Influence of Some Cutting Parameters on Frontal-Peripheral Surface Roughness of Oak Milled with Straight-Flute End Mill Tools

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The combined effects of grain orientation and CNC end milling parameters on wood surface quality remain poorly understood. This study investigated the surface quality of tangential oak during frontal milling and radial oak during peripheral milling using straight-flute end mill tools with diameters of 8 and 10 mm, four stepover values (30%, 50%, 70%, and 90% of the tool diameter), and two cutting depths (1 and 3 mm). Surface quality was evaluated through roughness parameters and profiles, microscopic observations, and compared with reference surfaces obtained by shaving and P150 sanding. ANOVA revealed that stepover is the primary factor governing roughness, followed by tool diameter, while cutting depth had no statistically significant impact. Increasing the stepover beyond 50% substantially degrades the surface due to severe fiber lifting and tool ridges. The 8 mm tool produced smoother surfaces than 10 mm tool, in both milling operations and at 30% stepover closely approached the ideal shaved baseline. In frontal milling, stepovers of 30% and 50% outperformed sanding, whereas in peripheral milling, only the 8 mm tool yielded superior quality. Utilizing a smaller tool diameter at a low stepover ratio guarantees a finish-ready surface directly from the CNC machine.

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INTRODUCTION

Surface quality is one of the most important indicators of machining performance in wood processing because it directly influences the appearance, bonding behavior, coating adhesion, and service life of the final product. In modern manufacturing, end mills are among the most widely used cutting tools due to their ability to perform both frontal (face) and peripheral (edge) milling operations while maintaining high flexibility in the production of complex geometries. Consequently, CNC machining has become increasingly important in the woodworking industry, where it enables the efficient processing of components with intricate shapes and tight dimensional tolerances (Gawroński 2013; Jin and Wei 2021; Wang *et al.* 2024). Despite these technological advances, obtaining a finish-ready wood surface directly from the CNC machine remains a significant challenge. In industrial practice, woodworking operations require an intermediate sanding stage prior to the application of varnishes or lacquers to eliminate machining marks and ensure proper coating adhesion. However, the cost and efficiency of wood finishing are strongly dependent on the surface smoothness obtained before finishing (Williams *et al.* 2000; Coelho *et al.* 2008; Söğütlü *et al.* 2016; Gurău and Irle 2017). Eliminating this intermediate sanding step by directly generating a finish-ready surface during CNC milling could significantly reduce processing times, operational costs, and energy consumption in wood manufacturing.

The complexity of this challenge originates from the nature of wood itself. Unlike homogeneous engineering materials, wood is an anisotropic, heterogeneous, and hierarchical biological composite whose machining behavior is controlled by both anatomical and technological factors. Grain orientation, density, moisture content, vessel distribution, fibre arrangement, and cell-wall structure strongly influence the interaction between the cutting edge and the material. Qing *et al.* (2018) demonstrated that a significant proportion of measured roughness originates from natural anatomical features such as vessels, fibres, rays, and cell lumens rather than from machining marks alone. Similarly, Jankowska (2020) reported that roughness measured perpendicular to the grain can be approximately twice as high as roughness measured parallel to the grain and that radial surfaces generally exhibit higher roughness than tangential surfaces. Their results further showed that vessel diameter has a stronger influence on roughness than wood density. Adamčík *et al.* (2024) confirmed these observations during CNC milling of oak, beech, and spruce, showing that roughness in oak is largely controlled by deep earlywood vessels, whereas spruce roughness is associated primarily with fibre fuzziness and protruding fibres.

These anatomical influences are particularly important when machining ring-porous hardwoods such as oak. Large earlywood vessels create pronounced topographical depressions that can dominate conventional roughness measurements and complicate the interpretation of machining quality. Pinkowski and Szymański (2010) have shown that surface roughness in oak varies considerably according to anatomical orientation, with radial and semi-radial surfaces generally producing rougher textures than tangential surfaces. Zhong *et al.* (2013) also reported substantial differences in roughness among wood species commonly used in furniture manufacturing, highlighting the importance of species-specific anatomical characteristics. Among the hardwoods investigated, roughness varied considerably despite similar processing conditions, confirming that the anatomical structure of wood must be considered when evaluating machining performance.

The complexity of wood surface characterization has generated considerable debate regarding the suitability of conventional roughness parameters. The arithmetic mean roughness parameter R_a remains the most commonly reported descriptor in the literature because of its simplicity and widespread industrial acceptance. Numerous investigations, including those of Pinkowski *et al.* (2013), Zhong *et al.* (2013), Sofuoğlu (2019), Yang *et al.* (2023), and Wang *et al.* (2024), have used R_a as the principal indicator of machining quality. Nevertheless, several authors have questioned its ability to accurately represent wood surfaces. Qing *et al.* (2018) observed that R_a cannot distinguish between machining-induced irregularities and naturally occurring anatomical cavities. Fujiwara *et al.* (2004) showed that conventional profile analysis can be distorted by deep vessel depressions, particularly in hardwood species, and proposed three-dimensional roughness descriptors based on Robust Gaussian Regression Filtering to better correlate with tactile perception.

Because this traditional metric averages the surface height profile, it is heavily distorted by the deep, natural anatomical valleys of earlywood pores rather than exclusively capturing the physical marks left by the cutting tool (Fujiwara *et al.* 2004; Qing *et al.* 2018; Adamčík *et al.* 2024). To overcome this bias, advanced measurement studies recommend the use of Abbott–Firestone amplitude distribution curve parameters (R_k, R_{pk}), and their synergistic sum (R_k+R_{pk}) (Costes and Larricq 2002; Aghakhani and Khazaeian 2014; Csanády *et al.* 2015). These stratified parameters filter out isolated natural cavities, allowing a robust, independent evaluation of the core roughness and raised fibers generated by processing.

Besides anatomy, machining conditions strongly affect surface formation. Among the technological parameters investigated in the literature, feed rate is consistently identified as one of the most influential factors controlling roughness. Pinkowski *et al.* (2013), Çakıroğlu *et al.* (2019), İşleyen and Karamanoğlu (2019), Sofuoğlu (2019), Yang *et al.* (2023), and Talić and Hodžić (2024) all reported that increasing feed rate generally leads to higher roughness values. This behavior is typically associated with larger feed per tooth, increased chip thickness, and greater deformation of wood fibres during material removal. Rahman *et al.* (2025), in a comprehensive review of CNC milling studies, concluded that feed rate is generally the dominant parameter affecting surface roughness across a wide range of materials, including wood.

Spindle speed and cutting speed also play a major role in determining surface quality. Costes and Larricq (2002) reported that increasing cutting speed improved the surface quality of dry beech during transversal milling, while Guo *et al.* (2021) reported that higher cutting speeds reduced both cutting forces and roughness during milling of Manchurian ash and Chinese fir. Similar observations were reported by Sofuoğlu (2019), Yang *et al.* (2023), Wang *et al.* (2024), and İlşekerci and Sofuoğlu (2025), who found that increasing spindle speed generally improved surface quality. Nevertheless, Adamčík *et al.* (2024) observed that excessive spindle speed may increase vibration and occasionally deteriorate surface quality, indicating that optimal spindle speed depends on both machine dynamics and material properties.

Depth of cut represents another important technological factor. Sofuoğlu (2019), Jin and Wei (2021), Wang *et al.* (2024), and Talić and Hodžić (2024) all observed that increasing cutting depth generally increases roughness and cutting forces. Greater tool engagement generates thicker chips, higher cutting loads, and more severe fibre deformation, leading to reduced surface quality. These observations indicate that the selection of cutting depth must balance productivity and surface finish requirements.

Tool geometry and cutting edge condition play an important role in determining machining performance and surface quality. The inclination angle of helical cutters influences both cutting forces and roughness (Jin and Wei 2021), while progressive tool wear increases roughness, fibre damage, and cutting resistance (Pinkowski *et al.* 2010; Kazlauskas *et al.* 2017). Furthermore, cutting edge treatments affect wear development and power consumption during oak milling (Koleda *et al.* 2019).

The interaction between machining parameters and cutting forces has also received considerable attention. Mandić *et al.* (2015), Đurković and Danon (2017), and Hodžić *et al.* (2025) demonstrated that cutting forces depend strongly on wood density, grain orientation, cutting depth, feed per tooth, and mechanical properties. Their findings indicate that machining performance cannot be fully understood without considering the complex interaction between wood anatomy and cutting mechanics. Wang *et al.* (2024) further showed that chip morphology is closely related to surface quality, with thinner and more fragmented chips generally corresponding to smoother machined surfaces.

Surface quality is also influenced by stepover. Sütcü and Karagöz (2012) reported that increasing stepover increased surface roughness during CNC face milling of MDF. Similar observations were made by Ergin and Sofuoğlu (2023), who found that 50%

stepover produced the lowest roughness, whereas 100% stepover resulted in the roughest surfaces during milling of Siberian pine. Likewise, Rodzi *et al.* (2025) showed that smaller stepover values improved surface finish by reducing the ridges formed between adjacent tool paths.

Recent investigations have increasingly incorporated advanced modelling and optimization techniques to improve machining performance. Gawroński (2013), Hazir and Koc (2018), Gürgen *et al.* (2022), and Yang *et al.* (2023) applied artificial neural networks, genetic algorithms, and mathematical optimization methods to predict roughness and identify optimum machining conditions. These approaches have confirmed the highly nonlinear nature of wood machining and the importance of considering multiple interacting variables simultaneously.

