The Influence of CO_2 Laser Beam Power Output and Scanning Speed on Surface Roughness and Colour Changes of Beech (*Fagus sylvatica*)

Lidia Gurau,* Adrian Petru, Anca Varodi, and Maria Cristina Timar

The literature provides very little information about engraving or decorating wood using a laser beam. No study was found that considers the surface roughness of wood after such treatments. This paper therefore aimed to find the influence of varying the laser power output and scanning speed of a CO_2 laser beam on the surface roughness and colour of beech wood (*Fagus sylvatica*) for aesthetic applications such as decorative drawing. Laser power outputs from 5.6 to 6.8 W were tested in combination with scanning speeds from 100 to 500 mm/s. The surface roughness was assessed with a robust filter and by following measuring and evaluation recommendations from previous research to reduce the bias from the wood anatomy. The surface roughness measured by a series of roughness parameters (R_a, R_q, R_t, R_k, R_{pk}, R_{vk}) and total colour difference ΔE increased with laser power and decreased with scanning speed. A good correlation was found between surface roughness and wood colour change. Such correlations can be useful for selecting the laser power-scanning speed combinations capable of giving the chosen colour change at a minimum surface roughness.

Keywords: Laser power; Laser scanning speed; Wood surface roughness; Wood colour change; Robust filtering; Roughness parameters

*Contact information: Transilvania University of Brasov, Faculty of Wood Engineering, Universitatii Str. 1, 500036 Brasov, Romania; *Corresponding author: lidiagurau@unitbv.ro*

INTRODUCTION

The laser can be regarded as a device for producing a finely controllable energy beam, which, in contact with a material, generates considerable heat. The energy of a laser beam is focused on a small spot diameter to achieve the necessary power density. Part of the energy of light contained in the laser radiation is absorbed by the workpiece and transformed into thermal energy.

Laser beam technology has multiple applications in almost all known materials, but it has been extensively researched only for the metal industry. The main application areas of lasers are marking, drilling, micro-milling, cutting, engraving, welding, and heat treatment/hardening in the automotive, aircraft, and microelectronic industries (Pritam 2016).

A review of the application of CO_2 laser beams as a cutting tool for various materials was made by Radovanovic and Madic (2011), who also mentioned the application of a laser beam on cutting MDF, citing the work of Lum *et al.* (2000).

Laser engraving is the practice of using lasers to engrave or mark an object. Laser engraving is the removal of material from the top surface down to a specified depth. Few studies exist on the engraving of metals, and there are even fewer studies concerning wood engraving. An important review was performed on laser engraving for various materials, including wood, by Patel *et al.* (2015), who investigated the influence of the process parameters (laser power, scanning speed, and laser frequency) on the engraving depth and surface roughness. Patel *et al.* (2015) acknowledged the work of Leone *et al.* (2009), who investigated wood engraving using a Q-switched diode pumped frequency doubled Nd:YAG green laser working at a wavelength of 532 nm. The examined parameters were the pulse frequency, the beam speed, the number of laser scans, and the engraved depth. Experimental results showed that this type of laser can be successfully used to machine different types of wood, obtaining decorative drawing and 3D engraved geometries without burning. However, the authors stated that more studies are needed to correlate the wood species with appropriate process parameters, with a goal of achieving deep engraving without carbonization and still retaining a homogeneous carving.

Lin *et al*. (2008) investigated the effect of feed speed ratio and 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. Colour difference values increased at a lower feed speed ratio and a higher power and resulted in a brownish color in the engraved zone. The advantage of this study was that the engraved depth and colour difference values of Moso bamboo could be predicted and estimated by regression analyses.

Patel and Patel (2014) used surface roughness as the response for various parameters in laser engraving of stainless steel. The measured parameter was R_a. It was found that surface roughness increases with higher laser frequency and a lower engraving speed. Similarly, Pritam (2016) found that the surface roughness described by R_a and the engraving depth of stainless steel decrease with an increase in the scanning speed and a decrease in the laser power. The target was for a minimization of surface roughness, while maximizing the engraving depth. To achieve deeper cavities, but with less roughness, the author recommends an increased number of laser scans at a lower power and a higher scanning speed.

In 1986, Barnekov *et al*. concluded that laser applications on wood have great potential, but they were not yet sufficiently explored. This statement is still valid today. One of the main factors influencing laser-wood interaction is the character of the wood itself, primarily its density, moisture content, extractives, and optical properties.

Kubovsky and Kačik (2009) stated that the value of exposure to laser radiation has a considerable influence on the changes produced in the main wood components. A maple (*Acer pseudoplatanus* L.) board was irradiated by a CO_2 laser beam at different values of exposure energy (expressed as irradiation dose). When increasing the irradiation dose, the degradation of hemicelluloses was predominantly observed, while lignin was degraded at a lower irradiation dose. At a higher energy dosage, lignin condensation occurred. In another study by Barcikowski *et al.* (2006), a significant thermal modification of lignin within the cell walls occurred mostly at the surface of *Pinus sylvestris* when it was cut by a laser.

Petutschnigg *et al.* (2013) explored the option to treat wood surfaces with laser beams to develop new aesthetic possibilities and found an application in ski design. This study deals with different laser treatments for samples from various wood species: beech, ash, lime, and spruce. The authors varied the laser beam intensity from 40 to 120 W and the number of laser points on the surface, while keeping a constant scanning speed, and measured the resulting colour. The intensity of laser beams affected the colour changes in different patterns and was species-dependent.

In summary, the effect of a laser beam on wood surfaces has scarcely been studied and no research has explored the effect of a laser beam on the surface roughness of wood or on the combined factors of surface roughness and colour change.

This paper aims to find the influence of varying some parameters of a CO_2 laser beam (laser power output and scanning speed) on the surface roughness and colour of beech wood (*Fagus sylvatica*) for aesthetic applications such as decorative drawing. It is important to develop such information to understand the effect of the two parameters on the surface quality and colour of beech when estimating superficial decoration with minimum engraving (below 1 mm) using lasers.

EXPERIMENTAL

For superficial decorative engraving/drawing, a CO_2 laser (model SLG-4030 lsct with LaserCut software version 4.03 included, imported from China by SpotLine, Bucharest, Romania), with a wavelength of 10.6 μm, a lens of 73 mm focal length, and maximum output power of 40 W was used. The scanning gap was 0.0254 mm and the pulse frequency was 20,000 Hz.

For laser treatment, two parameters were varied, namely, the laser output power and the laser speed. Laser output powers used for this study were fractions from the maximum output power of 40 W: 13% (5.2 W), 14% (5.6 W), 15% (6 W), 16% (6.4 W), and 17% (6.8 W). For simplicity, they are symbolized in this paper as L13, L14, L15, L16, and L17, respectively. The tested scanning speeds were 100, 200, 300, 400, and 500 mm/s. The target was to analyse their influence on the colour changes occurring on laser scanned beech wood as well as on surface roughness parameters. An exception was made for laser power L13, which was analysed only for colour change.

