The History of Wood Hardness Tests

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Abstract. The purpose of the article is, to review the relative and absolute hardness tests with relevance for the wood industry. It will be seen, how these hardness test methods were developed or almost forgotten, what are their importance. It will be shown, what kind of advantages, disadvantages they have and the situations, it will come into sight, in which cases their applicability is recommended or rejectable. We present in this article the history of the currently practiced static hardness test methods from 1860 till nowadays, considering the applied tool geometry and the definition as well as calculation of wood hardness.

1. Definition and importance of hardness
From a practical point of view, the hardness of the wood plays role both during the manufacturing technologies and in the mechanical durability. The definition itself is by Sándor Rejtő: “The hardness of a material is practically its resistance against the penetration of a tool” [1]. The resistance of wood against penetration depends on the shape of the tool, the manner and on the anatomic direction of the penetration [2]. Depending on the duration of the load which can be instantaneous or a longer period, static and dynamic material testing methods can be differentiated, however, this paper deals only with static methods. The static hardness-measuring methods can be divided to two different groups: relative and absolute. The first one is more provisional, it compares different materials, while an absolute measuring method gives much clearer numerical results.

2. Relative hardness measuring methods
The examination of hardness become significant in the last 300 years, but the examination of wood hardness started later, in the last 160 years. The first statements regarding hardness came from Reamur (1722): the harder metal scrapes the softer metals [3]. The minerologist C. F. Mohs used this principle to create his famous ten-unit scraping hardness scale regarding minerals in 1822 [4] [5]. The first person who tried to describe wood hardness was H. Nördlinger (1860). He grouped wood materials by their traversal sawability [2] [6] and defined eight units of hardness in wood materials used for buildings [7]. The list of Nördlinger is incomplete, not numerical, although it shows the correspondence between density and hardness [8] and according to the’s manuscript of Pallay from 1951, it satisfied the practical requirements of the industry for a long period [2]. The first person who wrote down the correlation between hardness and density was L. de Buffon in the 1700s [9].
3. Absolute hardness measuring methods

To ease the review of the different hardness test methods, we present figure 1.

![Figure 1. Shematic representation of absolute hardness test methods:](image)

3.1. Brinell (1900)

The hardness measuring method of Brinell has a great significance, despite it was created to measure the hardness of metals, is the basis of several processes used in the wood industry. Brinell defined hardness as the quotient of a force applied to a steel ball and the indented surface made by the ball. For the examination he used a ball with 10 mm diameter as a tool. In case of softer metals he used a loading force of 5 000 N, for harder metals a loading force of 30 000 N and for wood a loading force of 500 N [6],[8, 10]. Brinell examined 25 wood species [10]. The Brinell hardness can be calculated by the following formula (equation 1):

$$H_B = \frac{F}{\pi h} = \frac{2F}{\pi(D^2-d^2)}$$

where $H_B$ is the Brinell hardness (N/mm²), $F$ is the applied loading force (N), $d$, $D$ are the diameters of the indentation (mm) and $h$ is the deepness of the indentation (mm).

3.2. Büsgen (1904)

Büsgen (1904) defined the hardness by measuring the weight necessary to press a steel needle 2 mm deep into the material [7, 11]. Using this technique, he examined 182 wood species [12] and made a hardness scale consisting eight groups, which was based on Nördlinger’s work. The value of hardness is one-hundredth of the measured value in grams. The groups contain values between 1 and 10, 11 and 20, 21 and 30, and so on [7].

3.3. Janka (1900, 1906, 1908)

The first studies of G. Janka in this field has been made in a collaboration A. Hadek. In these studies, they examined Austrian wood materials used for buildings, analyzing their hardness and flexibility and the factors of these abilities [13]. Janka published the first study regarding hardness in 1906. In this study a stamp-method has been described (1900). Janka used a steel cube with 10 cm² cross section as an indentation tool, which was used on smooth-surfaced wood samples. The other method which made him famous and what is a major material testing process in many countries was published in 1906, inspired by the work of Brinnell. The tool was changed to a ball with a diameter of 11.284 mm,
pressed 5.642 mm deep into the wood so its projection was exactly 1 cm². The Janka hardness value is determined by the force necessary to do the process (Equation 2) [6]:

\[ H_J = \frac{F}{A} = \frac{F}{100} \]  

In the equation \( H_J \) means the Janka hardness (N/mm²), \( F \) is the applied loading force (N) and \( A \) is the indented area.