While extensive literature has focused on optimizing operational inputs such as feed rate, spindle speed, and tool wear to control surface deterioration, the combined geometric interactions of tool diameter, stepover ratio, and cutting depth require deeper systematic exploration—particularly regarding the comparative differences between frontal (face) and peripheral (edge) routing on ring-porous woods. To address these challenges, this paper aims to achieve two primary objectives:

1. Evaluate the influence of specific processing parameters (stepover values, cutting depths, and straight-flute end mill tool diameters) on the resulting surface quality of frontal and peripheral oak milling. This quality is evaluated in direct comparison to two structural references: an ideal smooth surface obtained by high-precision super surfacing (shaving) and a standard industrial smoothing baseline obtained *via* P150-grit belt sanding.
2. Identify the processing parameter combinations capable of producing a finish-ready surface quality that entirely eliminates the need for intermediate sanding before lacquer application.

EXPERIMENTAL

Materials

The evaluation of CNC-machined wood surfaces requires suitable reference surfaces that represent established quality benchmarks. In industrial practice, sanding with medium-fine abrasives such as P150 is commonly used to prepare surfaces for coating applications, while super surfacing (shaving) is recognized for producing exceptionally smooth surfaces with minimal surface damage and fibre deformation. Therefore, in this study, CNC milled surfaces were compared with both P150 sanded and super surfaced reference surfaces in order to provide a meaningful assessment of machining quality.

Oak (*Quercus robur*) samples had a mean moisture content of 9.6%, within the typical 8 to 10% range for interior furniture and joinery. With a mean density of 717 kg/m³, the samples were prepared with tangentially oriented surfaces by straightening and planing, followed by cross-cutting to final dimensions of 100 × 100 × 20 mm. In this way, all faces had a tangential grain orientation, while their edges in the longitudinal direction were radial. Thirty-two samples were directed to CNC machining on one face and two longitudinal edges per sample. These covered the cutting variables considered in this study for frontal milling, namely: four stepover values, two cutting depths, and two diameters of the straight-flute end mill tools, considering two replicates for each parameter combination (4 × 2 × 2 × 2 = 32). Each of the 32 samples was also peripherally routed, on both longitudinal radial edges, with the same end tool as their faces.

In order to provide surfaces processed by shaving and sanding as references to CNC processing, boards with the same grain orientation were considered (tangential and radial). Three oak boards per orientation, 500 × 100 × 20 (mm) were prepared for both types of reference processing: shaving and sanding. This meant a total of 6 boards for shaving and 6 for sanding.

Methods

Processing by CNC

The 32 prepared samples were machined by a CNC milling machine (FlatCom XL GFV, isel Germany GmbH, Eiterfield, Germany) along the grain direction on tangential face and radial edge surfaces using the following variables: two straight-flute end mill tools of 8 and 10 mm diameter, two depths of cut (1 and 3 mm) and additionally for frontal cutting, four values of stepover ratio (30%, 50%, 70% and 90% of irrespective tool diameter). Although the transverse edge surfaces were also processed, they were disregarded, since their evaluation would be more complex and would require a separate and more comprehensive investigation, which is beyond the scope of the present study.

The machining process was performed using two straight-flute end mill tools: a 10 mm diameter tool (Leitz România S.R.L., Brașov, Romania) and an 8 mm diameter tool (Technowood S.R.L., Brașov, Romania), which routed with 15000 rpm, the maximum possible at this CNC machine, at 4 m/min feed speed. The tools feature cutting edges along their cylindrical sides for peripheral/lateral milling and on the bottom (end) flat face for frontally cutting (Fig. 1).

Both cutters were manufactured from tungsten carbide and featured a positive helix orientation, extending from the face side of the workpiece toward the bottom, which promoted efficient chip evacuation and improved dust extraction. Figure 1(a) shows the straight-flute end mill cutter with two-flute cutting edges. To ensure consistent cutting performance, both tools were new, and their cutting edges were examined microscopically to confirm the absence of manufacturing defects or wear.

Figure 1(b) illustrates the clamping configuration used for face milling, while Fig. 1(c) presents the fixing arrangement applied during edge milling, which involved top clamping. This fixation method was required to prevent the workpiece from being lifted or pulled out of position during tool exit from the material, a phenomenon that occurred in previous tests. Face milling was performed first and was immediately followed by surface roughness measurements in order to avoid any potential negative influence on surface quality of the clamping conditions necessary for edge milling.

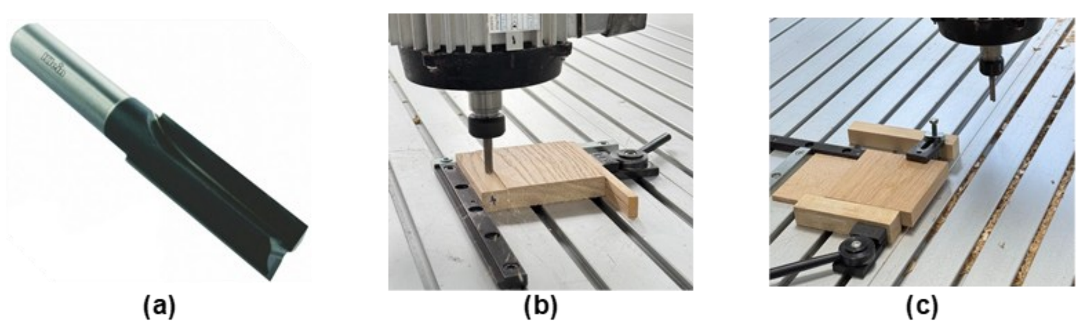


Fig. 1. Machining on CNC: (a) straight flute end mill, (b) face/frontal milling, (c) edge/peripheral milling

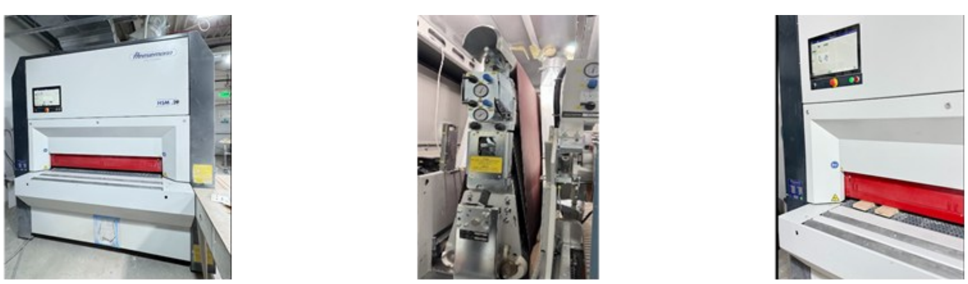
Processing reference surfaces

Wood surface shaving was carried out using a super surfacer (New Royal 10, Marunaka Tekkosho Inc., Shizuoka, Japan) a high precision woodworking machine developed for ultra fine surface processing.

This processing was selected as the best example of a very fine surface, where the marks of the processing tool are minimised and the anatomical structure is the least altered. The machine operates with a fixed 390 mm blade positioned transversely in the working table at an angle of 20° to the feed direction, allowing a slicing type cutting action as the samples were fed longitudinally across the blade. Material transport was ensured by a rubber conveyor belt system that maintained constant pressure and stable movement of the workpiece over the blade, enabling the uniform removal of a 0.1 mm surface layer and the production of continuous full-width shavings while preserving the anatomical structure of the wood. Five successive passes were performed on each of the 6 boards (three with tangential face, three with radial face) to ensure the complete removal of all planing marks from previous operation.

The second type of reference surface, was the sanded surface. Sanding is the common smoothing process in the woodworking industry, which follows the machining operations and precedes finishing with various types of varnishes. The costs of finishing are strongly dependent on the surface smoothness obtained before the application of the finishing layer. Usually, sanding prepares the support by a sequence of three passes, which use grits from coarse to very fine. In case of oak, a final grit size of P150 is a common value meant to assure a proper surface quality before lacquering. In this study, three boards with radial and three with tangential reference surfaces were prepared through three successive sanding passes in order to ensure that the final surface morphology contained only the traces generated by the P150 abrasive paper, while eliminating any marks remaining from the previous processing stages. The sanding operations were carried out using a wide belt sanding machine (Fig. 2, a) equipped for longitudinal sanding of flat wooden surfaces. The machine allowed controlled adjustment of the feed speed, abrasive belt speed, and contact pressure in order to ensure stable and repeatable sanding conditions throughout the experiments.

During sanding, the abrasive belt (ZK713X, VSM · Vereinigte Schmirgel- und Maschinen-Fabriken AG, Hannover, Germany) operated at a cutting speed of 5 m/s, whereas the feed speed of the samples was maintained at 3 m/min. The zirconia alumina abrasive belt with P150 grit size and full resin bonding was used for all tests (Fig. 2, b). The abrasive material was specifically designed for wood machining applications. The abrasive backing consisted of X polyester support, providing increased dimensional stability and resistance during sanding.



(a) (b) (c)

Fig. 2. Processing by sanding: (a) Heesemann 2023.07.271 sanding machine, (b) ZK713X zirconia alumina abrasive belt, (c) sample processing.

The use of successive sanding passes (Fig. 2, c) combined with constant technological parameters ensured consistent surface preparation and good comparability between the sanded reference surfaces and the milled and shaved specimens analysed in the study.

Surface quality measurements

For surface characterization, a MarSurf XT20 equipment from MAHR Göttingen GmbH (Göttingen, Germany) was used, which worked with a stylus with 2 µm radius and 90° tip angle to collect profile data from the surface. The scanning speed was 0.5 mm/s and the lateral resolution was 5 µm.

