Holz als Roh- und Werkstoff 58 (2000) 91–95 © Springer-Verlag 2000

Influence of grain angle on Brinell hardness of Scots pine (*Pinus sylvestris* L.)

H. Holmberg

Brinell hardness has been measured on wood surfaces of Scots pine (*Pinus sylvestris* L.) at various angles to the grain. Results show that hardness is highly dependent on grain direction. The hardness value of a radial surface; i.e. when load is applied in tangential direction, is about half of the end–grain surface hardness. For angles between 0 and 90°, hardness measurements are well described by Hankinson's formula. The relation between hardness and density at each load direction has also been studied.

Einfluß des Faserwinkels auf die Brinell-Härte von Kiefernholz

Die Brinell-Härte wurde auf der Oberfläche von Kiefernholz (*Pinus sylvestris* L.) unter verschiedenen Winkeln zur Faser gemessen. Die Ergebnisse zeigen, daß die Härte stark von der Faserrichtung abhängt. Die Härte in radialer Richtung, d.h. wenn die Last in tangentialer Richtung aufgebracht wird, beträgt nur etwa die Hälfte des Wertes, der an Hirnholz gemessen wird. Für Winkel zwischen 0 und 90° werden die Meßergebnisse gut durch die Hankinson-Formel wiedergegeben. Die Beziehung zwischen Härte und Dichte für jede Lastrichtung wurde ebenfalls untersucht.

1 Introduction

The hardness of a wood species can sometimes restrict its commercial application. For example, by tradition, the end grain surfaces of wood have been used for situations of wear and abrasion, such as factory floors (Gäumann, 1943). It is well known that the cross section of wood is harder than radial- and tangential sections (e.g. Mörath, 1932).

Many reports (e.g. Wood handbook, 1987) give hardness values for end- and side surfaces, often without differentiating between radial and tangential surfaces. Mörath (1932), however, presented hardness values for radial-, tangential- and cross sections. He found that the difference in hardness between, cross- and side sections decreased with increasing density (Mörath, 1932). In addition, several authors have reported a linear relationship between hardness and density (Kollman and Côte, 1968; Miyajima, 1963; Ylinen, 1943).

Surface hardness measurements of wood have been described by several authors (Brinell, 1900; Janka, 1906a, b; Mörath, 1932; Kollman and Côte, 1968; Trendlenburg, 1933). Several investigations have shown the influence of different material parameters on wood hardness, such as wood species, density, moisture content as well as variations resulting from different measuring techniques.

A summary of the different techniques used to measure the hardness of wood are outlined in Table 1. The methods can be divided in two groups according to the relationship between applied force and indentation. One group is characterised by measuring the applied load nessecary to indent a tool with specified geometry into wood up to a given depth, e.g. the Janka method. The other group is characterised by measuring the size of indentation using a specific tool and specified load e.g. Brinell method. Hardness measuring methods can also be categorised according to the shape of the tool used for wood indentation, such as balls, cylinders, wedges and needles. See also Table 1 (Curtu and Ghelmeziu, 1984; Doyle and Walker, 1984). The most common tool used is the steel ball in both the Brinell- and Janka-methods.

Common problems when measuring the hardness of wood are strain and compression. Both phenomena are dependent on the tool used for indentation. When using tools with the shape of a wedge, cone or pyramid, the strain is independent of the depth of the indentation (Johnson, 1970). Compression is always present when measuring hardness and causes an increasing zone of compressed wood beneath the tool (Doyle and Walker, 1984; Ylinen, 1943). The size of the compressed zone is dependent on the tool shape and causes different resistance against indentation for different tools.

Around an indentation on a wooden surface produced by a load applied in radial or tangential direction, a phenomena called "sinking in" can be observed (Doyle and Walker, 1984). "Sinking in" causes problems in determining the actual size of the indentation when using area as a measure of indentation. Therefore, problems exist to give precise values of hardness since all values are theoretically based upon an indentation with a geometry that precisely matches the tool.

