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INFLUENCE OF PRESSING PARAMETERS ON SURFACE PROPERTIES OF COMPRESSED BEECH WOOD

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ABSTRACT

The influence of press conditions on wood properties was studied on densified beech wood. The pressing parameters affected the surface properties of wood specimens: hardness, roughness, and colour change. The effects and impacts varied among the individual pressing parameters and among the individual wood properties. Hardness was considerably improved by compression. The 40 % compression increased the hardness of the specimens by 2.4 to 3.4 times that of the original wood. The compression also noticeably reduced the wood surface roughness and smoothed the differences in roughness between the parallel and perpendicular directions. A higher pressing temperature and longer pressing time also caused significant changes in the wood colour. Lightness decreased, with the a* coordinate shifting to red and the b* coordinate shifting to yellow. The analysis of the results showed that the most suitable conditions for beech wood compression were: initial moisture content of 17 to 20 %, pressing temperature of 180 to 200°C, and pressing time, corresponding to the thickness of specimens, at least 10 min. For density, hardness, and roughness, more favourable results were obtained under 40 % compression.

KEYWORDS: Pressing, beech wood, moisture content, pressing temperature, pressing duration, roughness, hardness, colour.

INTRODUCTION

The performance of compressed wood is noticeably affected by the pressing parameters (wood moisture content and temperature during pressing, pressing time, and compression degree) and the wood species. Kúdela et al. (2017) evaluated the influence of particular pressing parameters on wood density as well as its dimensional stability after pressing and subsequent conditioning. These properties are essential for the quality of the compressed wood. Compressed wood surface properties are equally important as they play a big role in wood surface treatment and gluing. From this viewpoint, wood surface roughness is important as it considerably affects wood wetting with liquids and, consequently, negatively affects the consumption of coating materials and glues.

Wood anatomical elements create a highly diverse heterogeneous porous system developed step by step with the wood formation. This structural design varies within the wood species, primarily for the pore shape, their size, the degree of their interconnections, and their distribution (Kúdela 2005). Due to the complex wood surface morphology, no ideally smooth surface can be obtained for wood. In the case of wood surface, the impact of manufacturing tools on the wood surface roughness is another factor to consider (Liptáková et al. 1995).

Methods working with mechanical or thermo-mechanical "smoothing" have been proposed to reduce wood roughness (Gáborík and Žitný 2010, Gáborík et al. 2017). Wood pressing technology seems appropriate to rank among them, too.

If compressed wood is intended for use as a flooring material, there are high demands on the hardness of its surface layers, because a harder surface means more resistance against abrasion. In such cases, the wood pressing is purpose-oriented to improve its surface hardness.

Several works (Wang and Cooper 2005, Kutnar et al. 2008, Kúdela and Rešetka 2012, Rešetka and Kúdela 2013, Kúdela et al. 2017) pointed out that the compressed wood density is not homogenous in its cross-section (the pressing direction). These works reported variable density distribution, confirming that the compression in the pressing direction is not uniform. In most cases, the density of the surface layers was higher than in the inner layers. This density distribution in the compressed wood also implies differences in its mechanical properties between the compressed wood surface and the inner parts. The higher the density of surface layers, the higher the hardness (Palko et al. 2012, Rešetka and Kúdela 2013, Laine et al 2013).

Wood pressing at high temperature also induces changes in the wood colour. These changes must be determined precisely, as they may indicate altered wood quality (Hrčka 2010). The measurements of colour spaces of individual wood species show that these spaces practically do not overlap (Katuščák and Kučera 2000, Babiak et al. 2004). Wood colour can be modified considerably by heat and moisture (Bourgois et al. 1991, Sundqvist 2002, Johansson et al. 2006,Varga and van der Zee 2008). There are many processes, such as steaming or boiling, generally associated with colour changes, but, up to this time, it has not been possible to obtain desired colour changes.

High pressing temperatures enable better wood stabilisation; on the other hand, the change of wood colour may be more conspicuous in the case of a higher temperature. An important factor is wood moisture content. These colour changes may mean an advantage or a disadvantage, depending on the context. A disadvantage may be a loss of the original wood colour; an advantage may be balancing of non-required differences (sapwood, false heartwood) and imitating the hues of an exotic wood species (Kúdela 2005, Reinprecht and Vitholdová 2011). So, there is an urgent need to identify the wood colour changes generated in the pressing process under the influence of variable pressing parameters and to find out how these colour changes could be controlled through an appropriate setting of the parameters.

