The Influence of CO_2 Laser Beam Power Output and Scanning Speed on Surface Quality of Norway Maple (*Acer platanoides*)

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The effects of varying the laser power output, from 5.6 to 8 W, and the scanning speed, from 100 to 500 mm/s of a CO_2 laser beam on the surface quality of Norway maple (*Acer platanoides*) were investigated. The results showed that the roughness parameters (R_a, R_{sk}, R_t, R_k, R_{pk}, and R_{vk}) increased with increased laser power and decreased with decreased laser scanning speed. The roughness parameters had a linear trend with the laser power and a logarithmic correlation with the laser scanning speed. The best correlation was found for the composed parameter $R_k + R_{pk} + R_{vk}$, which may be the best descriptor of the laser action on wood, closely followed by R_a, R_k, and R_t. R_{pk} was the most affected parameter by the laser action on wood. The roughness parameters correlated best with the laser power for a laser scanning speed of 300 mm/s. An ablation effect on wood combined with protruding latewood bands visible as surface ridges was more pronounced with an increase in the laser power and with a decrease in scanning speed. The high laser powers (7.2, 7.6, and 8 W) combined with the lowest scanning speed, 100 mm/s, burned and visibly degraded the surface.

Keywords: Laser power; Laser scanning speed; Wood surface roughness; Norway maple; Robust filtering; Roughness parameters

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INTRODUCTION

Laser cutting has been a widely used processing method for a variety of materials, including wood (Li *et al*. 2018). Different types of lasers have the advantage of high precision and narrow kerf width (Hattori 1995; Li *et al*. 2016). Carbon dioxide lasers are the most used in cutting operations of wood (Barcikowski *et al*. 2006; Hernandez-Castaneda *et al*. 2009; Eltawahni *et al*. 2013). Most researchers have focused mainly on CO_2 lasers because the laser beam is absorbed almost completely by wood (Grad and Mozina 1998). The CO_2 laser induces chemical and structural modifications on Scots Pine, which was studied by Barcikowski *et al*. (2006). They concluded that the laser causes modifications most intensely at the treated surface and decreases to levelling off at 35 to 45 µm distance from the surface. The authors found a significant thermal modification of lignin within the cell walls. Kubovsky and Kačik (2009) irradiated maple (*Acer pseudoplatanus* L.) *via* a CO_2 laser beam at different values of exposure energy and noticed that increasing the irradiation dose led to the predominant observation of the degradation of hemicelluloses, while lignin was degraded at a lower irradiation dose.

Apart from cutting wood and wood-based materials, laser has been used for wood decoration, a popular method for producing artistic items from wood (Yakimovich *et al*. 2016). Laser engraving is the practice of using lasers to engrave or mark an object. Laser engraving consists in the removal of material from the top surface down to a specified depth. Petutschnigg *et al.* (2013) explored the option of treating wood surfaces with laser beams to develop new aesthetic possibilities and found an application in ski design. Wood colour was measured for various species treated with a CO_2 laser beam intensity of 40 to 120 W, and it was found that laser beams affected the colour changes in different patterns and was species-dependent. Li *et al.* (2018) studied the effect of laser power, feed speed, and sweep width on the color changes of poplar (*Populus* L.). They used Response surface methodology (RSM) for modeling and analysis of the effects of processing variables with a CO_2 laser on the colour changes of wood. The colour change, ΔE^*, decreased with an increase in feed speed and sweep width and increased with an increase in the laser power.

In a study by Yakimovich *et al*. (2016), the highest aesthetic value of engravings with a CO_2 laser on beech were obtained for laser powers ranging from 5 to 10 W, combined with scanning speeds of 600 to 800 mm/s. The evaluation of surface quality was made by the perception of experts, using grades from 1 (low) to 5 (high quality).

Lin *et al*. (2008) investigated the effect of feed speed ratio and CO_2 laser power on the engraved depth and colour difference of moso bamboo lamina. It was found that the laser engraved depth became deeper for either a higher laser power or a lower feed speed ratio.

The main research areas on laser engraving for the metal industry are the process parameters and the resulting surface roughness (Agalianos *et al*. 2011). However, no study has been reported on the investigation of the surface roughness of wood engraved by the laser in spite of its importance for surface finishing and aesthetics.

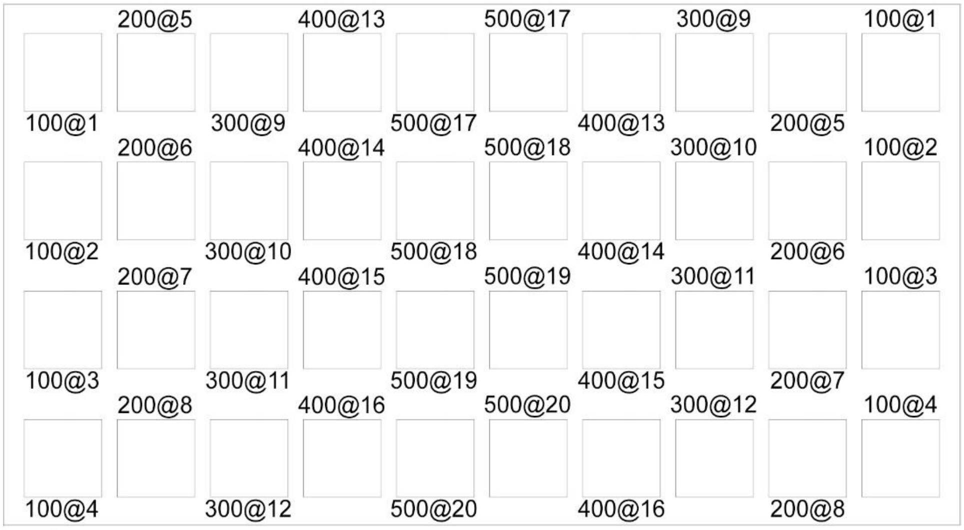
This paper aims to study the effect of varying the laser power output and scanning speed of a CO_2 laser beam on the surface quality of Norway maple (*Acer platanoides*) for aesthetic applications such as decorative drawing/engraving. Previous literature studies on surface roughness have mainly focused on metals processed by the laser; such studies generally used a simple Gaussian filter for separating the roughness from longer wavelength irregularities and to roughness parameters as R_a (Eltawahni *et al*. 2013; Patel and Patel 2014; Pritam 2016) and R_z (Agalianos *et al*. 2011). However, heterogeneous materials, such as wood, require robust filters for roughness and more roughness parameters that better evaluate and provide a greater understanding of the various aspects of the surface (Gurau and Irle 2017). Therefore, a robust filter for delimiting the surface roughness and a range of roughness parameters capable to give specific information about the stratified structure of the surface are employed in this paper.

