Analysis of the influence of surface roughness of various types of wood on the results of their hardness measured by the Leeb method

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Abstract. Determining the hardness in the Leeb scale consists in measuring the velocity of the impact mass before and after hitting the sample. The result is the speed of the impactor shall after the rebound divided by the speed before the rebound (multiplied by 1000). The measured hardness ranges from 0 to 1000 and is largely dependent on the Young’s modulus of elasticity. The article presents the Leeb hardness measurement tests of six various species of wood. The samples were machining before testing in such a way that there were places with different surface roughness on its surface. The research showed the differentiation of the hardness test results for the same tree species depending on the roughness of the surface.

1. Introduction
Wood, as any material, has a multitude of human-defined properties, such as Young’s Modulus, Specific Gravity, moisture content and hardness [1,2]. The hardness of the wood provides the user with information about i.e. machinability or resistance to accidental surface damage, thus being a highly appreciated feedback. A century ago, the hardness was defined by S. Rejtő [3] as “the ability of the material to withstand the penetration of tool”, and while it is oversimplified in the general meaning of hardness of all materials, in the case of wood (scarceley being used as a tool) it provides a nice overview on the machinability.

The timber properties are resultant of combination of interwoven hardwood and sapwood fibers, which configuration varies strongly between species [4]. Engineers and scientists work on different methods to assess those parameters. There exists multitude of approaches in hardness measurement, for instance depending on the usability of specimen after testing (destructive/non-destructive) or depending on the type of output information (relative/absolute) or depending on the duration of the load applied to the sample (static/dynamic). The differing methods of wood hardness testing are shown in a more clear way in the Table 1.

Table 1. Comparison of different approaches to test hardness of a particular material

| Type of approach | Hardness testing | Examples | Distinguishing feature |
|------------------|------------------|----------|-----------------------|
| Basing on duration | Static | Janka index | Destructive, stationary wood |
of load hardness assessment

| of load     | Rockwell          | Vickers          | Small indentations on metallic materials |
|-------------|-------------------|------------------|------------------------------------------|
| Dynamic     | Equotip (Leeb’s)  | Shore            | Non-destructive, portable hardness assessment |
| Basing on the effect on sample after test | Destructive testing (DT) | Janka index | The sample is damaged with visible indentations |
| Non-destructive testing (NDT) | Equotip (Leeb’s) |                  | Small or none indentations remain on the sample after testing |

| Basing on output information | Relative | Mohs scale | Relative hardness of examined minerals compared to particular mineral types |
|-------------------------------|----------|------------|-------------------------------------------------|
| Absolute                      | Janka index |            | Exact values expressed in Newtons |

Usually, the destructive testing methods provide the user with reliable information, however they require specifically prepared samples and – as the name says – the samples are treated as sacrificial. On the other hand, non-destructive testing provides slightly less feasible data, but can be applied “on-the-go” and the tested material or product with small indentations can still be at full value[5].

As regards the timber, the most popular and commercially applied hardness assessment method is Janka test. It is used for over a century [6], initially being a method of evaluation whether particular wood is eligible to be used in flooring. In time, it became a normalized test with its own standard, being ASTM D143[7]. The test itself is based on following principle: a specifically sized cuboid (namely 50x50x70mm) is put under press with pressure gauge and is pressed with a steel ball of 11.28 mm in diameter in such a manner, that the ball is embedded halfway. The resultant indent is a hemisphere, which makes 100 mm² (one square centimetre) in its cross-section. The pressure required to make the indent is multiplied by the aforementioned area and the result is expressed in force in Newtons.

On the other hand, the Leeb rebound hardness test (which is also described in literature as Equotip) is based measuring the coefficient of restitution, namely the loss of the kinetic energy of defined impact body on the tested specimen. The falling impact body rebounds slower from the softer materials and faster from the hard ones [8]. The biggest advantage of examining the hardness with Leeb method is the small amount of time required to perform the test (approx. 2 seconds per singular measurement) and relatively small indentation left on the material surface.

The Leeb method is hitherto used mainly for metallic [9,10] and mineral materials [11,12]. By this time the authors have found no publications utilizing this method to estimate the hardness of timber. There were some attempts to correlate the static and dynamic hardness tests, for instance Meyer et al. performed comparative hardness measurements on 24 different wood species with Brinell method and dynamic methos [13]. In 2012, Vincent M. et al developed a model to establish a connection between nanoindentation and standard Brinell method, however they performed the experiment only on one wood type, namely jack pine [14]. In the beginning of 2021 Koczan et al. made an attempt to unify three scales of hardness: Monin, Brinell and Janka, utilizing Meyers Law. Their effort resulted in a formula to predict Janka index basing on the results of Brinell test [15].