2 Materials and methods

2.1 Materials

The material used in this investigation was taken from 17 quarter sawn boards of Scots pine (*Pinus sylvestris* L.). The boards where cut and planed to 55 × 55 mm cross

H. Holmberg
Royal Institute of Technology
Manufacturing Systems, Wood Technology and Processing
SE-100 44 Stockholm

Table 1. Examples of the different methods used for hardness testing of wood, the indentation tools and type of measurements made
Tabelle 1. Beispiele für verschiedene Methoden zum Prüfen der Härte des Holzes, für die verwendeten Werkzeuge und die Art der Messungen

Method	Shape of tool							Measuring	
	Ball	Cylinder	Wedge	Prism	Cone	Nail	Needle	Area	Force
Brinell	x							x	
Janka	x								x
Stamer	x								x
Krippel	x							x	
Chalais Meudon		x						x	
Hoeffgen				x					x
Büsgen						x			x
Hoppler					x			x	
Doyle Walker			x					x	x
Meyer Wegelin							x		
Monnin		x						x	

sections and cut into 77 pieces with a length of 600 mm. These 600 mm pieces, without knots and other structural defects, were cut at different angles, (θ) to achieve seven specimens with an interval of 15° in every section (Fig. 1). The thickness of the specimens was 20 mm. When the cutting angle was 0°, the surface of the specimen was radial. In the same way when the cutting angle was 90° a cross section was achieved. Before measuring hardness, all specimens were conditioned at 20 °C and 65 % RH for a period of four weeks.

2.2
Methods

2.2.1
Specimens

From each sample with 0° cutting angle, a specimen was taken to measure density. All density values were based on dry weight and volume.

The width of annual rings were determined on the same samples as used for density measurements.

On all specimens hardness was measured at five points, located on two diagonals across the surface (Fig. 2). Cutting an originally square piece of wood with a different angle resulted in specimens with rectangular and wedge shaped parts at the ends, (Fig. 1). In order to prevent tilt during measurements the diagonals were centred over the rectangle between the wedges. The first indentation was made at the centre of the specimen and the others were placed symmetrically around the centre at a given distance.

2.2.2
Hardness measurements

In the present investigation, hardness was measured according to Brinell (Brinell, 1900; Mörath, 1932) with one exception. Here, the diameter was measured only in the radial direction. When performing hardness measurements on wood, there is a problem with elliptical indentations caused by “sinking in” in the fibre direction (Doyle and Walker, 1984). In order to reduce this problem, the measurements were done on the minor axis (radial direction) of the ellipse for all indentations. All measurements were done using a steel ball of 10 mm diameter and load of 490.5 N. Brinell hardness is given by the formula (1)

$$H_B = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})} (\mathrm{N/mm^2}) \qquad (1)$$

Where F (N) is applied load, D (mm) the diameter of the steel ball, d (mm) the diameter of indentation.

The angle, φ, between the load and fibre direction varied between 0 and 90°, i.e. φ = 0° corresponds to longitudinal load and φ = 90° load angle corresponds to tangential load (Fig. 3). Between 0 and 90° the angle of

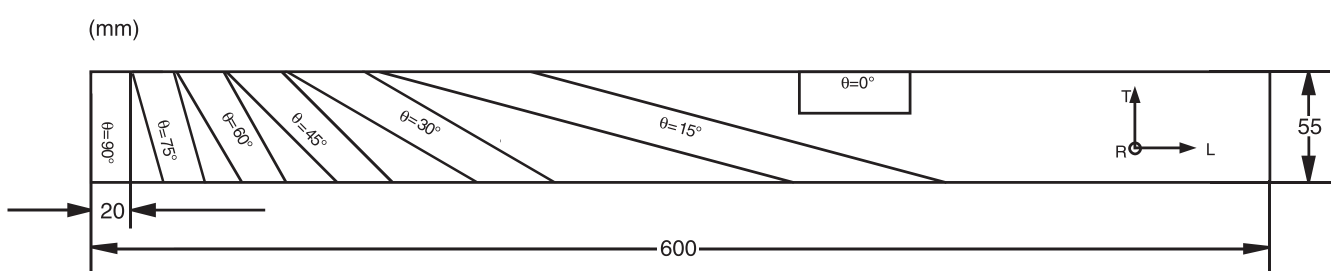

Fig. 1. The specimens were cut from 600 mm long boards with 15° change in cutting angle, (θ). When the cutting angle was 90° the specimen achieve a cross section. When the cutting angle was 0° the specimen was in radial section. In the figure T, R and L indicates the tangential, radial and longitudinal directions

Bild 1. Die Proben wurden aus einem 600 mm langen Brett geschnitten. Die Schnittwinkel (θ) unterschieden sich um jeweils 15 Grad. 90 Grad entspricht einem Querschnitt. Bei 0 Grad liegt ein Radialschnitt vor. T, R, L bedeuten tangential, radial, longgitudinal

