º, followed by 75º and 90º. Raised bundles of fibers were observed on the edge of V flanks cut with 30º and 45º and mostly for the 3 m/min feed speed. The edges of the V flanks for oak samples had rupture and pull out with the highest values for 60º for both feed speeds, followed by 30°, then by 75° and 90°.

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