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ORIGINAL ARTICLE

Assessment of a modification to the Brinell method for determining solid wood hardness

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Abstract Purpose of this study was to assess a modification to the hardness determination method in order to mitigate the effect of visual measurements on the consistency of Brinell method and accuracy of the results. The amendment has been previously proposed by other researchers and refers to the automated determination of indentation diameter and relies on the ability of modern testing machines to accurately measure indentation depth, through which the calculation of indentation diameter is possible. From the results of this study it was shown that the hardness values acquired by the proposed modification presented statistically significant difference compared to those acquired using the visual method described in EN1534 (Wood and parquet flooring—determination of resistance to indentation (Brinell)—test method, 2000). Moreover, compared to the standard methodology, the application of the proposed amendment led to hardness values which are better correlated to density as well as Janka hardness for the six different solid wood species tested. Furthermore, the proposed modification resulted to hardness values which seem to be less affected by the presence of varnish coatings.

Keywords Wood · Hardness · Brinell · Modification · Janka · Indentation depth

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1 Introduction

Hardness is an important mechanical property frequently determined in the quality control of wood and is useful especially for commercially important wood species used for flooring, furniture as well as other applications [6, 12]. Furthermore, hardness is characterized by the advantage of relatively inexpensive determination without involving significant damage to wood; therefore it can be used for low-cost quality control purposes. Hardness could also be estimated non destructively because, as several authors have reported, appears to be linearly correlated to density [19]; [10]; [2, 7–9, 14, 16]. It shoud be noted though, that its precise estimation is complicated and cannot depend only on density.

A few standard methods for the determination of wood hardness exist [16], with the most frequently used being Janka and Brinell methods [6]. In Janka method (ASTM D 143-[1]) a steel spherical indenter with a diameter of 11.28 mm is loaded halfway into the material. The applied load is used for the calculation of the Janka hardness. In Brinell method [4] a steel sphere with a diameter of 10 mm is pushed on the surface of the wood specimen with a constant load of 1,000 N for 25 s. The Brinell hardness is calculated using the diameter of the indentation mark which is measured with a resolution of 0, 2 mm.

Brinell method, although the most used in Europe and proposed over Janka method [7], is accompanied by certain disadvantages that have been already discussed by Niemz and Stubi [13]. One of the most important among these problems occurs due to the fact that the diameter of the indentation on wood is rather difficult to be accurately and consistently measured visually [11]. [3] reported that an effect called "sinking in" can be observed around an indentation on a wooden surface produced by a load applied in radial or tangential direction. This effect is causing problems in the visual determination of the actual size of the indentation when using area as a measure of indentation. As a result, the precise determination of hardness is hindered since all values are theoretically based upon an indentation with a geometry that precisely matches the tool [8]. Various modifications of the standard hardness determination procedure have been proposed [2, 8, 16, 17] in order to address the above problem, some of them involving the measurement of the indentation depth taking advantage of the high accuracy capabilities of modern testing equipment. With the use of modern universal testing machines, the indentation depth can be measured with a resolution of 0.001 mm and can then be used to calculate the indentation diameter [5, 7, 11, 13–15]. The determination of indentation depth does not take into account the precise shape of the indentation created on wood. Nevertheless, with the use of the above method, information about surface elasticity of wood can also be obtained [5, 14]. Niemz and Stubi [13] used the indentation depth for the determination of Brinell hardness using some wood materials which were tested at different loads and moisture contents and recommended additional measurements on solid wood. However, no assessment of the proposed modifications has been published yet.

The aim of this study was to assess a previously proposed modification for the improved determination of Brinell hardness values of wood. The modification has been proposed by other researchers [5, 7, 11, 13–15] and involves the measurement of the indentation depth and consequently the geometrical calculation of the indentation diameter. For the assessment of the modification, the correlation of Brinell hardness (with and without the modification) against density of wood as well as Janka hardness was determined.

2 Materials and methods

For the conduction of this research six species were used namely: (i) beech (*Fagus* sp.), (ii) chestnut (*Castanea* sp.), (iii) oak (*Quercus* sp.), (iv) pine (*Pinus* sp.), (v) merbau (*Intsia* sp.) and (vi) ipé (*Tabebuia* sp.). These wood species were obtained in the form of flooring planks by a Greek manufacturing and trading company. Merbau and Ipé samples were acquired also with a transparent surface finish.

