INDENTATION HARDNESS OF WOOD

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ABSTRACT

An historical background to hardness testing of wood is given, and the advantages and disadvantages of the methods used are reviewed. A new method, using a wedge indenter, is suggested and a rationale presented that includes discussion of the deformation patterns beneath indenting tools.

Keywords: Ball, Brinell, cone, cylinder, hardness, Janka, Meyer, Monnin, wedge.

INTRODUCTION

Hardness testing of wood has made little progress since Janka (1906). Although there have been many studies leading to a variety of tests, there are shortcomings with all of them. Furthermore, the various hardness values are not easily comparable one to another and do not allow comparison with those for other materials, where testing procedures have a more rational basis. The wedge test that we advocate does allow for comparison with other materials while also taking account of wood anisotropy.

Hardness implies the ability of a body to resist deformation. In a typical test a hard tool of known geometry is forced into the body, and the hardness is defined as the ratio of the applied force to the size of the indentation. This size depends on whether it is determined under load or on unloading. With elastic materials it is determined under load as there will be little or no permanent deformation, whereas with plastic materials the size of the permanent indentation is measured (Tabor 1951).

With wood there are difficulties in measuring the impression, especially for shallow indentations where the imprint is indistinct. Further, there is evidence of "sinking in" around the edge of the tool as the adjacent material becomes densified and is carried down with the tool, it now being easier to displace the wood lying further away. In consequence, the surrounding densified tissue acts as an enlarged indenter. The effect is particularly noticeable in the fiber direction. Sinking in exaggerates the size of the permanent indentation. However, even if this is allowed for, measuring the size of the recovered indentation is of questionable value.

Wood is a compressible material containing voids, is highly anisotropic, and its elastic modulus to yield stress ratio (E/Y) perpendicular to the grain is low; therefore, recovery is greater in timber (where E/Y lies in the range 20–60) than for metals (where E/Y is between 100 and 1,000) because the strain over which wood deforms elastically is larger than that for metals. Sawada et al. (1955) point out the illogicality that arises if the permanent indentation is used to calculate the hardness of wood, namely that green timber with its greater elastic recovery

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has a smaller permanent indentation and so appears harder than in the dry state; therefore it is preferable to deduce the true contact area under indentation. However, for *routine* testing of wood and wood-based products calculating the contact area from the nominal tool penetration has the advantage of simplicity.

Hardness can be calculated in one of two ways. *Brinell* hardness is defined as the ratio of the applied force to the area of surface contact, whereas *Meyer* hardness is the ratio of applied force to the projected contact area. Thus when a ball is pressed into half its diameter, the area of surface contact is $2\pi r^2$ (r = ball radius) and the projected contact area is πr^2 (Janka 1906). The Meyer hardness will be twice the Brinell value. Meyer hardness is more meaningful (Tabor 1951), since the sum of the resultant horizontal forces over the whole surface of the indentation is zero, while the resultant vertical force is equal to the applied force.

THE CHOICE OF INDENTER GEOMETRY

Ball hardness

The Brinell test is most frequently used in material science. Here, a spherical tool is used to give a small, shallow permanent identation. Janka (1906) had difficulty in accurately measuring the size of any permanent indentation in wood, so he developed his own test in which an 11.28-mm diameter ball is pressed into half its diameter, giving a projected area of contact of 100 mm^2. Today, Janka hardness is simply the applied load (ASTM D 143-52 1981a), although Janka (1906) expressed his results as Meyer hardness (kg/cm^2). There are disadvantages associated with this test: it forms a deep indentation; large side-stresses act upon the ball as it approaches maximum penetration; the test is unduly affected by wood failure, friction, and cleavage. Indeed, dense timbers often split before the ball is fully embedded, and maximum Meyer hardness is achieved early in the test. Similarly, there is little further gain in hardness on drying below 10% as the wood becomes brittle and fails prematurely. However, Janka hardness correlates well with the compressive strength perpendicular to the grain (Lavers 1972).

In both Germany and Japan the standards uphold the Brinell test (Deutsche Industrie Norm C3011 1934, JIS Z 2117 1977). In the latter case a 10-mm ball is embedded to only $1/\pi$ mm ($\simeq 0.32$ mm), giving an estimated curved contact area of 10 mm^2: the size of the indentation is not measured. The small contact area can introduce much variability especially for wide-grained timbers. For this reason Miyajima (1963) preferred a larger 30-mm ball embedded $(5/(3\pi))$ mm ($\simeq 0.53$ mm), giving a calotte surface of 50 mm^2.