The aim of this work is the experimental verification of the influence of particular pressing parameters (initial wood moisture content, pressing temperature, pressing time, and compression degree) on the hardness, roughness, and colour modification of surface layers of beech.

MATERIALS AND METHODS

The experiments were carried out using the same beech specimens, treated under the same pressing conditions as in parallel investigations about the influence of beech wood compression on the dimensional stability and the density (Kúdela et al. 2017): two compression modes (20 and 40 %), four pressing temperatures (160, 180, 200, and 220°C), three compression times (8, 10, and 12 min. or 6, 8, and 10 min.), two initial moisture contents (18 and 34 %), and the tangential pressing direction were used.

Hardness evaluation

The hardness of the compressed wood was measured according to Janka (STN 49 0136). Corresponding to the thickness of the specimens, the pressing depth was R/2 (2.82 mm). In this case, the hardness was calculated according to Eq. 1.

$$H_J = \frac{4F}{3\pi R^2} \tag{1}$$

where: F - the force necessary to impress the ball to the depth required,
R - the ball radius.

Roughness evaluation

The compressed specimens were conditioned at a relative moisture content of φ = 65 % and 20°C, and the roughness of their radial surfaces was evaluated parallel and perpendicular to the grain. The evaluated length was 30 mm and the sampling length was 2.5 mm.

The measurements were carried out with the aid of a contact profilometer SURFCOM 130A, Tokyo Seimitsu Co. Ltd. Tokyo, Japan.

The following four roughness parameters (STN EN ISO 4287) were evaluated: the arithmetical mean deviation of the profile *Ra*, the root mean square deviation of the profile *Rq*, the maximum height of the profile *Rz*, and the total height of the profile *Rt*.

Colour assessment

The colour coordinates (hue, saturation, and lightness) were measured and the complete spectral analysis was carried out on specimens compressed under various pressing modes, using a spectrophotometer "Spectro-guide 45/0 gloss" manufactured by BYK-Gardner GmbH. The appliance measured the spectral reflectance within the range of the visible spectrum from 400 to 700 nm.

The specimens were illuminated with an LED (light emitting diode) with a constant wavelength. The measurements of colour changes followed the directions proposed by BYK-Gardner GmbH. The colour coordinates L*a*b* were determined at ten locations on the specimen – five on the upper surface and five on the bottom surface. The measurements were repeated in the same way after the pressing and conditioning at φ = 65% and 20°C.

The colours were expressed using three independent coordinates in the trichromatic space – *L*a*b**. The colour change Δ*E* was obtained based on the following equation (Eq. 2).

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \tag{2}$$

RESULTS AND DISCUSSION

The effects of pressing parameters (moisture content, pressing temperature, compression grade, and pressing time) and their interactions were evaluated by the four-way analysis of variance. The beech wood properties were found to be influenced by all the pressing parameters in concern.

Hardness

In all cases, the pressing of beech wood increased the hardness of the wood substantially (Fig. 1). The average hardness of the control specimens (before pressing) was 38 MPa. After the 20% compression, the specimens (initial moisture content of 18%) exhibited a 1.7-fold increase in hardness. For this compression degree, neither pressing temperature nor pressing time were identified as important factors influencing hardness. In the case of 40% compression, the hardness increased 2.4 to 3.4 times. In this case, the hardness increased with an increasing pressing temperature up to 200°C, as well as with a prolonged pressing time (Fig. 1). At a temperature of 220°C, a moderate drop in hardness was observed due to partial degradation of the wood surface layers beginning at this temperature.

The bullet was impressed to a depth of 2.82 mm; consequently, the hardness was higher mainly due to the surface layers having high density.

The qualitative changes observed in the specimens with an initial moisture content equal to the fiber saturation point (FSP) were similar, while their hardness under the same pressing conditions was lower (Fig. 1). This difference may be due to the density reduction resulting from a bigger spring-back and a higher final moisture content.

