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WOOD SURFACE MORPHOLOGY ALTERATION INDUCED BY ENGRAVING WITH CO_2 LASER UNDER DIFFERENT RASTER DENSITY VALUES

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ABSTRACT

The subject of this work was to study changes in surface morphology in three wood species differing in their structure, engraved with a CO_2 laser under different raster density values. From the physical viewpoint, the morphology variation was assess based on the roughness parameters. Qualitative changes in the anatomical structure were inspected with the aid of light microscopy. Significant influences on roughness parameters have been confirmed for all the three factors acting during engraving (raster density, anatomical direction, wood species). Over the entire study range, increasing raster density caused increasing roughness parameters parallel to a well as perpendicular to the grain course. Significantly higher roughness variation was recorded perpendicular to the grain course. Significant influence of wood species on roughness parameters was explicitly confirmed in the case of roughness measuremrents perpendicular to the grain in radial direction. The most conspicuous changes were observed in spruce wood, the lowest in beech wood. The results of microscopical observations were effective for explaining the species-related differences in roughness in wood treated with a CO_2 laser.

Key words: engraving, CO_2 laser, spruce wood, beech wood, oak wood, morphology, roughness

INTRODUCTION

Material treatment technology using a laser beam leads to very narrow cutting gaps. Consequently, such technologies have found a wide range of use in material cutting and boring. In addition, there are emerging new potentials concerning the surface treatment of both metallic and non-metallic materials by engraving (PATEL *et al.* 2017, YANG *et al.* 2019, KUBOVSKÝ *et al*. 2020, YUNG *et al*. 2021). Engraving wood surface with a laser is done with the aim to alter the colour or morphology of the surface treated in this way. Wood treatment with a laser means a considerable benefit: for the given absorption coefficients it is possible to set the amount of the energy supplied by the laser beam onto the wood surface and thus to control the structure and properties of the treated surface (KAČÍK and KUBOVSKÝ 2011, VIDHOLDOVÁ *et al* 2017, KÚDELA *et al.* 2019, 2020).

Chemical, physical, and morphological alterations of the properties of engraved wood surface depend on the energy amount supplied by the laser beam onto the treated surface. This amount can be controlled through adjusting the laser power, the movement speed of the laser head, the focal position, and the raster density (LIN *et al*. 2008, KUBOVSKÝ and KAČÍK 2013, HALLER *et al.* 2014, KUBOVSKÝ and KAČÍK 2014 GURAU *et al.* 2017, GURAU and PETRU 2018, Li *et al*. 2018, KÚDELA *et al*. 2020, ANDREJKO *et al.* 2020).

The energy concentrated in the laser beam and supplied to a specific area on the engraved surface is transformed to heat. At the very moment of contacting the wood surface, the great amount of heat concentrated within the laser beam with a very small diameter causes a very thin surface layer to sublimate immediately. Besides to the amount and concentration of the energy supplied, the thickness of the layer sublimed is dependent on the wood species, due to the inter-specific differences in wood structure and hardness. (ARAI and KAWASUMI 1980, BARCIKOWSKI *et al*. 2006, WUST *et al*. 2005, HALLER *et al.* 2014, DOLAN 2014, KÚDELA *et al*. 2020, ANDREJKO *et al.* 2020).

The microscopic observations show (HALLER *et al.* 2014, DOLAN 2014) that the wood surface treatment with a laser beam can reduce the wood roughness by melting but not carbonising the wood cells down to a depth of several micrometres. KÚDELA *et al*. (2019) report considerable morphological changes manifested through more roughness as late as under an irradiation dose of 75 $J\cdot cm^{-2}$, primarily due to the carbonisation of the surface wood layer. GUO *et al.* (2021) used for ablating milled and ground surfaces a nano-second pulse laser. The engraving, however, may induce nn opposite effect (GURAU *et al.* 2017, GURAU and PETRU 2018, KÚDELA *et al.* 2020, ANDREJKO *et al.* 2020). The last cited works show that the wood surface roughness depends considerably on the laser power, head movement speed, raster density and other parameters.

KÚDELA *et al.* (2020), applying a CO_2 laser on beech wood surface, observed moderately decreased roughness parameters in the fibre course direction at a low laser power (4 %). Their measurements resulted in finding lower values compared to the referential (non-treated with laser) ground specimens. This was caused by removal of released libriform fibres during the CO_2 laser treatment process. The cells concerned were the ones maintained on the wood surface after grinding. For higher laser power (8 %), these authors report roughness increasing with increasing raster density. The roughness parameters values were considerably higher compared to the ground surface.

ANDREJKO *et al*. (2020), engraving oak wood surface, confirmed significant influence of all the factors studied (laser power, laser density, wood anatomical direction) on the roughness parameters *Ra* and *Rz*. The last cited work identified the major impact of the raster density. Over the whole study raster density range, the increasing raster density was followed by increasing roughness parameters, both parallel to and perpendicular to the grain course. This paper also demonstrates that the oak wood surface roughness after CO_2 laser treatment also depended on the heterogeneous oak wood structure as such. The trench after the laser beam was deeper in early wood with the major share of early vessels than in the late wood containing less vessels. This was reflected in more conspicuous roughness variation observed perpendicular to the grain.