Five beech (*Fagus sylvatica*) specimens, conditioned at 20 °C and 65% relative humidity of the ambient air, were prepared by first planing, then dimension cutting, then calibration with P60, and finally manual sanding with P100 grit size to their final dimensions of 340 mm x 100 mm x 8 mm. The surfaces were semi-radial, which were preferred to tangential because they have less colour and anatomical wood variation along the surface. The beech species was selected because of its availability.

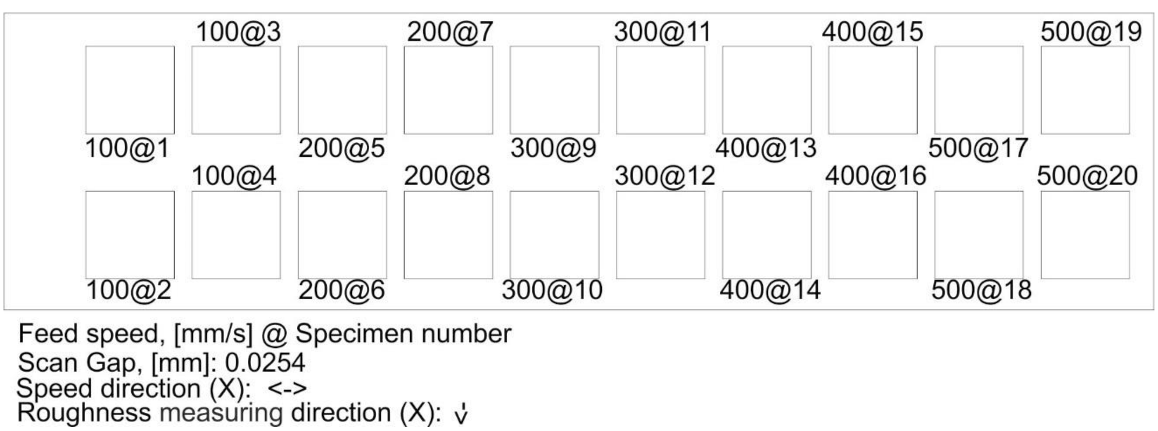


Fig. 1. Schematic representation of a wood sample scanned with a laser beam on 25 mm x 25 mm areas for five scanning speeds and four replicates for each speed

Each of the five specimens was scanned with a different laser power output (from L13 to L17) as described above. On each specimen and for each output power, 20 areas (25 mm x 25 mm) were laser scanned with scanning speeds from 100 to 500 mm/s, so that for each scanning speed there were four replicates (Fig. 1).

Colour measurements were performed for each laser power and scanning speed, as well as on unprocessed wood with an Ava Spec USB2 (Avantes, Apeldoorn, Netherlands) spectrometer with AvaLight–HAL (S) light source and optical fibres at a measuring geometry 90°/0°, 2° standard observer, under standard illuminant D65, employing the AVA SPEC version 7.7 software (provided by Avantes, Apeldoorn, Netherlands) for colour applications. The CIE $L^*a^*b^*$ colour coordinates, respectively the lightness L^* (varying from 0 for black to 100 for white), the chromaticity coordinates a^* (varying from negative values for green to positive values for red on the green-red axis), and the b^* chromaticity coordinate (varying from negative values for blue to positive values for yellow on the blue-yellow axis), were measured, amounting to a total of four measuring areas per each test area. Therefore, there were 4 random colour measurements for each wood sample and 4 colour measurements for each laser power-scanning speed combinations applied (replicated) on the same wood sample. Average values were computed for each measurement type.

Total colour differences between laser scanned areas at a certain power and scanning speed and the surrounding unprocessed wood were calculated from mean values and based on Eq. 1,

$$\Delta E = \left(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}\right)^{1/2} \tag{1}$$

where ΔE is the total/global colour difference, ΔL^* represents the change in lightness, Δa^* is the change in redness, and Δb^* is the change in yellowness. The total colour differences of laser engraved areas as compared to unprocessed wood were plotted against the laser scanning speed for each laser power.

Surface quality measurements were performed using a MarSurf XT20 instrument manufactured by MAHR Gottingen GMBH (Göttingen, Germany), fitted with a MFW 250 scanning head with a tracing arm in the range of ±500 μm and a stylus with a 2-μm tip radius and 90° tip angle, which measured the beech 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, so that, for each laser power (except L13) and scanning speed, four profiles were analysed. For all laser powers (L14 to L17) and five scanning speeds, there were 80 scanned profiles in total.

Those profiles and their roughness parameters were compared with similar 20-mm-long profiles of untreated wood, stylus scanned in the immediate vicinity of the laser modified areas (Fig. 2b), so that each laser power/scanning speed combination corresponded to one roughness profile from unmodified wood. This meant that for each specimen, five wood profiles were analysed, resulting in a total of 20 profiles for all laser powers examined (L14 to L17). 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, another group of profiles, 40 mm long, were scanned so that they covered half a laser engraved region and half unprocessed wood (Fig. 2c). This meant five mixed profiles for each specimen, 20 mixed profiles in total.

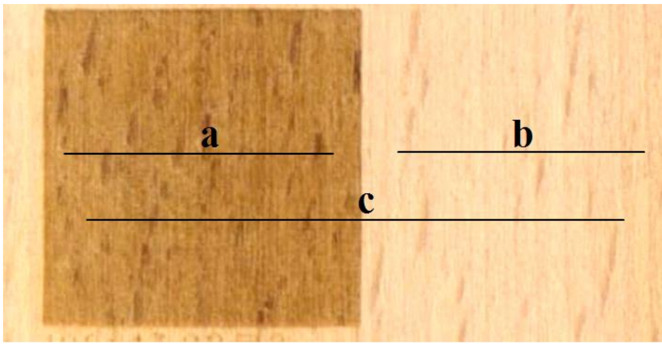


Fig. 2. Details regarding the profiles measurement: a: profile from laser modified area (20 mm long); b: profile from unprocessed wood (20 mm long); c: mixed profile measuring laser scanned and unprocessed wood (40 mm long)

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).

The procedure with profiles is standard. Any measured profile contains not only roughness, but also form errors and waviness (ASME B46.1 2009). A flat surface processed by sanding and then scanned by the laser is best characterized by surface roughness. This means that it is necessary to extract the roughness from the measured profile. Therefore, the form errors characterizing the machining accuracy were removed following the procedure given in ISO 3274 (1996). Furthermore, to obtain the roughness profiles, a filter should be applied to straighten the profile. However, it was found that common filters, such as the simple Gaussian filter, can alter the measured profile, causing some artificial "push-up" in areas with deep wood pores (Fig. 3). This drawback can be avoided by using a more recent and robust filter called RGRF (robust Gaussian regression filter) contained in ISO 16610-31 (2010). This filter was tested and found useful for wood surfaces because it is more robust than the simple Gaussian filter (Fig. 3) and does not introduce bias related to wood anatomy (Gurau *et al.* 2006).