EXPERIMENTAL

As in the authors previous study on beech surfaces (Gurau *et al*. 2017), a CO_2 laser (model SLG-4030 lsct with LaserCut software version 4.03 included, imported from China by SpotLine, Bucharest, Romania) was used in this research for laser decorative engraving and drawing on maple. The laser scanning gap was 0.0254 mm and the pulse frequency was 20,000 Hz. The laser had a wavelength of 10.6 μm, a 73-mm focal length lens, and maximum output power of 40 W.

For laser treatment, two parameters, the laser output power and the laser speed, were varied. For this study, the laser power output represented fractions from the maximum output power of 40 W: 14% (5.6 W), 15% (6 W), 16% (6.4 W), 17% (6.8 W), 18% (7.2 W), 19% (7.6 W), and 20% (8 W). A larger range of laser power fractions were tested from the previous study of Gurau *et al*. (2017). The purpose of this study was to observe the effects on surface morphology and to determine any law of variation of the laser power with the surface roughness of wood after laser scanning. The fractions of laser power were symbolized L14, L15, L16, L17, L18, L19, and L20. The second parameter tested was the laser scanning speed, which was varied from low to high, 100, 200, 300, 400, and 500 mm/s, and was combined with all laser powers. The target was to analyze the influence of the laser power and scanning speed on the surface roughness, judged by the specific roughness parameters.

The specimens, 300 mm × 160 mm × 13 mm, were cut from Norway maple (*Acer platanoides*), supplied by Losan SRL, Brasov, Romania, conditioned at 20 °C with a 65% relative humidity of the ambient air, by the following sequence of operations: planing, dimension cutting, calibration with abrasive paper of P60 grit size and manual sanding with P100 grit size (abrasive supplied by SIAROM SRL, Brasov, Romania). The specimens were processed from the same board to minimize wood variability. Maple is very common for laser drawing and engraving because its colour is light and uniform. Four specimens with radial surfaces were used for this study, in order to display an even sequence of earlywood-latewood areas. The specimens were laser scanned with all laser powers and scanning speed combinations on areas (25 mm × 25 mm), with 4 replicates for each combination. For each laser power combined with all scanning speeds, there were 20 scanned areas. The size of each specimen allowed 40 scanned areas on the same face of the sample. A single specimen was scanned by two different laser power fractions. They were grouped on the four specimens as follows: L14 to L15, L16 to L17, L18 alone, and L19 to L20. Grouping the laser powers on the same piece of wood can be advantageous, because the wood variation is reduced to a minimum and the changes in surface roughness and wood colour caused by the laser action can be analysed with a higher degree of confidence. The schematic arrangement of the scanned areas is presented in Fig. 1, where the scanning speeds for every two laser powers appear as viewed in a mirror.



Feed speed, (mm/s) @ Specimen number
Scan gap, (mm): 0.0254
Speed direction (X): <->
Roughness measuring direction (X): ↓

Fig. 1. Schematic representation of a wood sample scanned with laser beams with two different laser powers, on 25 mm × 25 mm areas for five scanning speeds and four replicates for each speed

Surface quality measurements were performed using a MarSurf XT20 instrument manufactured by MAHR Gottingen GMBH (Göttingen, Germany). The device was fitted with a MFW 250 scanning head with a tracing arm in the range of ± 500 µm, a stylus with a 2-µm tip radius and 90° tip angle that measured the maple specimens across the grain at a speed of 0.5 mm/s, a low scanning force of 0.7 mN, and a lateral resolution of 5 µm.

From each laser processed area, one profile, 20 mm long (Fig. 2a), was stylus scanned across the grain for surface roughness analysis of the combined effect of laser power and scanning speed. For each laser power-scanning speed combination, four profiles were analyzed, one from each replicate. This makes a total of 20 profiles per laser power and 140 profiles for all laser powers and scanning speed combinations.

Those profiles and their roughness parameters were compared with similar 20-mm-long profiles of untreated wood. They were stylus scanned in the immediate vicinity of the laser-modified areas (Fig. 2b). For each laser power/scanning speed combination, one roughness profile from unmodified wood was measured. This was taken from the wood area located in the vicinity of the first replicate. This meant that for each laser power, five wood profiles were analyzed, corresponding to five scanning speeds. For the total of seven laser powers analyzed, 35 unprocessed wood profiles were measured. Those profiles were used as references to observe any increase in surface roughness of laser-scanned surfaces caused by the laser action.

To visualize those roughness differences and the laser engraving effect, another group of profiles, 40-mm-long, were scanned so that they covered half of a laser engraved region and half of unprocessed wood (Fig. 2c). Five mixed profiles for each laser power-scanning speed combination resulted in 35 mixed profiles in total. These mixed profiles were also taken from the first laser replicate and its unprocessed vicinity.

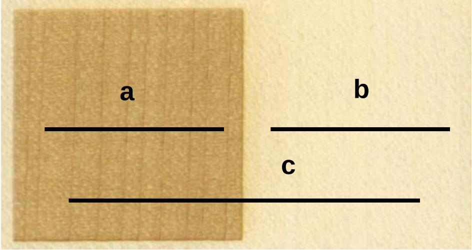


Fig. 2. Details regarding the profiles measurement: a: profile from laser-modified area (20-mm-long); b: profile from unprocessed wood (20-mm-long); c: mixed profile measuring laser-scanned and unprocessed wood (40-mm-long)

Furthermore, the scanned profiles were processed with MARWIN XR20 software provided by the instrument supplier (Göttingen, Germany). The profiles were also saved as ASCII files with the possibility to be separately examined and visualized with MathCAD 2000 Professional (PTC, Needham, MA, USA).

