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Article

Comparative Surface Quality of Maple (*Acer pseudoplatanus*) Cut through by CNC Routing and by CO_2 Laser at Different Angles as Related to the Wood Grain

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Abstract: The evaluation of surface quality is an important criterion to understand the effect of the cutting angle in relation to the grain and of the processing tool on wood. This paper examines, in a comparison, the surface quality of maple cut through by CNC and CO_2 laser, for different angles with regard to the wood grain: 0°, 15°, 30°, 45°, 60°, 75°, and 90° and at different feed speeds of the CNC router: 2; 2.5; 3; 3.5 and 4 m/min. The direction of processing as related to the grain was a more significant factor in comparison with the feed speed when CNC was used, with best options for 0°, 90° and 75° and worst for 15°, where fuzzy grain was predominant, followed in order by 30°, 45°, and 60°, where pull-out material prevailed. The laser smoothed the core roughness, Rk, with no significant differences as related to the wood grain direction and enhanced an anatomical waviness earlywood-latewood, with the earlywood processed deeper. As the cutting advanced from along to across the grain, the laser uncovered more wood anatomical details and with less destruction. No significant differences in Rk between CNC cutting and laser processing were found for angles: 0°, 60°, and 75°, but surfaces processed at 15°, 30°, and 45° were significantly rougher in the case of CNC cutting. Comparative FTIR investigation of surfaces cut by laser and CNC (at 0° and 90°) clearly revealed temperature-induced chemical changes, such as hemicelluloses degradation, possibly demethylation and advanced condensation in the structure of lignin, in the case of laser processing.

Keywords: surface quality; CNC routing; CO_2 laser cutting; maple; grain angle; microscopy; chemical changes

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1. Introduction

Computerized numerical control (CNC) routing and laser cutting are two processing methods that can be used for obtaining geometric fretted patterns on thin decorative furniture panels [1], also for applications in 3D flexibilization of wood-based panels by means of kerf/cut through patterns [2–5]. In both cases, the cutting patterns imply that wood material (wood, plywood) is cut under different angles in relation to the grain, which can have a different impact on the surface quality [1,6,7]. Changes that occur in surface topography when processing with both CNC and laser, can affect the product aesthetic as well as the costs of finishing [8–10]. Therefore, the evaluation of surface quality is an important criterion. Furthermore, CNC and laser have different principles of action upon the surface, which will depend not only on the cutting angle but also on the wood species and processing parameters.

As far as the processing with CNC routing is concerned, Goli et al. [6] studied the influence of the grain angle as related to the cutting plane on the surface quality, when routing radial surfaces with the grain and against the grain. The species were Douglas fir (*Pseudotsuga menziesii* Franco var. *menziesii*) and oak (*Quercus robur* L.) processed at different grain angles (from 0° to 90°, in increments of 10°), with different depths of cut, feeding speeds, and revolutions per minute, on a three axes CNC. Surfaces processed with the grain were smoother than those processed against the grain. The best surface quality, measured by the primary profile parameters Pa and Pt, was obtained when the cutting took place along the grain (0°). However, the primary profile parameters measure not only surface roughness, but also waviness and in this case can be unpredictably affected by an elastic response of the wood surface, as well as by any vibration occurring during processing. The wood elastic response consists in the appearance of some waves/bumps as a different reaction of earlywood and latewood after cutting [1,6].

In a later report, Goli et al. [7] studied and classified the mechanisms of surface formation which occur when processing wood. They processed Douglas fir, oak, and beech with a straight blade, on a 3-axis routing machine by up and down-milling at different grain angles, from 0° to 90° and in steps of 10°. The intermediate angles were processed with the grain and against the grain direction. They found that failure split occurs when the wood elements are sloped as related to the cutting plane, and is caused by the poor strength of wood in the transverse section. The wood elements were subjected to transverse tension when cutting was against the grain and to compression, when wood was cut with the grain.

Iskra and Hernández [8] examined the surface roughness obtained by CNC face routing of paper birch wood (*Betula papyrifera* Marsh.) for different cutting parameters, such as: grain orientation (0°, 45°, 90°, 120°, 135°, and 150°), feed speed, and depth of cut. They found that surface roughness (Ra) increased linearly with the feed speed and the surface quality worsened significantly when cutting was against the grain, especially for angles between 120° and 135°.

The cutting direction (along the grain and perpendicular to the grain) was a significant factor affecting the face surface roughness of pine and beech edge-glued panels routed on a CNC machine, as reported by Sütçü [11]. The measurements were made on the bottom of the processed surface.

Hazir et al. [12] studied the surface roughness, evaluated by Ra and Rz, of Cedar of Lebanon pine (*Cedrus libani*) processed by a CNC routing machine. The roughness increased with a decrease in spindle speed, increase in feed rate, and depth of cut. The same surface roughness trend was reported by the study of Gürgen et al. [9], for the Ra parameter, when routing pine (*Pinus sylvestris*).

There is still limited information in the literature concerning the impact of laser parameters on the surface roughness of wood. Among the studies, the majority have focused on the effect of laser engraving on wood [10,13–15] and only a few explored the surface roughness of laser-cut surfaces [1,16,17].

Yakimovich et al. [13] evaluated the surface quality of beech engraved with a CO_2 laser, by using the visual perception of experts attributing grades from 1 (low) to 5 (high quality). The best results were obtained for laser powers ranging from 5 to 10 W, combined with scanning speeds of 600 to 800 mm/s.

Gurau and Petru [14] found that roughness parameters (Ra, Rsk, Rt, Rk, Rpk, and Rvk) increased with increased laser power and decreased with decreased laser scanning speed when engraving Norway Maple *(Acer platanoides*) on radial faces with a CO_2 laser. The laser power output varied from 5.6 to 8 W, and the scanning speed, from 100 to 500 mm/s. The roughness parameters had a linear trend with the laser power and a logarithmic correlation with the laser scanning speed.

Kúdela et al. [15] investigated the surface quality of beech wood engraved by a CO_2 laser moving along the grain on the radial face. At 8% laser power (11 W), the roughness parameters (Ra, Rq, Rz, and Rt) and waviness parameters (Wa, Wt) measured parallel as well as perpendicular to the grain increased proportionally with the increasing raster density.

Li et al. [10] examined the surface roughness expressed by Ra and Rz of poplar engraved along the grain by a CO_2 laser at powers of 11, 13, and 15 W and 300, 350, and 400 mm/s scanning speed. They found that surface roughness increased with an increase in the laser power and a decrease in the feed speed and in the scanning gap. The roughness increase was attributed to the heat produced by the laser, which caused carbonization and vaporization of different wood constituents and consequently made the surface rougher by the destruction of wood surface tissues.

With regard to the laser cutting, the quality was assessed, by some authors [18–20], by measuring the kerf width and the depth of heat affected zone (HAZ), while few studies effectively explored the surface quality expressed by surface roughness parameters. As such, Ref. [18] studied the effect of cutting pine (*Pinus sylvestris* L.) with a CO_2 laser, at an output power of 2 kW and concluded that the area affected by the laser depends on the material, earlywood or latewood zones, cutting direction, and laser energy per section. The heat-affected zone (HAF) was smaller when laser cuts were parallel to the grain, compared with cutting perpendicular to the grain and latewood areas were less damaged in comparison with earlywood.

Eltawahni et al. [19] stated that the laser process parameters have a great influence on the width of kerfs and quality of the cut edges. When cutting plywood of different thicknesses the upper and lower kerf increased with the laser power and decreased with the cutting speed. A slow cutting speed and high laser power, will melt, carbonize and evaporate more material due to an increase in the local heat. Similar results were reported by [20] when cutting Norway spruce and by [17] when cutting beech, along the grain in a tangential plane, with a CO_2 laser.

Hernandez-Castaneda [16] looked at the surface quality (Ra) of pine wood cut by Ytterbium fiber laser and stated that cutting parallel to the grain produces a better surface quality than across the grain.

Rezaei et al. [17] compared CO_2 laser cut surfaces along the grain of beech with those processed by sawing and concluded that the Ra parameter was rougher in the case of the laser. The variation of Ra with the laser cutting speed (3 or 3.5 m/min) and location of the focal point (on the surface or in the middle of the specimen thickness) was not significant.

A single comparative study was found in the literature with regard to the surface quality of wood, cut through by both processing methods: CNC and laser and for different directions with regard to the wood grain. The surface roughness and waviness were analyzed by [1] on larch (*Larix decidua* Mill.) samples cut through with CNC routing and with laser, under different angles with regard to the wood grain: 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The results indicated the worst surface quality for processing angles of 15° and 60° in relation to the grain for both types of processing, while the best quality was obtained when cutting took place along the grain. Cutting by laser produced a melting effect in latewood areas resulting in a smoothing effect in comparison with earlywood. It would be interesting to see whether these results are common for other species or if they are species dependent.

Both processing methods, by CNC and by laser, taken together in a comparison regarding their effect on the surface quality of the same species cut at different angles in relation to the grain, can offer a deeper understanding of the resulting wood surface topography. The results can serve as a basis for process optimization and selection of the most appropriate option. Therefore, the purpose of this paper is to investigate and compare the quality of the surfaces obtained by cutting maple wood (*Acer pseudoplatanus*) by CNC and by CO_2 laser, at various angles in relation to the grain and at different feed speeds of the CNC routing. The authors performed a similar study on larch [1] and this current research on maple continues a series of studies on different wood species. The interpretation of the surface quality results will be supported by the stereo-microscopic images and analysis of the chemical changes.

2. Materials and Methods

2.1. Wood Samples

Three maple wood (*Acer pseudoplatanus*) panels, with radial cut faces, were first processed by straightening and planning to dimensions of 370 mm × 200 mm × 12 mm. Their moisture content was 11% and their mean density was 615 kg/m^3. Then, samples with sizes of 80 mm × 11 mm × 12 mm were cut out by CNC and by a CO_2 laser, so that their length was at 0°, 15°, 30°, 45°, 60°, 75°, and 90° in relation to the wood grain of the radial face. The cutting model for CNC processing is exemplified in Figure 1. For laser cutting, a similar model was used. Details regarding their processing are provided in Sections 2.1.1 and 2.1.2. The cutting direction was "with the grain" as described by [7]. Only the processed samples' edges (80 mm × 12 mm) were of interest for examining the surface quality, which meant two processed edges were examined per each cut-out sample.