Hardness modulus

Weatherwax et al. (1948) describe another procedure using the Janka tool. Initially the applied force increases roughly linearly with penetration. They used the slope of this line to derive a hardness modulus. The hardness modulus, as they define it, is identical to the Brinell hardness and should be recognized as such. The hardness modulus will differ slightly from the Brinell value if the linear part of the plot does not pass exactly through the origin. Lewis (1968) established a constant relation between Janka hardness and this modulus and noted the advantage in determining the Janka value indirectly from a shallow indentation, of the order of 2.5 mm. Although the Brinell hardness is roughly constant during the first 2.5 mm penetration, the Meyer hardness will have risen by almost 30%. This increase reflects the densification of the displaced plug of fiber under the tool and the increasing confinement of this material with penetration. The constant Brinell hardness is fortuitous: the increasing applied force is offset by the increase in area of surface contact relative to the projected contact area. The Brinell calculation masks the true picture; only Meyer hardness offers a meaningful perspective.

Cylindrical tools

In the Monnin test, a 30-mm diameter cylinder is pressed into the wood to a given load. The width of the indentation is measured and the depth calculated from geometrical considerations. The Monnin hardness, the reciprocal of the depth of penetration (AFNOR NF B 51-125 1972), does not vary linearly with Meyer hardness. Indeed, a comparison of Monnin values between woods does not relate to geometrically similar indentations: indentation geometry is a function of both wood density and applied force. It is not easy to measure accurately the width of the indentation (Sunley 1965), and consequently the hardness is subject to greater experimental error than in the Janka test. It would be preferable to measure penetration rather than width. However, the test has merits for high density timbers where the Janka tool induces splitting.

Cone hardness

Kumichel and Holz (1955), using a slightly truncated 53° cone, obtained a more extended scale of hardness with wood density and less variance within sample groups as compared to the Brinell ball. Indeed, Noack and Stockmann (1966) have successfully correlated cone hardness of particleboard surfaces with localized density variations.

Conical or pyramidal indenters differ from spherical and cylindrical tools in two important respects. First the *shape* of the indentation remains the same no matter how deeply indented. Consequently, the stress-strain pattern within the body remains geometrically similar with depth and some plastic flow must occur, even under minute forces. Second, the average strain beneath the indenter is a function of tool angle. With a sharp tool the strains are greater than under a blunt indenter as the displaced material is more strongly confined. Friction at the tool face will also be greater. This concept of geometric similarity is extremely useful, implying that hardness is independent of the depth of indentation, being rather a function of the confining pressure and directly relatable to cone angle. Conical and pyramidal tools give a Meyer hardness that is essentially constant. The projected contact area—and hardness—can be calculated more accurately if the tool has a rounded tip, as in the Rockwell test (ASTM E18-79 1981b). However, there are even greater benefits in adopting wedge tools.

Wedge hardness

A wedge is a two-dimensional analogue of a cone in the same way as a cylinder is to a ball. A wedge has the advantage of geometric similarity whatever the indentation depth, as does a cone, unlike a cylinder or ball. Also, a wedge has an advantage over a cone in that the projected area of contact increases linearly with indentation depth rather than with square of depth. The Meyer hardness of both

TABLE 1. *Hardness—influence of tool geometry.*

Tool	Problems	Advantages	Comments
Janka Ball	Deep indentation. Much damage. Force can fall off with penetration.	Constant depth. Geometric similarity. Size of indent not measured.	Hardness should be based on projected area of contact and expressed as Meyer hardness.
Brinell Ball	Hard to measure size of permanent indentation, especially for large balls.	Shallow indentation. Little wood failure. Better for high density woods than is the Janka.	Prefer geometrically similar indentations and calculating Meyer hardness.
Ball Hardness Modulus		As for Brinell balls. Linear force/penetration slope (*where observed*) easy to determine. Size of indent not measured.	No more meaningful than Brinell hardness. Linear force/penetration relation is fortuitous.
Cone	Force increases as square of penetration. Cones are not mathematically sharp.	Geometrically similar indentation requiring only small penetration.	A truncated cone or Rockwell tool is best. Sensitive to changes in density, giving extended hardness scale. Hardness increases as cone angle decreases.
Monnin Cylinder	Hard to measure indentation width. Specimen ends lift off base and exaggerate width. Analysis of eccentric contact is hard.	As for Brinell balls. Large contact area so averaging out localized density variations.	As for Brinell Balls. But no side shear as with balls and cones. Can investigate anisotropy. Test indents on radial face only. Monnin and Meyer hardness not linearly related.
Wedge	Wedges are not mathematically sharp. Initial contact may occur on one edge of the specimen before the other.	Force/penetration slope is linear once full contact occurs across the surface. Indentation shallow and geometrically similar.	As for Monnin cylinder. Hardness varies with wedge angle.

wedge and cone is a function of tool angle as this determines the degree of confinement of the wood tissue.