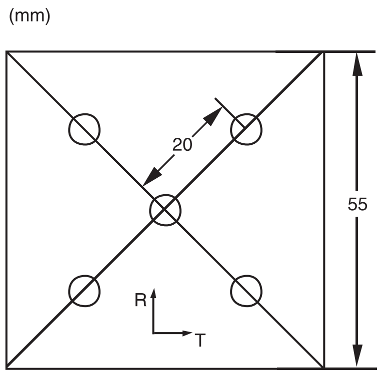

Fig. 2. Location of the indentations for hardness measurements. The first indentation was located at the centre of the specimen and other indentations were located symmetrically around it
Bild 2. Eindruckstellen für die Härtemessung. Der erste Eindruck erfolgte in Probenmitte, die übrigen wurden symmetrisch um diese Stelle herum angeordnet

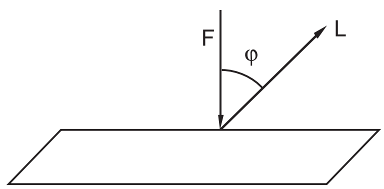

Fig. 3. Direction of loading, (φ), against the fibre direction. When φ = 0° the load is applied in longitudinal direction and when φ = 90° the load is applied in tangential direction and across the fibre axis
Bild 3. Winkel der Lastaufbringung (φ) zur Faserrichtung. Bei φ = 0 Grad wird die Last longitudinal aufgebracht, bei 90 Grad tangential und quer zur Faser

load was applied at intervals of 15°, and totally 7 different load cases were performed (Fig. 1).

Immediately after indentation, the surface was blackened with graphite to enhance the contrast between the area of indentation and wood surface. This was followed by measuring the indentation diameter using a magnifying glass equipped with a scale of 0.1 mm.

3 Results and discussion

3.1 Materials

Table 2 shows some characteristics of the wood specimens used. The specimens had a density ranging between 354–682 kg/m^3, and normal distribution with an average value of 499 kg/m^3. The annual rings had an average width of 1.8 mm with a minimum value of 0.8 mm and maximum value of 3.0 mm. The average values of both density and annual ring width are typical for Scots pine (Boutelje and Rydell, 1989).

Table 2. Density and the width of growth rings for the specimens used in the investigation
Tabelle 2. Dichte und Jahrrringbreite der untersuchten Proben

	Average	Max	Min
Density (kg/m^3)	499	682	354
Annual ring width (mm)	1.8	3.4	0.8

3.2 Hardness

Figure 4 shows average hardness values as a function of angle between loading direction and fibre direction. Hardness decreased from 49 N/mm at 0° (cross section) to ca 20 N/mm at 90° (radial section). The decrease in hardness was greatest between 15 to 45°, while there was no noticeable difference at angles between 75 and 90°.

$$HB(\varphi) = \frac{HB_0 \cdot HB_{90}}{HB_0\ \sin^n(\varphi) + HB_{90}\ \cos^n(\varphi)} \quad (2)$$

A modified version of Hankinson's formula (Hankinson, 1921; Kollmann and Côté, 1968) Eq. (2) has been used as a model to describe the Brinell hardness in Fig. 4. HB_{90} and HB_0 denote boundary hardness values when the load is applied at 90 and 0° respectively. The average values from the investigation have been used for HB_{90} and HB_0. φ is the angle of the load direction. The factor n is derived using the least square method comprising all measured indentations and was found to be 1.98.

It can be seen that there is a fairly good agreement between the measured values and Hankinson's formula as shown in Fig. 4. The decrease in hardness was more pronounced for load directions close to the fibre direction than for loads applied across the fibres. However, when comparing the results for each load case, there were