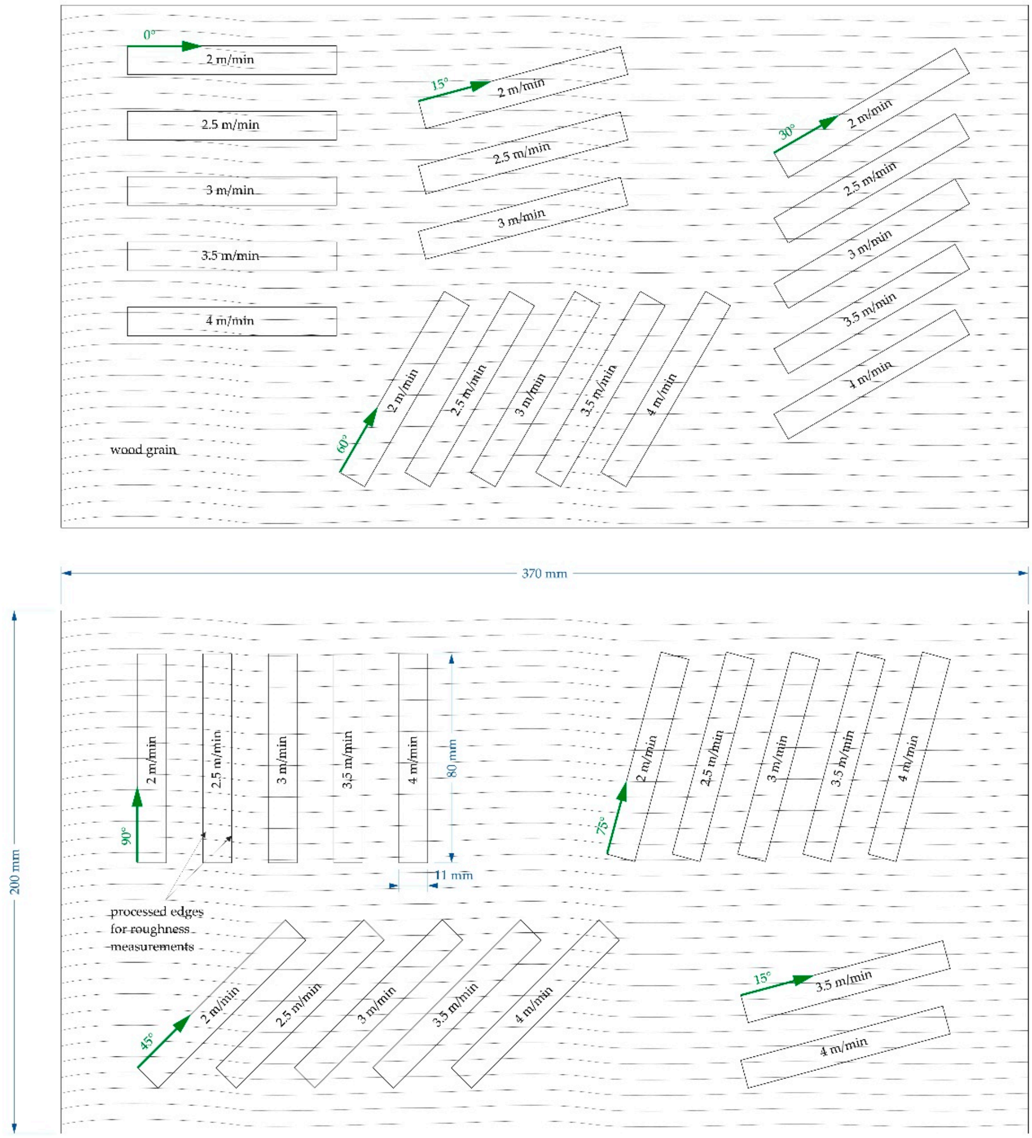


Figure 1. Cutting model for CNC routing of samples cut out from maple panels.

2.1.1. Samples Processed by CNC Routing

For cutting the samples, a CNC router, type ISEL GFV, German production, with 3 axes was used. The processing parameters were: spindle speed of 15,000 rpm and feed speeds of 2 m/min, 2.5 m/min, 3 m/min, 3.5 m/min, and 4 m/min. The cutting depth was set up at 2 mm since this value was also found suitable for a reduced surface roughness by [12]. The tool was an integral helical CMS milling cutter (Figure 2), with Z = 2 UPCUT DR, a diameter of 3 mm, and a length of 40 mm as in [1].

Figure 2. Milling cutter used for cutting out the maple samples.

One sample was cut out for each combination of feed speed (2 m/min, 2.5 m/min, 3 m/min, 3.5 m/min, and 4 m/min) and cutting angle as related to the grain (0°, 15°, 30°, 45°, 60°, 75°, and 90°), so that a total of 35 samples processed on both edges were provided for investigation (Figure 1).

2.1.2. Samples Processed by Laser

The laser equipment was a CO_2 laser engraving and cutting machine OmniBEAM 150 (COHERENT, INC., Santa Clara, CA, USA), with a maximum power of 150 W, 10.6 µm wavelength, and maximum cutting speed of 50.8 m/min, working with nitrogen as the purge gas. Maple samples were cut out using the same angles in relation to the grain as in the case of CNC routing: 0°, 15°, 30°, 45°, 60°, 75°, and 90°, so that seven samples were available, one for each cutting angle. The position of the samples on the panel was configured with BeamHMI software and the cutting power was set to 100%.

2.2. Surface Quality Measurements

The equipment used for surface quality measurements was a MarSurf XT20 instrument manufactured by MAHR Gottingen GMBH (Göttingen, Germany), fitted with an MFW 250 scanning head with a tracing arm in the range of ±750 µm and a stylus with a 2 µm tip radius and 90° tip angle. The specimens' edges were measured along the processing direction, at a speed of 0.5 mm/s, a low scanning force of 0.7 mN, and a lateral resolution of 5 µm. Three profiles, 50 mm long, were recorded for each measured surface, so that a total of six profiles were analyzed for each processing combination. This meant a total of 252 measured profiles for both processing methods (210 for CNC router and 42 for laser).

Further, the measured profiles were processed with MARWIN XR20 software provided by the instrument supplier (Göttingen, Germany). First, form error was removed by fitting a polynomial regression which best fits the measured data. By subtracting the best fit curve from the measured profile, a primary profile is obtained, according to [21]. The primary profile contains irregularities of two types of wavelengths: waviness and roughness. The longest wavelengths correspond to waviness and the shortest to roughness. They were separated by a robust Gaussian regression filter [22], with a cut-off length of 2.5 mm recommended for wood [23–25]. The two sets of data, waviness and roughness profiles, issued the W parameters and R parameters, respectively [21]. Mean values of parameters were calculated, such as: Rv (the largest absolute profile valley depth), Rsk (skewness of the profile), Wa (arithmetical mean deviation of the waviness profile) from [21]. Other calculated parameters were the Abbot-curve parameters: Rk (the core roughness depth), Rpk (the reduced peak height), and Rvk (the reduced valley depth) from [26]. The calculation of Abbot-curve parameters and detailed description is contained in [1]. All roughness parameters are useful because they describe a certain aspect of a surface and their interpretation must be correlated with the material that is measured.

The reason for selecting a diverse series of surface quality parameters is because wood is a complex material, containing a variable anatomical structure overlapping on the roughness caused by processing. Therefore, when examining the quality of wood surfaces, it is recommended to analyze a large set of parameters for a good evaluation [27].

2.3. Stereo-Microscopy Analysis

A stereo-microscope NIKON SMZ 18-LOT2 (Nikon Corporation, Tokyo, Japan) with 405× total magnification was used for the microscopic investigations of the cut edges. Micrographs were taken from all the samples processed by CNC router and by laser and were analyzed in combination with the results obtained by surface quality measurements.

2.4. Chemical (FTIR) Analysis

Fourier transform infrared spectroscopy (FTIR) investigation was employed to reveal the temperature-induced chemical changes on the wood surfaces cut by laser. An ALPHA Bruker spectrometer (ALPHA, Bruker, Ettlingen, Germany) equipped with an attenuated total reflectance (ATR) unit was employed. FTIR—ATR spectra in the range 4000–400 cm^{-1} at a resolution of 4 cm^{-1} and 24 scans/spectrum were recorded on thin (of about 0.2–0.4 mm) samples (with surfaces of about 5 × 8–10 mm. The samples were extracted by cutting with a sharp chisel from the edges of the maple wood specimens previously processed by laser at an angle of 0° and 90° in relation to the wood grain (see Section 2.1). Similarly, samples extracted from CNC cut specimens were investigated as controls. Spectra were registered on three randomly chosen measuring areas from one replicate of each category of wood samples. All spectra were further processed for baseline correction and smoothing, and average spectra were computed employing OPUS software (version 7.2, Bruker, Ettlingen, Germany) for each type of sample. The average spectra were further normalized (min–max normalization) and analyzed in order to highlight specific chemical features of the wood material and the chemical changes brought about by laser processing. Assignment of the characteristic absorption bands was based on references in the literature. Furthermore, a series of relevant absorption bands from the FTIR spectra were integrated employing the OPUS software and some ratios of relevant absorption bands were calculated in order to better highlight the chemical changes of the surface wood chemistry as a result of laser cutting.

3. Results

3.1. Processing with CNC

If anatomy is not removed for wood surfaces, then Rk appears to be the most useful indicator of the processing roughness because Rk is the parameter least affected by the presence of wood anatomy [1,25,27–29]. The parameter Rk is depicted in Table 1 and Figure 3. It shows an increase with the feed speed, with the lowest values for 2 m/min. A value of 2 m/min feed speed was also found suitable for a reduced surface roughness by [12]. The core roughness, Rk, had the highest values for a cutting angle of 15°, followed by 30° and then 45°, 60°, 75°, 0°, and 90°. When analyzed with ANOVA and Duncan test, the feed speed seems to have a less significant effect on the processing roughness in comparison with the cutting angle with respect to the grain. The result was similar to the observations of [1] which studied the processing of larch. For example, when processing along the grain, Rk increased with app. 30% for a feed speed of 4 m/min, compared with 2 m/min. However, changing the cutting angle from 0° to 15°, has increased the processing roughness more than triple, for u = 2 m/min (Table 1), as for larch in the study of [1]. Lowest Rk was obtained for the 90° angle, but the difference in quality (Rk) between 0°, 75°, and 90° was not significant whatever the feed speed, as tested with ANOVA and DUNCAN test ($p < 0.05$) in Table 1.

At a 15° cutting angle in relation to the grain, the tool cuts sequential zones of earlywood and latewood, having different anatomy and cell strength. The detached fibers are shorter than when cutting parallel to the grain, are not completely removed from the surface, and remain with one end attached to the surface. The resulting effect is a fuzzy surface with the maximum occurrence observed for 15° as seen in the micrograph in Figure 4c (encircled with red). This observation is confirmed by the comparison of roughness profiles in Figure 5, as well as by the highest values of Rpk in Figure 6. Rpk is a measure of the isolated peaks, which for a processed wood surface could be raised grain and fuzziness [1,28]. Rpk increased more than three times when the cutting angle changed from 0° to 15° and for u = 2 m/min and increased even six times for u = 3 m/min.