The study of Janka in 1906 was significant, because he made correlations between density, compressive strength and hardness. An interesting fact, that in 1908 Janka published the results of the ball-based method alongside the with the stamp-hardness measuring experiment made in 1906, in which Janka used a cone with exactly 1 cm² area (5.642 mm in diameter), with 10 mm height and a flat top as a tool [14].

3.4. Meyer (1908)
E. Meyer, based upon practical experiences [15] set up a correlation regarding how does the diameter of the ball and the deepness of indentation affect the Brinell hardness value when used on metals:

\[ P = a \cdot d^n \]  
in which: \( P \) is the load (kg), \( a \) is the force needed to create a 1 mm diameter dent (kg), \( d \) is the diameter of the indentation (mm) and \( n \) is a constant value depending on the material.

Both K. Huber and A. Pevzoff found that this correlation can be used for woods as well. In case of conifers \( n < 2 \), for hardwoods \( n \sim 2 \).[8]

3.5. Ludwik (1908)
Ludwik intended a 90° cone into the wood to determine the wood hardness by measuring the applied force and the penetrated surface of the cone by the depth of the indentation[11, 15, 16]. He thought that the value of hardness will be independent of the applied force, when the force is uniformly distributed To accomplish this he tried to make the shape of the tool similar to the applied force. [16]

3.6. Rejtő (1920)
Rejtő modified the Brinell-hardness test and used a ball with 40 mm diameter. Since he was aware of the fact that, in measurements made with balls, the load increases only in the first period and it is constant until the cracking of the wood, he made measurements until the maximum force has been reached. After releasing the load, he examined the remaining diameter of the sphere in the wood and divided the force with the measured area [1].

3.7. Worschitz (1931)
Worschitz performed tests on larch end-grains, using a ball with a diameter of 31.78 mm. The deepness of the indentation never reached the ¼th of the diameter (7.95 mm). During his tests he determined the necessary forces by the place of origin of the wood (15 000 N, 12 000 N, 16 000-18 000 N), however, he could not keep the forces at a constant value due the fluctuation of the testing machine’s mercury column. He noted, that the size of the examined area has a high scatter, the values differ according to the year-ring structure of the pressured surface. He took into consideration the location of the sample inside the trunk and he averaged the values in order to make them comparable [17]

3.8. Mörath (1932)
In 1932, Mörath modified Brinell’s method in a way to be able to use on all wood materials [11, 18]. He measured 153 wood species and he changed only the applied force: on very hard, medium-hard and softer wood species he used forces equal to a load of 100 kg, 50 kg and 10 kg, respectively. Mörath defined the duration of the load: the maximum load had to be reached within 15 seconds, after that it has to be kept at same level for 30 seconds, finally the load must be removed gradually in another 15 seconds [8]. The method of the calculation of the results is the same as in the case of the Brinell hardness.
3.9. Monnin (1932) – Chalais – Meudon method
Monnin constructed the Chalais – Meudon method, giving up the idea of examining the end-grain hardness. He measured the radial direction of the wood samples. In this way there was no need to worry about the splitting of the fibers or about occurring unwanted forces that could affect the results [8]. In this method the wood was pressed with a steel cylinder with a diameter of 30 mm, in a manner that the longitudinal axle of the cylinder was parallel with the examined surface. The length of the cylinder must exceed the width of the wood sample. In France mostly samples with 2 x 2 cm area is used, which surfaces are pressed with a load of 20 N/cm² (= 0.2 MPa) for 5 seconds. In case of soft woods the load is lowered to 10 N/cm² (= 0.1 MPa)[8, 19]. To calculate the Chalais – Meudon hardness the first step is to determine the depth of the indentation using Equation (4):

\[
t = 15 - \frac{1}{2} \cdot (900 - l^2)^{\frac{1}{2}}
\]

(4)

where t is the depth of indentation (mm) and l is the width of indentation (mm).

The Chalais – Meudon hardness is given by the reciprocal of the depth of the indentation [11].

