Impact Bending Strength and Brinell Hardness of Densified Hardwoods

Miroslav Gašparík,[a,*] Milan Gaff,[a] Lenka Šafaříková,[a] Carlos Rodriguez Vallejo,[b] and Tomáš Svoboda [a]

The objective of this research was to determine the influence of wood species (*Fagus sylvatica* L. and *Populus tremula* L.), thickness (4, 6, 10, 18 mm), and degree of densification (0%, 10%, and 20%) on the impact bending strength (IBS) and Brinell hardness (BH) in the radial direction. Three-factor analysis of variance confirmed that the difference in IBS was significantly related to the wood species and wood thickness. Wood densification did not have a significant effect on IBS. In addition, beech wood exhibited higher IBS values than aspen wood. The IBS values increased proportionally with increasing thickness. All factors affecting Brinell hardness were statistically significant, although thickness had the smallest influence overall. The Brinell hardness values were substantially higher in beech wood than aspen wood, and in some cases were more than three times greater. On the other hand, densification exhibited a more positive effect on increasing Brinell hardness for aspen wood than beech wood.

Keywords: Impact bending strength; Brinell hardness; Beech; Aspen; Densification; Thickness

Contact information: a: Department of Wood Processing, Czech University of Life Sciences in Prague, Kamýcká 1176, Prague 6 – Suchdol, 16521 Czech Republic; b: Department of Forestry Engineering, Campus de Rabanales s/n, University of Cordoba, 14071 Cordoba, Spain;
** Corresponding author: gathiss@gmail.com*

INTRODUCTION

Wood is generally recognized as one of the most important renewable resources and among the most versatile and widely used materials. On the other hand, much of its uses depend on the species, because while some tree species are used almost everywhere, others have limited application. The application of wood is directly influenced by its physical and mechanical properties.

European beech (*Fagus sylvatica* L.) is a native wood that grows throughout Europe (Eilmann *et al*. 2014). Beech is one of the most commonly used hardwoods in Europe (Pöhler *et al*. 2006; Gryc *et al*. 2008) for furniture, floors, toys, veneer products, and musical instruments, as well as for the production of stairs, cladding, and glued load-bearing elements in construction (Ohnesorge *et al*. 2010; Aicher and Ohnesorge 2011; Guntekin *et al*. 2014). On the other hand, European aspen (*Populus tremula* L.) wood has only occasional uses. In the woodworking industry, aspen is used in the manufacturing of wood-based materials (plywoods, particle, and flakeboards), in the furniture industry for underlying veneers or surface veneers for backside or nonvisible surfaces (Kärki 2001), and for the facings of ceilings or saunas where high strength or hardness are not necessary (Möttönen *et al*. 2015). In the past, aspen was primarily used for the production of matches; currently, it has application in the production of biomass fuel, paper, and pulp (Kärki 2001; Heräjärvi and Junkkonen 2006).

The uses for these wood species are closely related to their mechanical properties. Mechanical properties differ by wood type because they depend not only on the type of loading (tension, pressure, and bending), but also on the loading's character (static or dynamic loading) (Bal and Bektaş 2012). In general, wood can resist static loading to a greater extent than dynamic loading. Static loading is characterized by an increasing loading force over time, while dynamic loading is where a maximal force acts over a very short duration or instantly (Bal and Bektaş 2012).

The mechanical properties of wood can be altered in various ways, depending on the requirements. Wood densification is one of the most common methods for the modification of mechanical properties. It works with the principle that these properties are directly dependent on changes in wood density and has been confirmed by a number of authors dealing with either surface densification (Lamason and Gong 2007; Gong *et al*. 2010; Rautkari *et al*. 2009, 2011; Laine *et al*. 2013, 2014) or volumetric densification (Navi and Girardet 2000; Kamke 2006). The final densification effect also depends on other conditions and their mutual combinations, such as the use of plasticizing, temperature, moisture content, presence of chemical substances, *etc*.

One of the most important properties for dynamic loading is the impact bending strength (IBS). It is the ability to resist immediate maximal loading, which means absorbing and dissipating energy through impact bending (Požgaj *et al.* 1997; Bal and Bektaş 2012). IBS refers to the numerical expression for the amount of work consumed in breaking (cracking) wood under given conditions (Bal 2016). Wood with a high IBS is referred to as tough. On the other hand, if the impact bending strength is low, wood is described as brittle (Bučar and Merhar 2015).

Wood quality can be characterized according to the type and shape of the fracture after breaking. Tough wood creates a fibrous, spiky fracture. Brittle wood usually produces blunt, non-fibrous, stepped fractures. In brittle fractures, the deformation is relatively low and the fracture happens suddenly. Certain wood species can have relatively high strength but still be brittle in terms of their IBS (Kollmann 1967). Impact bending strength is influenced by various factors, such as density, fiber orientation, moisture content, and temperature.

Hardness refers to the ability of wood to resist the penetration of another object into its structure (Heräjärvi 2004; Kurt and Özçifçi 2009). Hardness is important not only when machining the wood with cutting tools (sawing, milling, peeling, *etc*.) (Grekin and Verkasalo 2013), but also for wood products that are subject to scratches or abrasion (floors, wooden stairs, *etc*.) (Rautkari *et al*. 2013). The main disadvantage of hardness is that its value is markedly influenced by the testing method and its associated conditions (Niemz and Stübi 2000; Hirata *et al*. 2001). To determine wood's hardness, only the Brinell and Janka methods are widely used. While the Janka method is used almost exclusively in North and South America, the Brinell method is most widely used in Europe (Grekin and Verkasalo 2013).

This research focuses on examining the IBS and Brinell hardness of beech and aspen wood while testing perpendicular to the grain in the radial direction. The main goal was to determine the effects of densification and wood species on the IBS and Brinell hardness values.