Table 1. Checking the significance on Rk of varying the cutting angle in relation to the grain for various feed speeds.

Cutting Angle, in °	Data	Rk, in µm, at Various Feed Speeds				
		2 m/min	2.5 m/min	3 m/min	3.5 m/min	4 m/min
0	Mean Rk (STDEV) [1] Significance	14.40 (2.72) A [2]	16.16 (2.16) A	18.19 (2.97) A	17.89 (1.81) A	19.23 (1.29) A
15	Mean Rk (STDEV) Significance	52.82 (6.88) E	60.31 (9.60) D	58.75 (14.74) D	60.18 (3.80) E	63.06 (19.91) D
30	Mean Rk (STDEV) Significance	46.1 (4.91) D	48.83 (4.54) C	46.51 (6.69) C	47.37 (3.79 D)	42.84 (6.45) C
45	Mean Rk (STDEV) Significance	29.78 (2.42) C	30.33 (3.24) B	32.64 (2.58) B	36.21 (3.96) C	37.48 (1.97) BC
60	Mean Rk (STDEV) Significance	20.89 (3.09) B	24.70 (3.01) B	24.68 (3.08) AB	25.16 (2.28) B	26.77 (4.25) AB
75	Mean Rk (STDEV) Significance	16.21 (1.73) AB	17.11 (1.70) A	16.95 (2.54) A	17.71 (0.98) A	19.47 (2.74) A
90	Mean Rk (STDEV) Significance	13.64 (1.93) A	13.61 (0.48) A	15.19 (1.32) A	15.59 (1.56) A	17.75 (2.59) A

[1] Standard deviation. [2] Groups with the same letters in columns indicate that there was no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test.

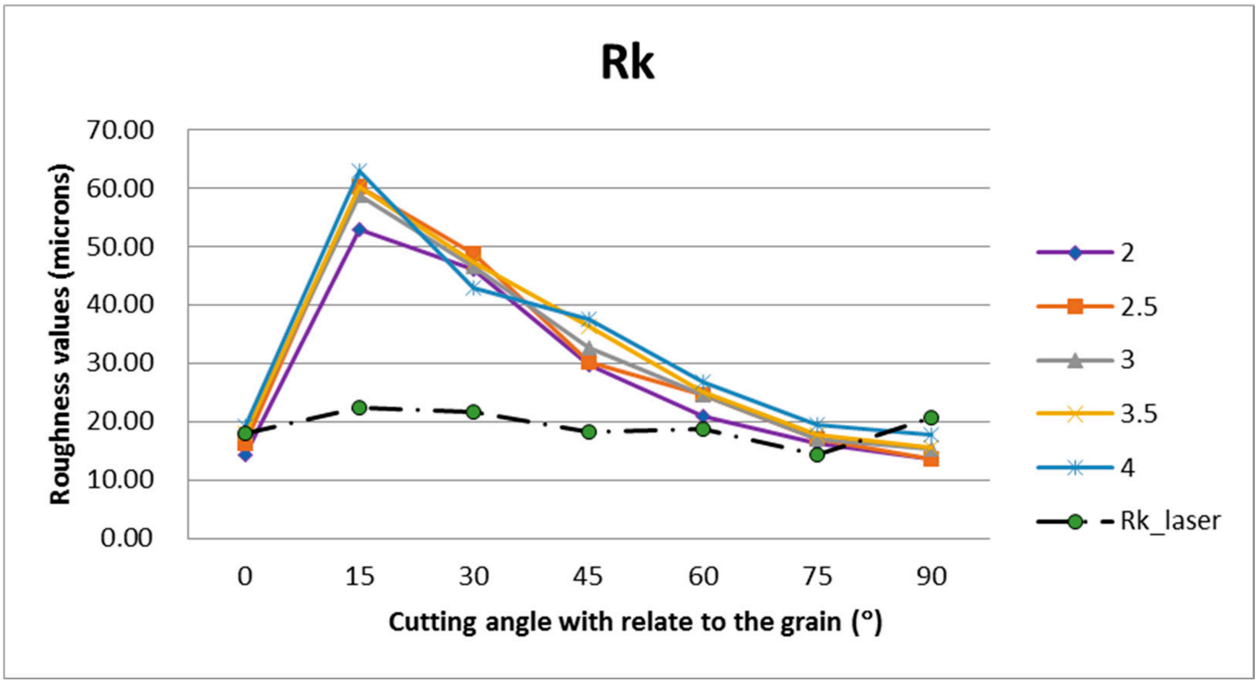
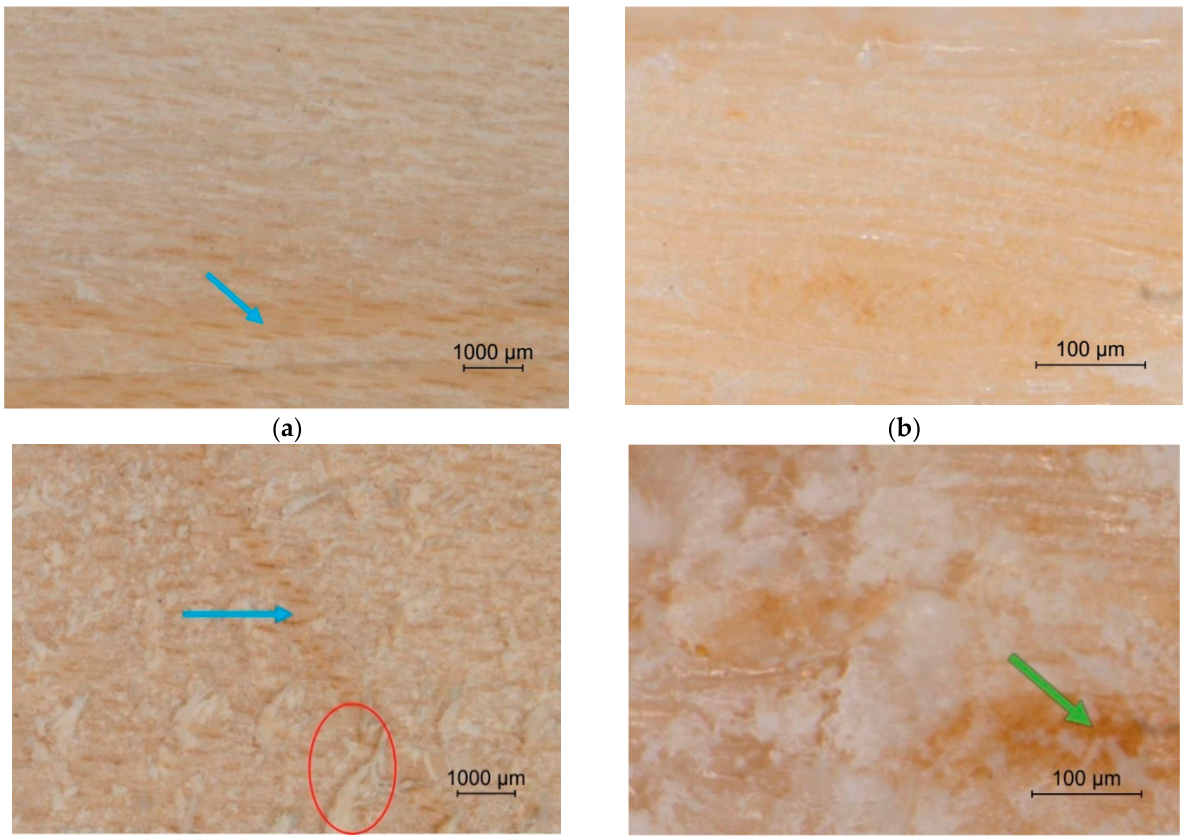


Figure 3. The variation of the roughness parameter Rk (mean values) for different feed speeds (m/min) with the cutting angle at CNC routing. With dashed line, Rk values for laser processing.

The presence of fuzzy grain for cutting at 15° is also shown by Rsk in Figure 7. According to [21], surfaces with a positive skewness, Rsk > 0 have fairly high peaks that protrude above a smoother plateau and in this particular case are an indication of predominant fuzziness. A similar observation was made for larch processed by CNC with identical cutting parameters and at 15° as related to the grain [1]. An increase in fuzziness was also observed by [6] for oak processed at narrow angles (10°/20°) and this phenomenon was more pronounced in lower-density areas (earlywood), while denser areas (latewood) displayed a good surface aspect. Indeed, the wood zone at the growth limit (marked by blue arrows) and characterized by a higher density, looks less affected by fuzziness in Figure 4, for all cutting angles.

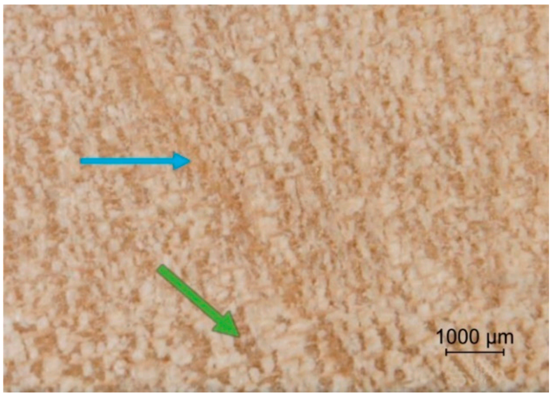
Another noted effect was the occurrence of occasional deep surface gaps. This was observed in the micrographs beginning with a 15° angle (Figure 4c,d), but with a maximum happening for 30° (Figure 4e,f) then 45° (Figure 4g,h), and much less in 60° (Figure 4i,j). In the micrographs, the surface gaps are shown by green arrows. The same effect is visible in the profiles of Figure 5, where examples of deep surface gaps are encircled with green. These observations were also confirmed by the values of Rvk in Figure 8 and Rv in Figure 9. Rvk is a measure of isolated surface gaps caused by material being pulled out during processing and/or anatomical cell lumens that exceed the depth of the processing marks [1,28].