3.10. Krippel, Pallay (1937, 1938)
The Krippel – Pallay method eliminates the greatest problem with the Brinell-Mörath method, the usage of three different forces: similarly to the Janka method, it defines the depth of the indentation. M Krippel and N Pallay determined originally 2.5 mm (1937) indentation depth, then they took in consideration Stamer’s research results [10] and modified the depth to 2 mm. They looked for an indentation depth which does not cause the splitting of the fibers in neither coniferous woods or hardwoods. In order to get a more accurate average value, they noticed that, the ball’s surface must be enlarged to a point when it can reach multiple year-rings. The ball used by Krippel and Pallay had a diameter of 31.834 mm, which has been pressed into the wood in 2 mm depth – in this case the diameter of indentation will be 15.154 mm and the area of the indented sphere will be exactly 2 cm² [10, 18, 20]. As an interesting fact, it should be mentioned that in case both of the stamp-method of Janka and the ball-based methods the surfaces of the tools that are in contact with the wood are roughly 2 cm². The Krippel – Pallay hardness can be determined with the following formula (Equation 5) [20, 21]:

\[
H_{K-P} = \frac{F}{200} \text{(N/mm}^2\text{)}
\]

(5)

where \(H_{K-P}\) means the Krippel-Pallay hardness and F the is the applied load (N).

3.11. Hoeffgen (1938)
During the first tests Hoeffgen used rectangle-shaped stamps with areas of 2.5x20, 5x20 and 10x20 mm. These stamps were pressed in the samples 10 mm deep parallel to the direction of the grains [22]. In the later tests the hardness measurements has been done using wood with 12% moisture content and the tool has been pressed 1 mm deep into the sample. The value of hardness is given by the force needed to penetrate 1 mm deep in the sample. Although Hoeffgen [22] did not mention but Kovács [23] wrote that different sized stamps must be used according to the density of the tested wood materials. The dimensions of the stamps have to be 2.5x20 mm in case of lighter wood species , 5x20 mm in case of medium-heavy or heavy wood species and 10x20 mm in case of very heavy wood species. It was confirmed by Hoeffgen, that a larger stamp width lowers the area of the shear [22]. Hoeffgen used a loading time of 30 seconds and examined the influence of moisture content and the correlation with compressive strength and Janka hardness [22].

3.12. Weatherwax, Erickson and Stamm (1948) – hardness modulus
These three researchers modified the Janka hardness in a way, that woods with very high density (guaiac wood or compressed wood) and very low density wood materials (for example balsa wood) could be measured as well [11, 24]. During the original experiments the applied force and the depth of penetration increased roughly linearly. Weatherwax et al. derived the modulus of hardness from the graph [25]. In order to determine the modulus of hardness they used a tool similar to Janka’s. The samples were conditioned at 75oF (≈24° C) temperature and 50% relative humidity, the results were
recorded in 0.025 mm accuracy [11, 25]. They noticed, that over 0.25 inch (=0.64 cm) thickness the hardness did not change with increasing thickness of wood. For safety's sake all of the samples were at least 0.5 inch thick. The modulus of hardness was derived from examining 11 both untreated and compressed wood species [25]. They found that there is a correlation between the modulus of hardness and density, which connection is the same as the Janka hardness/density ratio [11]. Lewis (1968) performed examinations to find out if there is a correlation between the modulus of hardness and the Janka hardness. After a few tests on different wood species he realized that the Janka hardness has a linear connection with the modulus of hardness [26].

3.13. Mayer-Wegelin (1950)
H. Mayer-Wegelin (1950) wanted to measure the differences inside the year-rings. For that purpose, he created the device known as „Härtetaster“, a simple but relatively accurate and fast machine [8][19]. In his method he used a rather thin, standard phonograph needle which was pressed in the wood with a given force (according to Kovács (1979) this is equal to 30 p – 133,45 N), meanwhile the pressured depth was measured with an accuracy of 0.01 mm [12, 23]. The depth of penetration directly gives the hardness itself. Its value in normal circumstances is between 0.2-2 mm. In case of balsa wood it is 4.14 mm, for guaiac wood it is 0.21 mm) [12].

3.14. Kumichel, Holz (1955) – Höppler hardness
Kumichel and Holz did not use ball-based methods, because they thought similarly to their predecessors, that in case of ball-based tests the different loads and the indentation of the balls do not show always geometrical similarities. To eliminate this, they used cone which is independent from the size of the tool and the chosen force [27, 28]. During their tests, Kumichel and Holz were the firsts who used a Höppler consistometer (1940) to measure hardness [11, 27]. Originally, the device was developed to analyze the rheological properties of different materials, such as viscosity plasticity and yield point [27, 29].