EXPERIMENTAL

Materials

European beech (*Fagus sylvatica* L.) and European aspen (*Populus tremula* L.) woods were used for preparing the samples. Samples of four thicknesses (4, 6, 10, and 18 mm) and 35 mm in width were produced. Sample length was 300 mm for IBS and 150 mm for Brinell hardness. Samples were conditioned to an equilibrium moisture content (EMC) of 8% (ϕ = 60 ± 3% and t = 20 ± 2 °C). The EMC represented the final moisture content of furniture and wooden joinery (flooring and cladding) for interior use, according to EN 942 (2007) and ČSN 91 0001 (2007). The samples of both wood species were divided into two groups: the first group was designated for densification and the second group consisted of non-densified (reference) samples. The investigation involved 288 total samples.

Methods

Densification

All samples designated for densification were cold-pressed in a UPS 1000 hydraulic press (RK MFL Prüfsysteme GmbH, Germany) without prior plasticizing. Pressing was carried out in three phases: The first phase consisted of closing the press and gradually densifying the samples to the required thickness value over 5 min. During the second phase, the samples were pressed for 2 min. The final phase consisted of gradually opening the press and unloading the samples over 3 min. Subsequently, the samples relaxed for 5 min. Table 1 contains the values of the pressing force used for densification of the individual sets of test samples.

Table 1. Pressing Force for the Densified Samples

Thickness (mm)	Pressing force (MPa)			
	Densification 10%		Densification 20%	
	Beech	Aspen	Beech	Aspen
4	3.550	1.080	3.950	1.500
6	2.100	1.850	3.900	2.100
10	3.750	2.150	4.500	2.500
18	3.650	1.720	3.680	1.800

For both wood species, the densities of the non-densified, as well as the densified samples, were evaluated (Table 2).

Table 2. Average Density Values for the Individual Groups

Thickness (mm)	Density (kg/m^3)					
	Non-densified		Densification 10%		Densification 20%	
	Beech	Aspen	Beech	Aspen	Beech	Aspen
4	693 (4.6)	400 (4.1)	725 (8.6)	421 (9.3)	784 (4.0)	488 (5.7)
6	665 (3.4)	533 (8.7)	703 (4.8)	557 (6.6)	751 (5.6)	620 (9.6)
10	694 (4.7)	528 (4.2)	733 (3.7)	564 (1.3)	788 (3.5)	604 (1.8)
18	735 (8.1)	529 (2.1)	744 (3.9)	568 (4.8)	747 (6.9)	589 (7.0)
Mean	697	498	726	528	768	575

Values in parentheses are the standard deviations

Impact bending strength (IBS)

The IBS was determined on a pendulum impact machine (impact head weight 20 kg), based on Charpy's principle and in accordance with ISO 3348 (1975). Charpy's principle can be briefly described as follows: a hammer falls along a circular trajectory from height h_1; if the hammer has no obstacle it reaches height h_0; it applies $h_0 < h_1$ because of friction resistance; if the hammer hits the experimental sample, it also reaches the left side but only to the position h_2; the work necessary for breaking the sample is recorded on the apparatus' dial (Fig. 1).

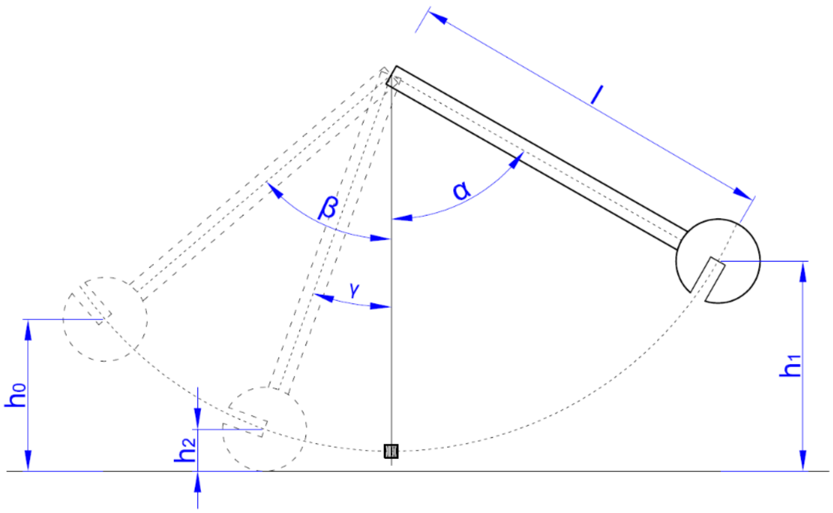

Fig. 1. Charpy's principle of the impact bending strength test

The samples were positioned so that the pendulum head would act in the radial direction, *i.e.*, on the tangential surface. The test was carried out with a constant span between the support centers of 240 ± 1 mm to allow for monitoring the influences of various sample thicknesses. The results of IBS for the non-densified samples were compared with the results of the samples densified at 10% and 20%.

Brinell hardness (BH)

Brinell hardness was determined in the radial direction (on the tangential surface of the sample) at three locations in the center of the sample's width (parallel to the sample's length), according to EN 1534 (2010), with some modifications. The measurement of hardness was performed using a DuraVision-30 hardness tester (Struers, Denmark) with a steel (carbide) indenter. The hardness tester automatically captured the loading force, measured the depth and diameter of the indentation, and subsequently calculated the hardness value from this data. The maximum loading force was reached at 10 s, held for 10 s, and then the force was released over the period of 10 s. The parameters for the BH measurement are given in Table 3.