(**a**) (**b**)

(**c**) (**d**)

Figure 4. *Cont.*



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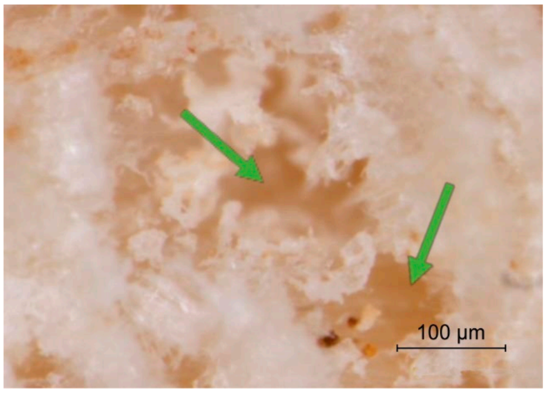

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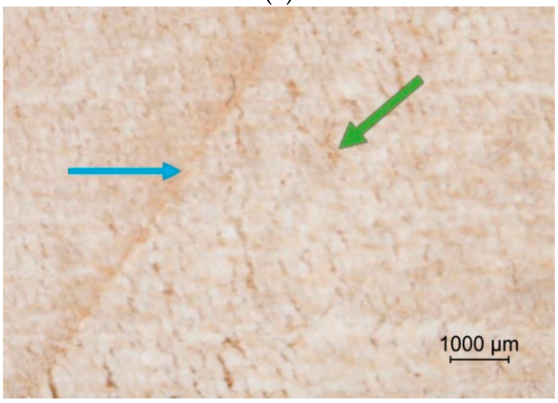

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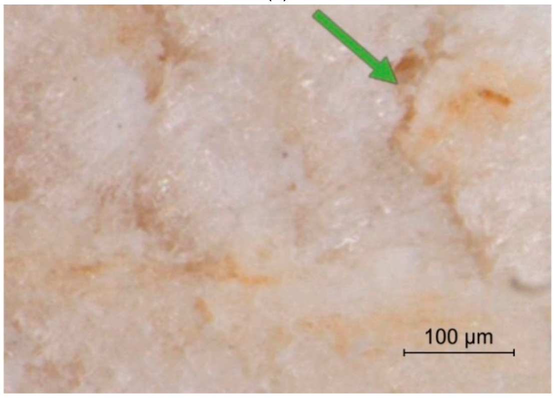

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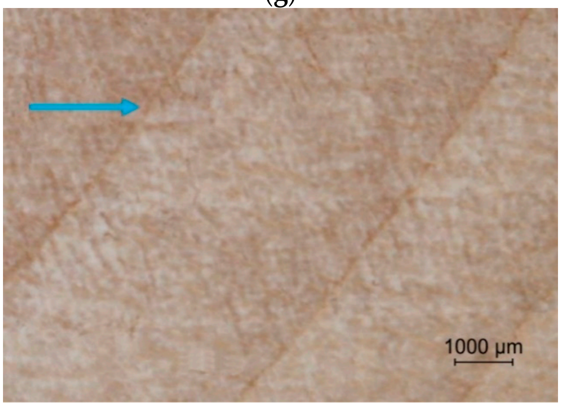

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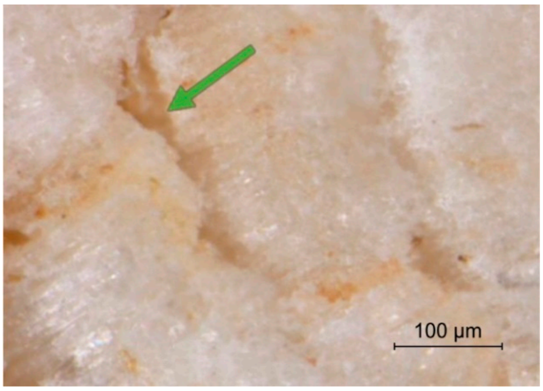

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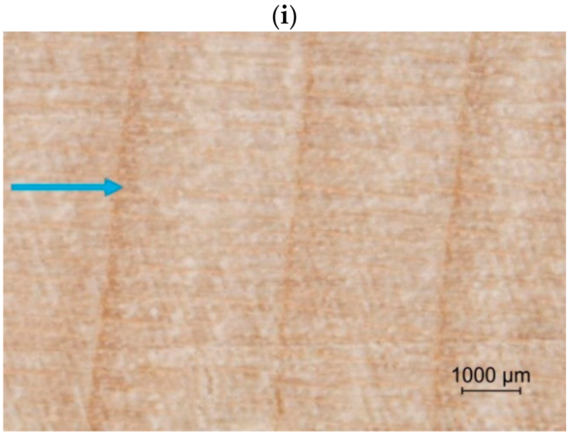

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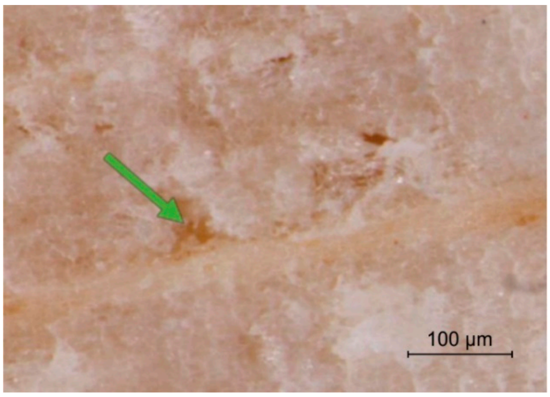

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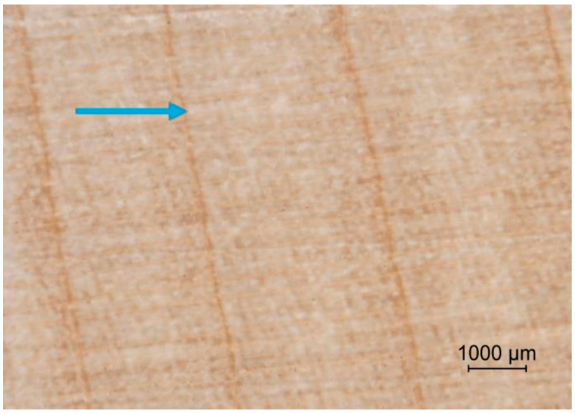
Figure 4. *Cont.*



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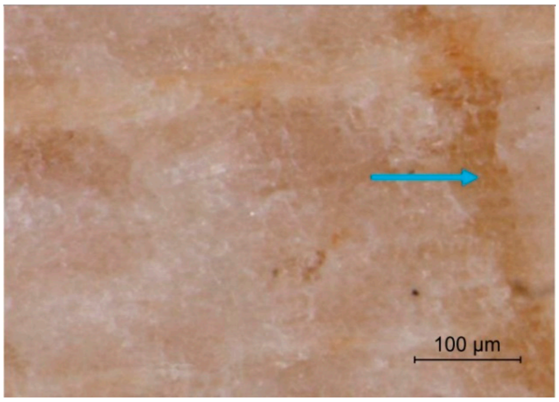
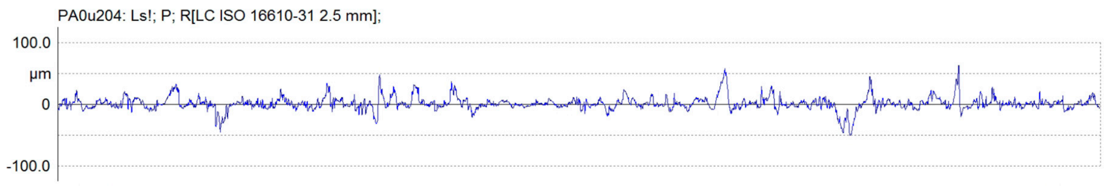


(**n**)

Figure 4. Microscopic images of CNC processed maple (u = 2 m/min) at different angles in relation to the grain and two magnifications, 22.5× and 405×: (**a**,**b**) 0°; (**c**,**d**) 15°; (**e**,**f**) 30°; (**g**,**h**) 45°; (**i**,**j**) 60°; (**k**,**l**) 75°; (**m**,**n**) 90°. Blue arrows point to the growth limit. Green arrows mark deep gaps. Raised wood fiber encircled with red.



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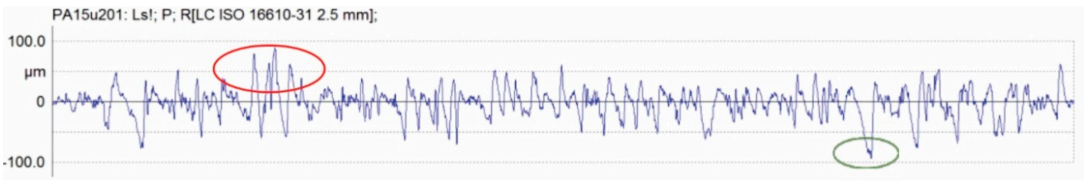

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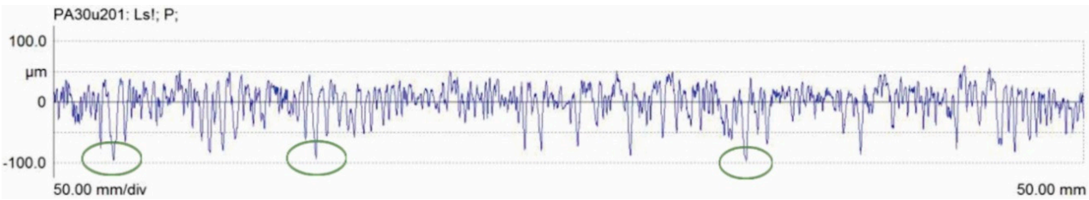

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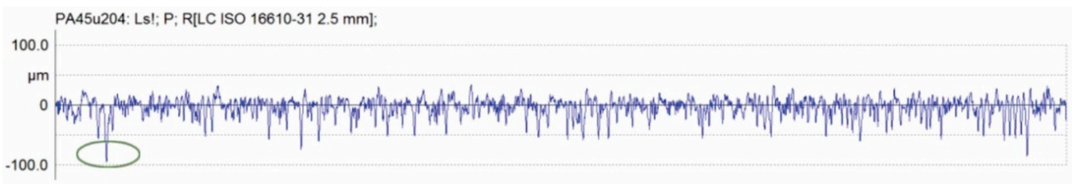

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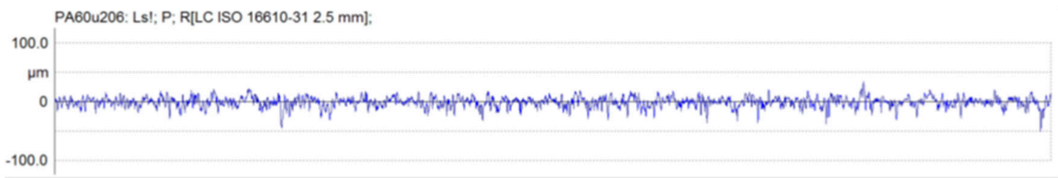


(**e**)

Figure 5. *Cont.*

(**f**)

Figure 5. Comparison of roughness profiles from CNC routed surfaces (u = 2 m/min): (**a**) along the grain; (**b**) at 15° (fuzzy grain encircled with red); (**c**) at 30°; (**d**) at 45°; (**e**) at 60°; (**f**) at 90° as related to the grain. Highlighted with green are surface gaps.