For all wood samples the non flat surfaces as well as all defects were mechanically removed in order to produce defect-free rectangular specimens with dimensions of 6 cm × 6 cm × 2 cm. All manufactured specimens were conditioned in a climate chamber at a temperature of 20 (±1) °C and relative humidity of 65(±3) % and were successively sanded with p80 and then with p120 abrasive paper in order to produce flat and smooth surfaces. All specimens were used for the determination of hardness according to Janka (ASTM D 143-[1]), Brinell [4] and the proposed modification of Brinell method. A stainless steel spherical indenter with a diameter of 10 mm was used for Brinell and modified Brinell hardness determination. According to [4], after each test the indentation diameter (d) was determined as the mean value of two diameters (one parallel and one perpendicular to wood fiber orientation) using a magnifying glass and a digital caliper with a resolution of 0.01 mm. After load removal, the two diameters of the indentation mark were measured and the hardness was calculated using the formula:

$$\mathrm{HB} = \frac{2F}{g\pi D\left[D - \sqrt{D^2 - d^2}\right]} \quad (1)$$

where HB is the Brinell hardness (N/mm^2), F is the Applied load (1,000 N), g is the Gravity acceleration (m/s^2), D is the Sphere diameter (10 mm), π is the 3.14, d is the Indentation diameter (mm).

Brinell hardness was also determined for the same indentations using the above modification in which the

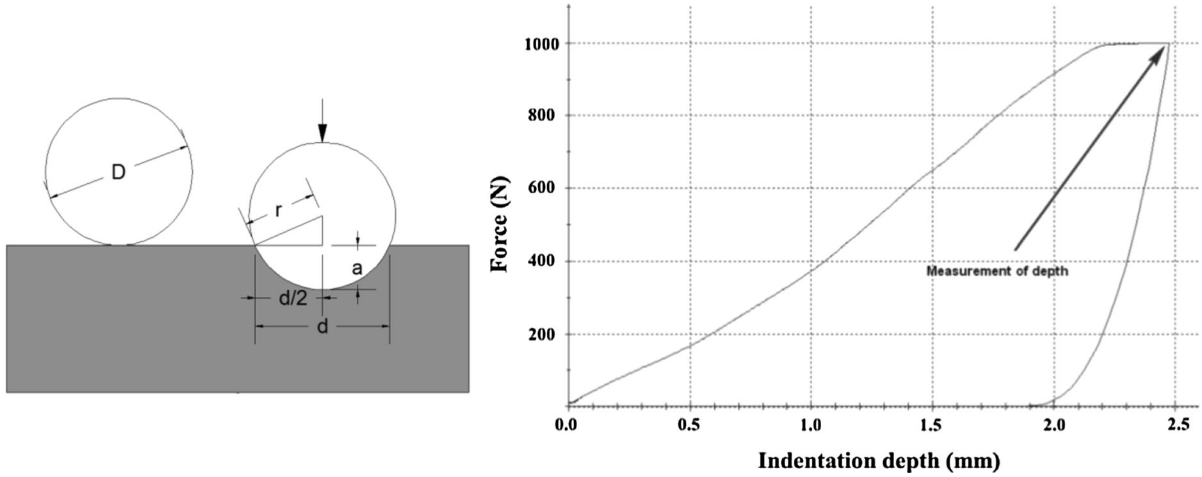

Fig. 1 (*left*) Calculation of indentation diameter (*d*) by measuring the indentation depth (*a*), (*right*) Indicative example of graph showing the applied force against indentation depth and the point of indentation depth measurement

indentation depth (*a*) was measured (Fig. 1) with a resolution of 0.001 mm. The indentation depth values were measured at their maximum values, which occurred when the metallic sphere was pushed into wood mass with a load of 1,000 N for 25 s (Fig. 2). The indentation diameter (*d*) was geometrically calculated using the formula:

$$d = 2\sqrt{2ra - a^2} \tag{2}$$

Substituting d value in formula 1 leads to:

$$\mathrm{HB} = \frac{F}{g\pi Da} \tag{3}$$

For comparison reasons, for each Brinell hardness, a corresponding hardness determination was also carried out at a distance of about 2 cm according to Janka method (ASTM D 143-[1]).

All indentations and depth measurements were made perpendicular to the grain using a Zwick-Roell Z020 testing machine. In each case that cracking was detected during loading, the corresponding specimen was rejected. After testing, each specimen was processed to remove the regions beyond the indentation marks and was used for the determination of density after reconditioning to temperature of 20 ($\pm$1) °C and relative humidity of 65 ($\pm$3) %. For the assessment of the proposed modification, the degree of linear dependence between hardness values and density was calculated in terms of the Pearson's correlation coefficient (*r*). Data analysis was carried out using PASW Statistics 18 software.