Thus, the surface morphology of CO_2 laser-treated wood depends on the laser technical parameters, on the irradiation methods and technology, and on the wood species used. The proper adjustment of parameters for a CO_2 laser treatment offers possibilities to control the surface morphology of the treated wood. Wood surface morphology assessment needs to comprise both the anatomical and the physical aspects. The physical assessment is performed based on roughness and waviness parameters (GURAU 2013, GURAU and IRLE 2017, CZANADY and MAGOSS 2011 KÚDELA *et* al. 2018).

The aim of this work was to study CO_2-laser-engraving-induced changes to surface morphology in three wood species differing in their structure. These changes were investigated under different raster densities. The surface geometry of the wood species concerned was evaluated in two ways: quantitatively, based on roughness parameters and qualitatively, with the aid of light microscopy.

MATERIAL AND METHODS

Wood surface engraving with a CO_2 laser was performed on three wood species differing in their anatomical structure. The coniferous wood species were represented by spruce, the broadleaved ones by beech and oak (disperse porous and ring porous). From these three species, there were prepared test specimens with dimensions of 100 mm × 50 mm × 15 mm (Fig. 1). In all specimens, there were irradiated their radial surfaces. Before the radiation, the surfaces were ground with a sandpaper with a grain size of 240. The moisture content in specimens ranged within 8–10 %.

The specimens were engraved with a CO_2 laser CM-1309, provided by the firm EAGLE and performing with a maximum power of 135 W (Fig. 2a, b). The distance between the irradiated surface and the lens focus was 17 mm. The laser head was moving over the specimen surface parallel to the grain course, with a constant speed of 350 mm·s^{-1}. Under constant laser power, the radiation intensity varied with varying raster density (number of paths per a one-millimetre width). The raster scanning course followed the perpendicular-to-grain in the radial direction, the numbers of paths per a width of one millimetre were 2, 5, 10, 20, and 30. Within one wood species, there were altogether five combinations, each comprising three specimens, plus three referential (control) specimens. Under the pre-set conditions, each specimen set was irradiated uniformly along its entire length and width.

Changes to wood surface morphology corresponding to different irradiation modes with a CO_2 laser were studied based on the roughness parameters and based on the morphological changes on the irradiated surface inspected with a light microscope. Roughness was measured on specimens´ radial surfaces parallel to the grain course, and evaluated through the values of roughness parameters *Ra* (mean arithmetic deviation), *Rz* (the maximum peak height plus the maximum depression depth within the cut-off, or sampling length), *Rt* (the maximum peak height plus the maximum depression depth within the entire evaluation length) a *RSm* (mean distance between the trenches – arithmetic mean calculated from distances between the profile unevennesses within the sampling length).

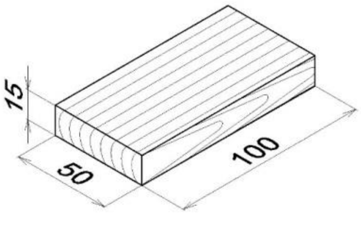

Fig. 1 Test specimen: shape and dimensions

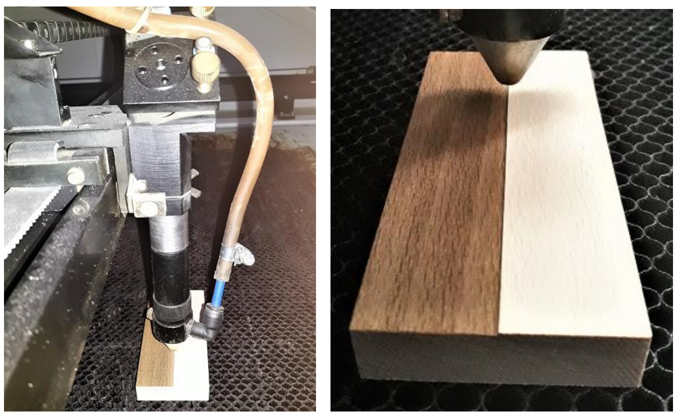

Fig. 2 Wood surface engraving

Surface roughness was measured with a mechanic profilometer Surfcom 130A (Carl Zeiss, Germany), consisting of two units: measuring one and evaluating one (Fig. 3). The profilometer was tuned in such a way as to measure the profile ranging from –800 μm to +800 μm from the central line (so the total measured profile was 1600 μm). The total measured length consisted of the starting-run segment, five sampling segments and stop-way segment. The sampling length was in all the cases the same - 8 mm (together making evaluation length 40 mm). The sampling length was established from the measured values of roughness parameters *R*a and *R*z. During the roughness evaluation, the waviness was filtered away from the roughness profile measured with the profilometer, and the obtained roughness curve was transferred onto the base line.