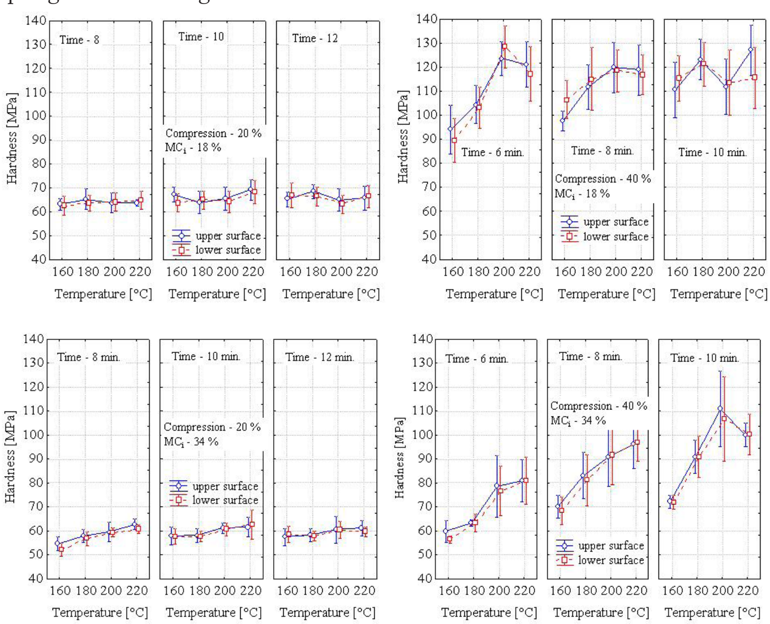


Fig. 1: Hardness of compressed beech specimens after conditioning. Reference hardness 38 MPa.

From the perspective of hardness, the compression degree was the most important. The more convenient initial moisture content was 18% and, the more suitable pressing temperature was 200°C. These pressing parameters can guarantee that the hardness of compressed beech wood may be even 120 to 130 MPa, which is much more than in the original wood. Beech wood compressed in this way can compare in hardness with species such as ebony or guaiac.

Qualitatively similar changes in hardness were also observed by Palko et al. (2012). Laine et al. (2013). Comparing the absolute hardness values with the literature data is not easy as the hardness values obtained are dependent on the method used (Kúdela 1998). The Brinell hardness values are in general lower than the values obtained based on Janka (Kokociński 1994, Požgaj et al. 1997, Kúdela 1998). Kúdela (1998) exemplified that the hardness values obtained according to Janka are, among others, influenced by the bullet impression depth; therefore, the comparison of the wood hardness values determined according to Janka with the literature is only possible if the indentation depth of the bullet is the same.

Roughness

Beech wood surface geometry was evaluated through the roughness parameters reported earlier. Roughness is recognised as the primary texture directly determined by the interactions within the internal wood structure, the wood mechanical pre-treatment before pressing, and the pressing itself.

The values of the individual roughness parameters obtained for the milled beech wood before pressing (Tab. 1) were used as the control for comparison with the parameters measured on the compressed wood.

Tab. 1: Reference values of roughness parameters.

Anatomical direction	Basic statistical characteristic	Roughness parameters			
		Ra	Rq	Rz	Rt
Parallel to grain	x (μm)	3.78	4.82	22.30	64.27
	s (μm)	0.62	0.79	3.61	17.11
	n	60	60	60	60
Perpendicular to grain	x (μm)	7.54	9.59	45.41	81.49
	s (μm)	0.76	0.91	3.84	14.04
	n	60	60	60	60

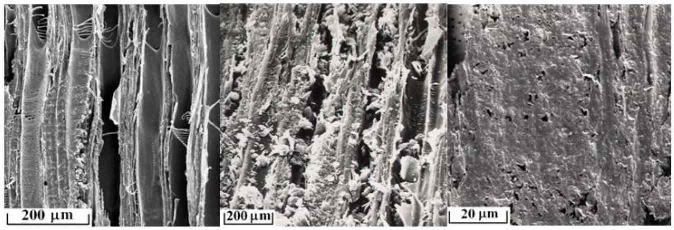
The roughness values display a high variability, due to the significant diversity of beech wood cell wall elements, milling treatment effects, and the interactions between these two factors (Liptáková et al. 1995, Kúdela and Liptáková 2005, Gurau et al. 2006, Gurau 2013). The roughness parameter values confirmed that unevenness (i.e. roughness) was a characteristic feature of the milled beech wood surfaces.

The values of almost all roughness parameters (except of *Rt*) perpendicular to the grain were about two times higher than the corresponding values parallel to the grain.