For each combination of the cutting parameters in the CNC frontal milling (stepover, cutting depth, tool diameter) and two sample replicates, four surface profiles with a length of 50 mm were measured perpendicular to the grain, resulting in a total of 8 profiles per combination, which evaluated a cumulated length of 400 mm. In the case of edge machining, the smaller edge width required multiple repeated measurements in order to obtain the same total evaluated length of 400 mm for a proper comparison with the quality of faces. Thus, for each parameter combination, ten profiles of 10 mm length were measured on each edge (10 profiles x 10 mm profile length × 2 edges per sample × 2 replicates = 400 mm). For the shaved and sanded surfaces, for both tangential and radial orientation, six measurements with a length of 50 mm each were performed across each board, making a total of twelve measurements per each machining process.

The surface profile data were analyzed using MARWIN XR20 software provided by the equipment manufacturer. In the first stage, the measured profiles were corrected by removing the form deviation through polynomial fitting, which enabled the extraction of the primary profile from the original measurement data (ISO 21920-2:2021). The resulting primary profiles contained both waviness and roughness components, associated with long and short wavelength irregularities, respectively.

For the evaluation of the roughness component, the primary profiles were filtered using a robust Gaussian regression filter with a cut-off length of 2.5 mm, according to recommendations for wood surface (Gurău 2004; Tan *et al.* 2012; ISO 16610-31 2016). The filtered profiles were then used to calculate standard roughness parameters such as R_a, R_v and R_{sk} (from ISO 21920-2 2021). Since wood presents a complex hierarchical and anisotropic structure, Abbott–Firestone parameters, such as R_k and R_{pk}, as well as their sum R_k+R_{pk}, were additionally determined in order to better describe the stratified structure of the machined surfaces (ISO 21920-2 2021). The sum R_k+R_{pk}, adds the magnitude of the tool marks (R_k) to the raised fibers (R_{pk}), reflecting the synergistic processing effect of the tool-species interaction. The relevance of these parameters for wood topography assessment has been demonstrated in previous studies (Magoss 2008; Tan *et al.* 2012; Gurău and Irle 2017; Gurău *et al.* 2021).

The statistical significance of the processing parameters was evaluated by three-way factor ANOVA.

In addition, the original measured data as ASCII measurement files, was separately processed in MathCAD Professional 2000 (MathSoft Inc., Cambridge, MA, USA) to generate individual primary and roughness profiles, allowing a visual comparison of the surface morphologies obtained with different tools and machining conditions.

Stereomicroscopy and SEM analysis

The surface morphology of all specimens was further investigated using a NIKON SMZ 18-LOT2 stereomicroscope (Nikon Corporation, Tokyo, Japan) with a maximum total magnification of 405×. Microscopic images were obtained from the CNC machined surfaces together with the shaved and sanded reference surfaces on both tangential and radial wood grain orientations and the resulting morphological observations were further correlated with the measured surface quality parameters.

For deeper microscopic details, an electronic microscope type Phenom XL G2 Desktop SEM, produced by Thermo Fisher Scientific, Eindhoven, The Netherlands, with an electron optical magnification range between 160 and 200000x was used. This equipment is suitable for morphological and structural analysis for various materials, including electrically non-conductive samples with a certain moisture content such as wood. The microscope is also endowed with an EDS detector for chemical elements identification.

RESULTS AND DISCUSSION

Surface Quality of CNC Machined Oak by Frontal/Face Milling

This section presents a detailed evaluation of the surface characteristics after CNC face milling of oak. The quantitative quality evaluation by roughness parameters is combined with qualitative information obtained from the visualization of the measured profiles and microscopic observations. The analysis focuses on the surface morphology generated under controlled machining conditions, with particular emphasis on the influence of the tool diameter, cutting depth, and stepover.

Table 1 presents the mean values and standard deviations of the surface roughness parameters for oak, obtained using straight-fluted end mills with diameters of 8 mm (D8) and 10 mm (D10), at cutting depths of 1 mm and 3 mm, and stepover values of 30%, 50%, 70%, and 90% of the tool diameter. The results for the shaved and the P150 sanded surfaces are also included, defining a reference interval between an ideal high surface quality provided by shaving and the quality of sanding as the usual operation prior to finishing.

The purpose of this comparison is to assess whether the CNC milling process can achieve a surface quality level sufficiently high to enable a direct transition to finishing operations, thereby eliminating the need for an intermediate sanding stage.

The results in Table 1 indicate that R_a is not a reliable parameter for evaluating the surface quality of oak. R_a, which is influenced by wood anatomy, does not reflect the real quality differences between the four processing. The sanded surface (P150_TG) shows R_a values comparable to or even lower than the super surfaced reference (R_TG), although the latter is known to exhibit superior quality. This is caused by the open porous structure of oak, which strongly affects R_a, as a mean height parameter, by including in its calculation the deep anatomical valleys rather than the machining marks. Furthermore, the negative values of skewness (R_{sk}) confirm the predominance of valleys in the surface profiles, mainly of the earlywood pores, while the high and random R_v values quantify their irregular depth distribution, independent on machining and inherently present in the surface topography. Therefore, for a stratified morphology of wood, especially in case of processed ring porous species as oak, Abbott Firestone surface parameters are more appropriate. The analysis in this study is based primarily on them, as recommended by previous authors (Gurău 2004; Magoss 2008; Gurău *et al.* 2022; Angelescu *et al.* 2025).

Table 1. Mean Values Roughness Parameters (R.P.) in µm Measured for Tangential Oak Surfaces CNC Processed by the D8 and D10 Tools, at 1 and 3 mm Cutting Depths (C.D.), Compared with Tangential Faces from the Super Surfacer (R_TG) and the Sanded Tangential Ones (P150_TG)

R.P. [µm]	C.D. [mm]	R_TG	D8 (30%)	D8 (50%)	D8 (70%)	D8 (90%)	D10 (30%)	D10 (50%)	D10 (70%)	D10 (90%)	P150_ TG
R_a	1	9.96	8.85	16.04	14.55	16.03	7.85	8.50	19.06	22.47	9.06
		(1.83)	(2.85)	(2.62)	(3.76)	(1.78)	(0.98)	(1.47)	(1.52)	(1.80)	(2.34)
	3	9.96	8.93	12.38	14.73	18.28	12.92	16.18	19.65	21.19	9.06
		(1.83)	(1.98)	(2.12)	(1.48)	(2.05)	(2.22)	(1.49)	(3.76)	(3.12)	(2.34)
R_v	1	165.04	218.74	190.57	228.23	234.85	149.61	173.00	219.93	264.37	150.97
		(8.98)	(15.93)	(26.70)	(41.37)	(14.88)	(17.98)	(8.16)	(22.54)	(25.39)	(23.07)
	3	165.04	191.09	215.94	285.78	231.89	192.81	219.15	225.89	238.48	150.97
		(8.98)	(3.89)	(26.00)	(15.80)	(19.95)	(23.77)	(20.69)	(25.85)	(17.13)	(23.07)
R_{sk}	1	-3.82	-4.86	-3.08	-3.55	-3.48	-4.33	-4.59	-3.02	-2.89	-4.24
		(0.43)	(1.09)	(0.16)	(0.32)	(0.39)	(0.28)	(0.79)	(0.20)	(0.14)	(0.99)
	3	-3.82	-4.39	-3.93	-4.19	-3.16	-3.39	-3.44	-3.01	-3.02	-4.24
		(0.43)	(0.43)	(0.44)	(0.42)	(0.26)	(0.26)	(0.44)	(0.30)	(0.35)	(0.99)
R_k	1	6.46	5.65	10.83	11.03	11.74	7.55	10.10	12.97	16.23	13.97
		(0.62)	(0.58)	(0.37)	(0.73)	(0.32)	(0.27)	(0.72)	(1.17)	(2.14)	(1.68)
	3	6.46	6.68	9.61	12.93	14.21	8.90	12.14	14.33	17.85	13.97
		(0.62)	(0.27)	(0.59)	(0.37)	(1.04)	(0.34)	(0.72)	(0.97)	(2.04)	(1.68)
R_{pk}	1	2.37	5.95	4.36	10.13	13.87	8.02	5.50	9.39	18.14	3.87
		(1.44)	(2.80)	(0.99)	(4.84)	(3.85)	(0.65)	(0.31)	(2.76)	(9.25)	(0.60)
	3	2.37	6.30	6.54	5.29	13.09	4.57	6.60	13.27	6.95	3.87
		(1.44)	(0.77)	(2.57)	(0.37)	(1.91)	(0.80)	(0.79)	(9.37)	(0.85)	(0.60)
R_k+R_{pk}	1	8.83	11.60	15.19	21.16	25.61	15.57	15.61	22.35	34.37	17.84
		(1.90)	(2.96)	(0.68)	(5.55)	(3.74)	(0.42)	(0.58)	(2.60)	(9.45)	(2.06)
	3	8.83	12.98	16.15	18.22	27.31	13.48	18.74	27.60	24.80	17.84
		(1.90)	(1.02)	(2.42)	(0.66)	(1.58)	(1.07)	(1.30)	(10.02)	(1.78)	(2.06)

Note: Stepover values are given in brackets as a percentage of the tool diameter. Standard deviations are provided in brackets below the mean values.

Alongside the core roughness parameter R_k, which provides a robust estimation of the central portion of the surface profile and can be associated with the tool marks left in wood, the evaluation must also consider the contribution of surface peaks, quantified by the R_{pk} parameter, which approximates the raised fibers during machining. Both parameters, together, estimate the processing quality. R_k and R_{pk} are obtained after a threshold removes the isolated deep valleys, which are disregarded from their evaluation rendering the evaluation of the effect of processing more reliable compared to R_a.