In this paper the authors describe their attempt to measure hardness of six different wood species using the dynamic Leeb Rebound Hardness Tester (LRHT). The wood species utilized in the experiment are divided into two groups – popular European species (Oak, Pine and Beech) and exotic hardwoods (Ebony, Rosewood and Boxwood). The resultant data is compared with values in commonly used
Janka hardness index. The main goal of this paper is to establish whether static and destructive approach in Janka scale can be related to the values of Leeb dynamic and non-destructive approach. Additionally, the Authors will test whether the surface quality affects the outcome of dynamic Leeb testing.

2. Materials and Methods

For the experiment, 6 different types of wood specimens were prepared in form of round bars. Specifically:

- West African ebony (*Diospyros crassiflora*),
- San Domingo Boxwood (*Phyllostylon Brasiliense*),
- Rio Rosewood (*Dalbergia nigra*),
- Beechwood (*Fagus sylvatica*),
- Oakwood (*Quercus robur*),
- Pinewood (*Pinus silvestris*).

Selection of such species was dictated by their country of origin (3 European and 3 exotic species of trees), as well as because of their broad applicability in woodworking industry.

Before measurements each sample was seasoned over one year duration in enclosed area with air average humidity of 45% ± 30% and constant temperature of 20°C ± 3°C. On Fig. 1 it is visible, that all specimens are divided into subzones, with different surface roughness parameters. The subzones were created by turning the bars on Takisawa-Nex 908 CNC turning center, using 4 different cutting tools – pointed straight tool insert (T1), round insert (T2), threadcutting tool insert (T3) and grooving insert (T4).

**Figure 1.** Photograph of specimens used in research - (a) West African ebony, *Diospyros crassiflora*; (b) San Domingo Boxwood, *Phyllostylon Brasiliense*; (c) Rio Rosewood, *Dalbergia nigra* (d) Beechwood, *Fagus sylvatica*; (e) Oakwood, *Quercus robur*; (f) Pinewood, *Pinus silvestris*.

**Figure 2.** Rosewood specimen prepared for measurement with measurement subzones shown.
Processed surfaces prepared for Leeb hardness tests are shown on Fig. 2. Each specimen was cut with 3 different depths of cut ($a_p 0.5 – 1.5$) and with 4 different cutting tools mentioned earlier (T1 – T4), with constant cutting speed of 200 m/min, and feedrate of 0.2 mm/rotation. Prepared surfaces were examined with surface roughness measuring system Mitutoyo Formtracer SV-C3000 with measurement head SV-C4500. Each subzone (for example $a_p 0.5/T3$), was assessed in constant distance intervals with 12 measurement lines, from which arithmetic average roughness ($R_a$) was calculated.

![Figure 3. Leeb E hardness measurement on ebony wood specimen](image1)

![Figure 4. Hardness measurement points distribution](image2)

Each subzone on all 6 prepared samples were then examined to obtain Leeb E hardness of the specimens, using Proceq EquoTip 550 hardness tester with Leeb E measurement head. As visible on Fig. 3, during the experiment, samples were mounted on 2 holders in a stable position. After every hardness trial, the specimen was rotated by hand, to obtain 11 evenly distributed measurement points on the cylindrical surface of the specimen (along the wood fibers). Distribution of measurement points along the surface of sample is schematically shown on Fig. 4. For each wood specimen, total of 132 hardness measurements were done.

3. Results and discussion

The obtained values of arithmetic average roughness $R_a$ and Leeb hardness in this place for different species of wood are shown in the Table 2 as well as in the Figures 5 and 6.

| Species of wood | Cutt. depth, $\mu$m | T1 $R_a$, $\mu$m | Leeb Hardn. | T2 $R_a$, $\mu$m | Leeb Hardn. | T3 $R_a$, $\mu$m | Leeb Hardn. | T4 $R_a$, $\mu$m | Leeb Hardn. |
|-----------------|---------------------|-----------------|-------------|-----------------|-------------|-----------------|-------------|-----------------|-------------|
|                 |                     |                 |             |                 |             |                 |             |                 |             |