Liptáková et al. (1995) observed that the damage to a beech wood structure was the least serious when the wood surface had been microtomed. The surface treated in this way was only influenced by the wood anatomical structure (Fig. 2a). The radial beech wood surface consists of early- and latewood vessels, libriform fibres, and parenchyma ray cells, mostly cut longitudinally.

The quality of the milled beech wood surface was different from the microtomed surface. During the plain milling, the cell walls were deformed, compressed, and cut imperfectly (Fig. 2b). Several wood fibres were dragged out. These effects were aggravated with a blunt cutting edge.

The temperature at the interface between the cutting tool and the substrate can rise expressively for a short moment (Prokeš 1982). This causes the thermoplastic polymers (mostly lignin) in the wood surface layers to soften and melt. The deformed cell walls in this study were frequently covered with an amorphous melt substance (Fig. 2c).



a) b) c)

Fig. 2: Radial beech wood surface: microtomed (a), milled (b) and (c).

Pressing significantly reduced the roughness of the material (Fig. 3). This was mostly due to reduction of surface unevenness generated from interactions between the wood and the cutting tool during surface milling. The reduction was mainly obvious in the secondary structure which had regularly spots of unevenness repeated with a wave length longer than the sampling length used in the roughness measurement. A substantial smoothing was also observed for the unevenness in the primary structure resulting from the interactions between the internal structure of the milled wood surface and the pressing effects.

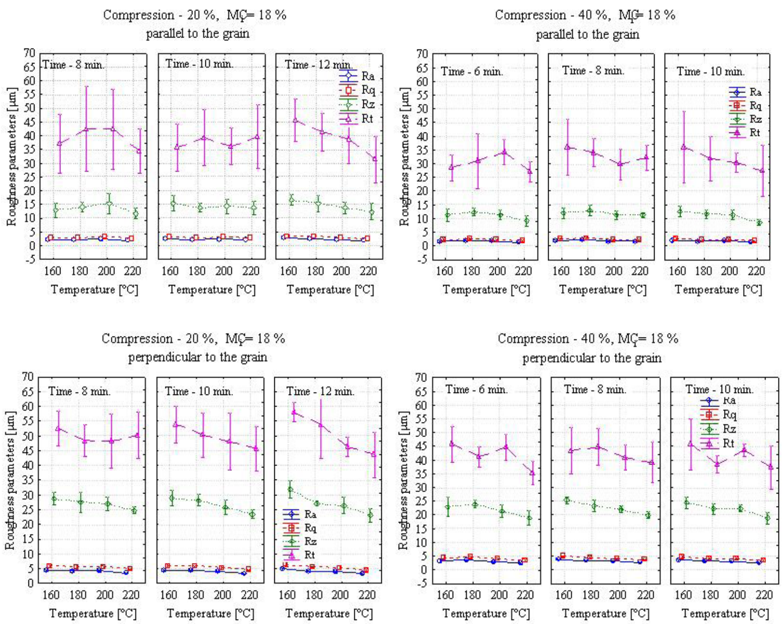


*Fig. 3: Roughness parameters R under various pressing modes. *Reference values shown in Tab. 1.*

Beech wood surface morphology is very complex; accordingly, no ideal smooth wood surface could be obtained for natural wood, even when using polished metal plates. The roughness values were in all cases higher than 500 nm, even after pressing. This means that the coarse surface was also characteristic of compressed beech wood. The roughness measured perpendicular to the grain was more distinct than that parallel to the grain. The differences, however, were smaller than for those of non-compressed wood.

The results also indicate that the pressing modes used did not significantly affect the roughness parameters. Slightly reduced roughness parameters were observed under a higher compression degree, due to better smoothing of the coarse unevenness. In the case of *Rt*, this parameter decreased with increasing pressing temperature (Fig. 3).

The roughness parameters also varied with the sampling length used for roughness evaluation (Fig. 4). The longer the sampling length, the more pronounced the roughness. Within the range 25 to 80 µm, no significant difference was detected in the wood surface roughness between the compressed wood and the original wood. This sampling length reúresented the width of several basic cell elements (fibres and vessels). The differences in surface roughness between the compressed and natural wood were discernible for longer sampling lengths (more than 250 µm). This means that the roughness differences were well observable when the sampling length represented the width of several cell elements.