For instance, although the core roughness (R_k) for the 30% step over in the case of the D8 tool (5.65 µm) was lower than that of the shaved surface (6.46 µm), the corresponding R_{pk} value was much higher for the routed surface (5.95 µm), being almost double that of the shaved reference (2.37 µm), indicating the presence of more pronounced surface peaks for the former. For this reason, the analysis was extended to the combined parameter R_k+R_{pk}, which describes the relevant portion of the surface topography, as reported by Angelescu *et al.* (2025).

As shown in Table 1, the best quality was obtained with the super surfacer, 8.83 µm (R_k+R_{pk}). For the sanded surfaces, R_k+R_{pk} was approximately 2 times higher (17.84 µm) than that for shaving.

The evolution of R_k+R_{pk}, as well as of R_k alone, showed a clear increasing trend with the increase in the stepover from 30% to 90% of the tool diameter for both end mills and both depths of cut, indicating a progressive deterioration of the surface quality as the overlap between adjacent tool paths decreases. The values obtained for D8 at 50% stepover were approximately 24 to 30% higher than the values recorded at 30% stepover, indicating a significant reduction in surface quality with the increase of the stepover. For both tool diameters and depths of cut, R_k+R_{pk} was doubled when the value of stepover increased from 30% to 90%. For example, for D8 tool, R_k+R_{pk} increased from 11.60 µm at 30% stepover to 25.61µm at 90%, for 1 mm depth of cut. For the D10 tool the roughness combined parameter increased from 15.57 µm to 34.37 µm over the same range. For 30% and 50% stepover, the surface quality for both tools was better than that for sanding.

In general, judged by the mean values, an increase in the cutting depth has produced an increase in R_k, as well as of R_k+R_{pk} (Table 1), similar with findings reported in the literature, where an increased cutting depth is generally associated with a deterioration of the surface quality (Sofuoğlu 2019; Jin and Wei 2021; Wang *et al.* 2024; Talić and Hodžić 2024). For example, increasing the cutting depth from 1 to 3 mm in case of D8, slightly increased the surface roughness (R_k+R_{pk}) with 6 to 11%, but in case of D10, the increase sometimes ranged around 20%, while sometimes increasing the cutting depth has led to slightly lower R_k+R_{pk} values, suggesting an apparent improvement in surface quality (Fig. 3). To understand the influence and significance of the depth of cut on the surface quality, a statistical interpretation was considered necessary and is included in Table 2.

In the majority of cases, especially for R_k, but also for R_k+R_{pk}, the surface quality was higher, with various magnitudes from 2 to 50%, when D8 was used compared with D10 end mill, which is in agreement with the findings of Demir *et al.* (2022).

The statistical significance of those results, as well as of the impact on the surface quality, R_k+R_{pk}, of the three variables used in this study: tool diameter, stepover and depth of cut, were analysed by a three-way ANOVA (Table 2). The variable with the highest significance seems to be the stepover judged from its largest individual effect size (η^2) ($p < 0.05$, $\eta^2 = 0.715$), followed by the tool diameter, which also showed a highly significant but moderate influence/effect size ($p = 0.006$, $\eta^2 = 0.149$), while the cutting depth had no significant separate effect on the surface quality ($p > 0.05$). No significant two-way interactions were observed, indicating similar stepover related trends for both tools overall. The three-way interaction was significant, Tool × Stepover × Depth (p = 0.008), indicating that the ideal cutting parameters depend on the specific combination of all three variables working together, though stepover remains the primary lever for controlling $R_k + R_{pk}$.

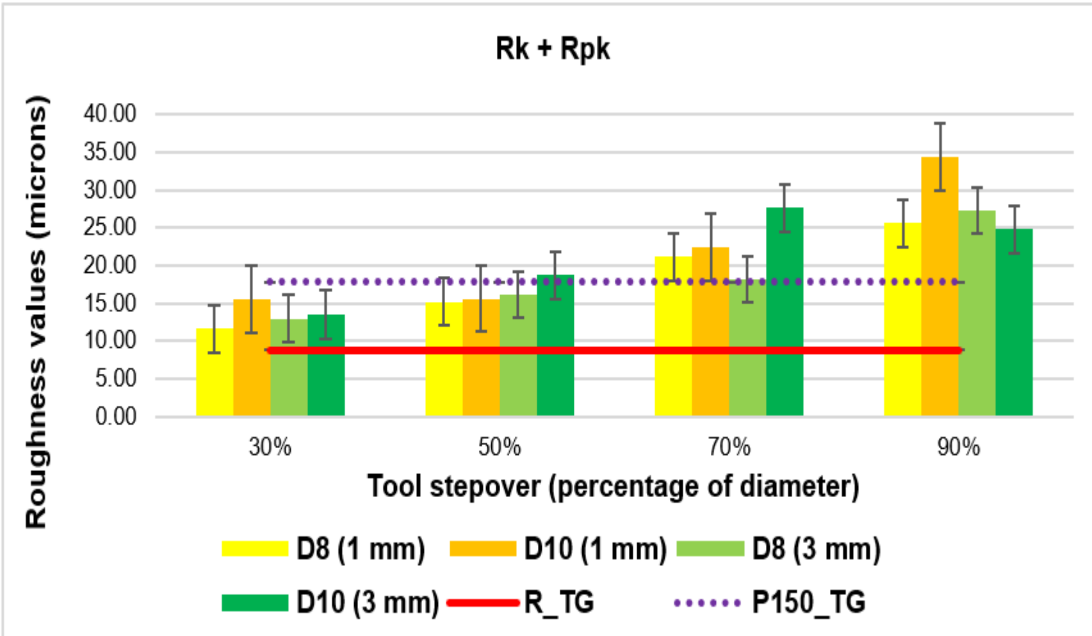


Fig. 3. Comparative analysis of the R_k+R_{pk} mean values in oak CNC machined with D8 and D10, referenced to the shaved surface (R_TG) and the sanded surface P150_TG. The values in brackets represent the cutting depth.

Table 2. Three-way ANOVA for R_k+R_{pk} for Frontal/Face Milling

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2481,887[a]	15	165,459	9,945	,000	,757
Intercept	25612,802	1	25612,802	1539,494	,000	,970
Tool	139,772	1	139,772	8,401	,006	,149
Stepover	2005,151	3	668,384	40,174	,000	,715
Depth	,589	1	,589	,035	,852	,001
Tool * Stepover	26,641	3	8,880	,534	,661	,032
Tool * Depth	3,478	1	3,478	,209	,650	,004
Stepover * Depth	87,541	3	29,180	1,754	,169	,099
Tool * Stepover * Depth	218,715	3	72,905	4,382	,008	,215
Error	798,584	48	16,637			
Total	28893,272	64				
Corrected Total	3280,471	63				
a. R Squared = ,757 (Adjusted R Squared = ,680)						

Given the fact that the stepover and the tool diameter were identified as highly statistically significant a comparative visual analysis is further presented in Figs. 4, 5, and 6.

The comparison includes both primary and roughness profiles obtained at a cutting depth of 1 mm, which was selected as representative for the fine milling, that generated the highest surface quality. It has to be mentioned that the profiles are offset one-another on the y-axis, in order to bring them together in a single comparative image. Therefore, the numbers on the y-axis do not represent the profiles' real location, with the exception for the profiles resulting from shaving, aligned against the "zero line", which is the correct "mean line" during filtration. Although the profiles are offset, they keep their real magnitude in the y-direction.

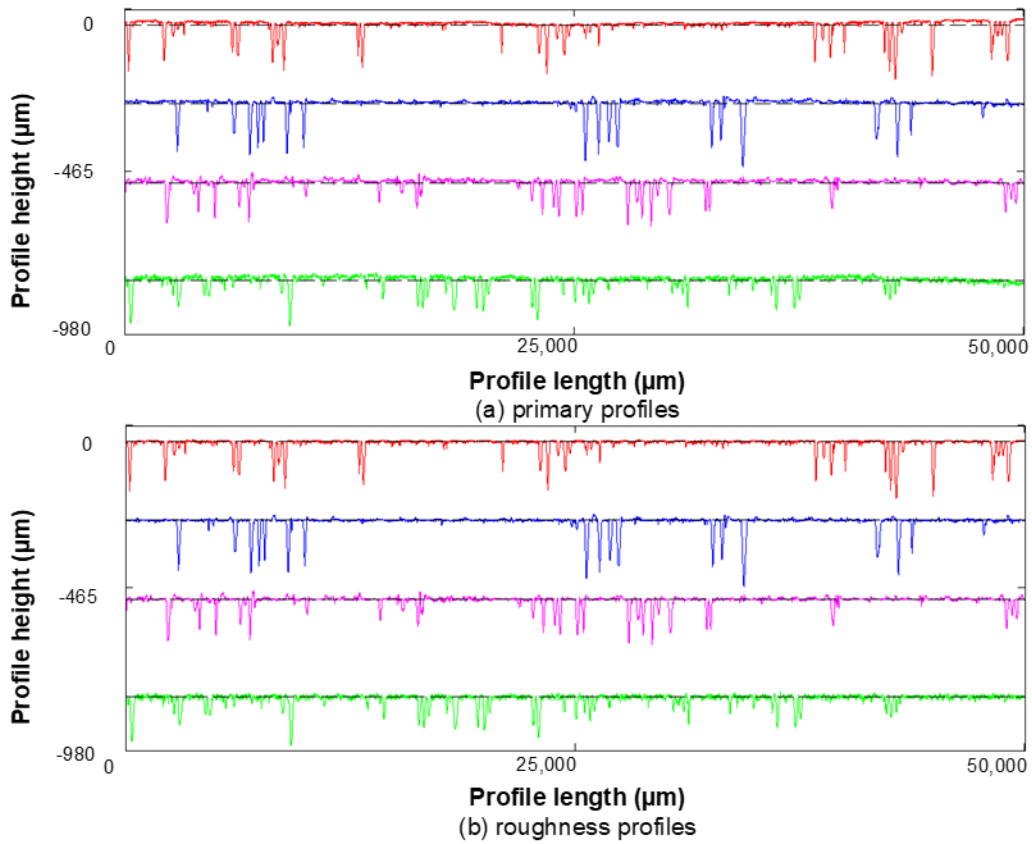


Fig. 4. Comparison between primary and roughness profiles of shaved surfaces, milled surfaces at a stepover of 30% and cutting depth of 1 mm and sanded surfaces with grit size of 150: red - shaved surface, navy blue – milled surface with 8 mm diameter, magenta - milled surface with 10 mm diameter, green - sanded surface