The measured profiles contained not only roughness, but also form errors and waviness (ASME B46.1 2009). To examine any laser engraving effect, the measured mixed profiles from laser scanned-unprocessed wood were kept as such, with no further processing. They were imported in MathCAD for visual comparison and to observe the transition from laser-scanned regions to the unprocessed wood. The other profiles, taken from laser-scanned areas and from unprocessed wood, followed the standard procedure. The software first removed the form errors and then filtered the profiles from waviness to get the roughness data. The roughness data represents the shortest wavelength irregularities of a surface and should best characterize the processing *via* laser. A robust filter called RGRF (robust Gaussian regression filter) contained in ISO 16610-31 (2010), was used because it is suitable for wood and does not introduce bias related to wood anatomy (Gurau *et al.* 2006; Tan *et al.* 2012).

The cut-off used in this research was 2.5 mm, as recommended in previous studies by Gurau *et al.* (2006).

After the roughness profiles were obtained, a range of roughness parameters was calculated for the profiles, such as R_a (arithmetical mean deviation of the assessed profile), R_{sk} (skewness of the profile), R_t (total height of the profile), from ISO 4287 (1997) R_k (core roughness depth), R_{pk} (reduced peak height), and R_{vk} (reduced valley depth) from ISO 13565-2 (1996). Their mean values and standard deviations were also calculated. The parameters were detailed in the authors' previous publication (Gurau *et al*. 2017). It is expected that the laser will influence all of the parameters, R_k, R_{pk}, and R_{vk}, which are responsible for the highest density data points in the core profile (R_k), the rised fibres or other type of isolated peaks (R_{pk}), and the deep isolated irregularities extending below the core roughness (R_{vk}). Therefore, a composed parameter comprising of the three regions was found useful in a previous research (Gurau *et al.* 2017) and was also used in this paper: $R_k + R_{pk} + R_{vk}$ to have a measure of the cumulative information from those parameters. In Gurau *et al*. (2017), it was observed that the laser has a strong effect on the surface peaks evaluated by R_{pk}. Therefore, it is expected that the ratio R_{pk}/R_{vk} can give useful information about the change in surface topography under the laser action and it was used in this study.

RESULTS AND DISCUSSION

Figure 3 shows examples of the areas scanned with all laser powers and scanning speed combinations. Their arrangement is similar to Fig. 1, with two laser powers on the same row (left to right) and scanning speeds decreasing from the margins to the center. The effect of these combinations or parameters on the colour of wood can be visually observed and compared.

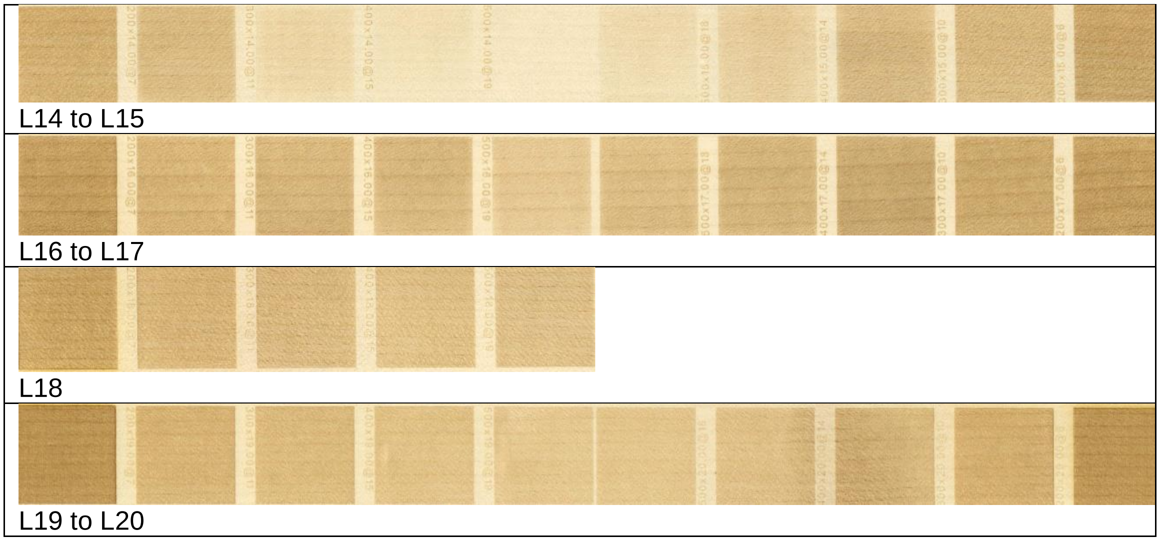


Fig. 3. Visual comparison of the colouring effect of laser power-scanning speed combinations on the surface of Norway maple

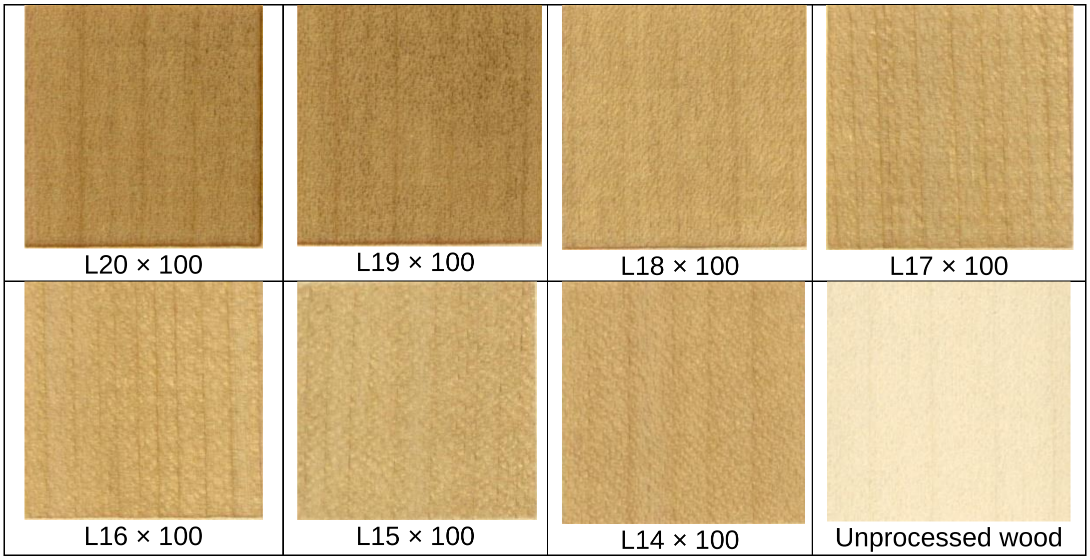


Fig. 4. Visual comparison of colour change for areas scanned with 100 mm/s at all laser powers and the unprocessed area of Norway maple

At first glance, the differences in colour and nuance for the same scanning speed do not seem very different. This is with the exception of L14, whose surface colour seemed to fade from 300 mm/s to 500 mm/s in comparison with higher laser powers. A selection of areas scanned with 100 mm/s is depicted in Fig. 4. for a closer look. The specimens L19 and L20 had a more intense visual effect on wood than the lower laser powers. However, it should be noted that the colour intensity and colour change were not parameters measured in this study. The surface roughness of those surfaces was the target of this study.