Wood surface smoothing by pressing can considerably decrease the wood wetting with liquids and it can also economize the application of painting and gluing materials. On the other hand, the wetting ability may decrease – as a result of enhanced surface hydrophobicity – due to the lignin melting at high temperatures and spreading over the wood surface. The worse wetting performance results in a reduction of the surface free energy and the adhesion work of coating materials, liquid and solid, to beech wood (Liptáková and Kúdela 2002).

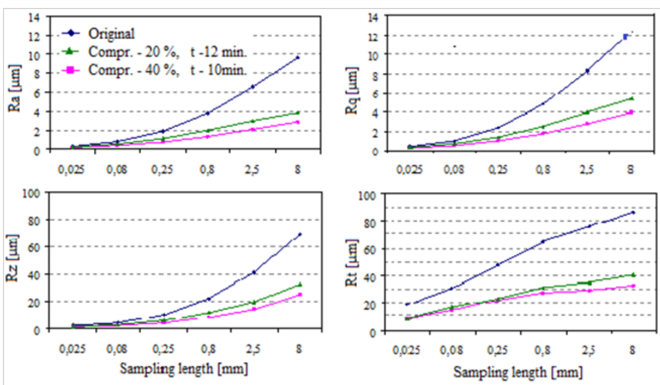


Fig. 4: Roughness parameters varying with the sampling length (temperature 220 °C)

Colour

The beech wood colour space was expressed through its coordinates measured in the CIE Lab system. Natural beech wood has its own characteristic colour space (Fig. 5, blue).

During the beech wood pressing process, the plasticization primarily concerned the surface layers, and this induced changes in the surface colour. The values of the colour coordinates in the CIE Lab system corresponding to the individual pressing modes are presented in Tab. 2. This table demonstrates that the lightness of beech wood decreases with an increasing pressing temperature and time, with the coordinate a* shifting to red and the coordinate b* shifting to the yellow area. The colour spaces of the individual beech wood sample sets subjected to the different pressing modes were practically disjunctive. The most distinct colour change was obtained at the pressing temperature of 220 °C and the pressing time of 12 minutes (Fig. 5, red).

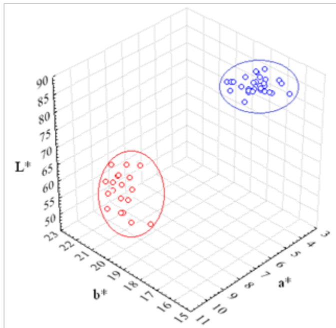


Fig. 5: Beech wood colour range in the CIE Lab system (blue – before pressing, and red – after pressing, at 220°C, 12 min).

Tab. 2: Values of beech wood colour coordinates in the CIE Lab system (MCi = 18%).

Pressing temperature (°C)	Basic statistical characteristic	Original colour of beech wood (reference values)								
		L			a			b		
	x	83.52			4.23			17.68		
	s	2.63			0.51			0.56		
	n = 30	Pressing time by compression 20%								
		8 (min)			10 (min)			12 (min)		
		L	a	b	L	a	b	L	a	b
160	x	82.29	4.81	19.11	82.61	4.71	19.51	82.17	4.85	19.35
	s	0.92	0.32	0.59	0.31	0.29	1.21	0.42	0.28	0.83
180	x	80.29	5.83	19.36	78.49	6.20	19.16	78.23	6.29	18.72
	s	0.89	0.41	0.55	0.53	0.30	0.74	0.99	0.38	0.54
200	x	72.45	7.62	20.34	70.17	7.63	20.05	68.61	7.89	19.68
	s	1.75	0.46	0.83	1.90	0.40	0.69	2.52	0.48	0.85
220	x	58.94	8.80	21.39	57.18	9.02	21.00	56.21	9.27	21.14
	s	3.39	0.44	0.24	3.46	0.44	0.60	3.07	0.47	0.51
	n =30	Pressing time by compression 40%								
		8 (min)			10 (min)			12 (min)		
		L	a	b	L	a	b	L	a	b
160	x	83.54	4.20	19.42	83.56	4.19	19.29	83.27	4.31	19.48
	s	1.50	0.57	0.47	0.71	0.25	0.79	1.23	0.34	1.08
180	x	79.65	5.76	20.16	79.08	5.93	19.55	79.41	5.88	19.57
	s	1.91	0.72	0.87	1.78	0.57	0.49	1.00	0.29	0.69
200	x	74.74	7.22	20.74	72.20	7.64	20.97	71.43	7.65	20.18
	s	2.53	0.55	0.66	3.78	0.46	0.37	3.21	0.67	0.58
220	x	62.92	8.65	21.89	60.14	8.85	21.75	57.77	9.65	22.28
	s	5.13	0.48	0.45	3.78	0.48	0.29	4.79	0.17	1.28