Table 3. Parameters of Brinell Hardness

	Brinell Hardness	
Wood species	Conditions	Description
Beech	H_{BW} $10^1/500^2/10^3$	[1] 10 = Diameter of carbide ball (indenter) (mm) [2] 250 and 500 = Constant loading force (N) [3] 10 = Measuring time (sec)
Aspen	H_{BW} $10^1/250^2/10^3$	

Evaluation and Calculation

The IBS and BH values were evaluated using MANOVA, specifically utilizing Fisher's F-test in STATISTICA 13 software (Statsoft Inc., Tulsa, Oklahoma, USA). The results were evaluated using 95% confidence interval which reflects a significance level of 0.05 ($P < 0.05$).

The IBS was calculated in accordance with ISO 3348 (1975) and Eq. 1,

$$A_w = \frac{Q}{bh} \tag{1}$$

where A_w is the IBS at the moisture content during the testing (J/cm^2), Q is the energy required for fracture of the sample (J), b is the width of the sample (cm), and h is the thickness of the sample (cm).

The IBS values were converted to the moisture content of 12%, according to Dubovský *et al*. (2003) and Eq. 2,

$$A_{12} = A_w\left[1+\alpha\left(w-12\right)\right] \tag{2}$$

where A_{12} is the IBS at the moisture content of 12% (J/cm^2), A_w is the IBS at the moisture content during the testing (J/cm^2), w is the sample moisture content during the testing (%), and α is the correction coefficient for moisture content, which was equal to 0.02 for all wood species.

Brinell hardness was calculated using a hardness tester, according to EN 1534 (2010) and Eq. 3,

$$H_{BW} = \frac{2F}{\pi.D\left(D-\sqrt{D^2-d^2}\right)} \tag{3}$$

where H_{BW} is the BH of wood (MPa), F is the maximum load force (N), D is the diameter of the carbide ball (mm), and d is the diameter of the residual indentation (mm).

The BH values were subsequently converted to the moisture content of 12%, according to Dubovský *et al*. (2003) and Eq. 4,

$$H_{BW_{12}} = H_B\left[1+\alpha\left(w-12\right)\right] \tag{4}$$

where $H_{BW_{12}}$ is the BH at the moisture content of 12% (MPa), H_B is the BH at the moisture content during the testing (MPa), w is the sample moisture content during the testing (%), and α is the correction coefficient of moisture content for hardness perpendicular to the grain, which was equal to 0.025 for all wood species.

The wood density was determined during testing according to ISO 13061-2 (2014) and Eq. 5,

$$\rho_w = \frac{m_w}{V_w} \tag{5}$$

where ρ_w is the density of the sample at moisture content w (kg/m^3), m_w is the weight of the sample at moisture content w (kg), and V_w is the volume of the sample at moisture content w (m^3).

The moisture content of the samples was determined according to ISO 13061-1 (2014) and Eq. 6,

$$w = \frac{m_w - m_0}{m_0} * 100 \quad (6)$$

where w is the moisture content of the samples (%), m_w is the weight of the sample at moisture content w (kg), and m_0 is the weight of the oven-dry sample (kg). Oven-drying was carried out according to ISO 13061-1 (2014).

RESULTS AND DISCUSSION

Impact Bending Strength

Table 4 presents a statistical evaluation of the influence of factors on IBS. Wood species and material thickness were statistically significant ($P < 0.05$). The degrees of densification, as well as the interaction of all factors, did not significantly influence the IBS.

Table 4. Statistical Evaluation of the Factors Influencing the Impact Bending Strength

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - test	Significance level
Intercept	3,874.679	1	3,874.679	1,283.366	0.001
Wood species (1)	134.220	1	134.220	44.456	0.001
Material thickness (2)	209.733	3	69,924	23.160	0.001
Degree of densification (3)	2.540	2	1.270	0.421	0.658
1*2*3	8.239	6	1.373	0.455	0.840
Error	289.839	96	3.019		

The mean IBS value for aspen samples (4.6 J/cm^2) was approximately 31.3% lower than that of beech samples (6.7 J/cm^2; Fig. 2a). This difference was caused by the different densities of the wood species. Aspen wood exhibited a lower density, ranging from 25.1% to 28.6%, for the individual groups in comparison with beech wood (Table 2).

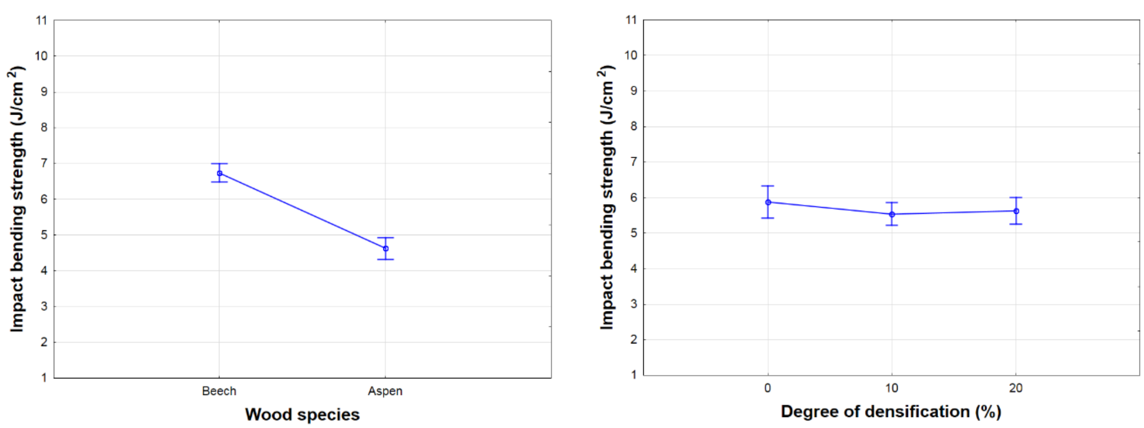

Fig. 2. a) Influence of wood species and b) degree of densification on the impact bending strength

In general, densification increased the mechanical properties of wood, which were directly dependent on rising density. The present results indicate that increasing the degree of densification did not have a significant influence on the IBS (P = 0.658) and resulted in a slight numerical decrease (Fig. 2b). Generally, wood densified at 10% exhibited a 6.8% lower IBS than non-densified wood. Densification at 20% exhibited a 5.1% decrease in IBS. Table 2 shows wood densities before and after densification. These differences possibly resulted from variability in the density of the tree trunks from which the samples were cut. The most notable differences were found in aspen wood. Heräjärvi and Junkkonen (2006), and Kärki (2001) found that aspen wood density within the trunk changes markedly in the direction from the pith to the cambium and also with increasing distance from the stump.