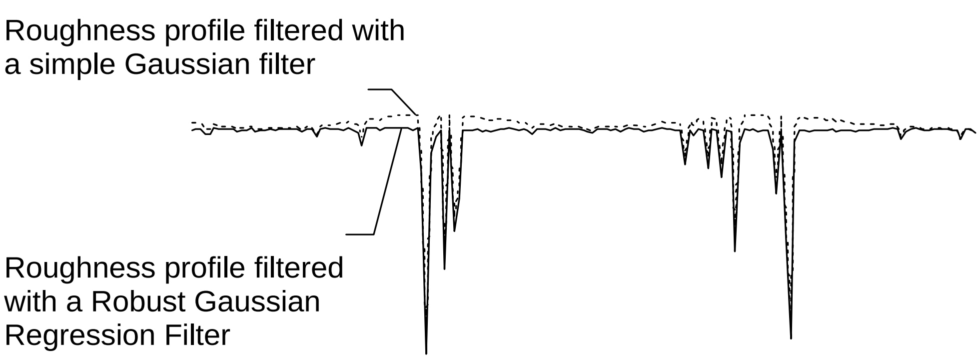


Fig. 3. Example of roughness profile filtered with a simple Gaussian filter (dotted line) with artificial "push-up" in comparison with filtering with a robust filter (continuous line)

This filtering procedure is quite new for wood surfaces and has the advantage of providing a more reliable result regarding the surface roughness of wood. 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 correctly obtained, a range of roughness parameters was calculated for profiles, such as R_a, R_q, and R_t from ISO 4287 (1997) and R_k, R_{pk}, and R_{vk} from ISO 13565-2 (1996). Their mean values and standard deviations were also calculated.

Mean parameters R_a (the arithmetical mean deviation of the assessed profile) and R_q (the root mean square deviation of the profile) are common roughness indicators, but they alone do not provide sufficient information about wood surface topography. Furthermore, it is expected that they will be influenced by deep wood anatomical irregularities. Similarly, R_t (the total height of the profile) is expected to be sensitive not only to processing with the laser but also to variations in local wood anatomy.

R_k (the core roughness depth), R_{pk} (the reduced peak height), and R_{vk} (the reduced valley depth) are interesting parameters. They are calculated by following a standard procedure in ISO 13565-2 (1996), where the surface irregularities are first ranked in descending order (Fig. 4). Then, the region with the highest concentration of data points is delimited by R_k, which is also the parameter that is least influenced by wood anatomical irregularities and whose values should approximate the contribution of processing (the marks caused by the processing tool). In the case of this study, the processing that preceded the laser scanning was sanding with grit P100. It is assumed that the grit particles have left specific sanding traces on the samples overlapping on the wood anatomical irregularities. Then, the laser affected the sanded beech surface by increasing the magnitude of peaks and valleys in the initial surface and presumably increasing the core roughness R_k. However, no study has explored how much laser power combined with a variation in the scanning speed contributes to this topographic change in the wood surface.

R_{pk} is a parameter that gives a measure of the magnitude of raised fibres above the core roughness, while R_{vk} measures the magnitude of deep irregularities extending below the core roughness (in the case of wood, associated with anatomical valleys). It is expected that the laser will influence all these parameters: R_k, R_{pk}, and R_{vk}. Therefore, a composed parameter comprising the three regions was also used in this research: $R_k + R_{pk} + R_{vk}$.

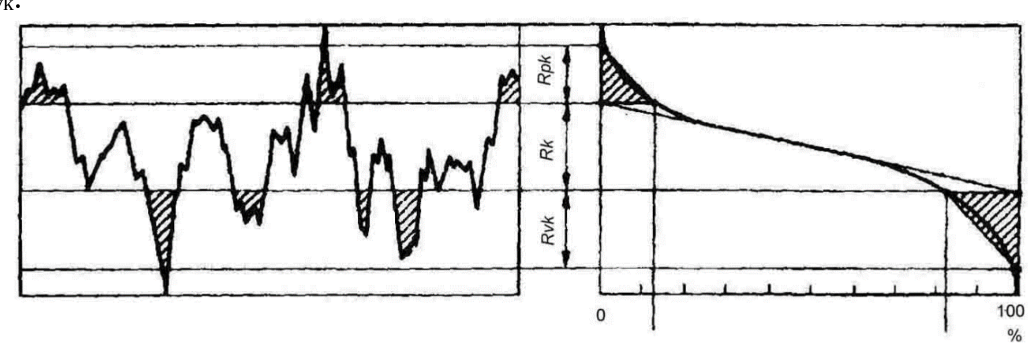


Fig. 4. Calculation of R_k, R_{pk}, and R_{vk} of a roughness profile according to ISO 13565-2 (1996)

In addition to calculating the roughness parameters, the measured data were imported into MathCad, and roughness profiles were visualized to compare the magnitude of irregularities from unprocessed beech with those where the laser was used.

The effect of the laser power output on the core surface roughness was made visible by calculating the location of thresholds that delimit the core roughness from the isolated peaks and valleys with a method derived from ISO 13565-2 (1996) (Fig. 4) and described in detail by Gurau *et al.* (2005).

The colour differences were then compared with surface roughness changes and correlations were analysed.

RESULTS AND DISCUSSION

The Influence of Laser Power Output and Scanning Speed on the Colour of Beech

The colour change coordinates for beech processed with different laser powers and scanning speeds as well as differences related to unprocessed surrounding wood are included in Table 1. Visual examples of areas scanned with combinations of laser power output-scanning speed are given in Table 2. The thick lines in Table 2 separate to the right the images where the laser visual effect on wood was reduced so much that it was hardly detectable.

Table 1. Variation of Colour Coordinates (Mean Values) of Laser Scanned Beech with Laser Power and Scanning Speed and Differences as Compared with Unprocessed Beech. In parenthesis, Standard Deviation Values.

Processing	Laser scanning speed (mm/s)	*L**	*a**	*b**	Δ*L**	Δ*a**	Δ*b**	Δ*E*
L13	100	71.80 (2.75)	7.49 (0.70)	19.60 (0.80)	-6.31	1.20	4.37	7.76
	200	75.44 (2.21)	7.10 (0.72)	16.64 (0.94)	-2.67	0.81	1.41	3.12
	300	78.70 (1.18)	6.03 (0.58)	15.19 (0.59)	0.59	-0.26	-0.04	0.64
	400	78.50 (2.45)	6.22 (1.05)	15.15 (0.80)	0.39	-0.07	-0.08	0.40
	500	77.93 (0.97)	6.20 (0.71)	15.95 (0.46)	-0.17	-0.09	0.71	0.74
Unprocessed beech		78.11 (0.76)	6.29 (0.20)	15.23 (0.30)	0	0	0	0
L14	100	61.55 (2.15)	8.39 (0.57)	20.61 (0.94)	-20.26	3.14	5.23	21.16
	200	69.00 (2.15)	8.05 (0.26)	20.15 (1.07)	-12.81	2.80	4.78	13.96
	300	75.30 (0.96)	7.29 (0.17)	18.45 (0.67)	-6.51	2.04	3.08	7.48
	400	76.75 (1.63)	7.00 (0.81)	17.90 (0.35)	-5.06	1.75	2.53	5.92
	500	78.43 (0.48)	6.38 (0.49)	17.02 (0.80)	-3.39	1.14	1.64	3.93
Unprocessed beech		81.81 (0.57)	5.25 (0.16)	15.37 (0.40)	0	0	0	0