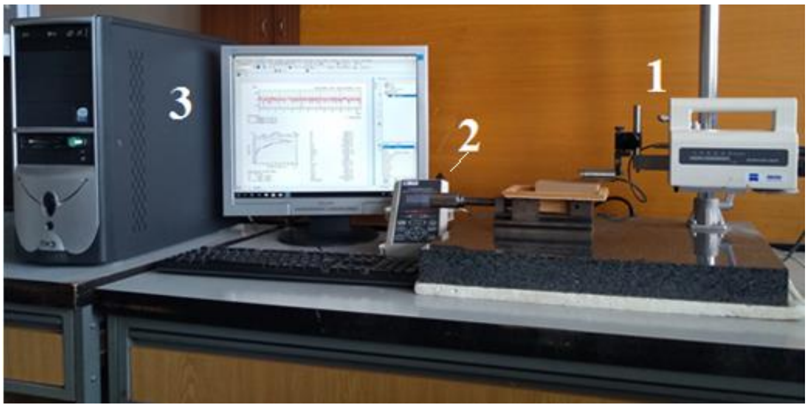

Fig. 3 Mechanic profilometer Surfcom 130A..1 – measuring unit, 2 – evaluating unit, 3 – PC

The structure of engraved surface of the tested wood species was studied with the aid of a digital microscope Dino-Lite EDGE; with the aid of a light microscope Leica MZ 9,5 on micro-cuts; and with a camera Leica EC 3. Microscopic slides representing transverse cuts were prepared from specimens softened in glycerine and modified with a transparent lacquer. Then, the micro-cuts were sealed in euparal. The carbonised cell layer on the surface had a very low stability, and as such, peeled off during the preparation of the micro-cuts. This required applying of an additional method for micro-cuts preparation. In this case, for each tested wood species, the micro-cuts were made from wood prisms modified with a synthetical resin (Technovit). Then the micro-cuts were sealed in euparal.

RESULTS AND DISCUSSION

The physical evaluation of surface morphology of the studied wood species subject to laser engraving was accomplished based on the roughness profiles obtained experimentally, parallel to and perpendicular to the grain course in the radial direction. All the measured profiles were evaluated through their roughness parameters *Ra, Rz, Rt* and *RSm*. The average values of these parameters together with other statistical characteristics for all the concerned three species, the entire raster density range, and the two anatomical directions are in Table 1. The results of three-way variance analysis confirmed that all the three parameters inspected (raster density, wood species, anatomical direction) exerted significant impacts on the roughness parameters concerned; either acting separately or in mutual interactions.

In all three wood species, the roughness parameters *Ra, Rz* and *Rt* of control specimens exhibited the lowest values both parallel to and perpendicular to the grain course. The species-related differences among these specimens were mainly due to different qualitative and quantitative presence of their cell elements. This fact was most obviously demonstrated on the roughness measured perpendicular to the grain course. Table 1 shows that the values of these parameters significantly increased with increasing raster density during CO_2 laser engraving. The raster-density dependent variance of all roughness parameters is illustrated in Fig. 4.

At the highest raster density (30 mm^{-1}), the roughness parameters *Ra, Rz* and *Rt* values parallel to the grain increased up to several times. The variability of these parameters was relatively high. Thus, we cannot state unequivocally in which wood species the CO_2 laser-induced changes in the surface geometry were the most obvious. Figure 4a shows that unlike the raster density, the wood species-related influence is omissible in practical context.

Tab. 1 Basic statistical characteristics of roughness parameters parallel to and perpendicular to the grain in engraved surfaces of tested wood species, dependent on different raster density values (laser power 8 %).

Raster density [mm^{-1}]	Basic statistical character.	Wood roughness parameter							
		Parallel to grain				Perpendicular to grain			
		Ra	*Rz*	*Rt*	*Sm*	*Ra*	*Rz*	*Rt*	*RSm*
		[μm]							
		Spruce wood							
Refer.	$\bar{x}$	7.25	50.73	76.25	1473.2	11.64	89.32	114.10	692.9
	s	2.86	21.13	26.55	660.8	1.58	19.20	26.28	284.2
2	$\bar{x}$	11.41	73.26	101.88	2070.5	37.85	214.36	239.85	504.9
	s	3.27	21.34	22.81	1150.2	1.34	16.32	19.01	25.4
5	$\bar{x}$	21.66	107.83	136.00	3107.3	44.34	229.59	257.39	214.7
	s	8.80	38.50	42.02	2015.3	2.17	22.33	22.63	19.0
10	$\bar{x}$	28.34	185.31	242.47	1173.8	103.72	497.03	560.16	1809.9
	s	8.13	44.99	44.36	558.8	18.18	76.13	67.72	509.2
20	$\bar{x}$	27.67	180.38	237.37	1118.3	210.73	903.06	1034.55	1950.8
	s	9.74	63.07	55.01	842.7	34.97	103.13	84.95	624.4
30	$\bar{x}$	36.27	231.14	299.69	869.4	273.03	1132.51	1244.20	1968.4
	s	9.69	60.18	61.25	327.6	17.56	70.12	43.23	691.4
		Beech wood							
Refer.	$\bar{x}$	6.96	51.44	69.36	1770.8	6.83	63.13	78.96	701.8
	s	1.81	11.70	14.14	753.6	1.21	12.03	10.06	265.4
2	$\bar{x}$	6.79	47.23	68.60	1774.9	38.82	195.37	217.32	499.5
	s	2.52	18.58	22.81	860.3	1.57	15.88	23.73	8.3
5	$\bar{x}$	13.35	79.92	113.49	2233.4	39.63	204.90	240.45	221.1
	s	3.97	24.61	22.03	1032.6	2.06	30.92	58.31	14.2
10	$\bar{x}$	24.85	148.49	188.58	1765.3	38.33	242.65	279.50	630.1
	s	7.30	38.80	44.07	681.0	3.51	25.12	27.41	164.6
20	$\bar{x}$	30.46	207.66	313.56	1371.1	62.21	378.18	476.48	1031.2
	s	10.03	75.32	105.08	664.1	4.64	63.01	100.56	375.8
30	$\bar{x}$	42.61	248.38	330.65	1606.8	76.42	474.87	583.07	1249.7
	s	7.96	45.15	32.82	687.7	8.63	87.82	151.82	431.5
		Oak wood							
Refer.	$\bar{x}$	5.15	38.18	88.59	1172.4	13.98	143.94	198.55	1937.7
	s	5.60	35.26	42.00	889.9	6.39	43.46	23.82	1081.1
2	$\bar{x}$	20.20	106.08	163.25	3030.5	50.03	264.29	293.34	499.9
	s	8.72	47.15	51.41	1703.8	4.20	24.01	12.28	16.5
5	$\bar{x}$	26.71	131.04	197.15	3733.2	48.97	328.43	400.99	589.6
	s	9.07	50.23	59.36	1796.1	7.46	51.44	54.56	233.7
10	$\bar{x}$	25.70	150.89	260.14	2443.6	69.95	437.17	530.21	1721.0
	s	13.06	77.78	71.78	1506.8	12.66	55.72	52.56	605.6
20	$\bar{x}$	35.09	202.19	303.87	2243.6	93.93	557.73	679.23	1870.2
	s	14.46	71.89	43.89	1315.2	19.34	76.24	46.09	681.7
30	$\bar{x}$	35.53	194.48	287.90	2055.7	115.36	674.38	845.69	1714.0
	s	17.16	77.85	78.80	1216.5	25.16	124.54	124.22	524.3