3 Results and discussion

Table 1 presents the mean values and standard deviations for the determined properties. Brinell hardness varied between 20.91 and 130.57 N/mm^2 while modified Brinell varied between 12.72 and 44.17 N/mm^2. The differences between Brinell and modified Brinell hardness for each separate as well as for the combination of species were examined with one-way ANOVA and proved statistically significant at the 0.01 level. The above is obviously attributed to the fact that the modified method is based on the measurement of the indentation mark under load, therefore does not involve the consideration of creep/relaxation phenomena occurring during the test. Furthermore, the modification of the Brinell method led to more homogeneous results than those acquired using the original method.

One-way ANOVA also showed that coating of ipe and merbau specimens resulted to statistically significant reduction of Brinell hardness compared to uncoated ones. Similar results have been reported by Gindl et al. [5]. On the contrary, for the modified Brinell, Janka, as well as density values, the coated and uncoated ipe and merbau specimens did not present statistically significant differences between them.

As can be seen in Table 2 as well as in Fig. 2, when each species was individually examined, Brinell hardness values, with the exception of merbau coated and chestnut specimens showed low to moderate correlation ($r = -0.078$–0.583) against density. For the combination of all species (Fig. 3) the respective

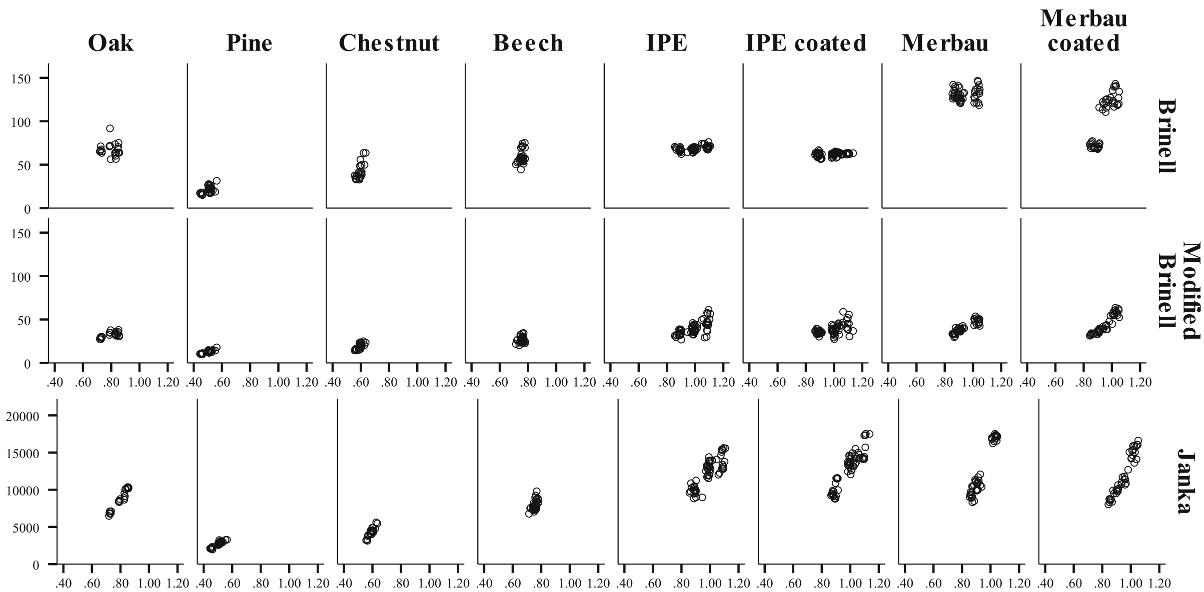

Fig. 2 Scatter-plot matrix of hardness against density for each tested species

Table 1 Descriptive statistics for density and hardness

	Oak	Pine	Chestnut	Beech	Ipe	Ipe coated	Merbau	Merbau coated
Density (g/cm^3)	0.80[a]	0.50	0.59	0.76	0.99	0.99	0.94	0.95
	(0.05)[b]	(0.03)	(0.02)	(0.02)	(0.08)	(0.08)	(0.07)	(0.07)
Brinell hardness (N/mm^2)	67.26	20.91	42.03	59.13	68.64	61.96	130.57	103.18
	(7.30)	(3.98)	(9.04)	(7.62)	(2.61)	(2.32)	(6.98)	(27.48)
Modified Brinell hardness (N/mm^2)	32.63	12.72	18.86	26.46	39.61	38.48	40.62	44.17
	(3.02)	(1.75)	(3.51)	(3.40)	(7.30)	(6.00)	(6.53)	(10.56)
Janka hardness (N)	8,764	2,699	4,282	7,986	12,323	12,788	12,552	11,876
	(1,355)	(379)	(609)	(698)	(1,870)	(2,410)	(3,379)	(2,722)
N	23	32	24	31	63	61	46	42