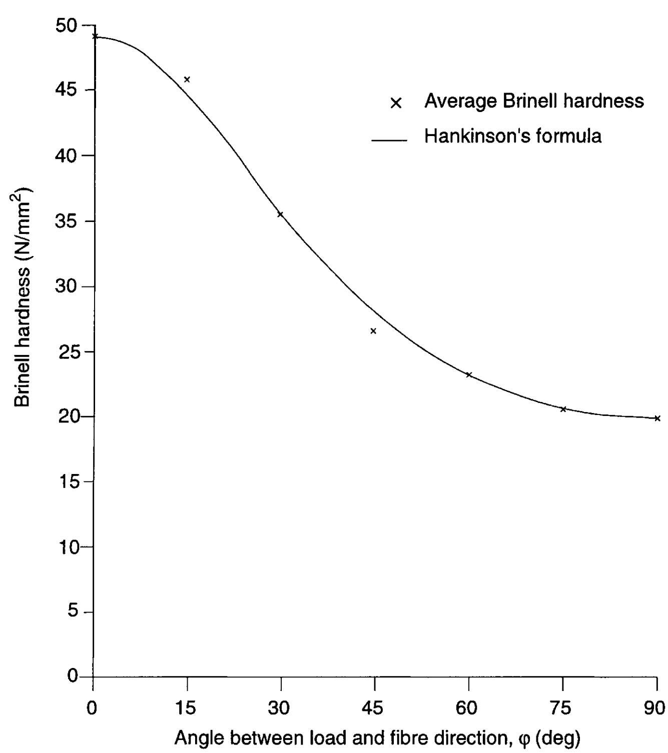

Fig. 4. Hardness vs. angle between load- and fibre direction. Each point represents an average of 385 indentations made on 77 specimens
Bild 4. Beziehung zwischen der Härte und dem Winkel zwischen Last- und Faserrichtung. Jeder Punkt stellt den Mittelwert aus 385 Eindrücken an 77 Proben dar

significant differences between each group at the 95 % confidence limit.

Increasing the load angle results in a considerable drop of hardness between 15 to 45°. This may be related to a combined effect of the amount of load carrying fibres and their stiffness. When the load is applied parallel to the fibre direction, it is spread over several fibres which are very rigid. However, when the load is applied at an angle to the grain, the amount of fibres carrying the load and their stiffness are lower than in the fibres direction.

Hardness measurements in this investigation are based on measuring the minor axis of the indentation to exclude subjective decisions involved in measuring the major axis, as a result of "sinking in", in the fibre direction. Since "sinking in" is much less across the fibres, this diameter was used for calculating Brinell hardness. If the major axis of the elliptical indentation would be included in the measurements, the difference between the end grain section and the radial section would be more pronounced since the elliptical nature of the indentation is more noticeable at larger angles between load and fibre direction.

As seen in Fig. 4 using a 30° load angle, the Brinell hardness was still about 70 % of the true cross section and shows about 50 % higher value in hardness, than the radial surface.

Figure 5 shows the average Brinell hardness plotted against density for each specimen, and for each loading angle the linear regression curve is drawn. As shown, the influence of density is more pronounced for decreasing angles between load- and fibre direction. Figure 5 also shows large changes in hardness for angles between 15 and 45°, as observed in Fig. 4.

As seen in Fig. 5, there is a fairly good correlation between density and hardness at certain load angles, although there is a better correlation for large load angles than for narrow ones. The coefficient of regression was between 0.70 and 0.77 for angles between 45 and 90° and 0.47 and 0.65 for angles between 0 and 30°.

It can be assumed that the difference between earlywood and latewood is more pronounced when the load is applied along the fibre direction rather than across the fibres, and thereby the greater difference is reflected as a smaller coefficient of regression. When loading along the fibres the load is close to ideally be absorbed by latewood if a latewood ring is in contact with the steel ball. When the load is applied across the fibre, it is absorbed by fibre walls bending into lumen and thereby giving a chance for the material to deform and become densified more smoothly than when the load is applied in the grain direction.