The angle of the cone was designed to be 53,13o. This way in the moment of reaching the largest indentation depth, the depth of indentation and the circle’s diameter made by the cone is identical, exactly 1 cm² [30]. Based on this, the Höppler hardness can be calculated with the following formula (Equation 6) [31, 32]:

\[ H_H = \frac{0.001024 + F}{(b+0.2)^2} \text{ (N/mm}^2\) \] (6)

where \( H_H \) is the Höppler hardness (N/mm²), \( F \) is the load (N) and \( h \) is the depth of indentation (mm).

Regarding the loading time, Höppler used 60 seconds and another 30 seconds to cease the load. This has been approved by Kumichel and Holz [27]. However, there are different opinions regarding the optimal amount of load. Kumichel and Holz used 40 kp (≈392 N) based upon their tests on beech and on scots pine [27], whereas Nedbal gave 25 kg (≈245 N) for northern spruce, 30 kg (≈294 N) for scots pine and 41 kg (≈402 N) pressure for beech [31].

3.15. Sachsee (1960)
To eliminate the mistakes of the Büsgen needle test method and the Mayer-Wegelin method, Sachsee performed tests to determine the proper needle geometry and to create a device to be able to make exact measurements. With the device (Strukturprüfer) and the needle made by Sachsee, he did a „structure examination“, which in fact only differed from the Mayer-Wegelin method by its needle geometry. Instead of using a sharp phonograph needle, he used a cylindrical one with a variable diameter of 0.2-0.5 mm [12].

3.15. Doyle (1980) – Wedge hardness
Doyle (1980) performed tests at 20 °C temperature and 55% relative humidity (that is resulted in samples with approximately 13% moisture content) with 5 different loading rates and 10 types of wedges on the radial surfaces of the same wood species with the same density. Doyle proposed the
use of wedges that are longer than the width of the samples. The designed wedges possessed a significant advantage over other tools: even though it may not be possible to establish initial contact across the whole width of the sample, this occurs the increase in area of contact, which is proportional to the increase of the depth of indentation. Moreover, if the principle of geometric similarity exists, the hardness can be calculated from the linear part of the force-penetration plot. The same is true for a slightly blunted wedge [11, 24].

3.17. Piazza, Turrini (1983)
Piazza and Turrini published their method in 1983, which was specially designed to measure structural wood materials on the field [33]. The examination resembles the Janka hardness method modified by Weatherwax, Erickson and Stamm (1948), because during these two methods the value of the hardness - and as Piazza and Turrini stated the modulus of elasticity - is derived from the gradient of the initial linear stage of the force-penetration plot [34, 35].

During the measurement, a 10 mm steel ball is pressed into the wood with a depth of 5mm, determining the force necessary to make the described indentation. The estimated modulus of elasticity can be calculated with the following formula, using the measured force (Equation 7):

\[ E_0 = \frac{\delta A R_0 \delta^5}{C} \text{(N/mm}^2) \]  

where \( E_0 \) is the estimated modulus of elasticity (MPa), \( \delta \) is correction factor (depends on quality), \( A \) is correction factor (depends on wood species and moisture content), \( R_0 \) –is the force needed to indent the ball into the wood (N) and \( C \) is correction factor (depends on moisture content).

The \( \delta \) could be 3 determined value (0.5, 0.68 and 0.8), which is according to the UNI11119:2004 standard and depends on visible failures of wood samples (for example size and quantity of knots, failures of the year-ring structure, cracks). The value of \( A \) is more various, for instance 350 for norway spruce and larch at a moisture content of 12-14% and 263 for chestnut. The value of \( C \) can be calculated from the following formula (Equation 8):

\[ C=1-0.0079 \times \Delta u \text{(N/mm}^2) \]  

where \( C \) is correction factor (depends on moisture content), \( \Delta u \) is difference of moisture contents (%). \( \Delta u \) is calculated from the difference of 15% and the moisture content of the examined sample measured during the test. J. M. Branco, P. J. S. Cruz and M. Piazza (2008) determined, that the Piazza-Turrini hardness values correlate well with the density and can be used to reliably derive the modulus of elasticity [29].

4. Conclusion
We can see, that 5 main type of hardness measuring methods were carried out: ball hardness, cone hardness, needle hardness, wedge hardness and cylindrical hardness. Industrially the mainly used test methods are Janka-hardness and Brinell-Mörath hardness, even if their known deposits, in French the method of Monnin is the standard. All researchers bear a purpose, to work out a method, that comply with the criterion, to rid of mistakes arised from wood anatomy as well as anisotropy. More or less they got across, but we should waiting for the perfect method.

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