Doyle (1980) advocated the use of wedges that are longer than the specimen width. Such a wedge possesses a significant advantage over other tools: even though it may not be possible to establish initial contact across the entire width of the specimen, once this occurs the increase in area of contact is directly proportional to the increase in indentation depth. Further, if the principle of geometric similarity holds, the hardness can be calculated from the linear part of the force-penetration plot. The same should be true for a slightly blunted wedge.

The wedge, like the cylinder, can be used to examine aspects of wood anisotropy. We advocate indentation on the radial face only, with the tool edge lying parallel to the radial direction—as for the Monnin test. This is preferred to loading on

TABLE 2. *Meyer hardness (a) and its first order derivative (b), (dF/dA), of* Podocarpus dacrydioides *(20 C 50% RH) as a function of penetration and tool geometry. Indenting @ 0.5 mm/min.*

Depth mm	Janka D = 11.28 mm	Monnin* D = 30.0 mm	136° Cone†	136° Wedge*	60° Cone†	60° Wedge*
(a) Meyer hardness, F/A (N/mm^2)						
0.05	10.6	—	24.9	16.4	—	50.2
0.1	11.4	4.5	19.2	16.4	63.2	50.2
0.15	12.4	6.9	18.2	16.2	59.9	49.3
0.2	12.2	8.1	17.7	16.1	52.6	48.3
0.4	13.6	11.1	16.9	16.0	42.5	45.6
0.8	15.2	13.2	16.2	15.8	35.9	42.5
1.2	16.5	14.6	16.3	15.5	34.0	41.1
1.6	17.5	15.3	15.5	15.3	32.1	39.2
2.0	17.9	16.0	15.3	15.3	30.3	37.7
2.4	18.4	16.6	14.9	15.2	30.6	36.6
2.8	19.4	16.9	14.5	—	30.7	35.9
(b) (dF/dA), (N/mm^2)						
0.0–0.05	10.6	4.5	24.9	16.4	63.2	50.2
0.05–0.1	13.0	4.5	17.3	16.4	63.2	50.1
0.1–0.15	14.5	11.3	17.5	15.8	52.2	47.[illegible]
0.15–0.2	11.7	13.6	16.9	15.9	36.5	45.[illegible]
0.2–0.4	14.9	16.7	16.6	15.9	36.1	43.0
0.4–0.8	17.0	17.8	16.0	15.5	32.7	39.4
0.8–1.2	19.3	20.7	16.3	14.9	32.2	38.4
1.2–1.6	21.2	19.7	14.6	15.0	29.3	33.5
1.6–2.0	19.8	22.4	14.8	15.0	26.9	31.8
2.0–2.4	22.1	23.3	14.1	14.9	31.2	31.1
2.4–2.8	28.3	21.6	13.4	—	31.0	31.8

† Adjusted for dulling of cone tool.
* Adjusting for slight eccentric contact.

the tangential face where the indenter penetrates alternate layers of earlywood and latewood, and the principle of geometric similarity cannot hold even for wedges and cones.

Table 1 summarizes the advantages and disadvantages of certain tools and notes the particular merits of wedge indenters.

Hardness and tool geometry

Table 2 sets out the nominal hardness of *Podocarpus dacrydioides* (A. Rich), a medium-density, uniform-textured New Zealand softwood, under various tools as a function of penetration calculated from the point of initial contact. With spherical and cylindrical tools under very small loads, the surface is deformed elastically, followed by a transition region and then by the onset of full plasticity (Tabor 1951). The Meyer hardness increases rapidly with penetration reflecting the early transition to full plasticity and goes on increasing as the deformed wood becomes increasingly confined and densified. In contrast, hardness with cones and wedges initially decreases with penetration. When geometrically similar indentations are compared, hardness values are broadly similar. There is a slight increase in going from ball, to cylinder, to cone, to wedge tool of the same occluded angle—not altogether unexpected as the displaced wood is more heavily confined and compressed under a wedge than under a ball.

Hardness values calculated from force-penetration data over the first 0.5 mm or so can be liable to error. Cones and wedges are not mathematically sharp, while cylinders and wedges can make eccentric contact. Table 2 includes adjustments for these factors which were determined by microscopic examination. Two observations arise. The first order derivative of Meyer hardness is less sensitive to errors in determining initial contact. Second, there is a real decline in hardness, with increasing penetration for cones and wedges, contrary to what one might have expected from the idea of geometric similarity. This is especially noticeable for the 60° tools. Two factors contribute to this: gross failure of the wood and strain rate.