The mean values of roughness parameters for the surfaces scanned with laser powers L14 to L20 combined with scanning speeds from 100 to 500 mm/s, as well as those measured from the unprocessed maple surfaces located in the proximate vicinity are contained in Tables 1 through 7. The standard deviation values were small, generally below 1 for R_a and R_{sk} and reasonably small for the other parameters.

Table 1. Comparative Mean Values of Roughness Parameters Measured From Laser Scanned Areas (Laser Power L14- 5.6 W) and From Neighboring Unprocessed Wood

Processing	**Laser Scanning Speed (mm/s)**	**R_a (µm)**	**R_t (µm)**	**R_{sk} (µm)**	**R_k (µm)**	**R_{pk} (µm)**	**R_{vk} (µm)**	**R_k+ R_{pk}+ R_{vk} (µm)**	**R_{pk}/ R_{vk} (µm)**
L14 (5.6 W)	100	10.9	101.0	-0.8	32.1	11.2	19.1	62.4	0.59
	200	6.6	63.4	-0.8	20.5	7.0	12.1	39.6	0.58
	300	6.6	63.6	-0.8	20.1	6.8	11.7	38.7	0.58
	400	6.8	70.3	-0.6	20.3	8.1	11.8	40.2	0.68
	500	7.6	70.6	-1.0	23.0	6.8	13.5	43.4	0.51
Unprocessed wood (vicinity of L14)	100	7.1	75.0	-0.7	20.4	9.7	13.0	43.1	0.75
	200	6.8	63.1	-0.7	21.7	6.4	11.4	39.5	0.56
	300	7.1	74.5	-0.7	21.0	7.2	11.8	40.1	0.61
	400	7.4	60.2	-0.7	23.4	6.7	12.3	42.4	0.55
	500	7.7	74.0	-1.0	23.5	7.2	13.4	44.1	0.53

Table 2. Comparative Mean Values of Roughness Parameters Measured From Laser Scanned Areas (Laser Power L15- 6 W) and from Neighboring Unprocessed Wood

Processing	Laser Scanning Speed (mm/s)	R_a (μm)	R_t (μm)	R_{sk} (μm)	R_k (μm)	R_{pk} (μm)	R_{vk} (μm)	R_k+ R_{pk}+ R_{vk} (μm)	R_{pk}/ R_{vk} (μm)
L15 (6 W)	100	10.8	93.6	-1.0	32.2	8.8	19.4	60.5	0.46
	200	8.8	80.2	-0.9	26.5	8.8	15.3	50.6	0.57
	300	7.7	72.3	-0.6	23.0	8.8	13.2	45.0	0.66
	400	7.3	69.4	-0.5	22.5	7.8	11.6	41.9	0.67
	500	7.0	67.5	-0.9	21.2	6.8	12.9	40.9	0.53
Unprocessed wood (vicinity of L15)	100	6.6	55.6	-0.6	22.0	5.5	9.4	36.9	0.58
	200	7.3	63.7	-0.6	23.1	6.3	11.6	41.1	0.54
	300	6.8	56.5	-1.0	19.8	6.2	12.1	38.0	0.51
	400	6.9	65.4	-0.8	20.3	7.4	12.3	40.0	0.60
	500	6.5	64.8	-1.1	19.9	5.4	13.2	38.6	0.41

Table 3. Comparative Mean Values of Roughness Parameters Measured From Laser Scanned Areas (Laser Power L16- 6.4 W) and From Neighboring Unprocessed Wood

Processing	Laser Scanning Speed (mm/s)	R_a (μm)	R_t (μm)	R_{sk} (μm)	R_k (μm)	R_{pk} (μm)	R_{vk} (μm)	R_k+R_{pk}+ R_{vk} (μm)	R_{pk}/ R_{vk} (μm)
L16 (6.4 W)	100	19.7	160.3	-0.2	61.8	24.1	25.7	111.7	0.94
	200	10.3	93.8	-0.9	29.7	10.8	19.0	59.5	0.57
	300	8.5	80.2	-0.5	26.6	10.2	14.3	51.1	0.71
	400	7.8	74.4	-0.7	23.6	8.7	13.1	45.5	0.66
	500	7.6	71.2	-0.7	22.1	8.7	13.3	44.1	0.65
Unprocessed wood (vicinity of L16)	100	6.7	60.8	-0.5	19.4	7.8	10.4	37.5	0.75
	200	7.0	69.8	-0.7	21.5	6.5	11.7	39.7	0.55
	300	6.8	62.7	-0.8	21.1	6.5	11.7	39.3	0.55
	400	6.6	56.9	-0.6	20.1	6.8	10.6	37.5	0.64
	500	7.1	61.0	-0.3	22.2	7.5	9.1	38.8	0.82

Table 4. Comparative Mean Values of Roughness Parameters Measured From Laser Scanned Areas (Laser Power L17- 6.8 W) and From Neighboring Unprocessed Wood

Processing	Laser Scanning Speed (mm/s)	R_a (μm)	R_t (μm)	R_{sk} (μm)	R_k (μm)	R_{pk} (μm)	R_{vk} (μm)	R_k+ R_{pk}+ R_{vk} (μm)	R_{pk}/ R_{vk} (μm)
L17 (6.8 W)	100	19.0	153.7	-0.2	59.1	23.3	27.4	109.7	0.85
	200	14.5	127.3	-0.8	44.5	13.5	23.3	81.2	0.58
	300	10.5	96.0	-0.9	31.4	9.9	19.6	60.9	0.50
	400	8.2	79.6	-0.6	24.9	9.9	14.4	49.2	0.69
	500	7.8	75.5	-0.8	24.0	7.4	12.9	44.4	0.58
Unprocessed wood (vicinity of L17)	100	6.9	65.7	-0.7	20.8	7.2	12.2	40.3	0.59
	200	6.8	66.6	-0.7	20.5	6.8	10.3	37.6	0.65
	300	6.9	65.2	-1.2	20.9	6.2	13.6	40.7	0.46
	400	6.9	65.1	-0.7	21.3	6.8	10.7	38.8	0.64
	500	7.8	68.2	-0.8	24.5	5.9	12.1	42.5	0.49