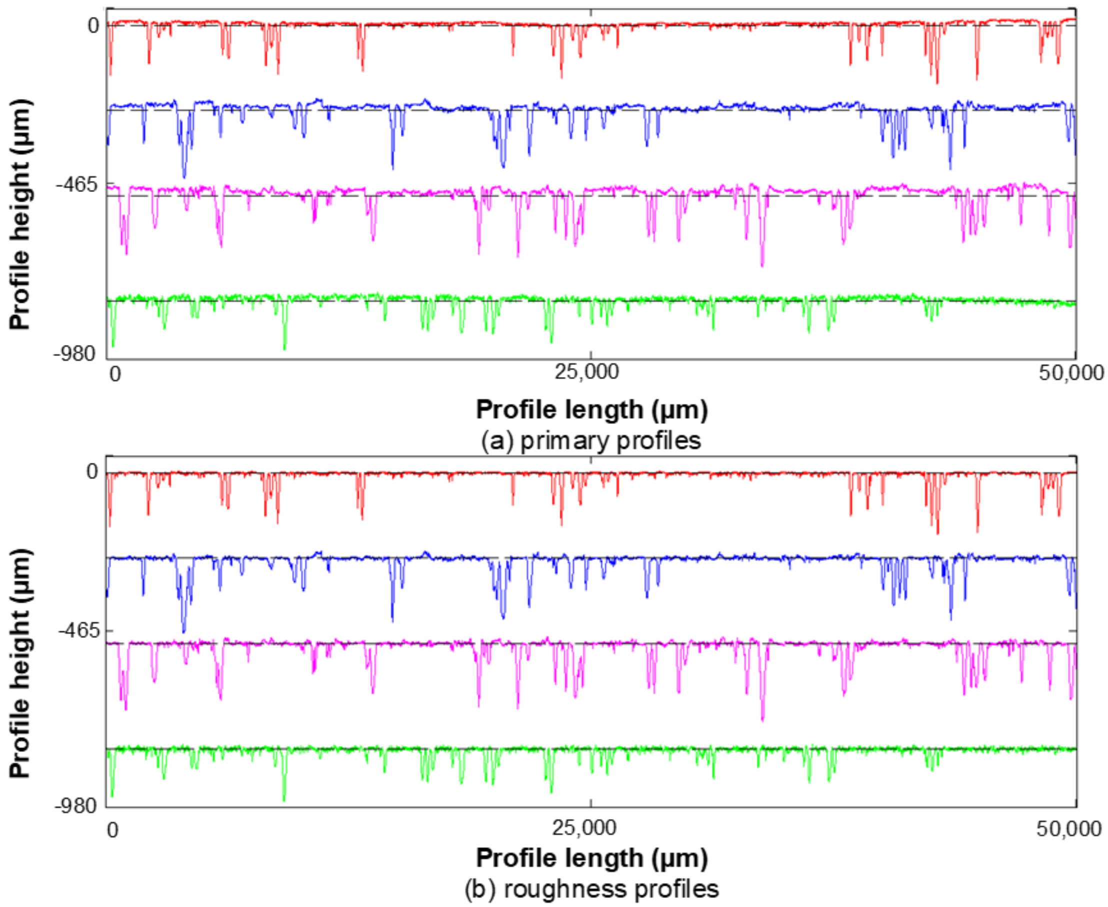


Fig. 5. Comparison between primary and roughness profiles of shaved surfaces, milled surfaces at a stepover of 50% and cutting depth of 1 mm and sanded surfaces with grit size of 150: red - shaved surface, navy blue – milled surface with 8 mm diameter, magenta - milled surface with 10 mm diameter, green - sanded surface

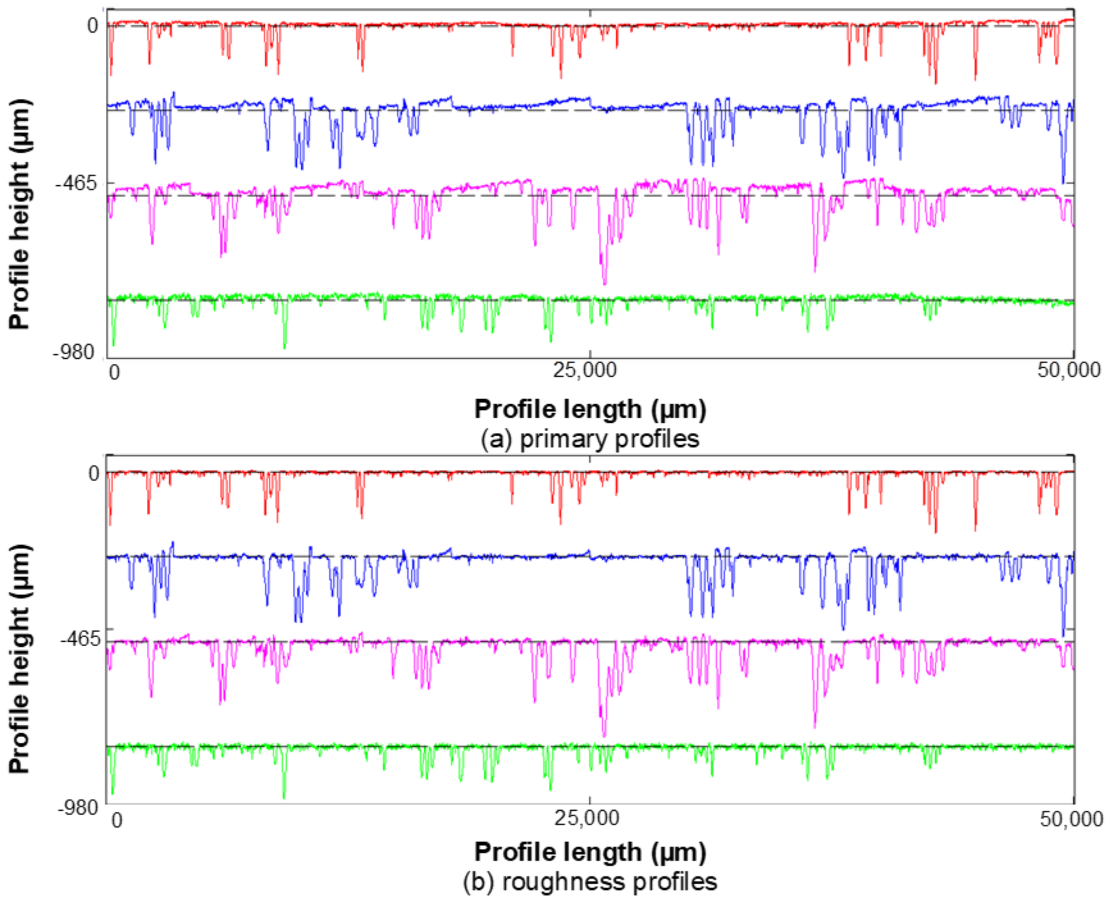


Fig. 6. Comparison between primary and roughness profiles of shaved surfaces, milled surfaces at a stepover of 90% and cutting depth of 1 mm and sanded surfaces with grit size of 150: red - shaved surface, navy blue – milled surface with 8 mm diameter, magenta - milled surface with 10 mm diameter, green - sanded surface

The primary profiles differ from the roughness profiles by an additional waviness component (longer wavelength irregularities), which appears as ridges on the surface, caused by the stepover of the tool, discrete for a stepover of 30%, but increasing their magnitude as the stepover increases. Those ridges are mostly eliminated in the process of filtering the roughness profiles, but they contribute to a further reduction in the surface quality, especially for stepover values higher than 50%.

The negative skewness in Table 1 as well as the R_v values in the range of the earlywood pores of oak, indicate that the valleys in the roughness profiles are measures of the pores' lumens, which appear grouped in the earlywood and go much deeper compared to the core roughness irregularities. As the pores occur as an anatomical feature, independent of machining, the profiles should be compared by observing the magnitude of irregularities in the profile core and in latewood areas. In this way, it can be observed in Fig. 4, that the P150 sanded surface presents the highest roughness in the central region of the profile. This is also reflected by the higher frequency and magnitude of the irregularities in this area, corresponding to the marks produced by the abrasive particles on the surface.

Another observation is that the sanded profiles seem to have lost the frequency of earlywood pores. Their number and depth diminished, which may be the result of sanding dust penetrating the cells lumens (de Meijer 2004; Gurău *et al.* 2015). This assumption was later confirmed by the microscopic surface examination. In contrast, super surfacing and fine milling with 30% stepover revealed well the anatomical depths of the earlywood. Compared to the 30% stepover, the 50% stepover (Fig. 5) generated more pronounced irregularities in both the primary and roughness profiles cores. In the primary profiles, the traces associated with the lateral step become visible for both milling tools, indicating a strong influence of the tool path on the surface morphology.

At the 90% stepover (Fig. 6), the primary and roughness profiles revealed deeper valleys (maybe due to material detachment) and higher irregularity amplitudes, while the ridges generated by the lateral step became accentuated for both tools, particularly for D10.