The number of measurements for parameters *Ra, Rz,* and *RSm* for each testing variant was 60. For parameter *Rt*, $n = 12$.

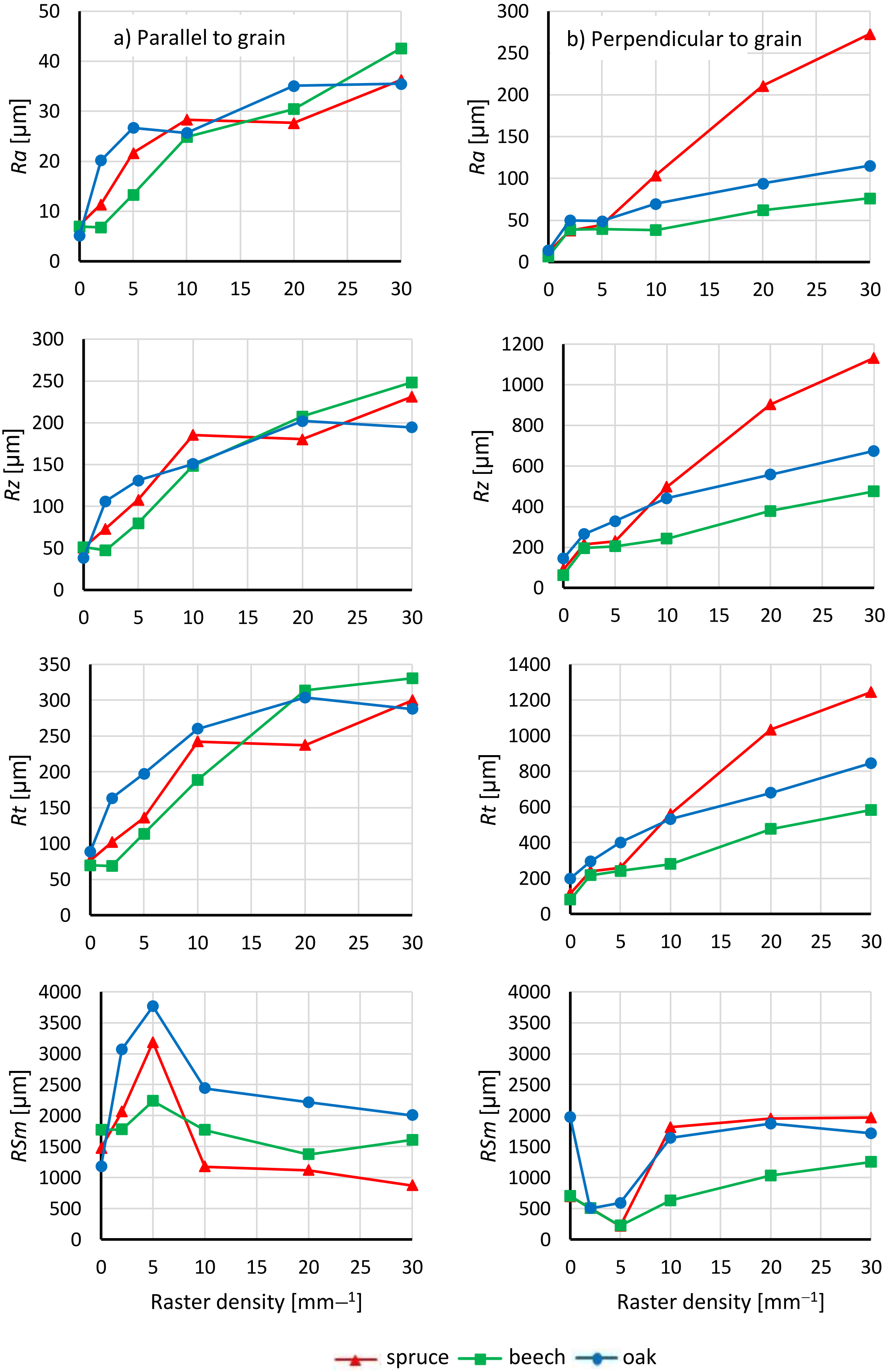

Fig. 4 Raster density influence on roughness parameters *Ra, Rz, Rt* and *RSm* in engraved surfaces of spruce, beech and oak wood. Laser power 8 %.