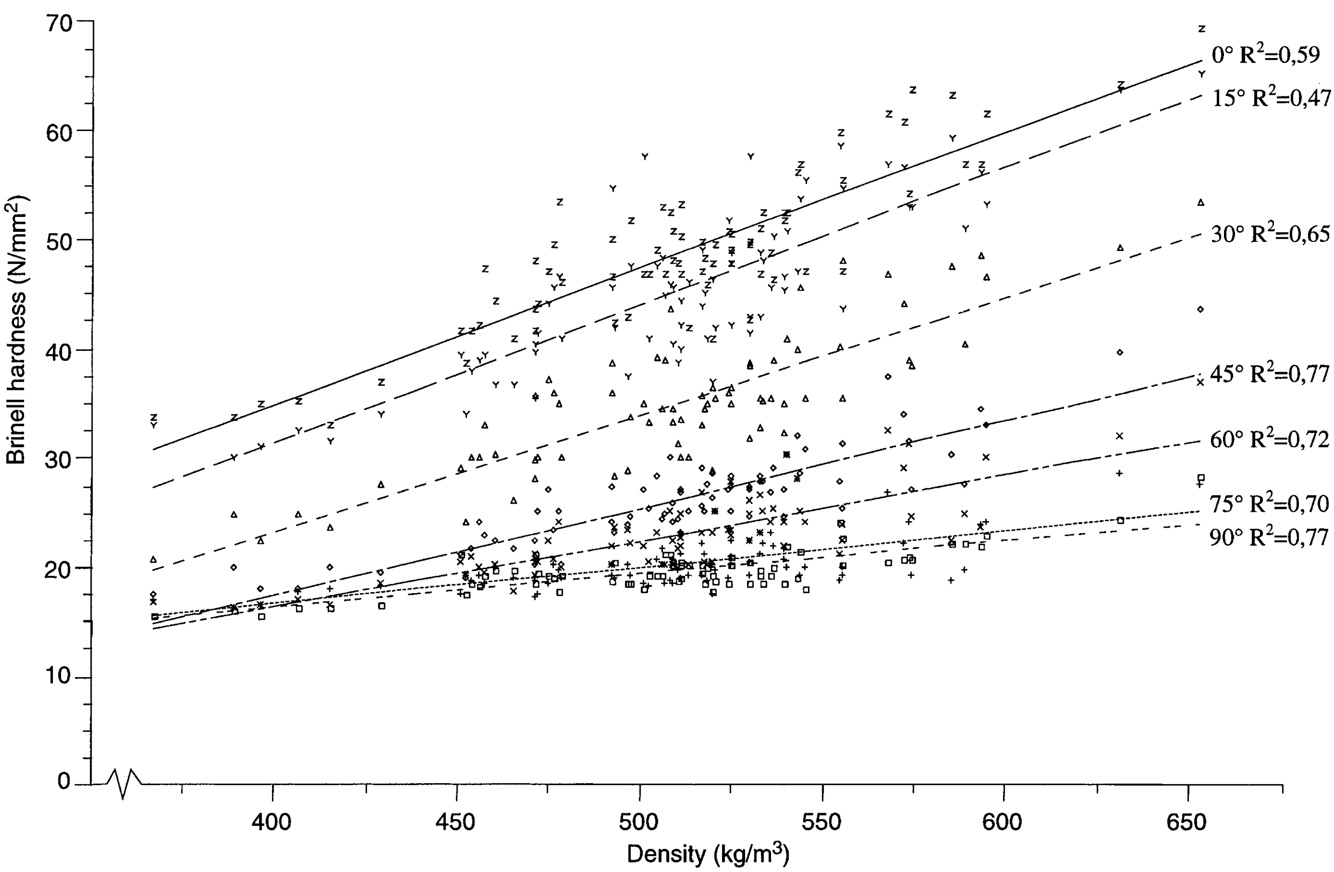

Fig. 5. Brinell Hardness vs. density with linear regression curves for each load angle. Each point is an average of five indentations made on each specimen. The cutting angle φ is denoted as: Z = 0°, Y = 15°, Δ = 30°, ◇ = 45°, X = 60°, + = 75°, □ = 90°

Bild 5. Beziehung zwischen Brinell-Härte und Dichte mit linearen Regressionen für jeden Winkel. Jeder Punkt entspricht dem Mittelwert aus 5 Eindrücken an jeder Probe. Der jeweilige Schnittwinkel φ ist folgendermaßen bezeichnet: Z = 0°, Y = 15°, Δ = 30°, ◇ = 45°, X = 60°, + = 75°, □ = 90°

As shown in Fig. 5 there was an interval, between 15 and 45° where the influence of density increases very rapidly. This implies that for load angles below 45° there would be more pronounced advantages of selecting high density timber than for larger load angles.

4 Conclusions

Brinell Hardness measured by loads applied at angles between 0 and 90° against the wood grain direction show a great dependency on the load direction.

Brinell Hardness, for loads applied across the fibre axis (90°), and in tangential direction are about half the hardness of the end grain surface (0°). When the angle between the load and grain direction increases, hardness decreases. For load angles between 30 and 45°, the change in hardness is more pronounced compared with other angles. The predicted hardness for different load angles can be well described using Hankinson's formula.

The measurements of Brinell Hardness at different load angles have shown that the influence of density on hardness was more pronounced for load angles less than 45° than for those closer to 90°.

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