Table 2. Leeb hardness values obtained in the test, depending on the type of wood species
West African ebony, Diospyros crassiflora

| Surface Roughness (µm) | Leeb Hardness E (mm) |
|------------------------|----------------------|
| 0.5                    | 4.19                 |
| 1                      | 4.16                 |
| 1.5                    | 5.17                 |

San Domingo Boxwood, Phyllostylon Brasiliense

| Surface Roughness (µm) | Leeb Hardness E (mm) |
|------------------------|----------------------|
| 0.5                    | 6.17                 |
| 1                      | 6.11                 |
| 1.5                    | 6.19                 |

Rio Rosewood, Dalbergia nigra

| Surface Roughness (µm) | Leeb Hardness E (mm) |
|------------------------|----------------------|
| 0.5                    | 5.70                 |
| 1                      | 5.13                 |
| 1.5                    | 5.02                 |

Beechwood, Fagus sylvatica

| Surface Roughness (µm) | Leeb Hardness E (mm) |
|------------------------|----------------------|
| 0.5                    | 10.42                |
| 1                      | 9.77                 |
| 1.5                    | 8.05                 |

Oakwood, Quercus robur

| Surface Roughness (µm) | Leeb Hardness E (mm) |
|------------------------|----------------------|
| 0.5                    | 6.23                 |
| 1                      | 7.59                 |
| 1.5                    | 7.57                 |

Pinewood, Pinus silvestris

| Surface Roughness (µm) | Leeb Hardness E (mm) |
|------------------------|----------------------|
| 0.5                    | 8.97                 |
| 1                      | 8.66                 |
| 1.5                    | 8.67                 |

Figure 5. Average Leeb hardness depending on the surface roughness obtained in tests for exotic wood species.
Figure 6. Average Leeb hardness depending on the surface roughness obtained in tests for European wood species.

The highest dynamic hardness values belonged to the ebony exotic hardwood, ranging from 469.5 to 453 for almost all types of surface, besides the one cut by T4 insert at ap=1.5mm, where the result was 383.9. The least hard material, measured with dynamic method was boxwood (270, T4, \(a_p=1.5\) mm), rosewood (290.6, T4, \(a_p=1.5\) mm) and beechwood (318.2, T4, \(a_p=1.5\) mm). The results do not match the Janka scale, since the pine has second highest hardness of all of the tested specimen, while in static scale it appears as the softest material. The comparison of rebound Leeb hardness (average of all types of surface quality for particular wood type) and Janka hardness values [16] is presented in the table 3.

| Type of the wood | Min. Leeb E | Max Leeb E | Avg Leeb E (+ std dev.) | Janka [N] |
|------------------|-------------|------------|--------------------------|-----------|
| Ebony            | 383.9       | 492.9      | 469.88 (30.21)           | 13 700    |
| Boxwood          | 270         | 384.7      | 349.05 (29.87)           | 8 050     |
| Rosewood         | 290.6       | 411.3      | 366.13 (33.38)           | 12 410    |
| Beechwood        | 318.2       | 397.1      | 363.17 (25.64)           | 6 460     |
| Oakwood          | 330.6       | 440.1      | 389.95 (31.89)           | 4 980     |
| Pinewood         | 290.6       | 411.3      | 391.92 (38.72)           | 2 420     |

Largest relative std. deviation was calculated for pinewood and rosewood (9.88% and 9.12% respectively). At the same time for both of those species, the difference between Janka scale and average of measurements in Leeb scale are most visible – for pinewood – in Leeb measurements it is the second hardest species, while in Janka scale, pinewood is softest of the selection. Rosewood according to Janka hardness, should be the second hardest of the selection, while it is the third softest according to Leeb E experimental results. The difference between the hardest specimen (ebony) and pinewood measured in Leeb E is equal to 16.6%. The difference for those species in Janka is visibly larger, amounting to 82.3%.
4. Conclusions

The method of estimation the wood hardness via Leeb dynamic testing utilized in the current study shown that there are discrepancies in the hardness values between different surface quality of the same type of timber.

While the exotic wood tend to have roughly similar debounce hardness, regardless the R_s parameter, the European species tend to have hardness inversely proportional to the surface roughness.

Pine wood is considered as one of the softest widely applied wood (the authors dismiss i.e. balsa wood as a construction material) and this study shown, that when this type of wood is tested dynamically, the rebound hardness level is almost as high, as the hardness of the ebony wood, being classified as a hardwood.

The Leeb scale of hardness seems to have no connection with the Janka hardness index. Authors do not recommend utilizing the Equotip method for estimating the hardness of timber-related materials.

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