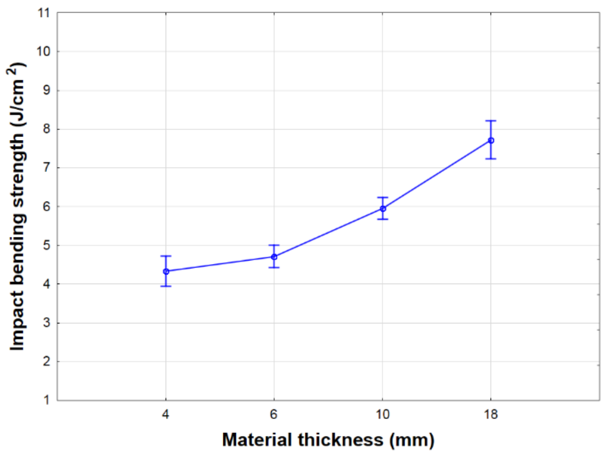

Fig. 3. Influence of the material thickness on the impact bending strength

The IBS values rose in a statistically significant manner (P = 0.001) with increasing material thickness (Fig. 3). The most marked increase of 29.8% was observed between the thicknesses of 10 mm and 18 mm. The lowest increase of 8.8% was observed between the values of the samples with a thickness of 6 mm and 10 mm. Different thicknesses results in a change of cross sectional areas of samples, thereby affecting the amount of energy required for its reassignment during the investigation of IBS.

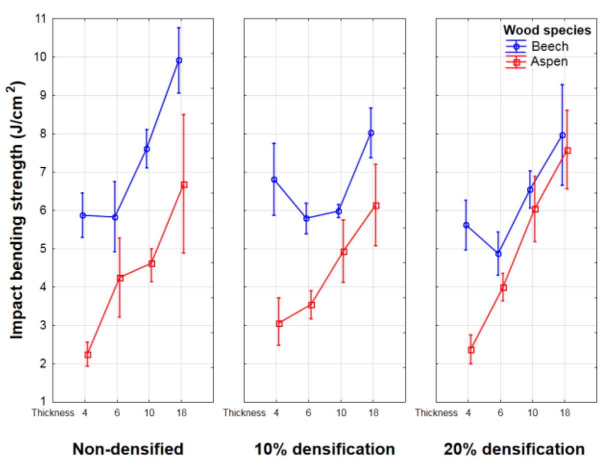

Fig. 4. Influence of the material thickness, densification, and wood species on the impact bending strength

The IBS of beech wood exhibited a different pattern than aspen wood (Fig. 4). Beech wood exhibited variable IBS values, which were not directly proportional to the sample's thickness. On the other hand, aspen wood exhibited IBS values that were positivity associated with its thickness. Densification had no clear influence on beech and aspen wood, which was an expected result. This can be explained by the fact that densification only concerns a certain surface layer of wood, which has generally little effect on the whole cross-section of the sample and is directly related to the energy required for breaking.

The IBS of non-densified beech wood was 7.6 J/cm^2 for a thickness of 10 mm (Table 5). Samples with this thickness are most suitable in terms of comparison with other results, because their cross-sectional area is closest to the area (4 cm^2) given by the standard ISO 3348 (1975). Previous studies presented similar results; for example, Bal and Bektaş (2012) reported an IBS for Eastern beech (*Fagus orientalis* Lipsky) of 7.2 J/cm^2, and Lokaj and Vavrušová (2010) determined a slightly lower IBS value of 6.9 J/cm^2. On the other hand, slightly higher IBS values were determined in other research. Skarvelis and Mantanis (2013) investigated the mechanical properties of beech wood from different locations in Greece and found IBS values of 7.8 J/cm^2 for Eastern beech (*Fagus orientalis* Lipsky) and European beech (*Fagus sylvatica* L.). Bektaş *et al.* (2002) determined an IBS of 8.5 J/cm^2 for Eastern beech (*Fagus orientalis* Lipsky) and Wagenfür (2000) stated the highest IBS values for beech wood of 10 J/cm^2.

Table 5. Mean Values of the Impact Bending Strength

Wood species	Thickness (mm)	Degree of densification (%)	Impact bending strength *A* (J/cm^2)	Wood species	Thickness (mm)	Degree of densification (%)	Impact bending strength *A* (J/cm^2)
Beech	4	0	5.9 (1.30)	Aspen	4	0	2.3 (0.68)
Beech	4	10	6.8 (2.10)	Aspen	4	10	3.0 (0.13)
Beech	4	20	5.6 (1.44)	Aspen	4	20	2.4 (0.27)
Beech	6	0	5.8 (2.05)	Aspen	6	0	4.3 (2.32)
Beech	6	10	5.8 (0.90)	Aspen	6	10	3.6 (0.39)
Beech	6	20	4.9 (1.28)	Aspen	6	20	4.0 (0.78)
Beech	10	0	7.6 (1.12)	Aspen	10	0	4.6 (0.42)
Beech	10	10	6.0 (0.38)	Aspen	10	10	4.9 (1.82)
Beech	10	20	6.6 (1.07)	Aspen	10	20	6.0 (1.87)
Beech	18	0	9.9 (1.90)	Aspen	18	0	6.7 (4.04)
Beech	18	10	8.0 (1.42)	Aspen	18	10	6.1 (2.36)
Beech	18	20	8.0 (2.96)	Aspen	18	20	7.6 (2.29)

Values in parentheses are standard deviations

The IBS of aspen wood retained similar characteristics for all cases. Although the IBS slightly increased with increasing thickness, densification exhibited an insignificant effect on IBS.