The parallel-to-the-grain values of roughness parameter *RSm* representing the mean distance between the trenches were increasing with increasing raster density up to 5 mm^{-1}, then a moderate decrease followed. This variation was qualitatively similar in all the three wood species; on the other hand, there were present interspecific differences in quantity (Fig. 4a).

The roughness parameters *Ra, Rz* and *Rt* measured perpendicular to the grain were significantly higher over the entire raster range. This was true for all three wood species. With increasing raster density, the values of these parameters manifested higher increase rates compared to those measured parallel to the grain (Fig. 4b). At the maximum raster density, the *Ra, Rz* and *Rt* values were by order higher compared to the referential specimens. On the other hand, their variability was found lower. Also, in the case of roughness measured perpendicular to the grain, the parameter *RSm* manifested different course compared to the roughness parameters discussed above. This parameter course with the varying raster density was opposite than in the case parallel to the grain (Fig. 4a, b).

In accordance with GURAU *et al.* 2017, GURAU and PETRU 2018, LI *et al.* 2018, KÚDELA *et al.* 2020, ANDREJKO *et al.* 2020), the morphological changes on the engraved wood surface depended on the energy amount supplied onto this surface with a laser beam. In the case of roughness measured perpendicular to the grain, the roughness parameters seem also significantly influenced by the wood species. In our case, the laser power, the laser head movement, and the laser focus distance were constant; the energy amount was only dependent on the varying raster density.

The energy concentrated in the laser beam and supplied onto the specified spot on the engraved surface was transformed to heat. The experimental wood temperature measurements performed with a thermo-camera up to its upper performance limit of 1000 °C demonstrated that, at moment of the beam reaching the surface, the temperature was mostly above 650 °C, episodically even close to the limit value that the thermo-camera could record. Such a high temperature concentrated within a very small diameter of the laser beam contacting the wood surface caused immediate burning and sublimation of a thin surface wood layer.

Experimental roughness measurements and microscopic observations revealed that the sublimated layer thickness was, beside the amount and concentration of the energy supplied, to a considerable extent influenced by the wood structure and properties (density, hardness) differing not only between the species but also varying within the particular ones. This fact has also been confirmed by (ARAI and KAWASUMI 1980, BARCIKOWSKI *et al.* 2006, WUST *et al.* 2005, HALLER *et al.* 2014, DOLAN 2014, KÚDELA *et al.* 2020, ANDREJKO *et al.* 2020).

The wood engraving at different raster density values tracked the wood surface with trenches causing surface roughness enhancement. With the raster path width (engraved track) of 0.14 mm, the treatment of the wood surface at a raster density of 10 mm^{-1} and more resulted in the tracks overlapping. This means that spots with raster overlapping had been supplied with energy repeatedly, which caused more deepening the relevant trenches.

Figure 4b demonstrates that the most conspicuous changes in roughness parameters measured perpendicular to the grain under specific CO_2 laser-engraving conditions were observed in spruce wood, the least ones in beech wood. As the examined surfaces were radial, the roughness variance concerned was to a considerable extent due to the density differences between the early and late wood.

In the case of spruce, the major density differences were between the early and late wood. MOLIŃSKI *et al.* (2009) report for spruce early wood an average density value of 300 $kg \cdot m^{-3}$, while for late wood about 750 $kg \cdot m^{-3}$. The last cited work reports that neither early nor late wood density varied significantly with the cambium age. Nevertheless, the cambium age affected the proportions of early and late wood in growth rings, and, in this way, also the width of these rings. With increasing cambium age, the width of growth rings became narrower, due to thinner early wood bands.

Figure 5a shows roughness profiles measured perpendicular to the grain: on a referential specimen and on a specimen engraved with the CO_2 laser performing at a power of 8 % and density of 20 mm^{-1}. Figure 5a demonstrates how the non-uniform wood substance degradation within a growth ring, occurring due to the density differences between the early and the late wood, was mainly reflected in the apparent depth increase of trenches in the early wood and, to some extent, also in the distance between the profile unevennesses. The scans of a radial surface and a transverse section (Fig. 5b, c) illustrate the related changes in the wood morphology. Figure 5c manifests the existence of distinctive boundary between early and late wood at the beginning of the growing season. At this phase, the early wood density is the lowest. This is also evident from the intensive wood substance degradation. During the growing season, early wood is transformed to late wood, the wood density gradually increases. Accordingly, the wood substance degradation rate under laser beam treatment decreased. Cell walls of early and late wood tracheids on the engraved spruce wood surface