Table 5. Comparative Mean Values of Roughness Parameters Measured From Laser Scanned Areas (Laser Power L18- 7.2 W) and From Neighboring Unprocessed Wood

Processing	Laser Scanning Speed (mm/s)	R_a (µm)	R_t (µm)	R_{sk} (µm)	R_k (µm)	R_{pk} (µm)	R_{vk} (µm)	R_k+ R_{pk}+ R_{vk} (µm)	R_{pk}/ R_{vk} (µm)
L18 (7.2 W)	100	22.4	187.4	0.1	69.4	30.8	28.1	128.2	1.10
	200	15.7	130.8	-0.5	48.7	15.9	22.8	87.4	0.70
	300	12.6	110.3	-0.5	39.3	13.8	18.3	71.4	0.75
	400	10.0	105.4	-0.7	29.7	11.6	17.7	59.0	0.65
	500	8.3	81.8	-0.7	25.3	9.6	15.3	50.2	0.63
Unprocessed wood (vicinity of L18)	100	7.1	56.9	-0.8	22.3	6.2	11.7	40.2	0.53
	200	7.4	71.6	-0.8	22.6	8.8	13.0	44.3	0.68
	300	6.9	61.7	-0.8	21.7	6.2	11.6	39.4	0.53
	400	6.6	54.2	-0.6	20.6	6.6	10.0	37.3	0.66
	500	7.2	56.6	-0.3	24.0	6.4	9.3	39.7	0.69

Table 6. Comparative Mean Values of Roughness Parameters Measured From Laser Scanned Areas (Laser Power L19- 7.6 W) and From Neighboring Unprocessed Wood

Processing	Laser Scanning Speed (mm/s)	R_a (µm)	R_t (µm)	R_{sk} (µm)	R_k (µm)	R_{pk} (µm)	R_{vk} (µm)	R_k+R_{pk}+ R_{vk} (µm)	R_{pk}/ R_{vk} (µm)
L19 (7.6 W)	100	24.5	189.5	0.2	77.4	32.3	27.9	137.5	1.16
	200	18.5	144.7	-0.3	58.7	20.3	24.3	103.3	0.84
	300	14.3	127.8	-0.8	44.4	13.3	24.0	81.7	0.56
	400	10.6	98.7	-0.6	32.5	11.5	16.2	60.3	0.71
	500	10.0	93.0	-0.9	30.9	9.6	18.8	59.3	0.51
Unprocessed wood (vicinity of L19)	100	6.9	104.0	-1.2	20.2	7.2	12.6	40.0	0.57
	200	7.4	86.3	-1.0	22.5	7.0	13.3	42.8	0.52
	300	7.1	70.6	-0.8	22.1	6.8	12.4	41.3	0.54
	400	7.0	68.6	-0.6	22.1	6.4	11.0	39.5	0.58
	500	7.3	76.5	-1.1	21.9	7.3	14.8	44.1	0.50

Table 7. Comparative Mean Values of Roughness Parameters Measured From Laser Scanned Areas (Laser Power L20- 8 W) and From Neighboring Unprocessed Wood

Processing	Laser Scanning Speed (mm/s)	R_a (µm)	R_t (µm)	R_{sk} (µm)	R_k (µm)	R_{pk} (µm)	R_{vk} (µm)	R_k+ R_{pk}+ R_{vk} (µm)	R_{pk}/ R_{vk} (µm)
L20 (8 W)	100	25.8	218.9	0.3	81.0	38.0	30.1	149.1	1.26
	200	19.6	157.4	-0.2	62.6	23.4	24.9	110.9	0.94
	300	15.5	134.6	-0.7	46.9	15.4	25.9	88.2	0.60
	400	12.3	98.0	-0.8	36.9	11.2	19.8	67.9	0.57
	500	9.7	89.4	-0.9	28.7	10.1	17.7	56.6	0.57
Unprocessed wood (vicinity of L20)	100	6.4	57.4	-0.5	20.5	7.7	10.3	38.5	0.75
	200	6.6	50.6	-0.4	21.1	6.8	9.5	37.4	0.71
	300	6.6	78.8	-0.7	20.9	6.6	9.9	37.4	0.66
	400	6.8	62.4	-0.5	20.5	7.1	10.8	38.4	0.65
	500	6.8	60.1	-0.5	21.5	7.4	10.8	39.7	0.68

An increase in standard deviation was noticed with laser power and for small scanning speeds of 100 and 200 mm/s. This may show that these surfaces were less homogeneous in comparison with the others.

Tables 1 through 7 show that the roughness parameters increased with the laser power and decreased with the laser scanning speed. By increasing the laser power and decreasing scanning speed, the ratio R_{pk}/R_{vk} increased and the skewness, R_{sk}, increased from negative towards positive values indicating a trend towards the prevalence of peaks in the profiles against valleys. The positive values of skewness occurred for the lowest scanning speed of 100 mm/s and for laser powers L18, L19, and L20.

In comparison with L14, L20 more than doubled the surface roughness for a scanning speed of 100 mm/s (2.37 times for R_a, 2.53 times for R_k, and 2.39 times for $R_k + R_{pk} + R_{vk}$) and tripled for a scanning speed of 200 mm/s, decreasing towards a scanning speed of 500 mm/s. This was because L14 caused a change in the surface roughness for a scanning speed of 100 mm/s. At higher speeds, the surface roughness was in the domain of variation of wood irregularities (Table 1). A similar observation for laser power L14 was made in a former study on beech surfaces (Gurau *et al*. 2017).