In this study, the mean IBS value of non-densified aspen wood was 4.6 J/cm^2 at a thickness of 10 mm. Slightly lower values of IBS were identified in previous studies, such as Požgaj *et al*. (1997) (3.8 J/cm^2 for aspen wood species) and Wagenfür (2000) (4 J/cm^2).

Makovická–Paulínyová *et al*. (2006) and Barcík *et al*. (2008) reported IBS values that were approximately 30% lower (3.2 J/cm^2) than the present study.

Brinell Hardness

For BH, all factors and their combined effects were significant (*P* <0.05; Table 6). The effect of material thickness was the least significant effect (*P* = 0.041).

Table 6. Statistical Evaluation of the Influence of Factors on the Brinell Hardness

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - test	Significance level
Intercept	507,195.4	1	507,195.4	20,967.37	0.001
Wood species (1)	138,580.0	1	138,580.0	5,728.87	0.001
Material thickness (2)	201.4	3	67.1	2.78	0.041
Degree of densification (3)	2,056.4	2	1,028.2	42.50	0.001
1*2*3	419.3	6	69.9	2.89	0.009
Error	8,127.8	336	24.2		

As expected, the BH of beech wood was much greater than that of aspen wood (Fig. 5a). The mean difference in BH was approximately 240%. On the other hand, beech wood density was approximately 200 kg/m^3 higher than that of aspen, and a similar difference in density was also observed upon densification (Table 2). Higher total density and less variability in the density between individual growth rings can contribute to a greater BH in beech wood.

In this case, gradually increasing the densification resulted in a proportionate increase in BH (Fig. 5b). While the mean BH of non-densified wood was approximately 35 MPa, wood densified at 10% was 7.1% greater in hardness, whereas wood densified at 20% increased in hardness by 17.1%.

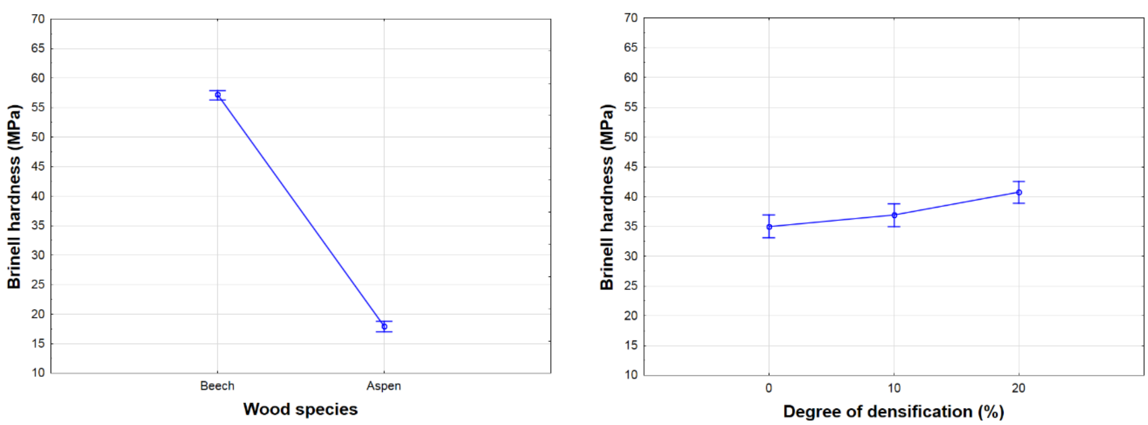

Fig. 5. a) The influence of wood species and b) the degree of densification on Brinell hardness

1

The influence of material thickness on the BH had the lowest statistically significant influence (*P* = 0.041) (Fig. 6). Although hardness increased with sample thickness, this increase was not proportional, and the differences in thickness reached an asymptote at 5.7%. To some extent, the thickness factor could be affected by the plane anvil of the hardness tester during the measurement. When the indenter was pressed into the sample, the wood surrounding the indentation was deformed and densified within its volume. Material thickness influences unequal densification to a certain degree. Completely removing this effect would ensure that the hardness of the wood would not significantly vary with the change in thickness.

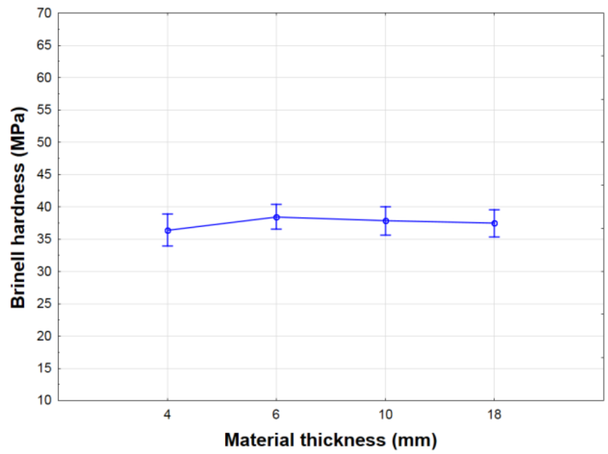

Fig. 6. Influence of material thickness on the Brinell hardness

As already mentioned above, the BH of beech wood was several times greater than aspen wood (Fig. 7). In certain situations, its BH values were as much as four times those of aspen wood. The effect of material thickness showed no clear trend, and changes in hardness were quite variable. As expected, the strongest influence on BH was achieved through wood densification. The wood layer beneath the surface was densified the most, and the indenter was pushed into this layer when measuring BH. Although both beech and aspen are diffuse-porous wood species, beech wood has a higher initial density and therefore was less influenced by densification than aspen wood. During gradual densification, the wood density increased to the values representing the density of cell walls (1,500 to 1,540 kg/m^3), which is similar for all woods (Gibson and Ashby 1999). Although beech started from a higher initial density (its libriform fibers are thin, thick-walled, and have a smaller lumen), further densification was not as intensive as in aspen. Lower-density aspen wood (with wider, thin-walled libriform fibers, with a larger lumen) can be densified more intensively (Požgaj *et al.* 1997).