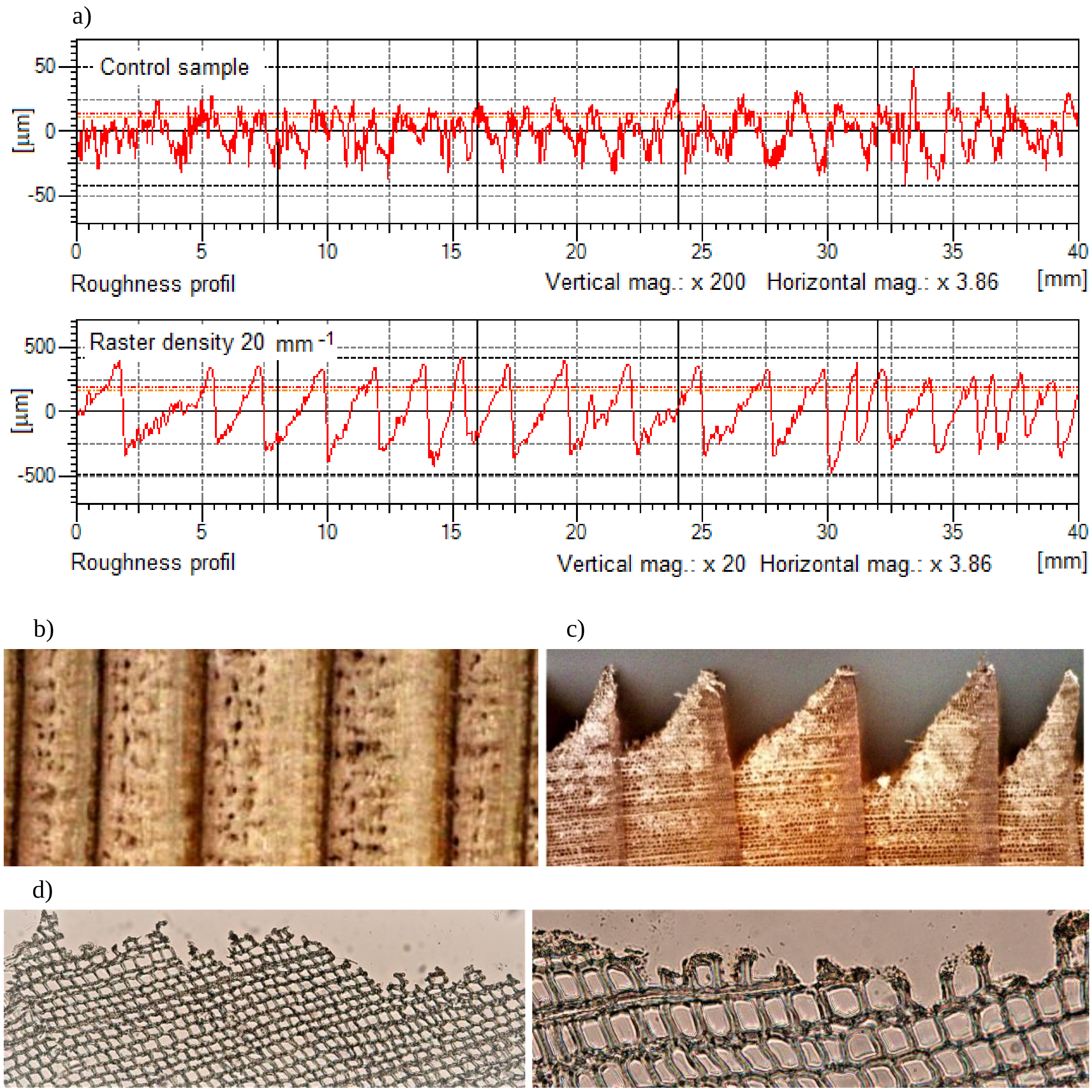

Fig. 5 Surface morphology of spruce wood engraved with a CO_2 laser perpendicular to the grain course, at a laser power of 8 % and raster density of 20 mm^{-1}. a) roughness profiles for referential specimen and specimen engraved with the laser, b) radial section, c) transverse section d) microscopic slides of transverse sections.

were carbonised (Fig. 5c). In the case of the wood surface layer consisting of early wood tracheids exclusively, the walls of these tracheids were often impaired due to the scorching with the laser beam, and due to the removal of the carbonised layer. This layer was very poor stable and, as such, frequently impaired during the specimen preparation.

Qualitatively similar trends were found for oak wood engraving. The differences compared to the spruce wood were on the background of the different anatomical structure. Figure 6 shows that, analogically as in spruce, the trench after the laser beam was deeper in the early wood than in the late wood. This fact was primarily responded by higher values of