In comparison with the unprocessed wood, the surface roughness for the wood processed with L20 and 100 mm/s scanning speed increased approximately 4 times (4.03 times for R_a, 3.95 times for R_k, and 3.87 times for $R_k + R_{pk} + R_{vk}$). As the scanning speed increased, the differences in surface roughness between the laser scanned and the unprocessed wood decreased. Therefore, for a scanning speed of 200 mm/s, roughness parameters were approximately 3 times higher for L20 in comparison with unprocessed wood. For a scanning speed of 300 mm/s, the surface roughness of L20 was approximately 2 times higher (2.36 times for R_a, 2.25 times for R_k, and 2.36 times for $R_k + R_{pk} + R_{vk}$). For a scanning speed of 500 mm/s, L20 increased the surface roughness approximately 35% to 40% (Table 7).

For the lowest laser power, L14, combined with 100 mm/s scanning speed, R_a increased 53%, R_k 57% and $R_k + R_{pk} + R_{vk}$ 45% compared to the unprocessed wood, which in absolute values meant 3.8 µm for R_a, 11.7 µm for R_k, and 19.3 µm for $R_k + R_{pk} + R_{vk}$.

In absolute values, L20 combined with 100 mm/s scanning speed increased R_a 19.4 µm, R_k 60.5 µm, and $R_k + R_{pk} + R_{vk}$ 110.6 µm, which corresponded to a very rough surface. The absolute difference decreased with an increase in the scanning speed, thus, for 500 mm/s, the difference of the laser processed - unprocessed wood became 2.9 µm for R_a with, 7.2 µm for R_k, and 16.9 µm for $R_k + R_{pk} + R_{vk}$. The highest absolute difference was measured for R_t, which was sensitive to extreme values (peaks and valleys).

The scanning speed of 100 mm/s increased roughness for all laser powers L14 to L20 because at a low laser scanning speed, the wood absorbs more heat from the laser,which causes changes in the surface morphology, as will be seen later in the paper. The lowest scanning speed of 500 mm/s produced notable absolute differences in surface roughness only for high laser powers L18, L19, and L20, but negligible for the other laser powers. The heat transfer from low laser powers to wood becomes negligible in combination with high scanning speeds.

The roughness parameters were correlated to the laser powers and scanning speeds in Tables 8 and 9, which display the R^2 values. It was found that the variation of roughness parameters with the laser power had a linear trend (Table 8). The best correlation was registered for the composed parameter $R_k + R_{pk} + R_{vk}$, which displayed a very good linear correlation with the laser power as measured by R^2 (Table 8 and Fig. 5).

Table 8. Values Represent R^2 Coefficients for the Linear Correlation between the Roughness Value and the Laser Power for Each Scanning Speed Tested

Roughness Parameter	Laser Scanning Speed (mm/s)				
	100	200	300	400	500
$R_k + R_{pk} + R_{vk}$	0.905	0.9868	0.9912	0.9602	0.7946
R_t	0.9017	0.9689	0.9858	0.7769	0.8502
R_a	0.9015	0.9815	0.983	0.9403	0.7843
R_a	0.8986	0.9772	0.9802	0.951	0.733
R_{pk}	0.9092	0.9792	0.9332	0.8528	0.8108
R_{vk}	0.8494	0.8823	0.9357	0.8892	0.6929
R_{sk}	0.8414	0.8249	-	0.4372	-

Table 9. Values Represent R^2 Coefficients for the Logarithmic Correlation between the Roughness Value and the Laser Scanning Speed for Each Laser Power Tested

Roughness Parameter	Laser Power (%)						
	L20	L19	L18	L17	L16	L15	L14
$R_k + R_{pk} + R_{vk}$	0.9985	0.9864	0.9906	0.9941	0.8773	0.9858	-
R_k	0.9934	0.9881	0.9971	0.9818	0.6708	0.9734	-
R_a	0.9971	0.9908	0.9979	0.9852	0.8667	0.9824	-
R_t	0.9898	0.9876	0.9694	0.9783	0.8887	0.9808	-
R_{pk}	0.9802	0.9745	0.9188	0.9356	0.8203	0.6136	-
R_{vk}	0.8662	0.7854	0.9847	0.9549	0.949	0.9022	-
R_{sk}	0.9796	0.8887	0.8745	0.5178	0.424	0.3978	-

The best observed correlation was obtained for a scanning speed of 300 mm/s. This was valid also for the other roughness parameters. The lowest correlation was observed for a 500 mm/s laser scanning speed. This was due to the fact that the laser effect on wood fades for such high scanning speeds. The variation of the roughness parameters depended on the local wood anatomy in which a 500 mm/s speed obscured the laser effect on wood.

Judging by the best correlation, a laser scanning speed of 300 mm/s combined best with the laser power. As the scanning speed decreased to 200 and 100 mm/s, the laser started changing the surface morphology, which decreased the correlation. These observations were made for the majority of the roughness parameters. A low scanning speed increased the heat transferred to the surface, and the wood surface reacted in an interesting way. The latewood bands, higher in density than the earlywood, seemed to expand. This may have been a result of a thermal dilatation or differences in thermal conductivity between earlywood and latewood that may have increased the local temperature in earlywood bands. This would have contributed to an easier vaporization and material removal as compared with latewood. However, some authors considered this phenomenon of surface undulation as being attributable, instead, to the differences in local wood density and to the fact that it takes longer time to the laser to remove the high-density latewood than the earlywood (Johansson and Sandberg 2007).

For all laser power values, the combination with a low scanning speed (100 mm/s) caused an ablation effect on wood. The material burned and volatized, but the laser processed surface appeared engraved as related to the unprocessed surface reference. This is clearly visible in Fig. 5, which shows examples of the measured profiles for each laser power scanned surface in the first half and the neighboring unprocessed wood in the second half. The profiles were placed in a single graph slightly distanced from one another to show the evolution of the laser effect from L14 (bottom) to L20 (top). A higher laser power resulted in a deeper engraving effect. A higher gap between the surfaces resulted in a more pronounced undulating surface of earlywood-latewood. The surfaces scanned with L20, L19, and L18 and a scanning speed of 100 mm/s, had a pyrolitic aspect with visible burns. It seemed that a longer interaction time between the wood sample and the gas jet enhanced the combustion process and removal of the vaporised material (Hernandez-Castaneda *et al.* 2009). The ridges were clearly visible with the naked eye for high laser powers, but they also occurred for low laser powers. However, these ridges were detected only by examining MathCAD profiles in Fig. 5. The surface gaps for a scanning speed of 100 mm/s ranged from approximately 15 microns for L14 to approximately 250 microns for L19 and L20. By increasing the scanning speed to 200 mm/s, the surface gap decreased to approximately 100 to 150 microns for L19 and L20, to approximately 50 microns in L16 and no effect for L15 and L14. The scanning speed 300 mm/s produced such effects for laser powers down to L17 (30 microns). The scanning speed of 500 mm/s caused no apparent gap, while 400 mm/s produced gap effects only for the highest laser powers, L19 and L20.