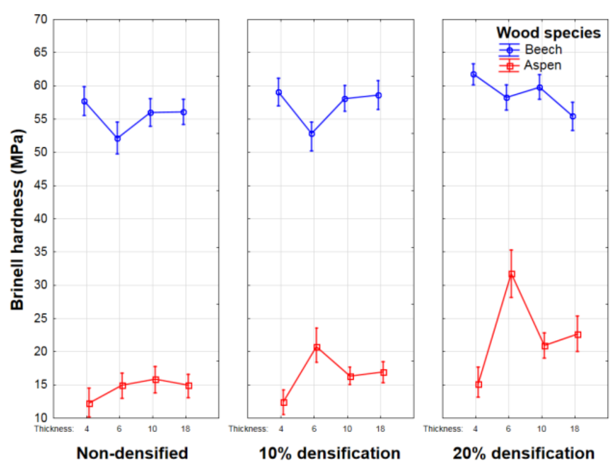

Fig. 7. Influence of material thickness, densification, and wood species on the Brinell hardness

In this research, the mean value of BH in the radial direction of non-densified beech wood was 55.5 MPa, which was notably higher than that of other studies. In comparison, Wagenfür (2000) found a BH value of 34 MPa in the direction perpendicular to the fibers for European beech. Pelit *et al.* (2015) investigated the influence of thermo-mechanical densification and heat treatment on beech veneers and found a mean BH value of 31.9 MPa for Eastern beech (*Fagus orientalis* L.). Some studies reported even lower BH values. Lo Monaco *et al*. (2015) examined the technical properties of beech wood from two areas in Central Italy and determined that the BH values were 29.8 and 27.7 MPa, respectively.

Non-densified aspen wood exhibited a BH value of 14.5 MPa in the radial direction, which was slightly higher than the literature. Wagenfür (2000) reported a BH value in the direction perpendicular to fibers of 11 MPa for European aspen. A similar value of BH (12 MPa) was reported by Fang *et al*. (2012) in research investigating the influences of densification and oil-heat treatment on aspen veneers. On the other hand, Cloutier *et al*. (2008) found a higher BH value of 17 MPa when studying the effect of densification and heat treatment on aspen veneers.

The hardness of wood is primarily influenced by the method of measurement and its associated processing conditions (Kúdela 1998; Niemz and Stübi 2000; Hirata *et al*. 2001). Different hardness values are mainly caused by different processing conditions (measuring time, loading force, *etc*.) that arise from different methods of study.

Table 7. Mean Values of Brinell Hardness

Wood species	Thickness (mm)	Degree of densification (%)	Brinell hardness H_{BW} (MPa)	Wood species	Thickness (mm)	Degree of densification (%)	Brinell hardness H_{BW} (MPa)
Beech	4	0	57.7 (4.36)	Aspen	4	0	12.2 (1.73)
Beech	4	10	59.1 (4.19)	Aspen	4	10	12.4 (1.81)
Beech	4	20	61.7 (2.17)	Aspen	4	20	15.2 (1.83)
Beech	6	0	52.1 (5.45)	Aspen	6	0	14.9 (1.22)
Beech	6	10	52.9 (2.56)	Aspen	6	10	20.8 (8.31)
Beech	6	20	58.3 (3.59)	Aspen	6	20	31.8 (13.24)
Beech	10	0	56.0 (4.22)	Aspen	10	0	15.8 (2.78)
Beech	10	10	58.1 (3.63)	Aspen	10	10	16.3 (1.40)
Beech	10	20	59.8 (3.30)	Aspen	10	20	20.9 (6.08)
Beech	18	0	56.1 (3.36)	Aspen	18	0	14.9 (0.75)
Beech	18	10	58.6 (4.65)	Aspen	18	10	16.9 (2.36)
Beech	18	20	56.4 (4.34)	Aspen	18	20	22.7 (9.41)

Values in parentheses are standard deviations

CONCLUSIONS

1. The IBS of wood was primarily influenced by the material's thickness and wood type. As expected, beech wood achieved higher IBS values in all instances (mean of 31%), whereas aspen wood exhibited lower IBS values. Material thickness exhibited no clear influence on IBS for beech, while the opposite was true for aspen. The IBS value of aspen wood increased with increasing thickness. The effect of wood densification was

not statistically significant ($P > 0.05$) and resulted in lower IBS values ranging from 5.1% to 6.8%.

2. Brinell hardness was primarily influenced by the degree of densification and wood type, while the effect of material thickness had the least significant influence ($P = 0.041$). Wood densification was closely associated with increasing density and exhibited the highest effect on aspen wood. The hardness of aspen wood, densified at 20%, increased by 24% to 53%, depending on the thickness. Densified beech wood achieved only slightly higher BH values, ranging from 1% and 10%.

ACKNOWLEDGMENTS

The authors are grateful for support of the University-Wide Internal Grant Agency (CIGA) of the Faculty of Forestry and Wood Science at Czech University of Life Sciences Prague, Project 4308-2016.