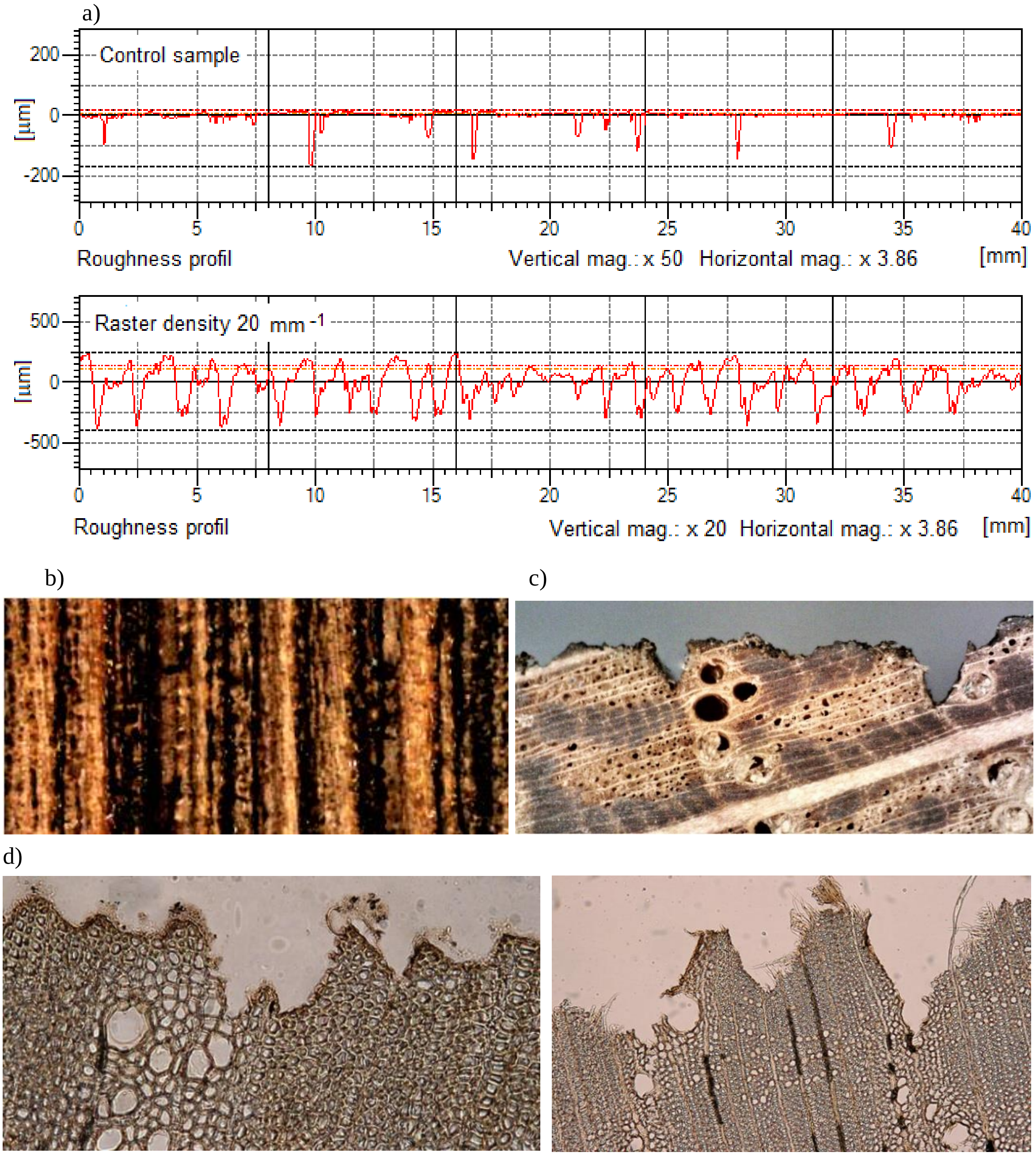

Fig. 6 Surface morphology of oak wood engraved with a CO_2 laser perpendicular to the grain course, at a laser power of 8 % and raster density of 20 mm^{-1}. a) roughness profiles for referential specimen and specimen engraved with the laser, b) radial section, c) transverse section d) microscopic slides of transverse sections.

the *Rz* parameter. Oak wood is ring-porous, with large lumina, namely in thin-walled early vessels – compared to libriform fibres with small lumen diameter and thick cell wall (POŽGAJ *et al.* 1997, KURJATKO *et al.* 2010). Roughness profiles measured perpendicular to the grain course in the radial direction were namely shaped by the displacement of these elements across the width of the growth rings. The energy supplied exerted more effects on the spot containing early-wood vessels than on the spots with the surface consisting of wood fibres (Fig. 6b–c). Similar results concerning oak wood roughness after CO_2 laser treatment can be found in ANREJKO *et al.* (2020). The authors of the cited work used the same raster density parameters for three power values. Their results suggests that the impact on wood morphology is stronger from the raster density than from the laser power. The same follows from the results reported by GURAU *et al.* (2017), KÚDELA *et al.* (2020).