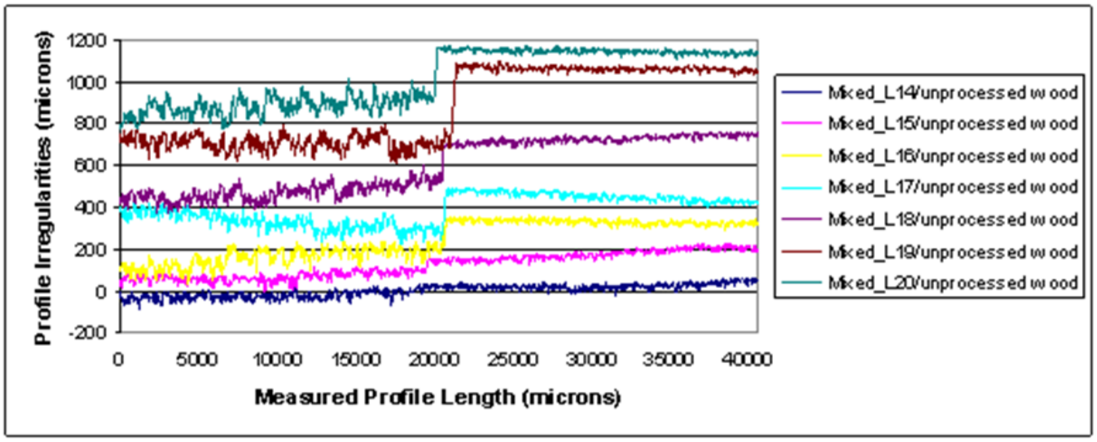


Fig. 5. Measured profiles on Norway maple, first half scanned by laser with a scanning speed 100 mm/s and second half unprocessed

Strong correlations were also found between the roughness R_a and R_k values and the laser power for each scanning speed tested (Table 8). Generally, these parameters are the least influenced by local variations in wood anatomy.

The parameter R_{pk} was influenced by isolated peaks and fuzziness that correlated well with the laser power. The correlation was weaker for R_{vk}, which was influenced not only by the laser, but also by the local variation in wood anatomy. A weak correlation was found for R_{sk} with the laser power for slow laser speeds 100 and 200 mm/s, while for 300, 400, and 500 mm/s speeds no correlation was found between the laser power and surface skewness. This suggested that the surface skewness for speeds higher than 200 mm/s was not influenced by the laser action, but probably was more influenced by the wood local variability.

From Table 9, it can be observed that the roughness parameters had a logarithmic correlation with the laser scanning speed for all laser powers with the exception of L14. The specimen L14 had little impact on the wood for a scanning speed of 100 mm/s, but for higher laser speeds, the roughness values were in the wood domain of variation, and it can be said that the laser action was negligible. The best correlation occurred for $R_k + R_{pk} + R_{vk}$

(Table 9 and Fig. 6). This was in agreement with results from a former study on beech wood scanned with the same type of laser with laser power fractions from L14 to L17 (Gurau *et al.* 2017). The parameter $R_k + R_{pk} + R_{vk}$ may be the best parameter selection to describe the laser action. This parameter, in comparison with the mean parameter, R_a, offered a coverage for all range of roughness levels (peaks, valleys, and core roughness). Taken individually, they all were modified by the laser action, increased laser power, and decreased in scanning speed. Good logarithmic correlations with the laser scanning speeds for laser powers higher than L14 were remarked also for R_k, R_a, and R_t.

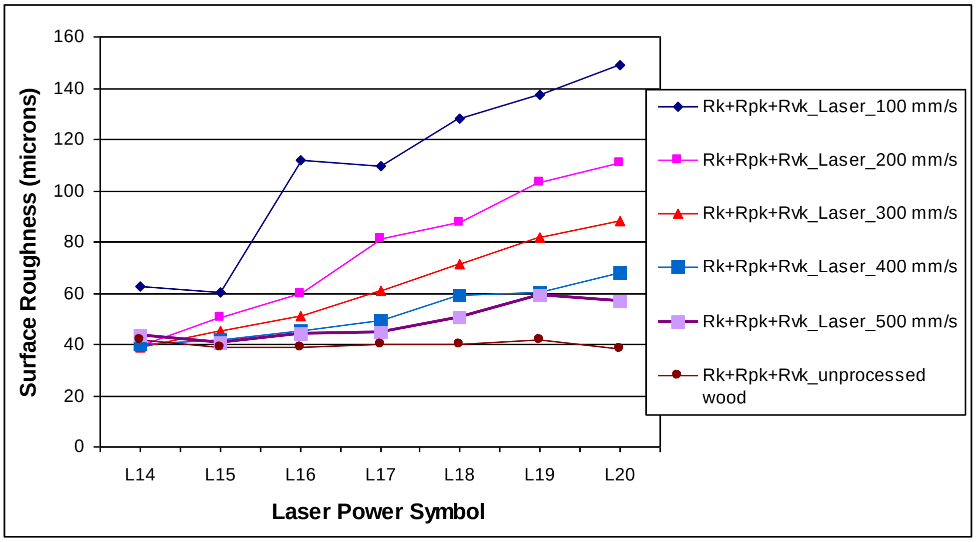


Fig. 6. Correlation between the roughness parameter $R_k + R_{pk} + R_{vk}$ and the laser power for each scanning speed tested

The logarithmic correlation of R_{pk} with the laser scanning speed was best for L20 and decreased with the laser power. This confirmed the fact that the laser influence on the surface fuzziness and isolated peaks on the surface increased with the laser power. High laser powers L20 and L19 caused an effect predominantly on the surface peaks and less on the surface valleys. This was demonstrated by a weaker correlation with R_{vk} in Table 9 and by an increase in the ratio R_{pk}/R_{vk} that was obvious for low laser scanning speeds (100 and 200 mm/s). The presence of ridges on the surface had a strong effect on R_{pk}, and this effect increased with the laser power and for low scanning speeds. Among all parameters, R_{pk} had the highest percentage increase, as related to the unprocessed wood, for high laser powers L19 (347.9% for 100 mm/s, respectively 190.19% for 200 mm/s) and L20 (394.7% for 100 mm/s, respectively 247.16% for 200 mm/s). The former study on beech surfaces (Gurau *et al.* 2017) provided the same observations; R_{pk} seemed to be the parameter most affected by the laser action on wood. By exception, for L14, an increase in R_{pk} was noticed only for a scanning speed of 100 mm/s (15.9%), while for higher speeds there was no influence.