The visual comparison of the primary and roughness profiles agrees with the comparison of roughness parameters in Table 1 and the evolution of R_k+R_{pk} in Fig. 3, indicating that frontal milling with stepovers higher than 50% leave a surface quality inferior to that of sanding, while the quality closest to the shaved surface is produced by the 8 mm end mill diameter, for stepover equal or less than 30%. To achieve a comprehensive understanding of the surface quality obtained when machining with the two tool diameters, a comparative analysis was performed based on the stereomicroscopic images presented in Figs. 7 and 8. Fig. 7 provides a visualization about how the anatomical structure is affected (left intact, impaired or obscured) by different processing conditions, namely super surfacing, milling with D8 and D10 tools, and sanding.

Fig. 7. Comparative microscopic images of oak tangential surfaces processed by: a - super surfacing; b - D8 at 1 mm depth of cut; c - D10 at 1 mm depth of cut; d - sanded with gritsize P150. Magnification x180.

The super surfaced samples revealed the highest surface quality, showing clearly visible uniseriate and pluriseriate rays, smooth fibre regions, and well-defined vessel boundaries without fibre detachment or anatomical damage (Fig. 7a). In contrast, the sanded surfaces presented extensive raised fibre areas and fuzziness, while the multiseriate rays and vessels became difficult to distinguish because of torn fibres (Fig. 7d). These observations are consistent with the roughness results (Table 1). Between the two straight-flute tools, the D8 cutter generated, for a stepover of 30%, surfaces, visually closer to the super surfaced reference. The anatomical elements remained comparatively well observable, with fewer raised fibres and fibre detachment zones (Fig. 7b). The quality observed for the surface processed with D10 (Fig. 7c), looks rougher than that of D8 and smoother than the one obtained by sanding.

Figure 8 compares the quality obtained with the two diameter tools for the four stepover values used. This representation enables the identification of surface morphology changes associated with increasing stepover, highlighting the influence of this parameter on surface quality.

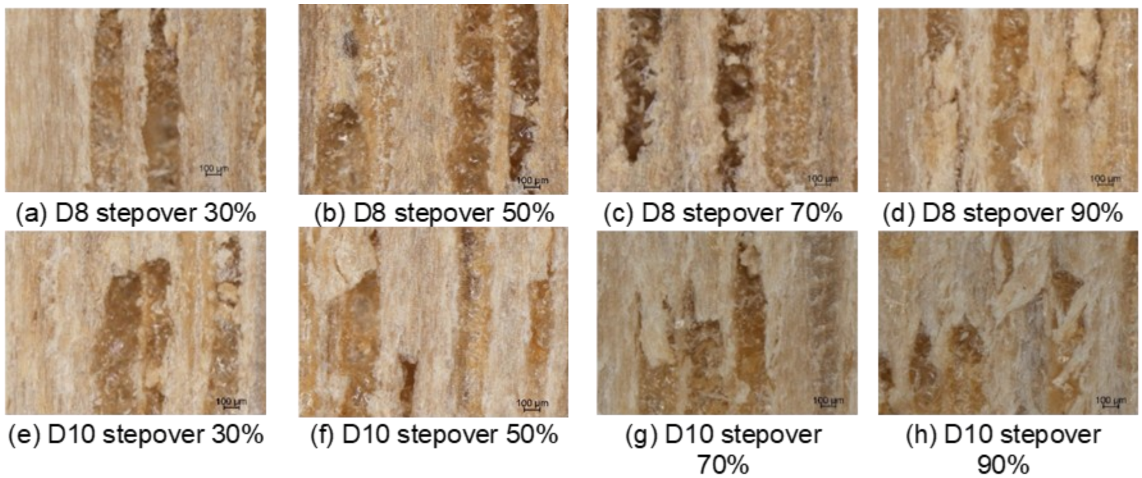


Fig. 8. Comparative stereomicrographs of oak processed by D8 and D10, for 1 mm cutting depth and 4 stepover values. Magnification x120.

The images in Fig. 8 show the deterioration of the oak surfaces with the increase of the stepover value, confirming the tendency observed in the mean roughness values. Higher stepover values produced more fibre tearing, fractured cell walls, and impaired anatomical structure. The D8 tool generated smoother surfaces, with reduced fibre damage, especially at 30% and 50% stepover. In contrast, the D10 tool produced larger areas with raised fibres and more severe fibre detachment, especially at 70% and 90% stepover values.

D8 produced the best milling quality at a stepover of 30%, which was shown not only by the values of the roughness parameters, but also by the stereomicrographs in Figures 7 and 8. This surface quality was closest to the shaved surface and finer than that of sanding. Figure 9 contains this comparison in SEM images, taken at a high magnification of x1000, which provides a much more detailed visualization of the surface morphology than the stereomicroscopic images, in terms of better sensing the machining defects and anatomical damage. The anatomical structure was still identifiable in surfaces processed with the D8 tool at 30% stepover but, in comparison with shaving, milling seemed to produce some local fibre fractures and small torn regions, as well as wood material compression.

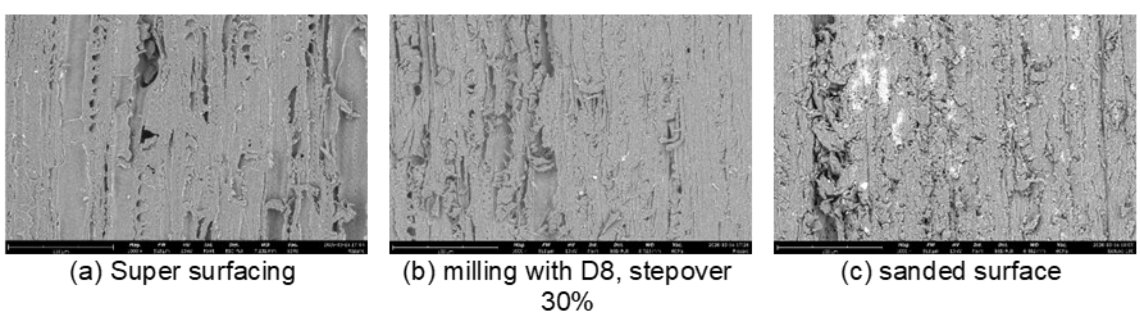


Fig. 9. Comparative SEM micrographs of oak tangential surfaces obtained by shaving (a) processed by D8 end mill at 1 mm depth of cut and 30% stepover (b) and sanded with grit size P150 (c). Magnification x1000

The sanded surface showed severe fibre tearing, compressed material, and irregular detached material deposits that partially masked the anatomical cells of wood, for example pores. Several bright areas were also observed on the sanded surface, corresponding to the abrasive paper residues remaining after processing. The chemical analysis performed on these white regions revealed, besides carbon and oxygen, traces of magnesium (Mg), silicon (Si), sulfur (S), titanium (Ti), zinc (Zn), and rubidium (Rb), indicating contamination originating from the abrasive particles of the P150 sanding paper.

It appears that the surface morphology depends on the physical mechanism of material removal. Super surfacing relies on a fixed, high-precision micro-blade acting transversely to the wood grain under uniform mechanical belt pressure. This continuous shearing action slices a uniform, micro-thin wood layer without destabilising the cell walls, leaving perfectly clear cell boundaries, intact ray alignments, and a minimally distorted anatomical structure. Conversely, sanding is an aggressive abrasive process in which grit particles mechanically gouge the material. This cutting mechanism subjects the fibers to intense friction, high compression, and multi-directional tearing. This leaves behind extensive sub-surface cell collapse, grain fuzziness, and compacted microscopic dust that masks pore pathways.

Furthermore, X-ray spectroscopy revealed that abrasive belt friction fractures the synthetic bonding matrices, embedding mineral contaminants directly into the porous wood substrate. Frontal cutting with end mills removes wood by rotating the cutters that shear fibers away cutting across and along the grain simultaneously. This can cause tear-out if the grain lifts against the cutter's direction. Even so, under controlled stepover and tool diameter, the quality can exceed that obtained through common sanding.

Surface Quality of CNC Machined Oak by Peripheral/Edge Milling

The reference surfaces processed by shaving and sanding (tangential for frontal milling and radial for peripheral milling) had very close R_k+R_{pk} values: 8.83 µm and 8.50 µm for shaving, respectively, 17.74 µm and 16.19 µm for sanding (Table 1 and Table 3).

For the longitudinal oak edges, exposing a radial wood section, the super surfaced radial reference (R_RAD) produced the highest surface quality, reflected by the lowest R_k+R_{pk} value, 8.50 µm (Table 3). In contrast, the radial sanded surfaces (P150_RAD) showed a pronounced deterioration of the surface morphology, as the R_k+R_{pk} parameter increased to 16.19 µm, almost 2 times higher than for the super surfaced samples. Among the two milling tools, the D8 cutter generated surfaces within the quality of the reference surfaces, with lower R_k+R_{pk} values, by 13 to 19%, at both cutting depths compared to D10.

As in case of frontal tangential surfaces, R_a and R_v are parameters influenced, therefore biased, by the earlywood pores and by their occurrence on the surface and are not useful for sensing the effect of tools on the oak surface quality (Table 3).