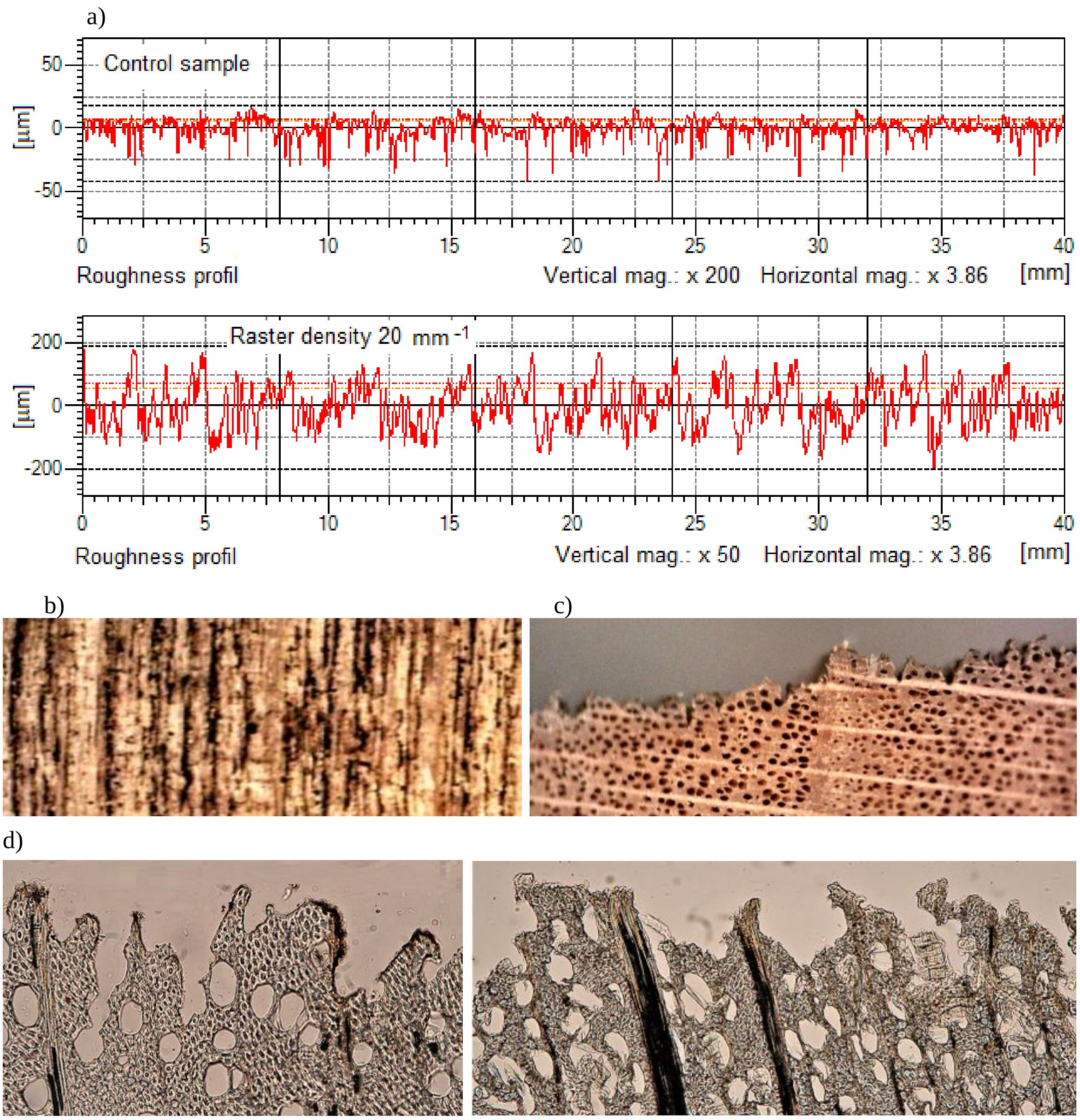

Fig. 7 Surface morphology of beech wood engraved with a CO_2 laser perpendicular to the grain course, at a laser power of 8 % and raster density of 20 mm^{-1}. a) roughness profiles for referential specimen and specimen engraved with the laser, b) radial section, c) transverse section d) microscopic slides of transverse sections.

In the case of beech wood, the influence of raster density on roughness parameters was found the lowest (Fig. 4b, 7a). This was caused by the fact that the beech growth rings are more homogeneous than in spruce and oak. Beech wood belongs to hard disperse-porous species. The vessels are dispersed across the entire growth ring width and the transition from the early wood to the late wood is smooth. The radial surface consists of vessels alternating with libriform fibres rather regularly. If the laser beam meets the fibres, the engraving is less conspicuous, because beech fibres have very thick cell walls and small lumina. In the case of laser beam contacting a surface with vessels, the beam penetrated more in depth (Fig. 7d), because the cell lumina were bigger and cell walls thinner compared to the fibres. Also, in the case of beech wood, there was observed more wood substance degradation in the early wood compared to the late wood (Fig. 7c). This transition, however, was not as abrupt as in spruce wood.

The study of surface morphology of spruce, beech and oak wood irradiated with a CO_2 laser revealed that the interactions occurring at the contact spot wood – laser beam are very complex. Their thorough and deep understanding needs, apart from morphological studies, also investigation of other surface properties and their relations. The issue is especially relevant meeting the needs of wood gluing and surface treatment.

CONCLUSIONS

The morphological changes of the spruce, beech and oak wood surface engraved with a CO_2 laser was the subject of the study. These changes were assessed based on the roughness parameters of the wood surface and based on microscopical observations. The obtained results allow us to derive the following conclusions:

Significant impacts on roughness parameters were confirmed for all the three tested factors (raster density, anatomical direction, and wood species) acting during the surface engraving.

Over the entire concerned raster density range, increasing raster density produced increasing roghness parameters both parallel to and perpendicular to the grain.

Significantly bigger roughness variance was recorded perpendicular to the grain than parallel to it.

Significant influence of wood species on roughness parameters was explicitly confirmed in the case of measurements performed perpendicular to the grain in radial direction. The most obvious changes were observed in spruce, the lowest ones in beech.

The microscopical analysis inferred that the roughness differences between the tested wood species were mainly due to the differences in their structural heterogeneity across the growth ring width.

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