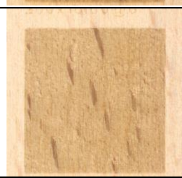
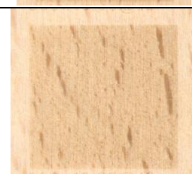
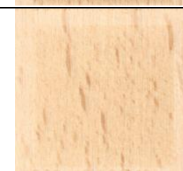
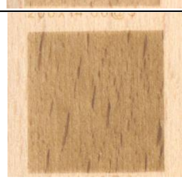
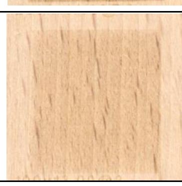
Processing	Laser scanning speed (mm/s)	*L**	*a**	*b**	Δ*L**	Δ*a**	Δ*b**	Δ*E*
L15	100	63.23 (1.73)	8.79 (0.54)	23.14 (1.15)	-18.98	3.80	6.35	20.37
	200	65.41 (2.19)	8.61 (0.34)	20.76 (0.88)	-16.80	3.62	3.97	17.64
	300	70.81 (2.11)	7.84 (0.48)	20.88 (0.56)	-11.40	2.85	4.10	12.44
	400	72.62 (1.88)	7.62 (0.58)	20.48 (1.39)	-9.59	2.63	3.70	10.61
	500	76.29	7.04	18.77	-5.92	2.05	1.99	6.57
Unprocessed beech		82.21 (0.33)	4.99 (0.25)	16.79 (0.29)	0	0	0	0
L16	100	64.58 (0.43)	8.51 (0.36)	22.90 (1.07)	-17.82	3.39	6.44	19.24
	200	70.61 (0.21)	7.59 (0.33)	21.82 (0.60)	-11.78	2.47	5.36	13.17
	300	70.50 (1.52)	7.57 (0.27)	20.06 (0.32)	-11.90	2.45	3.60	12.67
	400	73.59 (1.05)	7.04 (0.33)	21.06 (1.11)	-8.80	1.92	4.60	10.11
	500	75.70 (1.89)	6.61 (0.48)	19.37 (0.49)	-6.70	1.49	2.91	7.45
Unprocessed beech		82.39 (0.74)	5.12 (0.25)	16.46 (0.63)	0	0	0	0
L17	100	56.77 (1.74)	9.03 (0.56)	24.84 (2.50)	-23.11	3.49	7.88	24.66
	200	63.23 (1.03)	9.09 (0.14)	22.53 (1.12)	-16.65	3.55	5.56	17.91
	300	68.49 (2.33)	8.30 (0.27)	21.57 (0.95)	-11.39	2.76	4.60	12.59
	400	70.50 (1.59)	7.92 (0.41)	20.36 (0.65)	-9.38	2.38	3.39	10.26
	500	71.53 (1.93)	7.49 (0.54)	20.28 (0.82)	-8.35	1.95	3.31	9.19
Unprocessed beech		79.88 (0.35)	5.54 (0.32)	16.97 (1.19)	0	0	0	0

It was observed that Δ*E* decreased sharply from a scanning speed of 100 to 300 mm/s and generally increased with laser power.

For laser power L13, beginning with the scanning speed of 200 to 500 mm/s, there were almost no colour differences as compared with unprocessed wood (Fig. 5 and Table 2). This laser power had very little colouring effect for scanning speeds of 100 and 200 mm/s, much lower than the next tested laser power, L14. The laser power L14 combined with a scanning speed of 100 mm/s increased the colour difference from natural wood 2.7 times as compared with L13. It appears that working with L13 laser power is not reasonable for wood colouring/drawing with scanning speeds higher than 00 mm/s.

The overall colour difference, ΔE, was used as a reference for comparisons in Fig. 5. Experimental points were joined by trend lines, which were third-order polynomial functions. The coefficients of correlation were high (0.98 to 0.99).

Table 2. Example of Laser Scanned Areas for Various Laser Power-Scanning Speed Combinations

	100 mm/s	200 mm/s	300 mm/s	400 mm/s	500 mm/s
L17					
L16					
L15					
L14					
L13					

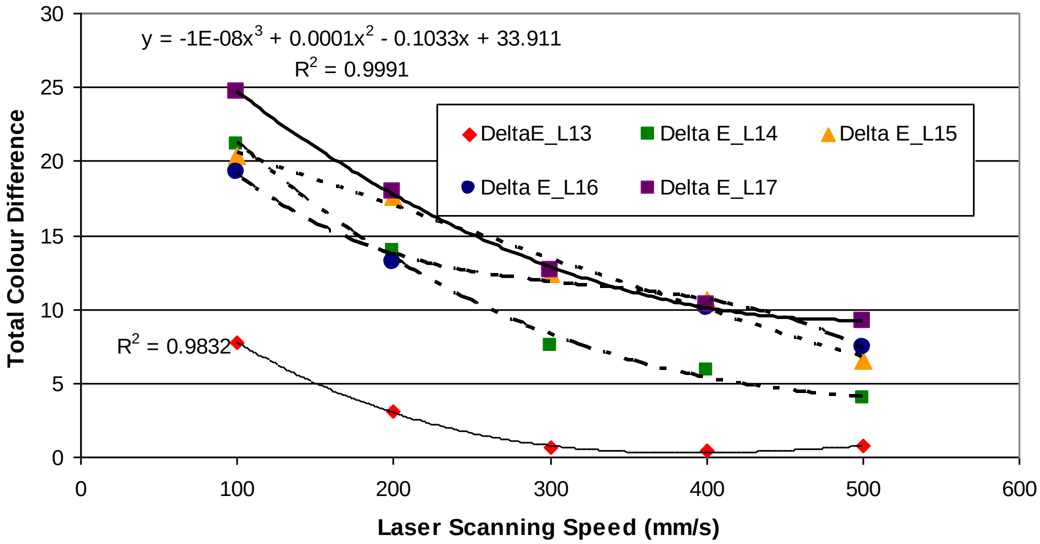


Fig. 5. Total colour differences Δ*E* (Delta *E*) of wood surfaces scanned with lasers of different output powers and scanning speeds as compared to unprocessed beech wood

Δ*E* for laser powers L15, L16, and L17 was not much different for scanning speeds from 300 to 500 mm/s (Fig. 5). The same trends were noticed for luminosity as for Δ*E*. As far as the redness was concerned, the highest colour differences occurred for L15, followed closely by L17. The yellowness was highest for L17, only for scanning speeds of 100 and 200 mm/s. For scanning speeds of 300 and 400 mm/s, the yellowness of L15, L16, and L17 were similar.