Table 3. Mean Values Roughness Parameters in µm Measured for Oak Longitudinal Radial Edges Processed by the D8 and D10 Tools, at a Cutting Depth of 1 and 3 mm, by the Super Surfacer on Radial Surface(R_RAD) and by the Sanded, Radial Surface (P150_RAD)

Roughness parameter (µm)	R_RAD	D8 (1)	D8 (3)	D10 (1)	D10(3)	P150_RAD
R_a	9.19	9.34	9.14	10.18	12.28	7.02
	(2.60)	(3.08)	2.50	3.31	2.92	0.91
R_v	217.60	145.72	137.79	136.14	149.85	135.14
	13.01	(43.64)	23.90	37.53	26.54	31.32
R_{sk}	-4.81	-4.16	-4.07	-3.63	-3.47	-4.60
	0.77	(0.93)	0.77	0.80	0.42	0.58
R_k	6.42	8.50	8.39	8.69	10.36	12.34

	1.06	(1.06)	1.13	0.94	1.19	0.56
Rpk	2.08	6.84	6.89	8.71	7.87	3.85
	0.80	(2.10)	1.90	7.60	2.99	0.52
R_k+R_{pk}	8.50	15.34	15.28	17.40	18.23	16.19
	1.45	(1.89)	2.40	8.08	3.10	0.94

Note: Cutting depth values are given in brackets in mm. Standard deviations are provided in brackets below the mean values.

The statistical analysis (Table 4) showed that the tool type significantly influenced the R_k+R_{pk} parameter (p = 0.009), while the cutting depth had no statistically significant effect (p = 0.683), similarly to the behaviour previously observed for the face milled surfaces. This indicates that increasing the cutting depth from 1 to 3 mm did not produce significant modifications of the roughness parameters, which represents an important practical advantage because higher material removal rates can be achieved without significantly affecting the surface quality. Furthermore, the interaction between tool and cutting depth was also not significant (p = 0.640), showing that the effect of the tool does not depend on the cutting depth used.

Table 4. Three-way ANOVA for R_k+R_{pk} for Longitudinal Radial Edge Milling

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	158,932[a]	3	52,977	2,517	,063
Intercept	26333,050	1	26333,050	1250,958	,000
Tool	150,751	1	150,751	7,161	,009
Depth	3,534	1	3,534	,168	,683
Tool * Depth	4,646	1	4,646	,221	,640
Error	1936,628	92	21,050		
Total	28428,610	96			
Corrected Total	2095,560	95			
a. R Squared = ,076 (Adjusted R Squared = ,046)					

Figure 10 confirms the tendencies observed in Table 1 for the R_k+R_{pk} parameter. The D8 tool generated lower roughness values than D10 at both cutting depths, maintaining the surface quality between the super surfaced reference and the sanded reference. In contrast, the D10 tool produced higher R_k+R_{pk} values, reaching 17.40 µm at 1 mm and 18.23 µm at 3 mm, thus exceeding even the roughness level of the sanded surface. To better understand these differences in surface generation, the roughness and primary profiles were further analysed in order to highlight the modifications produced in the anatomical structure and the distribution of surface irregularities after machining.

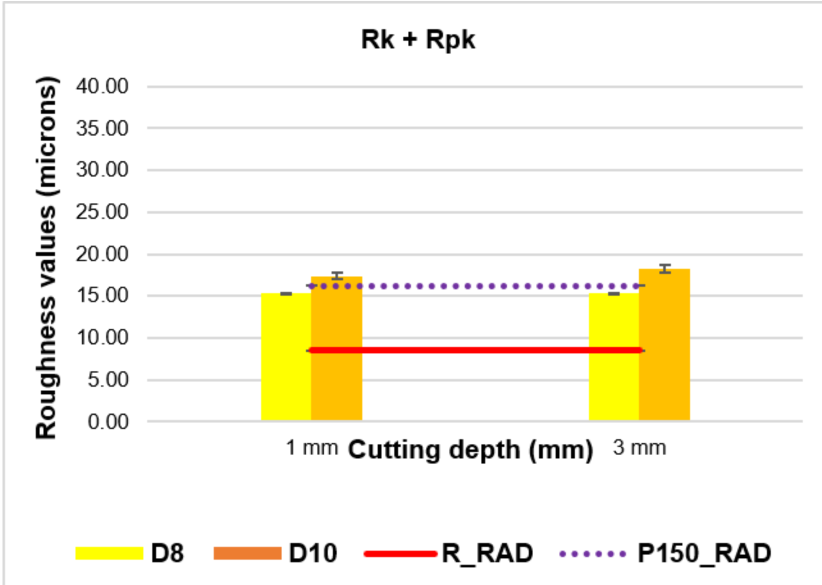


Fig. 10. Comparative analysis of the mean values of R_k+R_{pk} for oak edge milled with D8 and D10 tools, referenced against the radial shaved surface and the radial P150 sanded surface.

Figure 11 presents the primary and roughness profiles obtained for the super surfaced, milled, and sanded oak edge surfaces on radial surfaces. As in case of frontal tangential surfaces, the deep cavities in the profiles can be attributed to the wood pores of earlywood and are present for all types of processing, causing a strongly negative R_{sk}. Their number and distribution depend on the local anatomical variability and not on the processing. The primary profiles contain only the waviness caused by the differences in elasticity between earlywood and latewood, which is well filtered in the roughness profiles. No processing ridges are visible in the primary profiles because measurements were taken perpendicular to the milling direction (across the grain), as with the face-milled surfaces. This specific orientation enables an accurate separation of the Abbott-Firestone curve parameters, R_k and R_{pk}, from the natural anatomical cavities of the wood.

The P150 sanded surface presents a rougher central region of the profile compared to the shaved surface, distinguished by the higher frequency and magnitude of the irregularities distributed along the profile length. These irregularities are associated with the abrasive scratches left by the sanding particles on the wood surface, resulting in a denser distribution of surface peaks and valleys.

The D8 profiles look smoother in the core roughness than those of D10 and of the sanded surfaces, with some protruding irregularities, probably rised fibres, at a depth of cut of 3 mm. No notable differences produced by increasing the cutting depth can be observed in the roughness profiles, supporting the statistical results obtained for the R_k+R_{pk} parameter.

Figure 12 further confirms the differences in surface morphology observed in the roughness parameters and profile analysis. The super surfaced reference exhibits clearly visible anatomical cells, while only limited fibre disruption can be observed (Fig. 12 a, e). In contrast, the sanded surface presents a highly disturbed morphology characterized by extensive fibre fuzziness, compressed fibre regions (Fig. 12 d, h).

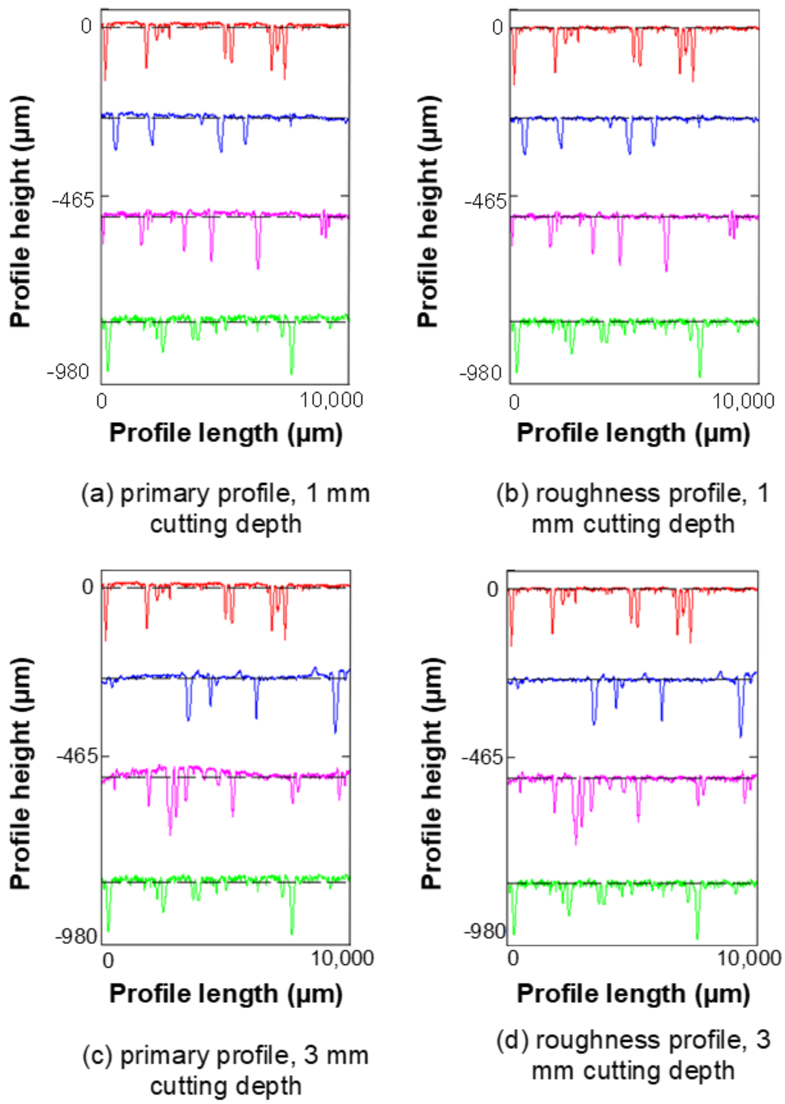
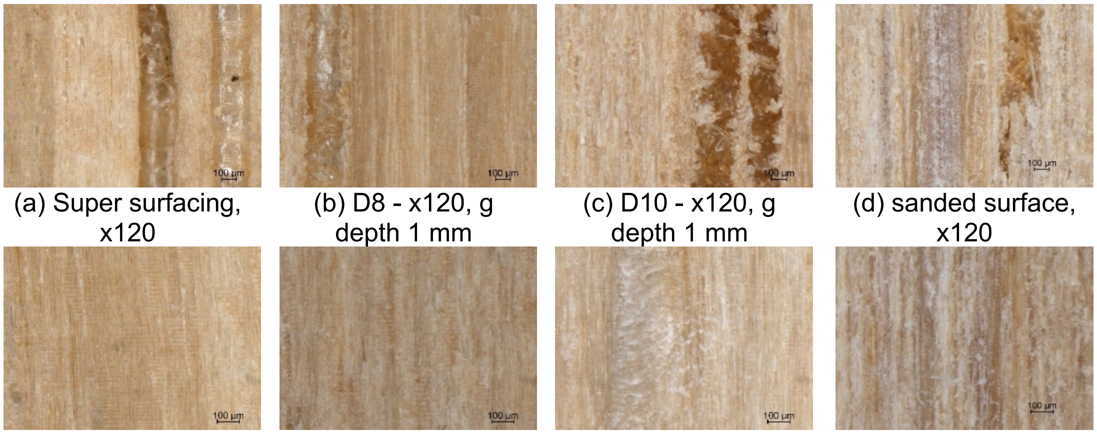