[a] Mean values

[b] Standard deviations

coefficient value was 0.600. In the case of modified Brinell hardness values, with the exception of beech specimens, a moderate to strong correlation for the individual species ($r = 0.647$–0.935, significant at the 0.01 level) and a strong correlation for the combination of all species tested ($r = 0.893$) against density was observed.

Concerning the correlation of density against Janka hardness values, it was observed that the related coefficients except beech ($r = 0.574$, significant at the 0.01 level) were high ($r = 0.836$–0.975, significant at the 0.01 level). This probably lies on the fact that Janka hardness is not influenced by the indentation characteristics but only on the applied load.

Furthermore, all Pearson coefficients concerning the correlation of Janka hardness against density showed slight difference from those reported by Wiemann and Green [18] for tropical hardwoods ($r = 0.94$) but differed more in the case of temperate hardwoods ($r = 0.91$) as well as temperate softwoods ($r = 0.73$) at a moisture content of 12 %.

In an attempt to assess the effects of coating on the correlation of density against the hardness values derived from the three used methods, it can be drawn

Table 2 Pearson's correlation coefficients of hardness against density

	Modified Brinell hardness		Modified Brinell hardness		Modified Brinell hardness		*N*
	r	Sig. (2-tailed)	*r*	Sig. (2-tailed)	*r*	Sig. (2-tailed)	
Oak	−0.078	0.723	0.647[b]	0.001	0.975[b]	0.000	23
Pine	0.583[b]	0.000	0.840[b]	0.000	0.927[b]	0.000	32
Chestnut	0.723[b]	0.000	0.747[b]	0.000	0.912[b]	0.000	24
Beech	0.327	0.072	0.123	0.508	0.574[b]	0.001	31
Ipe	0.512[b]	0.000	0.666[b]	0.000	0.836[b]	0.000	63
Ipe coated	0.304[a]	0.017	0.497[b]	0.000	0.920[b]	0.000	61
Merbau	0.094	0.535	0.910[b]	0.000	0.972[b]	0.000	46
Merbau coated	0.872[b]	0.000	0.935[b]	0.000	0.962[b]	0.000	42
All species	0.600[b]	0.000	0.893[b]	0.000	0.957[b]	0.000	322

[a] Correlation is significant at the 0.05 level (2-tailed)

[b] Correlation is significant at the 0.01 level (2-tailed)

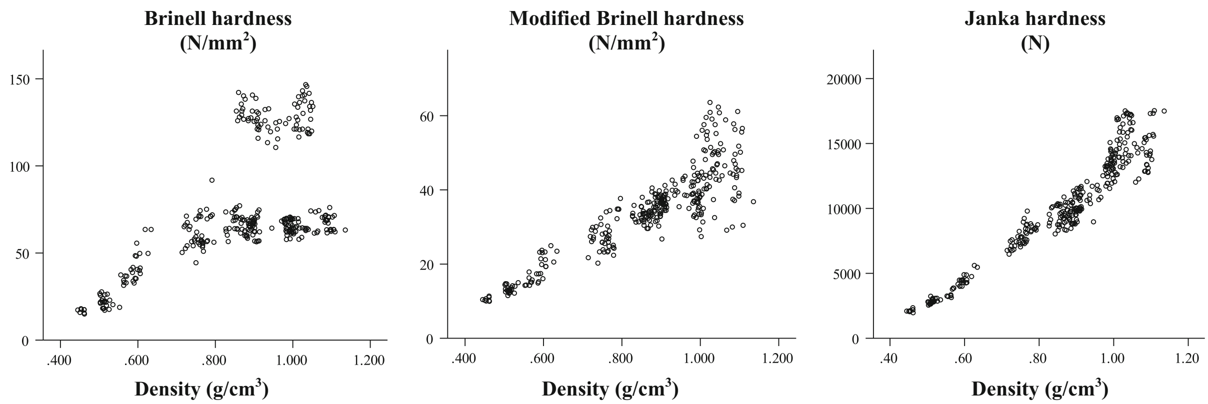

Fig. 3 Scatter-plots of hardness against density for the combination of all tested species