Gross failure.—Indentations can only be geometrically similar if indenter geometry is the same and if the material is homogeneous. Fractures or checks forming in the wood during indentation at *specific* locations no longer allow one to consider a deep indentation as being merely a magnified version of a shallow one. Wood failure is frequently encountered with sharp tools so one would expect the drop in hardness with penetration to be more noticeable for the 60° cone and wedge than for the 136° tools, as indeed we observe.

There is no visual evidence for cutting of fibers or of wood failure during the first 0.1 mm or so penetration, even with the 60° wedge, and the initial hardness is high (Table 2). Beyond this point, severing of the fibers is observed and hardness declines. In some samples, there is local failure and splitting behind the cutting edge. With the blunter 136° wedge, there is never any cutting at the tool edge, and tensile failure/fracture—which is generally parallel to the specimen surface—has limited effect as the principal mode of deformation is that of radial compression and crushing. While cutting and failure may account for the rapid decline in hardness with sharp tools, further explanation is needed for blunt tools.

Strain rate.—Even perfect elastic behavior of wood under low stresses is something of an illusion, due to limitations in experimental methods: time-dependent processes occur (King 1961), albeit their contribution to the total strain response may be very small. Under larger stresses, visco-elastic flow can contribute significantly to total strain. The physical picture is one of rearrangement in hydrogen bonding and molecular conformation of wood elements so as to reduce the applied stress. Local adjustments occur more easily than those involving longer range interactions: this generates a spectrum of relaxation times over which adjustments occur. High temperatures (more thermal energy), high stresses (to drive such readjustments), and high moisture content (water acts as a molecular lubricant) all enhance the rate of visco-elastic deformation.

During indentation the fibers are subject to varying stresses depending on their location. Fibers near the tip of the indenter experience the highest stresses, whilst those further away are only lightly stressed. Further, the magnitude of these stresses depends on the rate of penetration: visco-elastic deformation is continuously redistributing and dissipating these stresses. The degree to which this is achieved depends on the interrelationship between loading rate and indentation time. Not only should indentations be geometrically similar, but the wood should experience the same stress-strain history if the hardness is to be the same. Wood is harder and more resistant to penetration under higher loading rates: there is less time for stress relaxation. Both Meyer hardness and its first order derivative show an increase in hardness with loading rate for all tools (Table 3), whilst they both

TABLE 3. *Effect of loading rate on Meyer hardness $(F/A)_{1kN}$ and its first order derivative $(dF/dA)_{1kN}$ in N/mm^2. Indenting 20 × 20 mm section specimens.*

Loading rate	60°	90°	105°	120°	136°	150°	160°	170°
			Wedge angle					
(a) Meyer hardness, $(F/A)_{1kN}$								
5 mm/min	36.3	31.7	24.5	19.2	14.7	13.3	11.3	10.2
1 mm/min	34.4	27.8	22.9	18.8	15.9	12.6	10.8	8.5
0.5 mm/min	33.8	24.5	18.0	14.8	13.7	9.6	8.6	7.2
			Wedge angle					
(b) $(dF/dA)_{1kN}$								
5 mm/min	33.8	28.2	22.2	18.5	14.8	13.9	11.4	11.4
1 mm/min	29.8	25.8	21.3	17.4	15.2	13.5	11.3	9.7
0.5 mm/min	27.8	21.5	16.6	13.5	13.2	10.0	9.4	7.4

decrease with increasing penetration for wedges (Table 2). Murase and Ota (1972) have noted the same effect when indenting with balls at various cross-head speeds from 0.5 to 100 mm/min to a constant 10 kg load.

Of some curiosity is the apparent increase in hardness with penetration for the 150° to 170° wedges, such that $(dF/dA)_{1kN}$ is invariably greater than $(F/A)_{1kN}$. Obvious contributing factors such as machine stiffness, settling of the specimen, and eccentric contact were adjusted for or avoided (by holding samples under restraint and by accurate alignment). The average difference between the $(F/A)_{1kN}$ and $(dF/dA)_{1kN}$ values would be eliminated if the depth of indentation were 0.02 mm less than that assumed, thereby raising the $(F/A)_{1kN}$ hardness by a corresponding amount. Sinking in may be responsible.

SUMMARY

Procedures for hardness testing of wood differ from those used with other materials, and have a less rational basis. Of the tools considered, the wedge offers particular advantages. The results obtained are comparable to those from ball tests: in both cases indentations can be quite shallow. Hardness is a function of indenter geometry; elastic, radial compression, failure, shear and fiber cutting become in turn significant as the tool becomes progressively sharper. The principle of geometric similarity is established in general terms though modified to a degree by the effect of loading rate and time (depth of indentation). The application of wedge hardness testing to wood is recommended with the adoption of a 136° tool giving a good approximation to a linear force-penetration plot. Here, radial compression and densification appear to be the principal modes of deformation.

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