The parameter R_{sk} was also influenced by the surface peaks in the surfaces processed by L20, L19, and L18 combined with low scanning speeds (100 and 200 mm/s). The highest logarithmic correlation was found with L20, which decreased for L19 and L18. However, for the laser powers equal or lower than L17, there was no correlation with R_{sk}. The prevalence of valleys in the profiles, due to the local wood variation, made these parameters less sensitive to the laser action for laser powers less than L18.

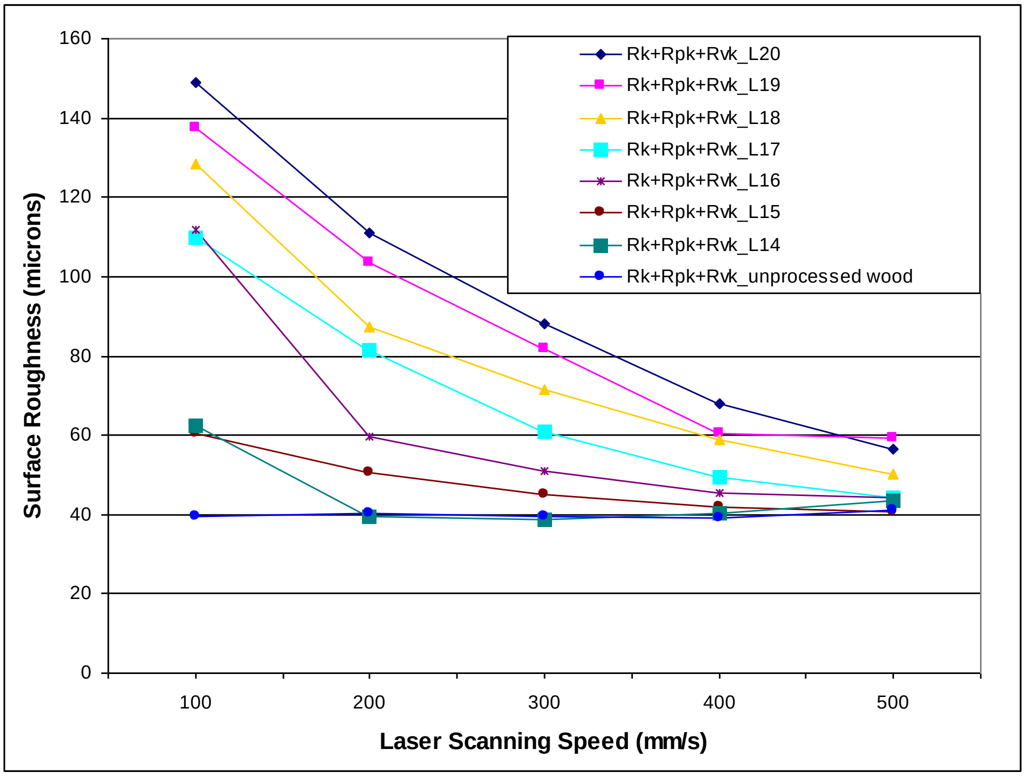


Fig. 7. Correlation between the roughness parameter $R_k + R_{pk} + R_{vk}$ and the laser scanning speed for each laser power tested

The analysis with different roughness parameters revealed various aspects of the surface scanned by the laser. Not only a single roughness parameter should be used in surface roughness analysis for a comprehensive interpretation of the surface status.

The observations and results from this study can be further extended to other species or scanning variables, such as the scanning gap, to evaluate the result on surface roughness and optimize the selection of processing parameters for a minimum roughness combined with the targeted engraving and colouring effect.

CONCLUSIONS

1. All roughness parameters increased with the laser power and decreased with the laser scanning speed.
2. The laser power L14 (5.6 W) caused a change in surface roughness only for a scanning speed of 100 mm/s (approximate 50% increase), while for higher speeds, the surface roughness was in the domain of variation of wood anatomical irregularities. For a scanning speed of 100 mm/s with a laser power L20 (8 W), the surface roughness of Norway maple was more than double in comparison with the laser power L14 (5.6 W) and approximately four times higher in comparison with the unprocessed wood.
3. It was found that the variation of roughness parameters with the laser power had a linear trend. A logarithmic correlation with the laser scanning speed was noticed for all laser

powers with the exception of L14 (5.6 W). The best correlation was found for the composed parameter $R_k + R_{pk} + R_{vk}$, which may have been the best parameter selection to describe the laser action. It was closely followed by R_a, R_k, and R_t. Both R_{sk} and R_{vk} were useful parameters for understanding the stratified structure of wood subjected to the laser action.

4. The roughness parameters correlated best with the laser power for a laser scanning speed of 300 mm/s. The lowest correlation was observed for a 500 mm/s laser scanning speed, and this was attributed to the fact that the laser effect on wood tends to become obscured by local wood anatomical irregularities (from L14(5.6 W) to L17 (6.8 W)).
5. The parameter R_{pk} seemed to be the most affected parameter by the laser action on wood. The laser had a clear effect on surface peaks, measured by R_{pk}, causing ridges on the surface that appear as push-up latewood bands. The effect increased with the laser power and with decreased scanning speed.
6. An ablation effect on wood was observed as a level difference between the laser scanned area and the unprocessed wood. This effect increased with the laser power and with a decrease in the scanning speed. The maximum effect was caused by L19 (7.6 W) and L20 (8 W), an approximate 250 microns gap, decreasing for L14 (5.6 W) to approximately 15 microns, for a scanning speed of 100 mm/s. The surfaces scanned with L20 (8 W), L19 (7.6 W), and L18 (7.2 W) and a scanning speed of 100 mm/s, displayed visible burns and the surface looked thermally degraded.

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