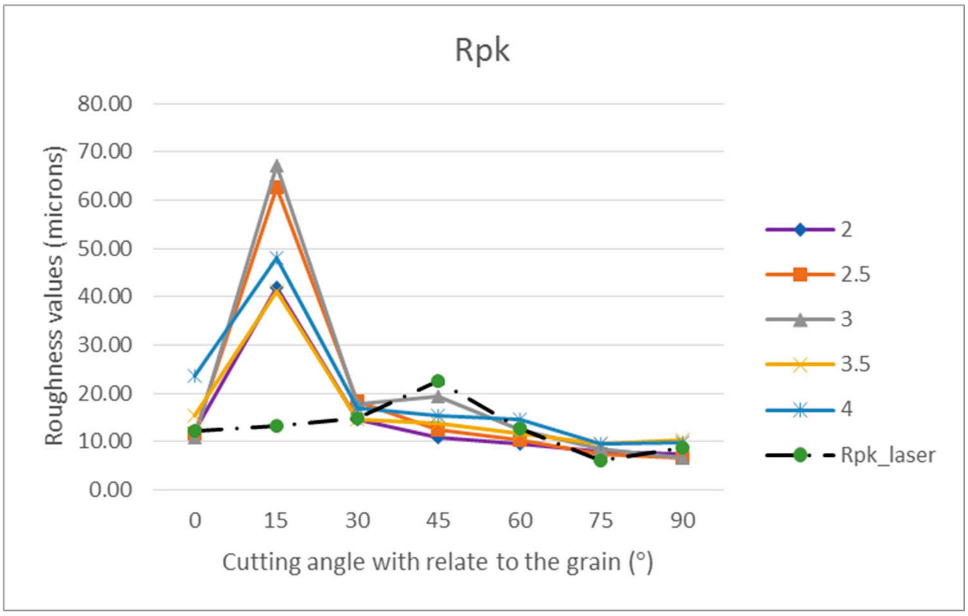


Figure 6. The variation of the reduced peak height parameter, Rpk (mean values), for various feed speeds (m/min), with the cutting angle at CNC routing. With dashed line, Rpk for laser processing.

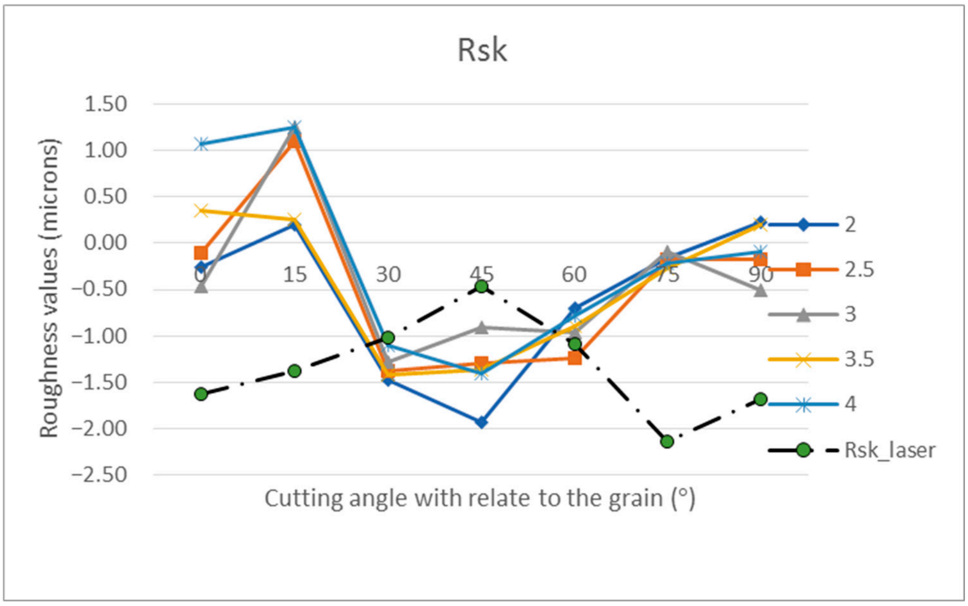


Figure 7. The variation of the skewness of the profile, Rsk (mean values), for various feed speeds (m/min) with the cutting angle at CNC routing. With dashed line, Rsk for laser processing.

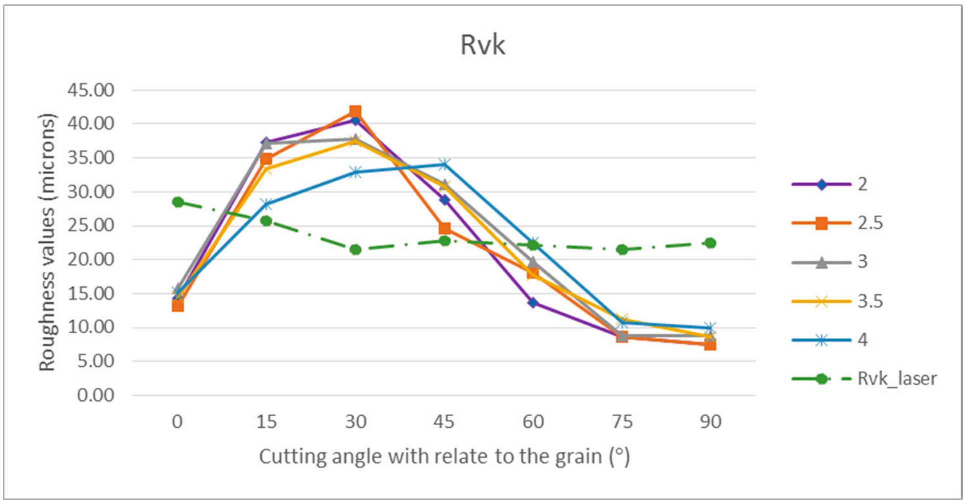


Figure 8. The variation of the reduced valley depth parameter, Rvk (mean values), for various feed speeds (m/min), with the cutting angle at CNC routing. With dashed line, Rvk for laser processing.

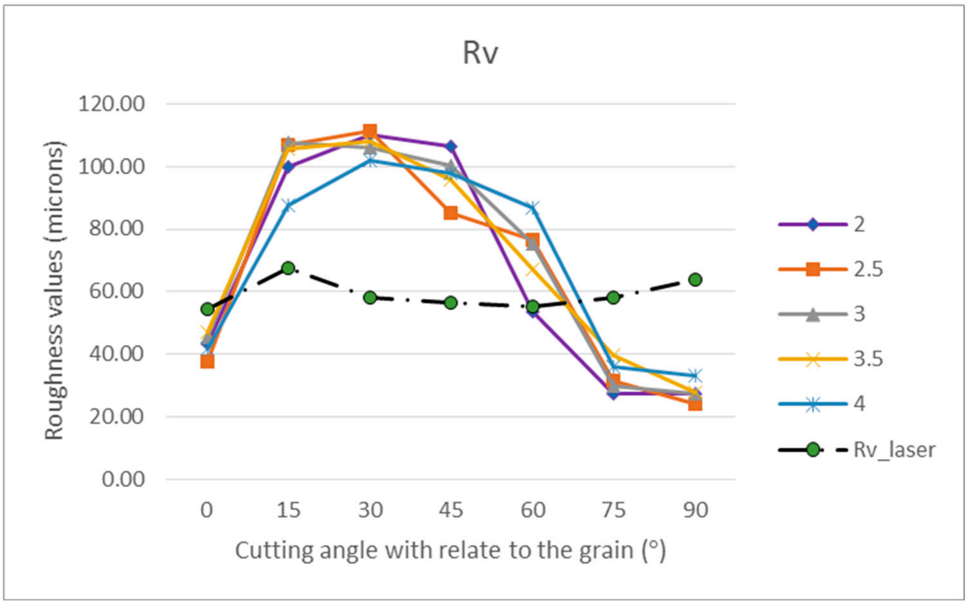


Figure 9. The variation of the largest absolute profile valley depth, Rv (mean values), for various feed speeds (m/min), with the cutting angle at CNC routing. With dashed line, Rv for laser processing.

Theoretically, those isolated valleys may be due to the material being pulled out from the surface or can be due to the vessels' cavities from earlywood. In order to clarify the origin of these isolated surface gaps, Rv, which measures the deepest irregularity value of a measured profile, was analyzed. Rv, had single values greater than the maximum diameter of maple pores: for example, for u = 2 m/min, 118.4 microns for an angle of 15°, 129 microns for an angle of 30° and 134.5 microns for an angle of 45°, when maximum reported earlywood pores are 70, occasionally 110 µm [30]. This is an indication that the deepest isolated gaps in the surface (Rv) are induced, at least, for these specific angles, by the wood interaction with the tool and not by the material anatomy. For 30° and 45°, the surface shows also the strongest negative skewness Rsk, which confirms the prevalence of isolated valleys in the surface as compared to the isolated peaks. Rsk for an angle of 15° was positive, in spite of the fact the surface also contained gaps, and this was because the fuzziness was predominant against the deep valleys. These results for the 15° angle are visible in Figures 5b and 7 and are also shown by a greater than one ratio Rpk/Rvk, which was 1.13 for u = 2 m/min to 1.70 for u = 4 m/min. The prevalence of fuzzy grain against pull-out material was also observed for larch processed at 15° and for all cutting speeds [1]. However, compared with maple, the occurrence of pull-out material in larch occurred from 15° to a maximum of 60°.

As the angle goes higher, namely for 60°, 75°, and 90°, shear efforts progress to efforts transversal to the grain, where wood resistance to split becomes higher. At 90°, was recorded the smoothest surface, with the lowest values of fuzziness (Rpk—Figure 6) and isolated gaps (Rvk, Rv—Figures 8 and 9). Although cutting transversal to the grain generates crosscut pores cavities, they are filled with processing dust (white dots in Figure 4m) and in consequence, Rvk and Rv are smaller than for cutting along the grain. However, the differences in quality in comparison with processing along the grain are not significant (Rk in Table 1). Furthermore, when comparing the micrographs in Figure 4, the visual evaluation indicates 0° as the best option. In the case of larch [1], the best processing roughness (Rk) was obtained when cutting along the grain, at a feed speed of 2 m/min, followed nearly double by angles of 90° and 75°, while the other intermediate cutting angles produced a much rougher surface in comparison with those. Goli et al. [6] observed the best surface quality of oak when routing took place along the grain, the quality decreasing with the cutting angle as related to the grain. However, the parameter they measured was a primary profile parameter, Pt, instead of Rk. Pt contained not only roughness but also waviness and may have suffered from the biasing effect of wood anatomy. Larger pores of oak in comparison with maple, most probably, exposed larger cavities when cutting took place at cross-cut angles. Further research by the authors will include oak in the analysis in order to understand the species-induced quality differences.