REFERENCES CITED

Aicher, S., and Ohnesorge, D. (2011). "Shear strength of glued laminated timber made from European beech timber," *European Journal of Wood and Wood Products* 69(1), 143-154. DOI: 10.1007/s00107-009-0399-9

Bal, B. C. (2016). "The effect of span-to-depth ratio on the impact bending strength of poplar LVL," *Construction and Building Materials* 112, 355-359. DOI: 10.1016/j.conbuildmat.2016.02.197

Bal, B. C., and Bektaş, I. (2012). "The effects of some factors on the impact bending strength of laminated veneer lumber," *BioResources* 7(4), 5855-5863. DOI: 10.15376/biores.7.4.5855-5863

Barcík, Š., Pivolusková, E., and Kminiak, R. (2008). "Effect of technological parameters and wood properties on cutting power in plane milling of juvenile poplar wood," *Drvna Industrija* 59(3), 107-122.

Bektaş, I., Güler, C., and Baştürk, M. A. (2002). "Principal mechanical properties of Eastern beech wood (*Fagus orientalis* Lipsky) naturally grown in Andırın Northeastern Mediterranean region of Turkey," *Turkish Journal of Agriculture and Forestry* 26(3), 147-154.

Bučar, D. G., and Merhar, M. (2015). "Impact and dynamic bending strength determination of Norway spruce by impact pendulum deceleration," *BioResources* 10(3), 4740-4750. DOI: 10.15376/biores.10.3.4740-4750

Cloutier, A., Fang, Ch., Mariotti, N., Koubaa, A. and Blanchet, P. (2008). "Densification of wood veneers under the effect of heat, steam and pressure," *Proceedings of the 51th International Convention of Society of Wood Science and Technology*, November 10-12, Concepción, Chile, pp. 1-9.

ČSN 91 0001. (2007). "Furniture -Technical requirements," Czech Office for Standards, Metrology and Testing, Prague, Czech Republic. (in Czech)

Dubovský, J., Babiak, M., and Čunderlík, I. (2003). *Textúra, Štruktúra a Úžitkové Vlastnosti Dreva* (*Texture, Structure and Utility Properties of Wood*), 3rd Edition, Technical University in Zvolen, Zvolen, Slovakia, pp. 106. (in Slovak)

Eilmann, B., Sterck, F., Wegner, L., de Vries, S. M. G., von Arx, G., Mohren, G. M. J., den Ouden, J., and Sass-Klaassen, U. (2014). "Wood structural differences between northern and southern beech provenances growing at a moderate site," *Tree Physiology* 34(8), 882-893. DOI: 10.1093/treephys/tpu069

EN 942. (2007). "Timber in joinery-General requirements," *European Committee for Standardization*, Brussels, Belgium.

EN 1534. (2010). "Wood flooring-Determination of resistance to indentation-Test method," *European Committee for Standardization*, Brussels, Belgium.

Fang, Ch.-H., Cloutier, A., Blanchet, P., and Koubaa, A. (2012). "Densification of wood veneers combined with oil-heat treatment. Part II: Hygroscopicity and mechanical properties," *BioResources* 7(1), 925-935. DOI: 10.15376/biores.7.1.0925-0935

Gibson, L. J., and Ashby, M. F. (1999). *Cellular Solids - Structure and Properties*, 2nd Edition, Cambridge University Press, Cambridge, UK, pp. 510.

Grekin, M., and Verkasalo, E. (2013). "Variation in and models for Brinell hardness of Scots pine wood from Finland and Sweden," *Baltic Forestry* 19(1), 128-136.

Gryc, V., Vavrčík, H., and Gomola, Š. (2008). "Selected properties of European beech (*Fagus sylvatica* L.)," *Journal of Forest Science* 54(9), 418-425, (http://agriculturejournals.cz/publicFiles/02194.pdf).

Gong, M., Lamason, C., and Li, L. (2010). "Interactive effect of surface densification and post-heat-treatment on aspen wood," *Journal of Materials Processing Technology* 210(2), 293-296. DOI: 10.1016/j.jmatprotec.2009.09.013

Guntekin, E., Ozkan, S., and Yilmaz, T. (2014). "Prediction of bending properties for beech lumber using stress wave method," *Maderas. Ciencia y Tecnología* 16(1), 93-98. DOI: 10.4067/S0718-221X2014005000008

Heräjärvi, H. (2004). "Variation of basic density and Brinell hardness within mature Finnish *Betula pendula* and *B. pubescens* stems," *Wood and Fiber Science* 36(2), 216-227.

Heräjärvi, H., and Junkkonen, R. (2006). "Wood density and growth rate of European and hybrid aspen in Southern Finland," *Baltic Forestry* 12(1), 2-8.

Hirata, S., Ohta, M., and Honma, Y. (2001). "Hardness distribution on wood surface," *Journal of Wood Science* 47(1), 1-7. DOI: 10.1007/BF00776637

ISO 3348. (1975). "Wood-Determination of impact bending strength," *International Organization for Standardization*, Geneva, Switzerland.

ISO 13061-1. (2014). "Physical and mechanical properties of wood-Test methods for small clear wood specimens. Part 1: Determination of moisture content for physical and mechanical tests," *International Organization for Standardization*, Geneva, Switzerland.

ISO 13061-2. (2014). "Physical and mechanical properties of wood-Test methods for small clear wood specimens. Part 2: Determination of density for physical and mechanical tests," *International Organization for Standardization*, Geneva, Switzerland.