Fig. 11. Comparison between primary and roughness profiles of radial shaved surfaces, milled edge surfaces at 1 and 3 mm cutting depth and radial sanded surfaces with grit size of 150: red - shaved surface, navy blue – milled edge with 8 mm diameter, magenta - milled edge with 10 mm diameter, green - sanded surface



(a) Super surfacing, x120
(b) D8 - x120, g depth 1 mm
(c) D10 - x120, g depth 1 mm
(d) sanded surface, x120
(e) Super surfacing, x180
(f) D8 - x180, g depth 3 mm
(g) D10 - x180, g depth 3 mm
(h) sanded surface, x180

Fig. 12. Comparative microscopic images of oak radial surfaces, processed by shaving (a, e), peripheral milling by D8 (b, f) and D10 (c, g) end mills and sanding with gritsize P150 (d, h)

Among the milled surfaces, the D8 tool generated morphologies closer to the super surfaced reference, maintaining well contoured vessels with limited fibre detachment, even at the 3 mm cutting depth. In contrast, the D10 tool produced more pronounced fibre deformation and torn regions, especially at the higher cutting depth, where the surface morphology became comparable to or even more deteriorated than the sanded reference (Fig. 12 c, g). These observations are consistent with the higher R_k+R_{pk} values obtained for D10 and confirm the more controlled cutting action provided by the D8 geometry.

Comparison between Frontal/Face Milling and Peripheral/Edge Milling

Tables 1 and 3 show that the only comparable qualities of the peripheral milling were with those for 30% and 50% stepover, since the quality for frontal milling deteriorates sharply for stepover values higher than 50%. The quality of radial peripheral milled surfaces, when the same tool was used, was rougher compared to the tangential frontal milling with 30% stepover, but similar, slightly better than that for frontal milling with 50% stepover (Fig. 13). This may be explained by the fact that the specific structural grain boundary exposed to the cutting tool further dictates material failure mechanics due to wood's directional anisotropy. Frontal face milling acts across tangentially oriented surfaces, where the tool path sweeps across flat-sawn annual rings. In this orientation, cutting forces fluctuate rapidly between softer earlywood bands and dense latewood bands, generating cyclic tool deflection and distinct kinematic ridges. In contrast, peripheral edge milling routes longitudinal grain sectors along a radial wood section. Here, the tool cutter meets narrow, vertically stacked growth increments and prominent medullary ray structures perpendicular to the face. This structural boundary exhibits higher shear resistance, rendering radial edge fibers highly susceptible to fracturing and detachment. This is why the effect of the tool action (frontal and peripheral) alone could be more reliably compared on face-edge surfaces with the same orientation (radial or tangential).

The D8 tool generated the lowest R_k+R_{pk} values for both peripheral and frontal milling at 30% stepover, the surface quality ranging between those from shaving and sanding with P150. The D10 cutter produced higher values than those of D8, for both frontal and peripheral milling. Particularly for the edge machining with D10, the roughness (R_k+R_{pk}) exceeded the sanding reference.

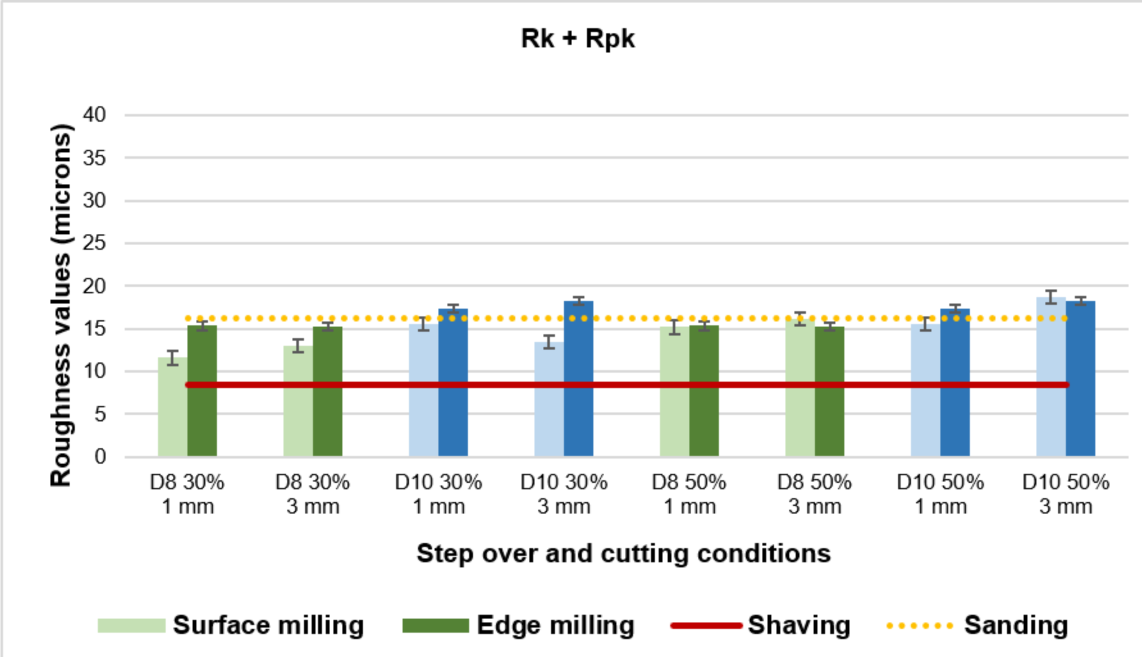


Fig. 13. Comparative analysis of the mean values of R_k+R_{pk} for oak edge and face milling at 30% and 50% step over using D8 and D10 tools, referenced against the shaved surfaces (R_RAD) and the radial P150 sanded surfaces.

A similar tendency was observed at the 50% step over. The D8 cutter provided similar values for both face and edge machining and within the reference surfaces, while the D10 tool showed a rougher surface than D8 and even than the sanded surfaces, especially at the 3 mm cutting depth. These observations are consistent with the previous statistical analysis, which showed that the tool geometry significantly influenced the R_k+R_{pk} parameter. The influence of the cutting depth was not statistically significant. Therefore, the surface quality was determined primarily by the tool diameter rather than by the increase in cutting depth from 1 to 3 mm.

CONCLUSIONS

1. The surface quality achieved by tangential oak frontal/face milling and radial peripheral/edge milling using two end mill tools with diameters of 8 and 10 mm was comparatively analysed for four stepover values (30%, 50%, 70%, and 90% of the tool diameter) and two cutting depths (1 and 3 mm). The quality was referenced, on the same type of wood orientation (tangential or radial), against almost ideally smooth surfaces produced by super surfacing (shaving) and against surfaces sanded with standard P150 abrasive paper as the final smoothing process before lacquering.
2. Among the analysed roughness parameters, R_k+R_{pk} proved to be the most reliable for evaluating the machining quality. The shaved reference surfaces exhibited the highest quality, revealing the oak anatomical structure with high clarity and negligible processing damage, whereas the sanded surfaces showed two times higher roughness than shaving and presented severe fiber tearing, compressed cell walls, accumulation of wood dust that masks anatomical details and contaminants on the wood surface with abrasive paper residues

3. The comparative morphological analysis of the face milled and edge milled oak surfaces did not reveal major differences in machining quality between the two machining orientations at the stepovers of 30% and 50%. However, increasing the stepover in frontal milling to 70% and especially to 90% caused a substantial deterioration of the surface quality, reflected by increased fibre lifting, torn regions, and significantly higher R_k+R_{pk} values. In general, for both face and edge milling, the 8 mm diameter tool generated lower R_k+R_{pk} values than the 10 mm diameter tool for both cutting depths and all stepover values, indicating reduced anatomical damage. Both tools promoted increased ridges and fibre fuzziness as the stepover increased over 50%. The stepover ratio was the primary factor controlling surface roughness, followed by tool diameter, while changing the cutting depth from 1 to 3 mm showed no statistically significant impact on quality.
4. In frontal milling, for 30% and 50% stepover and at 1mm cutting depth, both tools provided a smoother surface in comparison with sanding. In peripheral milling, only the 8 mm tool outperformed the quality of sanding for both cutting depths, while the 10 mm cutter produced more fiber detachment making it unsuitable for direct finishing. Of the two tested tools, the 8 mm diameter cutter operating at the cutting depth of 1 mm and at 30% stepover generated surfaces closely approaching the ideal shaved reference. This proves that, with a careful selection of milling parameters, the objective of transitioning directly from CNC milling to finishing without an intermediate sanding stage is fully achievable. Consequently, utilizing a smaller tool diameter at a low stepover ratio guarantees a finish-ready surface directly from the CNC machine.

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Conflict of Interest

The authors declare no conflict of interest.

Use of Generative AI

The authors declare no use of generative AI.

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