Referring to irregularities of larger scale wavelength, the lowest waviness (Wa) was remarked for u = 2 m/min (Figure 10). High waviness in comparison with other cutting angles is produced for 15° and 60°, especially for high cutting speeds. Similar observations were made on larch by [1].

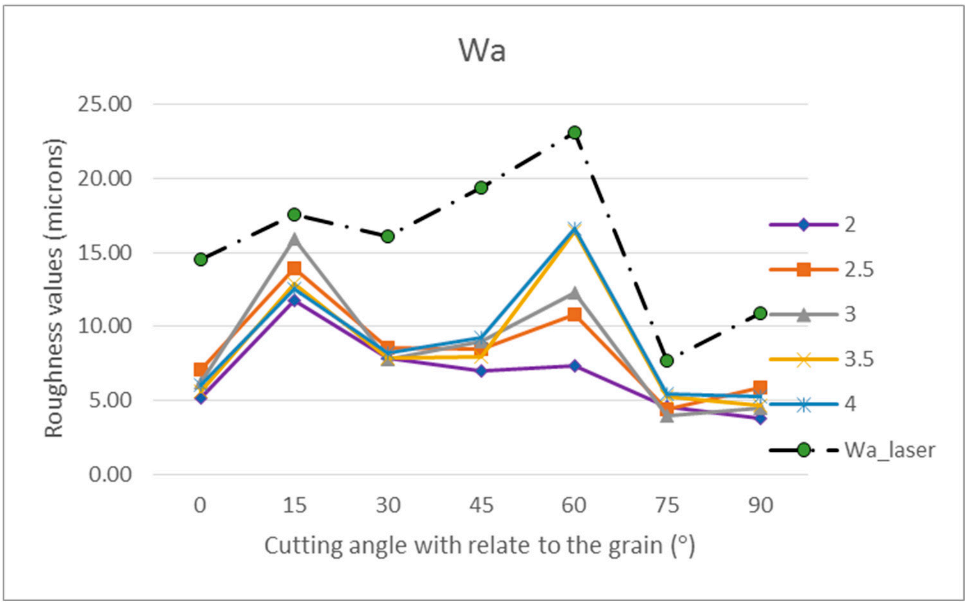


Figure 10. The variation of the mean arithmetic waviness, Wa (mean values), for various feed speeds (m/min), with the cutting angle at CNC routing. With dashed line, Wa for laser processing.

3.2. *Processing with Laser*

Laser cutting is a process that generates high heat, which affects wood through the following stages: melting, carbonization, and evaporation [19]. The laser–wood interaction is influenced by the wood local density, as well as by its different thermal conductivity as related to the grain. Due to those variables, the surface will appear with different degrees of destruction, the tissues being affected by different degradation speeds.

Higher thermal conductivity along the grain and the presence of air in the cells' cavities might have led for crosscutting angle (90°) to a rapid carbonization followed by material vaporization, so that, the remaining wood layer was left almost unaffected, with some molten material in the cavities and some carbonization in the cells' walls and growth transition areas (Figure 11m,n). Wood anatomy is perfectly identifiable. Haller et al. [31] also state that laser is capable of revealing the cellular structure.

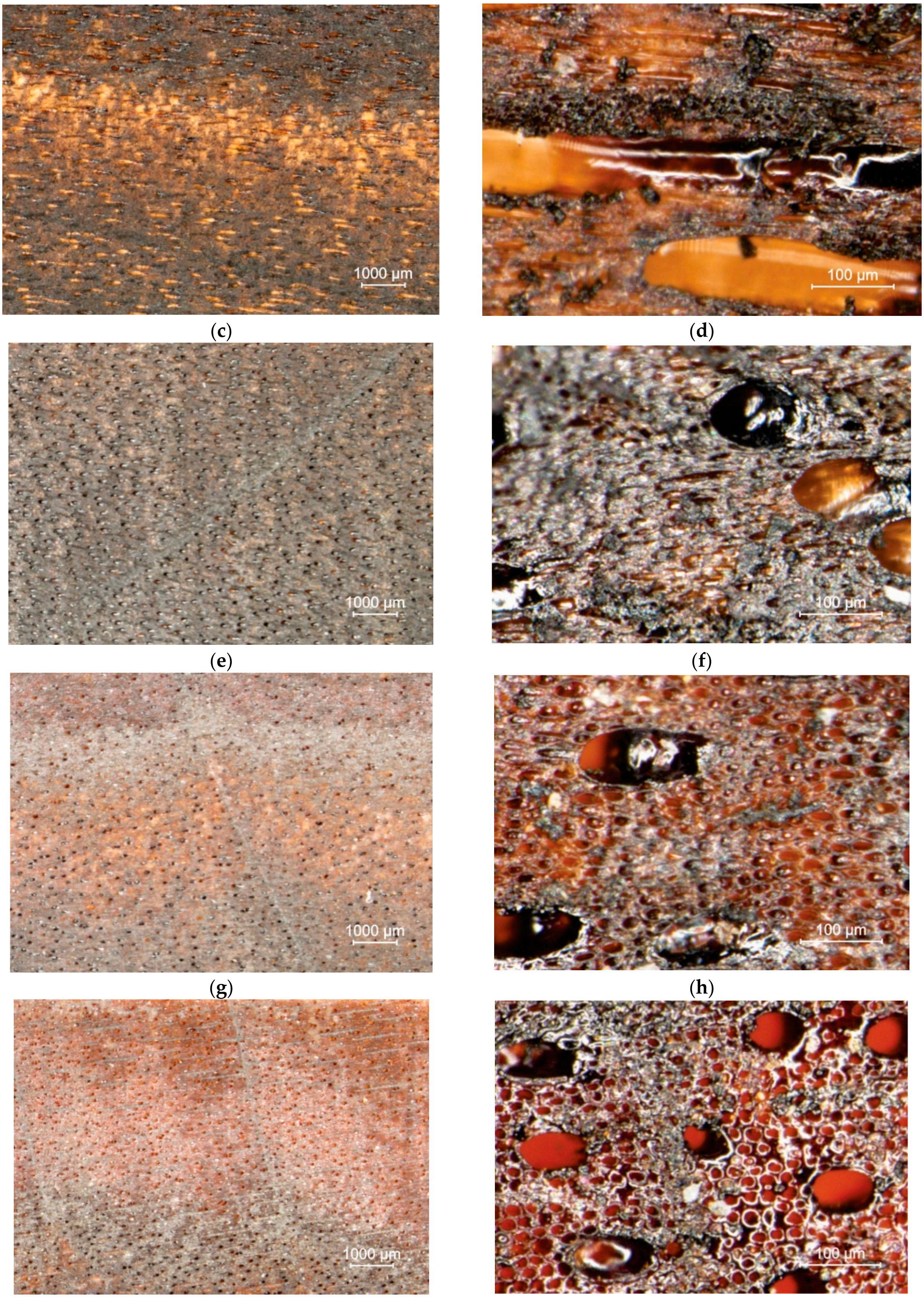
For crosscut directions, from 45° to 90°, the laser is carbonizing layers of wood, which disappear by volatilization, uncovering beneath wood anatomical details, such as cells' lumens of different sizes (Figure 11). This is proven not only by the micrographs but also by the measured roughness profiles (Figure 12), where attention should be given to the irregularities below the zero line and to their frequency. As the cutting progresses from parallel to the grain (0°) to perpendicular to the grain (90°), the wood anatomy uncovered by laser is more detailed and irregularities increase in frequency. When wood is cut parallel to the grain, the stylus traverses the vessels lengthwise and the fibers' cavities. The profile for 0° looks less detailed, with some isolated gaps (highlighted with green in Figure 12a), which may be the vessels from earlywood, due to their size measured by Rv (values from 49.5–64 microns). This is approximately the middle of the range for the maple vessels size ((25)30–50–70(110)) [30]. To be noted that the depth the stylus goes in the vessel or other anatomical cells, may be limited by its geometry. When cutting goes under an angle in relation to the grain, the wood cells are cut obliquely, showing a sequence earlywood and latewood of various widths. The 90° is a perfect crosscut when all anatomical cells show open lumens, which seem to be detected by micrographs (Figure 11m,n) and are visible in the profiles as an increased density of irregularities below the mean line (Figure 12g). Earlywood and latewood appear as a sequence of deep irregularities alternating with shallower ones.

It was interesting to observe that the parameter which measures the deepest irregularity within a profile, Rv (Figure 9), showed no significant difference between the different cutting angles (checked with ANOVA), which may be an indication that it captured the depth of the lumen vessels from earlywood, in all cases of cutting (the majority of measurements were in the range of 55–65 microns). If this is the case, Rv for CNC cutting at 15°, 30°, 45°, and 60° confirms the presence of pull-out material, as discussed before. In other words, processing with laser can contribute to a better understanding and interpretation of surface morphology when processing takes place by CNC. For 75° and 90°, Rv at laser processing shows a deeper pore penetration than along the grain. On the contrary, processing by CNC, particularly for the crosscut directions, has filled the pores with dust, as discussed before, which lowered Rv.