(Table 2) that the presence of coating on ipe and merbau specimens could result to significant differences on the related Pearson coefficients for the Brinell hardness values (0.512 and 0.304 for ipe, 0.094 and 0.872 for merbau). The above findings in combination with the fact that the differences of density among coated and non coated species were not statistically significant can lead to the conclusion that the Brinell hardness determination method could be susceptible to factors that are related to the presence of coatings and which may interfere with the reliability of the produced results. On the other hand, modified Brinell method seems to be less affected and Janka method is almost not affected by the same factor.

The results concerning the correlation of Brinell and modified Brinell hardness against Janka hardness (Fig. 4; Table 3) are generally in accordance with those against density. In more detail, for the combination of all species, the correlation of Janka against modified Brinell hardness was stronger ($r = 0.619$) than the one against Brinell hardness ($r = 0.885$, significant at the 0.01 level). In the case of individual species, with the exception of merbau coated ($r = 0.821$, significant at the 0.01 level) all species showed weak to moderate correlation of Brinell to Janka hardness values ($r = -0.097$–0.513) and with the exception of beech and ipe coated ($r = 0.319$ and 0.371 respectively) moderate to strong correlation of modified Brinell to Janka values ($r = 0.528$–0.950, significant at the 0.01 level).

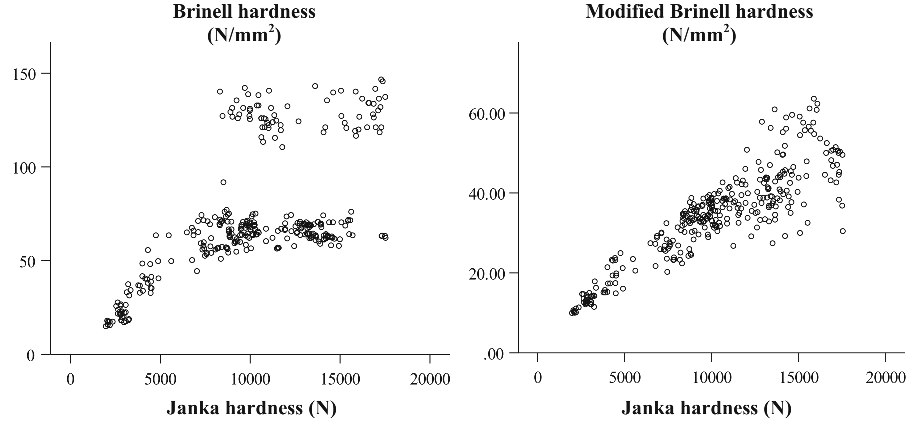

Fig. 4 Scatter-plots of Brinell and modified Brinell hardness against Janka hardness for the combination of all tested species

Table 3 Pearson's correlation coefficients Brinell and modified Brinell hardness against Janka hardness

	Brinell hardness		Mod. Brinell hardness		*N*
	r	Sig. (2-tailed)	*r*	Sig. (2-tailed)	
Oak	−0.097	0.660	0.615[a]	0.002	23
Pine	0.482[a]	0.002	0.712[a]	0.002	32
Chestnut	0.610[a]	0.002	0.595[a]	0.002	24
Beech	0.098	0.599	0.319	0.080	31
Ipe	0.513[a]	0.000	0.528[a]	0.000	63
Ipe coated	0.123	0.346	0.371[a]	0.003	61
Merbau	0.101	0.505	0.909[a]	0.000	46
Merbau coated	0.821[a]	0.000	0.950[a]	0.000	42
All species	0.619[a]	0.000	0.885[a]	0.000	322

[a] Correlation is significant at the 0.01 level (2-tailed)

4 Conclusions

From the results of this study, the following conclusions can be drawn:

- The automated measurement of indentation depth instead of visual measurement of indentation diameter can provide values of Brinell hardness which are better correlated to density.
- The proposed modification led to significant change of Brinell hardness values.
- The presence of a coating on wood surface could interfere with the reliability of hardness values in the case of the original Brinell method but seem to have lower influence on the respective modified Brinell and even lower on the Janka hardness values.

Further work is recommended by the authors in order to assess the feasibility of proposed modification to other wood species, treated wood as well as wood based composites. The variability of wood anatomy and structure characteristics that affect hardness should also be taken into account.

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