The colour change intensity in the process of hydrothermal plasticization by steaming or boiling depends on three factors: wood moisture content, pressing temperature and pressing time, and the interactions between them (Bourgois et al. 1991, Sundqvist 2002, Kúdela 2005, Johansson and Morén 2006,Vargaand van der Zee 2008). These authors approve that the most important factor is moisture content. The temperature effect is also considerable, in which wood turns intensively dark under high temperature (above 180°C). In general, heat has a greater effect on wood colour change when the moisture content is higher (Schmidt 1986, Reinprecht 2008).

In the case of the process shown, the initial moisture content (18 and 34%) did not affect the colour change significantly. This is because the 18% wood moisture content was sufficiently high and its effect was similar to the moisture content corresponding to the FSP. The pressing time was important under high temperatures (200 and 220°C). The influence of compression degree did not seem significant for the colour change.

The influence of heating conditions on colour changes in wood has been studied by several authors (Delijski1991, Tolvaj and Faix 1996, Tolvaj et al. 2002, Bekhta and Niemz 2003, Kúdela 2005, Reinprecht and Vitholdová 2011). The factors causing colour changes are manifold. Wood colour is determined by its components; however, it does not always depend only on the proportions of these components, but also on their expressiveness (Požgaj et al. 1997).

The changes in the wood chemical components occurring during the pressing process are not as strong as in the case of steaming or boiling. The role of extractives is important. These come into interaction with carbohydrates or with the products of lignin hydrolysis, and form compounds similar to lignin (Tolvaj and Faix 1996).

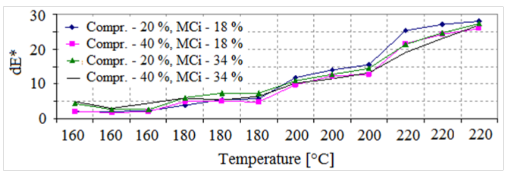


Fig. 6: Overall beech wood colour change under various pressing modes.

Kúdela et al. (2017) performed an analysis of the influence of selected pressing parameters on the dimensional stability, overall density, and cross-sectional density distribution in compressed specimens. In the present study, the influence of the same parameters on wood surface properties was studied. The results obtained in both parts show that the suitable initial moisture content in beech wood before pressing was 17 to 20%, the suitable pressing temperature was 180 to 200°C, and the suitable pressing time corresponding to the given thickness of specimens was at least 10 min. The compression degree needs to be adjusted based on the pressing purpose and the properties intended. From the viewpoint of density, hardness, and roughness, better results were attained with 40% compression.

CONCLUSIONS

The experimental results obtained with pressing of hydrothermally plasticized wood show that not all tested pressing parameters affected the wood surface properties to the same extent.

The beech wood hardness was mainly improved by a higher compression. The hardness after 40% compression was 2.4 to 3.4 times higher, attaining the values of a very hard exotic wood species.

Beech wood pressing significantly reduced the surface roughness. Also, the differences in roughness between the direction parallel and perpendicular to the grain were reduced. On the other hand, not all pressing parameters had a significant effect.

The values of beech wood colour coordinates in the CIE Lab system, related to the different pressing modes, have confirmed that the beech wood lightness decreased with an increasingpressing time and temperature, with the coordinate a* shifting to the red and the coordinate b* shifting to the yellow area. The colour areas of the individual beech wood specimens sets corresponding to the different pressing modes did not overlap. The most distinct colour change was obtained at a temperature of 220 °C and pressing time of 12 minutes.

The analysis of the influence of selected pressing parameters on the dimensional stability, overall density, and cross-sectional density distribution in the compressed specimens (Kúdela et al. 2017), and the results concerning the influence of the same parameters on the wood surface properties discussed in the present work show that the most suitable initial moisture content in beech wood before pressing was 17 to 20%. The most suitable pressing temperature was 180 to 200 °C and the pressing time most suitable for the given thickness of specimens was $\geq$ 10 min. From the viewpoint of density, hardness, and roughness, better results were attained with 40% compression.

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