(a)

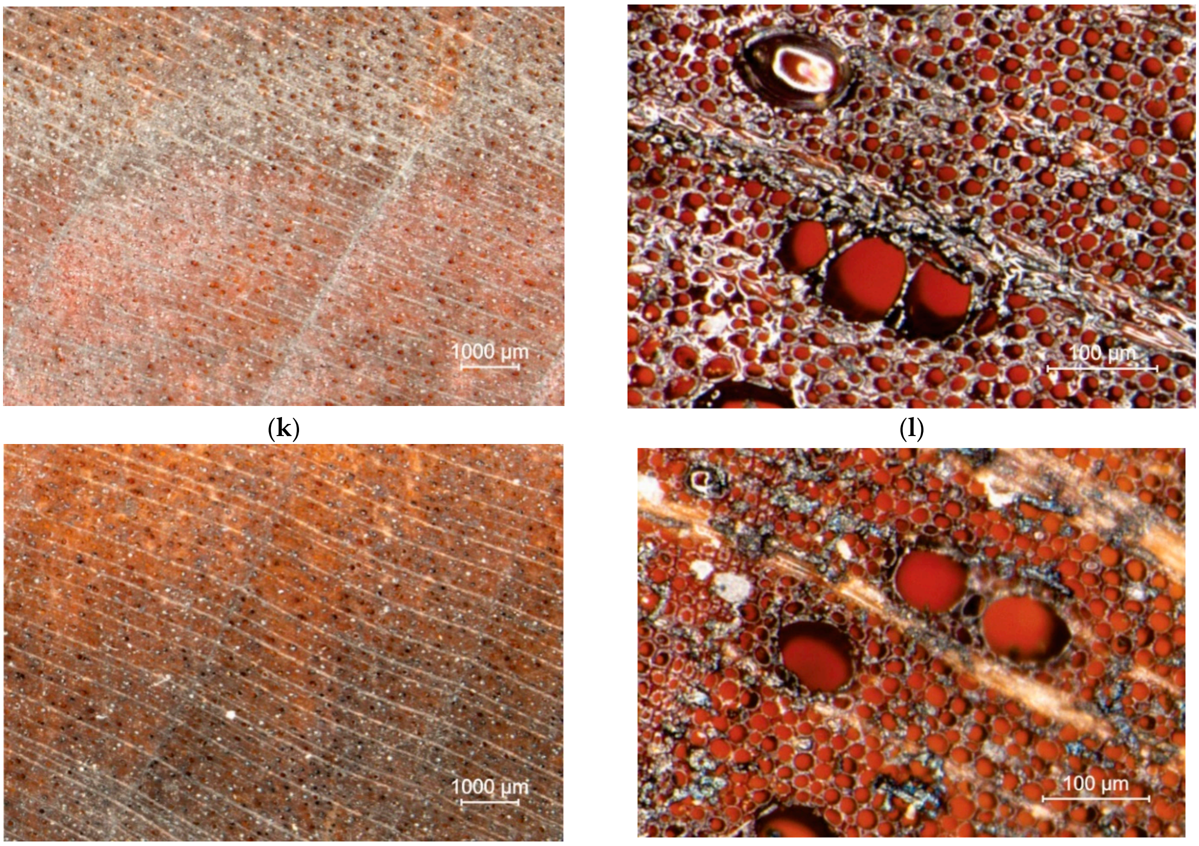
(b)

Figure 11. *Cont.*



(c) (d)
(e) (f)
(g) (h)
(i) (j)

Figure 11. *Cont.*



(**k**) (**l**)

(**m**) (**n**)

Figure 11. Microscopic images of laser processed maple at different angles in relation to the grain and two magnifications, 22.5× and 405×: (**a**,**b**) 0°; (**c**,**d**) 15°; (**e**,**f**) 30°; (**g**,**h**) 45°; (**i**,**j**) 60°; (**k**,**l**) 75°; (**m**,**n**) 90°.

The surface roughness in laser cutting is produced by heat interaction with wood causing different degrees of destruction [10]. In comparison with CNC cutting, laser has a tendency to smoothen the surface irregularities (Figure 3), similar to the observations on larch, by [1]. The parameter Rk for laser measurements had a very slight variation with the cutting angle, which was not statistically significant when checked with ANOVA. Neither the differences in Rvk or Rpk with respect to the wood grain were significant.

No significant differences in Rk between CNC cutting and laser processing were found for angles: 0°, 60°, and 75°. The 15° cutting angle produced the highest differences between the two processing methods. The surface processed with the CNC and u = 2 m/min was significantly rougher (tested with ANOVA), than the one processed by laser, more than double: Rk_CNC = 52.82 µm and Rk_laser = 22.47 µm. Processing with the CNC caused raised fibers, quantified by Rpk = 41.92 µm, as compared with laser with Rpk = 13.28 µm. In the case of a cutting angle of 30°, the difference in processing roughness between the CNC (u = 2 m/min) and laser is maintained, the surface being rougher for CNC more than double (Rk = 46.11 µm for CNC and Rk = 21.59 µm for laser). The processing at a 45° angle has diminished the quality difference between laser and CNC. Processing with the CNC (u = 2 m/min) caused 1.6 times rougher surfaces. It can be concluded that changing the cutting angle to 15°, 30°, and 45° is causing significant differences in quality between the two processing tools. At 90°, cutting with laser caused a 50% rougher surface than when cutting with CNC (u = 2 m/min). A possible reason may be the fact that laser reveals more anatomical details in comparison with the CNC and they bias the highest concentration of data points in evaluating Rk, in other words, anatomical irregularities may artificially increase Rk.

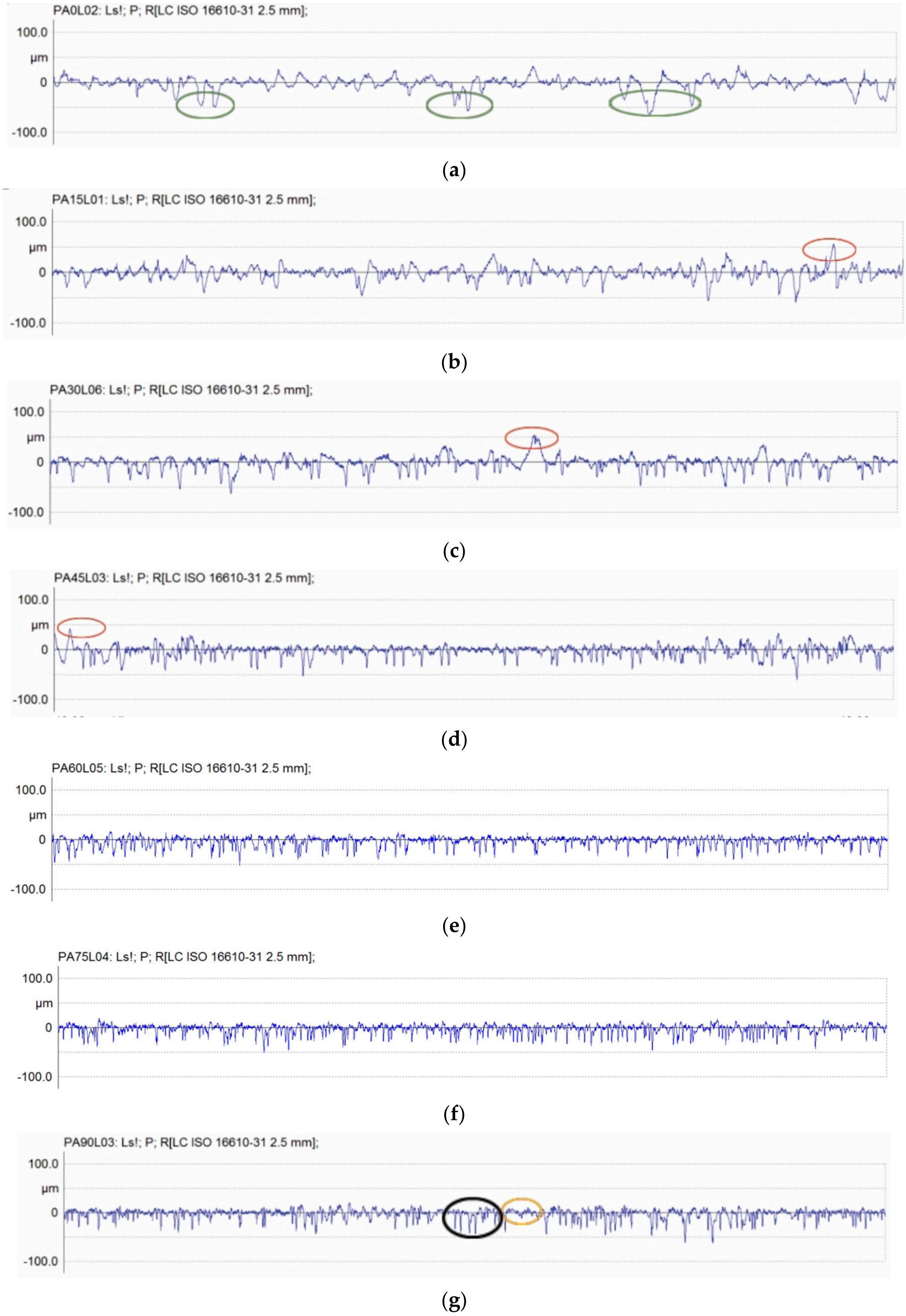


Figure 12. Comparison of roughness profiles from laser cut surfaces: (**a)** along the grain; (**b**) at 15° (fuzzy grain encircled with red); (**c**) at 30°; (**d**) at 45°; (**e**) at 60°; (**f**) at 75°; (**g**) at 90° as related to the grain. Highlights code: red—raised fiber; green—deep isolated valleys; black—earlywood; yellow—latewood.

Waviness, evaluated by Wa, was higher for the laser cutting in comparison with CNC (u = 2 m/min), from 1.4 to almost 3 times, as can be observed in Figure 10. At least, for laser cutting, the waviness was visibly associated with a wood response after interaction with the laser. In Figure 13, a measured profile containing both, roughness and waviness, was extracted from a surface processed by laser under a 75°. The red line indicates the location on the surface of the selected profile.

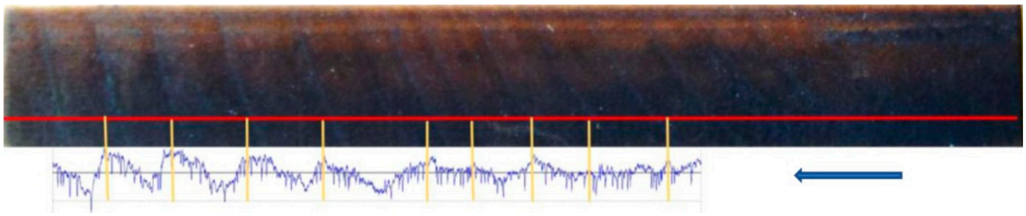


Figure 13. Anatomical waviness seen on a maple surface processed by laser at 75° as related to the grain and selected measured profile. The location of the selected profile is marked with the red line. With yellow, the border of the annual ring is marked. The arrow indicates the growth direction.

Sudden gaps are seen in the measured profile, which corresponds to the earlywood, at the border of the annual ring. Lesser dense earlywood compared with latewood was processed deeper by the laser. The measured profiles appear like indentations, with the highest peaks in the latewood and valleys in the earlywood. The laser seems to have more pronouncedly carbonized earlywood; especially, at the annual ring limit creating gaps below the processed surface. A similar observation was made by other researchers [32] when examining spruce engraved by the laser, or on cut-through larch [1].

When comparing the surface quality results in this study on maple wood with a similar study of [1] made on larch, it can be concluded that the direction of processing as related to the grain is a significant factor when CNC is used. From both studies, cutting along the grain is the safest option, followed by 90° and 75°, while the worst selections are 15° and 30°. Although the direction of cutting was less significant in the case of maple compared with larch, laser tends both to smoothen the surface irregularities in the core roughness and to enhance an anatomical waviness, with earlywood processed deeper. Melting or uncovering anatomical details seems to be a species-dependent matter.