The Influence of Laser Power Output and Scanning Speed on the Surface Roughness of Beech

Roughness parameters mean values for surfaces scanned with laser powers L14 to L17 combined with scanning speeds from 100 to 500 mm as well as those measured from unprocessed beech surfaces are contained in Table 3.

Table 3. Mean Roughness Parameters for Beech Scanned with Various Laser Power Outputs and Scanning Speeds in Comparison with Unprocessed Surfaces. In parenthesis, Standard Deviation Values.

Processing	Laser scanning speed (mm/s)	R_a (µm)	R_q (µm)	R_t (µm)	R_k (µm)	R_{pk} (µm)	R_{vk} (µm)	R_k+R_{pk}+R_{vk} (µm)
L14	100	11.8 (0.67)	15.8 (0.78)	112.3 (9.64)	33.6 (2.08)	10.2 (0.96)	24.2 (1.04)	68.0 (2.07)
	200	10.0 (0.32)	13.1 (0.44)	91.8 (5.81)	29.9 (1.56)	8.6 (0.75)	19.1 (1.20)	57.5 (2.51)
	300	9.9 (0.31)	12.9 (0.54)	83.6 (5.57)	29.1 (2.22)	7.8 (1.57)	19.5 (2.68)	56.5 (1.70)
	400	10.4 (0.74)	13.7 (0.95)	89.6 (7.17)	31.2 (2.90)	7.6 (1.75)	21.5 (2.45)	60.3 (4.53)
	500	9.6 (0.34)	12.3 (0.62)	80.9 (12.16)	29.9 (1.41)	10.4 (1.00)	15.7 (2.26)	56.1 (1.84)
L15	100	12.9 (0.91)	17.2 (1.49)	131.0 (20.70)	38.8 (2.94)	10.0 (0.90)	26.8 (4.64)	75.6 (6.90)
	200	10.9 (1.12)	14.6 (1.55)	111.0 (18.71)	30.7 (2.82)	10.1 (2.73)	22.6 (1.39)	63.4 (6.17)
	300	10.4 (1.08)	13.4 (1.58)	89.8 (18.03)	32.9 (3.60)	8.8 (2.35)	17.9 (2.79)	59.5 (6.77)
	400	10.0 (1.03)	13.0 (1.73)	86.3 (12.49)	30.7 (2.77)	7.5 (0.64)	18.7 (4.83)	56.9 (7.13)
	500	10.5 (0.48)	13.6 (0.69)	93.1 (16.84)	32.3 (3.05)	8.2 (1.63)	19.0 (3.27)	59.5 (5.07)
L16	100	16.1 (1.46)	20.9 (1.90)	130.3 (16.45)	48.2 (6.05)	12.7 (1.52)	29.4 (4.09)	90.4 (10.86)
	200	11.3 (0.84)	14.8 (0.97)	105.7 (9.14)	33.1 (4.06)	8.1 (1.25)	21.8 (3.35)	63.0 (4.09)
	300	11.0 (0.59)	14.2 (1.05)	94.4 (5.23)	34.0 (1.55)	8.9 (1.94)	18.9 (2.84)	61.7 (3.73)
	400	10.4 (0.79)	13.7 (1.31)	95.2 (2.24)	31.1 (1.57)	9.5 (1.85)	19.6 (3.91)	60.2 (5.60)
	500	10.4 (0.71)	13.7 (1.20)	91.9 (16.97)	31.3 (2.01)	11.2 (2.39)	18.9 (4.37)	61.4 (5.50)
Processing	**Laser scanning speed (mm/s)**	**R_a (µm)**	**R_q (µm)**	**R_t (µm)**	**R_k (µm)**	**R_{pk} (µm)**	**R_{vk} (µm)**	**R_k+R_{pk}+R_{vk} (µm)**
L17	100	22.0 (2.91)	27.8 (3.62)	170.7 (22.36)	69.5 (10.91)	18.2 (2.74)	33.8 (4.95)	121.4 (17.43)
	200	13.5 (0.29)	17.3 (0.38)	115.4 (4.59)	41.6 (1.31)	12.4 (1.64)	23.3 (0.68)	77.2 (1.94)
	300	10.8 (0.69)	13.9 (0.99)	96.8 (16.98)	33.4 (1.77)	11.5 (3.15)	17.6 (1.74)	62.5 (4.94)
	400	11.0 (0.81)	14.0 (0.95)	87.9 (3.25)	34.8 (3.15)	9.7 (1.12)	18.8 (2.05)	63.3 (3.29)
	500	10.7 (0.51)	13.9 (0.59)	103.9 (17.93)	33.2 (3.15)	11.9 (1.28)	19.2 (0.65)	64.2 (3.24)
Beech unprocessed	Mean from all areas (20 values)	**10.2 (0.84)**	**13.3 (1.16)**	**86.7 (7.81)**	**30.9 (2.80)**	**7.7 (1.26)**	**18.9 (2.92)**	**57.5 (4.66)**

Among the roughness parameters, the best correlation with the laser power and scanning speed was obtained for the depth of the profile $R_k + R_{pk} + R_{vk}$, which was further used as a reference for comparisons.

Figure 6 shows the variation of the combined roughness parameter $R_k + R_{pk} + R_{vk}$ with the laser power and scanning speed in comparison with the reference, for unprocessed beech. The best correlations were obtained for a third-order polynomial, which was fit for all laser power data points. The coefficients of correlations R^2 were high for all curves, with the highest values recorded for the laser power L17.

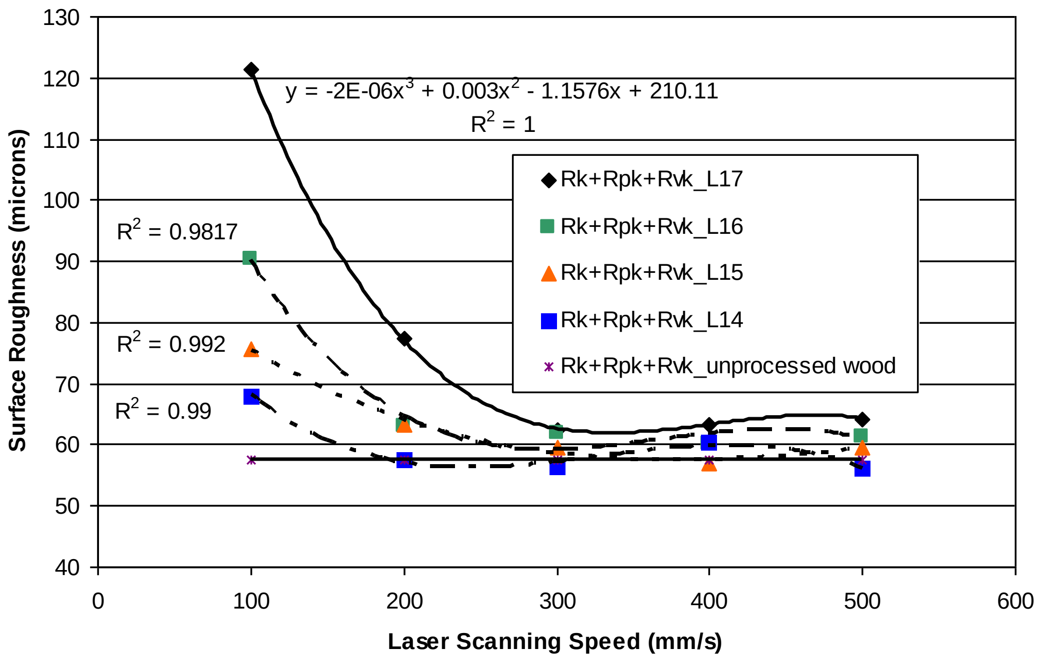


Fig. 6. Variation of the depth of the profile ($R_k + R_{pk} + R_{vk}$), with the laser power and laser scanning speed in comparison with unprocessed beech (solid horizontal line)