Kärki, T. (2001). "Variation of wood density and shrinkage in European aspen (*Populus tremula*)," *Holz als Roh- und Werkstoff* 59(1), 79-84. DOI: 10.1007/s001070050479

Kamke, F. A. (2006). "Densified radiate pine for structural composites," *Maderas. Ciencia y Tecnología* 8(2), 83-92. DOI: 10.4067/S0718-221X2006000200002

Kollmann, F. F. P. (1967). *Verformung und Bruchgeschehen bei Holz, als einem anisotropen, inhomog., porigen Festkörper* [*Deformation and Fracture Formed in a*

Wood, such in Anisotropic, Inhomogeneous, and Porous Solids], VDI-Forschungsheft Nr. 520, Düsseldorf, VDI Verlag. (in German)

Kurt, Ş., and Özçifçi, A. (2009). "Effect of various fire retardants on Brinell hardness of some wood," *BioResources* 4(3), 960-969. DOI: 10.15376/biores.4.3.960-969

Kúdela, J. (1998). "Analysis of wood hardness," *Proceedings of the 3rd IUFRO Symposium – Wood Structure and Properties*, August 25-27, Zvolen, Slovakia, pp. 199-203.

Lamason, C., and Gong, M. (2007). "Optimization of pressing parameters for mechanically surface densified aspen," *Forest Product Journal* 57(10), 64-68.

Laine, K., Rautkari, L., Hughes, M., and Kutnar, A. (2013). "Reducing the set-recovery of surface densified solid Scots pine wood by hydrothermal post-treatment," *European Journal of Wood and Wood Products* 71(1), 17-23. DOI: 10.1007/s00107-012-0647-2

Laine, K., Segerholm, K., Wålinder, M., Rautkari, L., Ormondroyd, G., Hughes, M., and Jones, D. (2014). "Micromorphological studies of surface densified wood," *Journal of Materials Science* 49(5), 2027-2034. DOI: 10.1007/s10853-013-7890-8

Lokaj, A., and Vavrušová, K. (2010). "Wood impact bending strength laboratory tests," *Transactions of the VŠB, Technical University of Ostrava, Civil Engineering Series*, 10(1), 1-6. DOI: 10.2478/v10160-010-0003-6

Lo Monaco, A., Calienno, L., Pelosi, C., Balletti, F., Agresti, G., and Picchio, R. (2015). "Technical properties of beech wood from aged coppices in central Italy," *iForest* 8(1), 82-88. DOI: 10.3832/ifor1136-007

Makovická–Paulínyová, J., Kotlínová, M., and Pivolusková, E. (2006). "Chosen physical and mechanical properties of poplar juvenile wood (*Populus tremula*)," *Proceedings of the 5th IUFRO Symposium – Wood Structure and Properties*, September 3-6, Sliač - Sielnica, Slovakia, pp. 305-309.

Möttönen, V., Bütün, Y., Heräjärvi, H., Marttila, J., and Kaksonen, H. (2015). "Effect of combined compression and thermal modification on mechanical performance of aspen and birch wood," *ProLigno* 11(4), 310-317.

Navi, P., and Girardet, F. (2000). "Effects of thermo-hydro-mechanical treatment on the structure and properties of wood," *Holzforschung* 54(3), 287-293. DOI: 10.1515/HF.2000.048

Niemz, P., and Stübi, T. (2000). "Investigations of hardness measurements on wood based materials using a new universal measurement system," *Proceedings of the First International Symposium on Wood Machining*, September 27-29, Vienna, Austria, pp. 51-61.

Ohnesorge, D., Richter, K., and Becker, G. (2010). "Influence of wood properties and bonding parameters on bond durability of European Beech (*Fagus sylvatica* L.) glulams," *Annals of Forest Science* 67(6), 601-601. DOI: 10.1051/forest/2010002

Pelit, H., Sönmez, A., and Budakçı, M. (2015). "Effects of thermomechanical densification and heat treatment on density and Brinell hardness of Scots pine (*Pinus sylvestris* L.) and Eastern beech (*Fagus orientalis* L.)," *BioResources* 10(2), 3097-3111. DOI: 10.15376/biores.10.2.3097-3111

Pöhler, E., Klingner, R., and Kunniger, T. (2006). "Beech (*Fagus sylvatica* L.) - Technological properties, adhesion behavior and colour stability with and without coatings of the red heartwood," *Annals of Forest Science* 63(2), 129-137. DOI: 10.1051/forest:2005105

Požgaj, A., Chovanec, D., Kurjatko, S., and Babiak, M. (1997). *Štruktúra a Vlastnosti Dreva* [*Structure and Properties of Wood*], 2nd Edition, Príroda, Bratislava, Slovakia, pp. 485. (in Slovak)

Rautkari, L., Properzi, M., Pichelin, F., and Hughes, M. (2009). "Surface modification of wood using friction," *Wood Science and Technology* 43(3-4), 291-299. DOI: 10.1007/s00226-008-0227-0

Rautkari, L., Laine, K., Laflin, N., and Hughes, M. (2011). "Surface modification of Scots pine: The effect of process parameters on the through thickness density profile," *Journal of Material Science* 46(14), 4780-4786. DOI: 10.1007/s10853-011-5388-9

Rautkari, L., Laine, K., Kutnar, A., Medved, S., and Hughes, M. (2013). "Hardness and density profile of surface densified and thermally modified Scots pine in relation to degree of densification," *Journal of Material Science* 48(14), 2370-2375. DOI: 10.1007/s10853-012-7019-5

Skarvelis, M., and Mantanis, G. I. (2013). "Physical and mechanical properties of beech wood harvested in the Greek public forests," *Wood Research* 58(1), 123-130.

Wagenfür, R. (2000). *Holzatlas*, [*Wood Atlas*], 5th Edition, Fachbuchverlag im Carl Hanser Verlag, Leipzig, Germany, pp. 707. (in German)

Article submitted: July 1, 2016; Peer review completed: August 10, 2016; Revised version received and accepted: August 15, 2016; Published: August 29, 2016.
DOI: 10.15376/biores.11.4.8638-8652