3.3. FTIR Analysis of Chemical Changes Produced by Laser Cutting

The FTIR spectra in the fingerprint region (1800–600 cm^{-1}) recorded for the laser-cut maple surfaces at two different angles (0°, 90° as related to the grain) are presented in Figure 14 in comparison with those corresponding to similar surfaces processed by CNC routing considered as controls.

The main absorption bands in the control spectra of maple wood and their assignment based on the literature are as follows: 1733 cm^{-1} (stretching of unconjugated carbonyl groups present as acetyl groups in hemicelluloses/pentosanes and C=O groups in lignin), 1645 cm^{-1} (vibration of conjugated carbonyl groups/aromatic ketones in the structure of lignin), 1594 cm^{-1} (aromatic skeletal breathing and C=O groups stretch in lignin), 1504 cm^{-1} (aromatic skeletal vibration in lignin), 1456 cm^{-1} (asymmetric deformation of aromatic C-H, asymmetric bending –CH3 in lignin), 1421 cm^{-1} (asymmetric C-H deformation in lignin and carbohydrates), 1369 cm^{-1} (symmetric C-H deformation in cellulose and hemicelluloses), 1324 cm^{-1} (C–O vibration in syringyl derivatives, syringyl ring breathing, C-O alkyl-aryl ether bond assigned to methoxyl groups in lignin), 1234 cm^{-1} (C-O stretch in lignin and xylan, syringyl ring), 1154 cm^{-1} (antisymmetric stretching of C-O-C ether bridge in cellulose and hemicelluloses), 1026 cm^{-1} (C-O stretching in cellulose/hemicelluloses and, alcoholic –OH groups) and 900 cm^{-1} (C-H deformation in cellulose ring) [33,34].

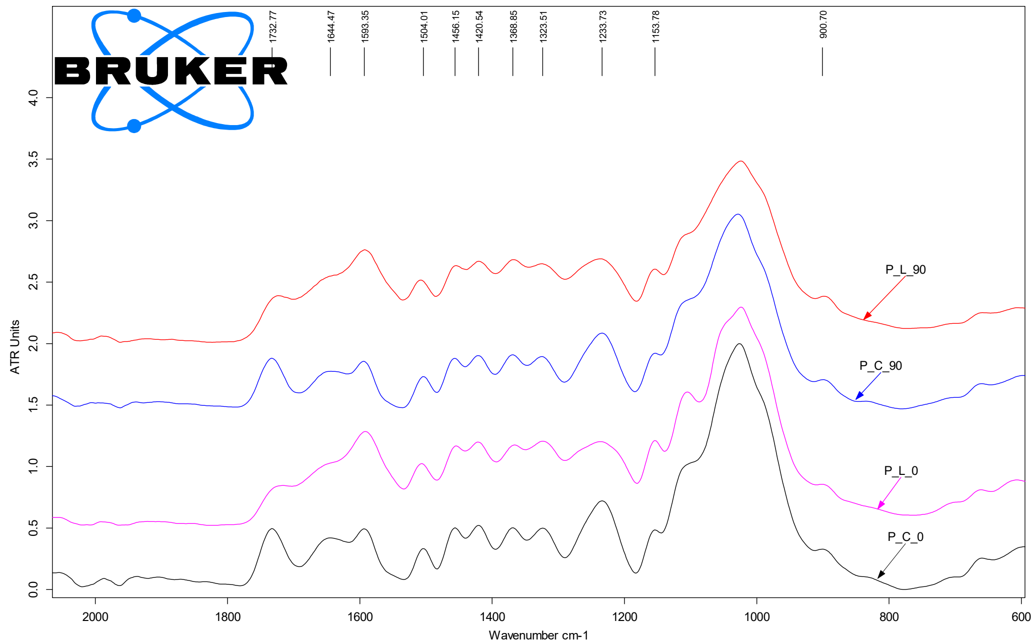


Figure 14. Comparative FTIR-ATR spectra in the fingerprint region (1800–600 cm^{-1}) of control (P_C_0, P_C_90) and laser cut through (P_L_0, P_L_90) maple (*Acer pseudoplatanus*) wood surfaces at angles of 0° and 90° as related to the grain.

As a result of the thermal effect of laser processing, some obvious alterations of the wood surface chemistry were highlighted by FTIR regardless of the cutting angle. First of all, an important decrease in the distinct absorption band at 1732 cm^{-1} (acetyl groups in hemicelluloses/pentosanes) occurs in parallel with a less important decrease in the absorption band at 1369 cm^{-1} (holocellulose), while the small absorption at about 900 cm^{-1} (assigned to cellulose) seemed only lightly affected, indicating deacetylation and further degradation of hemicelluloses, which are more sensitive to thermal degradation compared to cellulose. Another important change was the dramatic decrease up to almost total disappearance of the absorption at 1645 cm^{-1} (conjugated carbonyl, aromatic ketones in the structure of lignin), occurring in parallel with an important increase in the absorption band at 1594 cm^{-1}, characteristic of aromatic ring breathing, while the most characteristic absorption band of lignin at 1504 cm^{-1} (aromatic skeletal vibration) seemed only little affected. All these reflect structural changes in lignin, such as condensation processes, which may involve the reactive conjugated carbonyl groups in the α position of the propane side chain, as also suggested by [35]. They proposed a reaction pathway including oxidation of α-C=O groups followed by decarboxylation and further condensation with adjacent benzene rings in acidic medium leading to diphenyl-methane structures. Furthermore, the slight decrease in the absorption at 1324 cm^{-1}, visible for the laser-processed samples in Figure 14, may indicate cleavage of the C-O alkyl-aryl ether bond in the methoxyl groups, respectively, some demethoxylation of the syringyl units, which will favor further condensation of lignin due to more free reactive sites. The absorption at 1234 cm^{-1}, which cumulates a contribution of the syringyl ring with C-O vibration in lignin and xylan acetyl groups, decreased as intensity but became wider, supporting the previously presented changes in the structure of hemicelluloses and lignin. Finally, the absorptions at 1154 cm^{-1} (C-O-C ether bridges in the structure of polysaccharides) and 1105 cm^{-1} present as shoulders on the wider absorption band with a maximum at 1026 cm^{-1}, seem to become more evident after laser processing, indicating some changes in the structure of cellulose. These may include dehydration processes and cross-linking by new ether bridges, as suggested by [35].

The above-presented chemical changes are reflected also by the numerical data in Table 2, resulting from a semi-quantitative evaluation of the normalized average spectra based on the integration of the areas of some relevant absorption bands and calculation of the ratios of the corresponding areas for the laser processed and the control samples.

Table 2. Integrated areas and ratios of relevant absorption bands from FTIR spectra.

Absorption Band [cm^{-1}]	Areas (Integration Asolute Values)				Calculated Ratios $A_{Laser}/A_{Control}$	
	P_C_0°	P_C_90°	P_L_0°	P_C_90°	P_L_0°/P_C_0°	P_L_90°/P_C_90°
1732	14.93	12.82	3.80	5.69	0.26	0.44
1645–1594	27.41	23.35	31.46	29.43	1.15	1.26
1504	4.11	3.72	3.47	3.23	0.85	0.87
1369	3.06	2.71	1.65	2.06	0.54	0.76
1234	28.04	23.46	14.33	14.69	0.51	0.63
1026	211.84	174.72	173.74	140.97	0.82	0.81
900	1.23	1.58	0.83	1.20	0.67	0.76

To conclude, FTIR analysis of chemical changes in wood structure as a result of laser cutting in the conditions of the present research highlighted structural changes of polysaccharides consisting mainly in advanced deacetylation and degradation of hemicelluloses, possible loss of hydroxyl groups and cross-linking by ether bridges in the structure of cellulose, alongside advanced condensation of lignin through different pathways involving the reactive α-carbonyl groups and alkyl-aryl–ether linkages in subsequent processes of cleavage and condensation. As a result, a decreased content in polysaccharides and relatively increased content in lignin, as well as increased ratios of cellulose/hemicelluloses and lignin/holocelluloses are expectable on the laser cut surfaces as compared to those conventionally processed.

These findings are (at least partly) in accordance with other studies [18,34–36], which also highlighted the dependence of the chemical changes on the wood species, type and power of laser, and the actual processing conditions, such as irradiation dose, points per inch treatment.

4. Conclusions

Understanding the effect of cutting through by CNC or laser as related to the wood grain is important for surface quality optimization and selection of the best option.

For CNC cutting, it was observed an increase in processing roughness, expressed by Rk, with the feed speed, with the lowest values for 2 m/min. However, the feed speed had a less significant effect on the processing roughness in comparison with the cutting angle with respect to the grain. The best surface quality (Rk) was obtained for 90°, 0°, and 75°, while processing at 15°, 30°, 45°, and 60° caused raised fibers as well as pull-out material revealed by Rpk, Rvk, Rv, and Rsk parameters. The worst surface quality occurred for 15° (Rk increased more than triple compared to processing along the grain), characterized by the prevalence of fuzziness, followed in order by 30°, 45°, and 60°, where surface gaps were predominant. High waviness in comparison with other cutting angles was produced for 15° and 60°, especially for high cutting speeds.

Changing the cutting angle from parallel to the grain to across the grain is causing significant effects when CNC is used, but not for laser, whose tendency was to smooth the surface irregularities in the core roughness (Rk). No significant differences in Rk between CNC cutting and laser processing were found for angles: 0°, 60°, and 75°, but the surface processed by the CNC and u = 2 m/min was significantly rougher in comparison with laser for 15° and 30° (more than double) and for 45° (1.6 times).

As the cutting is advancing from along to across the grain, the laser is uncovering more wood anatomical details and with less destruction. At 75° and 90°, the CNC is clogging the pores with dust, while the laser opens them.

Waviness, measured by Wa, was 1.4 to 3 times higher for the laser cutting in comparison with CNC (u = 2 m/min), with a peak for 60°. This was due to the fact that processing with laser enhances the topographical sequence earlywood-latewood, with earlywood carbonized deeper.

Comparative FTIR investigation of surfaces cut by laser and CNC (at 0° and 90°) clearly revealed temperature-induced chemical changes, such as hemicelluloses degradation, possibly demethoxylation and advanced condensation in the structure of lignin, in the case of laser processing.

Although has increased the paper length, the combined study of surface morphology produced by CNC and by CO_2 laser proved useful, because has contributed to a better understanding of the irregularity's nature (anatomical or processing) as compared to studying them separately.

Further work will focus on other species, looking for similarities or species' individual behavior, when cutting with the CNC and the laser.

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