From Table 3 and Fig. 6, it can be seen that the roughness values increased with the laser power.

The laser scanning speed had a strong influence on the surface roughness values. The highest values were recorded for all laser powers at a scanning speed of 100 mm/s, which in case of high powers, L16 and L17, caused burning of the surface, which was perceived as a strong dark colour and as a level difference from the surrounding wood (engraving effect less than 1 mm).

It was interesting to evaluate how much roughness change was caused by the laser action on wood. In Table 4, the extreme cases of laser processing effect on wood were included. The minimum effect was obtained for laser power L14 combined with a scanning speed of 500 mm/s, which was compared with the roughness of wood measured in the proximate vicinity (as shown in Fig. 2 a and b). The increase in roughness in the laser processed area is presented as a percentage. Similarly, the maximum effect on wood was produced by the combination of laser power L17 and a scanning speed of 100 mm/s.

Table 4. Minimum and Maximum Effect of Laser Power-Scanning Speed on Surface Roughness of Wood in Comparison with Neighboring Unprocessed Wood

	Laser power L14 at 500 mm/s	Neighbouring wood	Roughness increase (%)	Laser power L17 at 100 mm/s	Neighbouring wood	Roughness increase (%)
R_a (μm)	9.6	9.59	0.10	22	9.44	133.05
R_q (μm)	12.3	12.18	0.99	27.8	12.1	129.75
R_k (μm)	29.9	29.6	1.01	69.5	29.3	137.20
R_{pk}(μm)	10.4	7.91	31.48	18.2	7.04	158.52
R_{vk}(μm)	15.7	15.4	1.95	33.8	17.02	98.59
$R_k + R_{pk} + R_{vk}$ (μm)	56.1	52.91	6.03	121.4	53.36	127.51

From Table 4, the greatest effect of laser action on wood was observed on R_{pk} (surface fuzziness), which increased by 31.48% for laser power L14 and by 158.52% for laser power L17. An increase in roughness was observed for all roughness parameters, but the parameter $R_k + R_{pk} + R_{vk}$ showed a strong cumulative effect: surface roughness of beech wood laser scanned with L17 at a scanning speed of 100 mm/s increased the surface roughness by 127.51%, corresponding to an absolute height difference of approximately 68 μm. The value R_k increased by 137.20%, corresponding to an absolute difference of 40 μm. For finishing applications, this surface is considered very rough. The rougher the surface is, the more finish (lacquer) it will absorb. It must be noted that the measurement was performed inside the laser engraved area and the parameters did not measure the level difference from the surrounding wood (the depth of the engraved area).

In the case of the laser power L14, with scanning speeds of 200 to 500 mm/s, the effect on surface roughness was obscured by local wood roughness (wood anatomical irregularities and irregularities from previous processing by sanding) (Table 3 and Fig. 6). In this domain of scanning speed, the roughness parameters for L14 had a pendular trend with respect to the wood roughness, possibly because of local wood anatomical variation.

For L15, the roughness decrease was sharp for scanning speeds of 100 and 200 mm/s, but with a tendency to stabilize from a scanning speed of 300 mm/s and, as above, with roughness parameters obscured by wood roughness from scanning speeds from 300 to 500 mm/s.

For laser powers L16 as well as for L17, the decrease in roughness for all parameters was sharp, from a scanning speed of 100 to 300 mm/s, then the values were rather constant as the scanning speed increased but always with higher roughness values than for unprocessed wood (Table 3 and Fig. 6).

Compared with the laser power L14, for a scanning speed of 100 mm/s, the core roughness R_k for L17 doubled, while R_k increased by 43.5% for L16 and by 15.7% for L15. This shows that the laser power has a strong impact on surface roughness for low scanning speeds.

The strong influence of laser scanning speed on the surface roughness of beech wood can be seen for laser power L17 in Fig. 7, where a mixed profile is presented with approximately half the length from the laser scanned surface and half from unprocessed wood. The first half of the profile shows a high magnitude of irregularities in comparison with the second half, where wood was left unprocessed. Those profile regions were separated and presented in Figs. 8 and 9, respectively, both containing thresholds which delimit the core roughness. It can be observed that the core roughness of beech processed with L17 was more than double the core roughness of unprocessed beech (see also R_k in Table 4).

In contrast, the core roughness of a profile taken from beech processed with laser power L14 at a scanning speed of 100 mm/s in Fig. 10 shows only slightly higher values as compared with unprocessed wood core roughness (Fig. 9). The value R_k for laser power L14 and a scanning speed of 100 mm/s was 8.6% higher than R_k for unprocessed beech (Table 3).

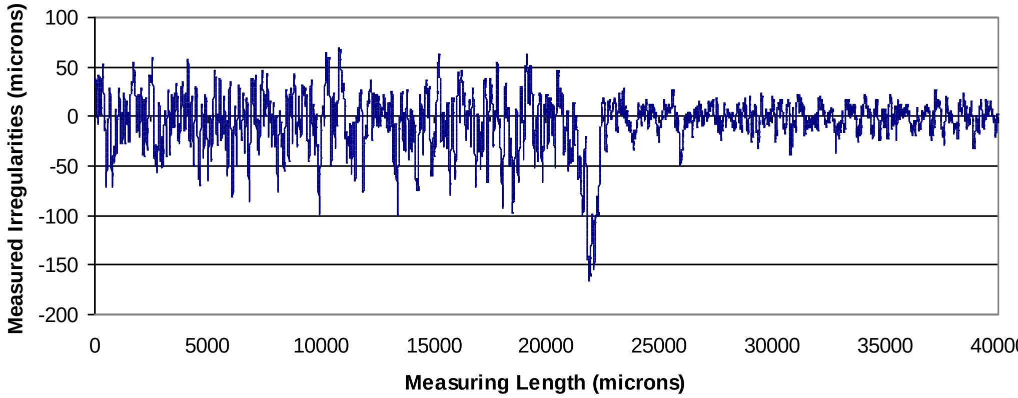


Fig. 7. Mixed profile measuring approximately half length from beech engraved with L17 laser power at 100 mm/s scanning speed and half from unprocessed beech. Profile length: 40 mm

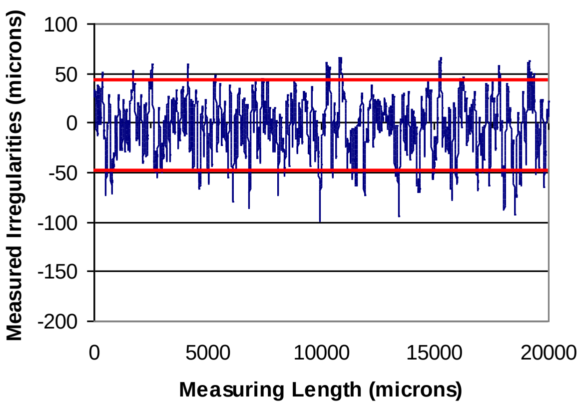


Fig. 8. Detail of the mixed profile from Fig. 7, representing only the laser scanned region (left part) of the profile (laser power L17 and 100 mm/s scanning speed). The red lines represent thresholds delimiting the core roughness. Profile length: 20 mm

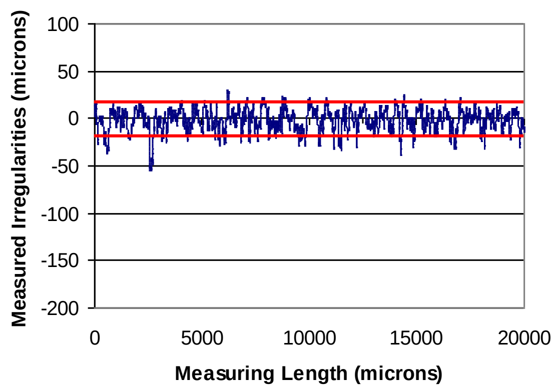


Fig. 9. Detail of the mixed profile from Fig. 7, representing only the unprocessed wood region (right part) of the profile. The red lines represent thresholds delimiting the core roughness. Profile length: 20 mm

Correlations between Colour Change and Surface Roughness for Beech Subjected to Laser Beam, Varying Power Outputs and Scanning Speeds

The correlation between colour change, expressed by the total colour difference ΔE and the surface roughness, measured by the composed parameter $R_k + R_{pk} + R_{vk}$, for beech surfaces scanned by laser of different power outputs and scanning speeds is presented in Table 5. They were calculated with the CORREL function available in Microsoft Office Excel 2003 for two groups of values. The colour change and surface roughness correlated very well, with high coefficients of correlation for all laser powers, combined with various scanning speeds. The coefficients ranged from 0.8 in case of L14 to 0.94 for L17.

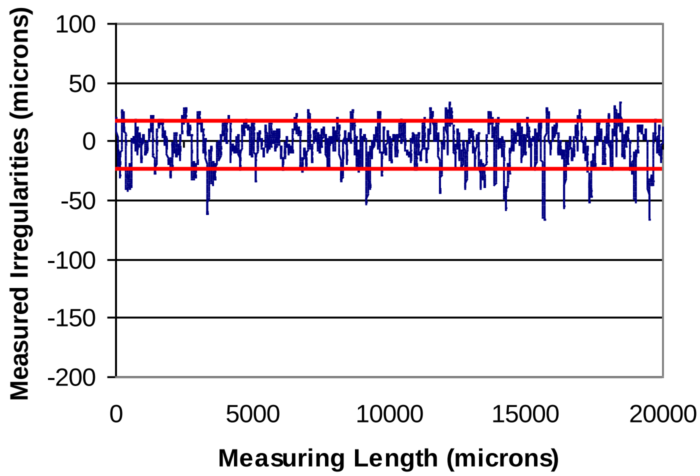


Fig. 10. Profile measured from beech scanned with L14 laser power at 100 mm/s scanning speed. The red lines represent thresholds delimiting the core roughness. Profile length: 20 mm

Table 5. Correlation between Total Colour Difference Δ*E* and Surface Roughness ($R_k + R_{pk} + R_{vk}$) for Scanning Beech Surfaces with Different Laser Powers and Scanning Speeds

Processing	Laser scanning speed (mm/s)	Δ*E*	$R_k + R_{pk} + R_{vk}$ (μm)	Correlation coefficients
L17	100	24.66	121.4	**0.94**
	200	17.91	77.2	
	300	12.59	62.5	
	400	10.26	63.3	
	500	9.19	64.2	
L16	100	19.24	90.4	**0.88**
	200	13.17	63.0	
	300	12.67	61.7	
	400	10.11	60.2	
	500	7.45	61.4	
L15	100	20.37	75.6	**0.82**
	200	17.64	63.4	
	300	12.44	59.5	
	400	10.61	56.9	
	500	6.57	59.5	
L14	100	21.16	68.0	**0.80**
	200	13.96	57.5	
	300	7.48	56.5	
	400	5.92	60.3	
	500	3.93	56.1	

Figure 11 shows the variation of the total colour difference, ΔE, with the composed roughness parameter, $R_k + R_{pk} + R_{vk}$. The correlations from Fig. 11 can be useful to select the laser power-scanning speed combination that will produce a similar colour change, but with a reduced surface roughness. Such an example is the scanning speed of 200 mm/s, where laser powers L15 and L17 caused a similar colour difference value (17.64 for L15 and 17.91 for L17), but the surface roughness ($R_k + R_{pk} + R_{vk}$) of L15 was lower (63.4 μm, as compared to 77.2 μm for L17). The scanning speed of 100 mm/s caused a darker colour for L14 than for L15 and L16 and a higher colour difference from the surrounding wood (ΔE of 21.16 for L14 compared to 20.37 for L15 and 19.24 for L16), but with a much smoother surface (63.4 μm for L14 compared to 77.2 μm for L15 and 90.4 μm for L16). Perhaps, when choosing an optimum laser power in conjunction with a scanning speed, one should consider the occurrence of a minimum surface roughness to which an important colour change corresponds.

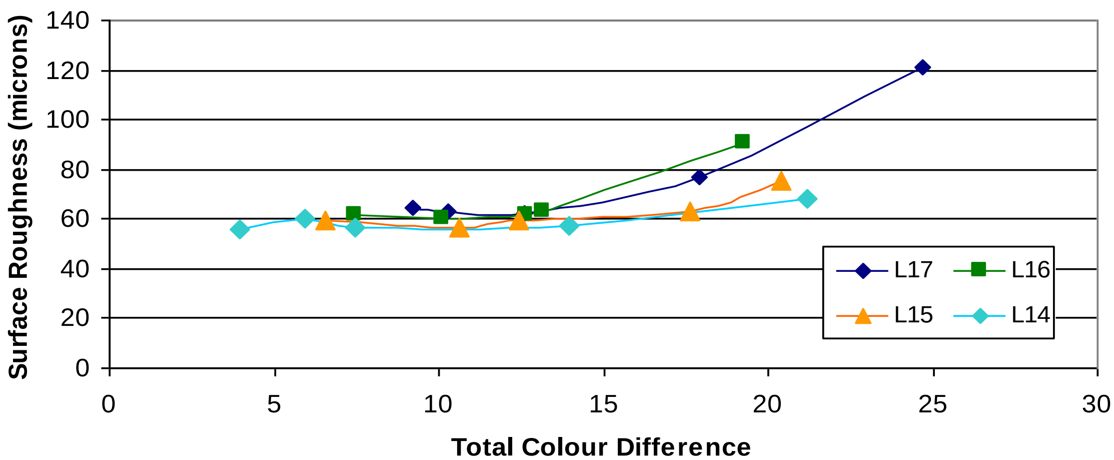


Fig. 11. Variation of the total colour difference, ΔE, with the composed roughness parameter, $R_k + R_{pk} + R_{vk}$

L16 and L17 laser powers caused wood burning for lower scanning speeds of 100 and 200 mm/s, but for a scanning speed of 300 mm/s they are not a reasonable choice because of an increased surface roughness compared with unprocessed wood, while the colouring effect on wood was not much different than using a lower laser power such as L15.

For each of the laser powers, for speeds of 300 to 500 mm/s, the surface roughness was similar, while the total colour difference slightly decreased.

This study can be extended for higher laser powers and different combinations of scanning speeds to understand how these parameters modify the surface colour and surface roughness.

CONCLUSIONS

1. The surface roughness and total colour difference as measured by ΔE increased with the laser power and decreased with the scanning speed. The highest changes as compared to unprocessed wood were obtained for the lower speeds of 100 and 200 mm/s. For speeds higher than 300 mm/s, the colour changed slightly while the surface roughness was nearly the same.
2. The laser power L13 (5.2 W) was too small to generate colour changes in wood for scanning speeds higher than 100 mm/s. The laser powers L16 (6.4 W) and L17 (6.8 W) caused surface burns and an engraving effect (depths below 1 mm).
3. The best descriptor of the surface roughness change due to laser action was the composed parameter $R_k + R_{pk} + R_{vk}$. The most pronounced topographic effect of the laser on wood was an increase in surface fuzziness as measured by R_{pk}, combined with an increased core roughness (R_k) and deeper R_{vk}.
4. The correlation curves of surface roughness and total colour difference can help when choosing the laser power-scanning speed combinations capable of giving the targeted colour change with minimum surface roughness.

ACKNOWLEDGMENTS

The authors acknowledge the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No 11/2009) for providing the infrastructure used in this work. This research was also supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), ID134378 financed from the European social fund and by the Romanian government.

REFERENCES CITED

ASME B46.1 (2009). "Surface texture (surface roughness, waviness, lay)," American Society of Mechanical Engineers, New York, NY.

Barcikowski, S., Koch, G., and Odermatt, J. (2006). "Characterisation and modification of the heat affected zone during laser material processing of wood and wood composites," *Holz als Roh- und Werkstoff* 64(2), 94-103. DOI: 10.1007/s00107-005-0028-1

Barnekov, V. G., McMillin, C. W., and Huber, H. A. (1986). "Factors influencing laser cutting of wood," *Forest Products Journal* 36(1), 55-58.

Gurau, L., Mansfield-Williams, H., and Irle, M. (2005). "Processing roughness of sanded wood surfaces," *Holz als Roh- und Werkstoff* 63(1), 43-52. DOI: 10.1007/s00107-004-0524-8

Gurau, L., Mansfield-Williams, H., and Irle, M. (2006). "Filtering the roughness of a sanded wood surface," *Holz als Roh- und Werkstoff* 64(5), 363-371. DOI: 10.1007/s00107-005-0089-1

ISO 3274 (1996 + Cor 1: 1998), "Geometrical product specifications (GPS). Surface texture. Profile method. Nominal characteristics of contact (stylus) instruments,"

International Organization for Standardization, Geneva, Switzerland.
ISO 4287 (1997+Amdl: 2009). "Geometrical product specification (GPS). Surface texture: Profile method. Terms, definitions and surface texture parameters," International Organization for Standardization, Geneva, Switzerland.
ISO 13565-2 (1996+Cor 1: 1998). "Geometric product specifications (GPS). Surface texture: Profile method. Surfaces having stratified functional properties. Height characterization using the linear material ration curve," International Organization for Standardization, Geneva, Switzerland.
ISO/TS 16610-31 (2010). "Geometrical product specification (GPS) – Filtration. Part 31: Robust profile filters. Gaussian regression filters," International Organization for Standardization, Geneva, Switzerland.
Kubovsky, I., and Kačik, F. (2009). "FT-IR study of maple wood changes due to CO_2 laser irradiation," *Cellulose Chemistry and Technology* 43(7-8), 235-240.
Leone, C., Lopresto, V., and De Iorio, I. (2009). "Wood engraving by Q-switched diode-pumped frequency-doubled Nd:YAG green laser," *Optics and Laser in Engineering* 47(1), 161-168, DOI: 10.1016/j.optlaseng.2008.06.019
Lin, C. J., Wang, Y. C., Lin, L. D., Chiou, C. R., Wang, Y. N., and Tsai, M. J. (2008). "Effects of feed speed ratio and laser power on engraved depth and color difference of Moso bamboo lamina," *Journal of Materials Processing Technology* 198(1), 419-425. DOI: 10.1016/j.jmatprotec.2007.07.020
Lum, K. C. P., Ng, S. L., and Black, I. (2000). "CO_2 laser cutting of MDF 1. Determination of process parameter settings," *Optics and Laser Technology* 32(1), 67-76. DOI: 10.1016/S0030-3992(00)00020-7
Patel, D. K., and Patel, D. M. (2014). "Analysis the effect of laser engraving process for surface roughness measurement on stainless steel (304)," *International Journal of Advanced Scientific and Technical Research* 4(3), 725-730.
Patel, S., Patel, S. B., and Patel, A. B. (2015). "A review on laser engraving process," *JSRD - International Journal for Scientific Research and Development* 3(1), 247-250
Petutschnigg, A., Stöckler, M., Steinwendner, F., Schnepps, J., Gütler, H., Blinzer, J., Holzer, H., and Schnabel, T. (2013). "Laser treatment of wood surfaces for ski cores: An experimental parameter study," *Advances in Materials Science and Engineering* 2013, 123085. DOI: 10.1155/2013/123085
Pritam, A. (2016). "Experimental investigation of laser deep engraving process for AISI 1045 stainless steel by fibre laser," *International Journal of Information Research and Review* 3(1), 1730-1734
Radovanovic, M., and Madic, M. (2011). "Experimental investigations of CO_2 laser cut quality: A review," *Nonconventional Technologies Review* 4, 35-42

Article submitted: May 21, 2017; Peer review completed: August 12, 2017; Revised version received and accepted: August 18, 2017; Published: August 22, 2017.
DOI: 10.15376/biores.12.4.7395-7412