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ORIGINAL ARTICLE

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Hardness distribution on wood surface

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Abstract For better understanding wood hardness, we developed a new hand-operated hardness tester that works with Brinell's method. With this tester we investigated the hardness distribution of wood minutely using a 2mm diameter ball tip. The following results were obtained: (1) On preliminary examination with medium-density fiberboard, we found that the value of Brinell's hardness decreased with the increase in the tip ball's diameter but that it was almost constant with the indenting velocity. (2) By using a small diameter tip, the difference of the hardness became clearer between earlywood and latewood. (3) With radial and tangential sections, we obtained hardness distribution patterns similar to those of wood grain. It seems that the hardness distribution reflects the distribution of density on wood surfaces.

Key words Brinell's hardness · Ball diameter · Handy-type tester · Two-dimensional distribution

Introduction

Hardness of wood has a good relation with its various mechanical properties.[1] For this reason, hardness is important as one of the main indices of wood quality. The merit of the hardness test is that we need only small test pieces and a rather simple testing machine. Hardness has been mainly used to indicate the average quality of tested materials. We thought that the properties of wood would become clearer and the new feature of wood would become apparent if the hardness distribution of wood is known in detail. For this purpose, we developed a new handy hardness tester that was equipped with a small diameter indentation tip and investigated the two-dimensional hardness distribution of wood minutely.

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Preliminary experiment and producing a handy hardness tester

Examination on the effect of ball diameter

The testing method employed by ISO 3350-1975 is Janka's hardness. With Janka's hardness, a steel ball of 11.284mm diameter is indented into a test piece to the depth of the hemisphere (the projection area is $1\,cm^2$). The applied load gives the value of the hardness. This method is not adequate for examining the hardness distribution of wood surface minutely.

In Japanese standard (JIS Z 2101-1994),[2] Brinell's hardness is employed. Brinell's hardness H_B (kgf/mm^2) is given by the following equation.

$$H_B = \frac{P}{\pi D h} \quad (1)$$

where D (mm) is the diameter of the steel ball, h (mm) the depth of indentation, and P (kgf) the applied load. In JIS, a ball diameter of 10mm and an indenting depth of $1/\pi$mm (about 0.32mm) are specified.

To obtain the minute hardness distribution of wood surface a smaller ball diameter is required. On the other hand, if the ball diameter is too small, the indenting depth is too small and the measurement is influenced easily by the surface roughness. Therefore, the effect of the ball diameter was first examined using Brinell's method.

The experiment was done with a universal testing machine (NMB TCM-5000C). Steel balls of 2, 2.5, 3, 5, and 10mm diameter were indented to $2/\pi$mm (about 0.64mm),

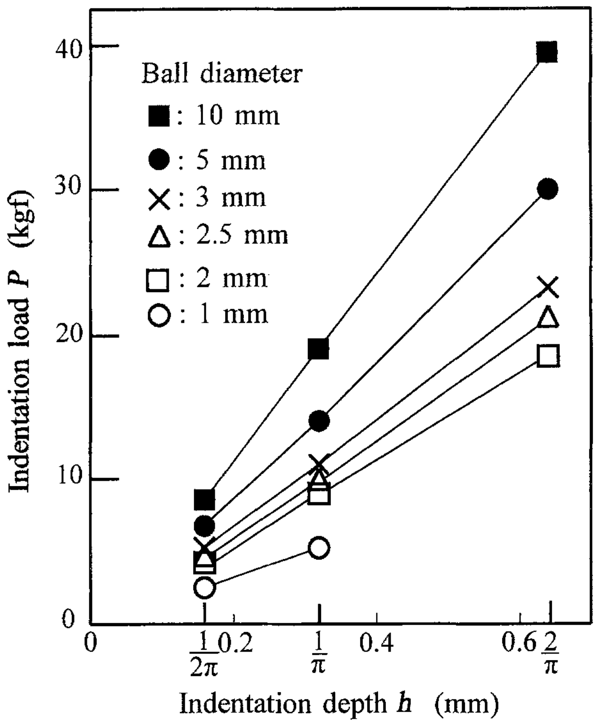


Fig. 1. Relations between indentation depth of steel ball and indentation load for medium-density fiberboard (MDF)

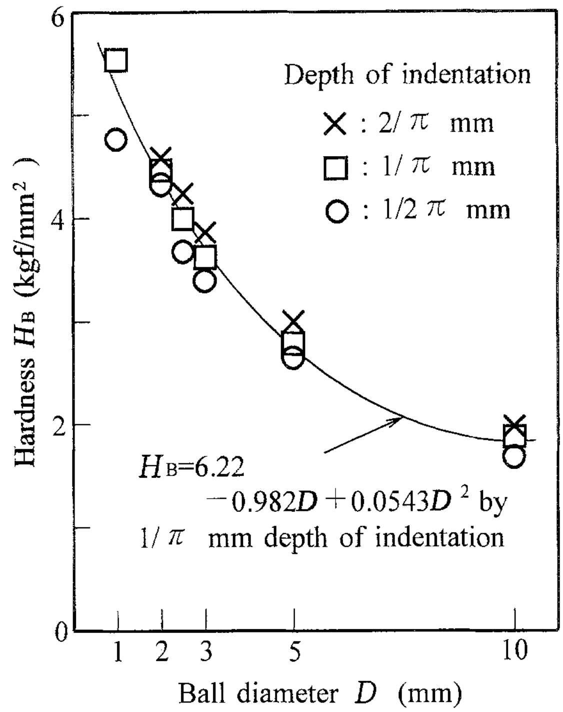


Fig. 2. Relations between ball diameter and Brinell's hardness for MDF. Indentation velocity of the steel ball is 0.5 mm/min

and a steel ball of 1 mm diameter was indented to $1/\pi$ mm. In this experiment, the test specimen should be homogeneous. Therefore, a medium density fiber board (MDF) (thickness 15 mm, density $0.64\,g/cm^3$) was used as the material for the test block. The indenting velocity of the steel ball was 0.5 mm/min.

Figure 1 shows the relations between the indentation depth and the indentation load with the various ball diameters. Each datum is the mean of six measurements. We can see that the indentation load is almost proportional to the depth h, and the required load to indent a constant depth becomes smaller for smaller diameter balls. Figure 2 shows the relation between the ball diameter and Brinell's hardness. We can see from this figure that the value of Brinell's hardness is affected by the diameter of a ball used as the plunging tip, although the effect of the indenting depth is not as large. Hence we thought that a small diameter tip is usable for measuring hardness; and if it is necessary to compare the hardness values with the JIS defined ones, we can use the regression curve indicated in Fig. 2.

Based on the regression curve in Fig. 2, the hardness obtained by a small diameter ball tip under $1/\pi$ mm indentation depth h could be converted to the JIS $H_{B(10)}$ (kgf/mm^2) value with the following formula.

$$H_{B(10)} = \left(0.237 + 0.0957D - 0.00191D^2\right)H_{B(D)} \qquad (2)$$

where D (mm) is the diameter of the steel ball, and $H_{B(D)}$ (kgf/mm^2) is Brinell's hardness when the ball diameter is D.

Examination on the effect of the indenting velocity

The indenting velocity defined by JIS is 0.5 mm/min on average, and it requires about 38 s to the depth of $1/\pi$ mm. Many measurement points are required to measure hardness distribution, and this method takes too much time. Furthermore, it is not possible to control the indenting velocity at such a low level by hand power. Therefore, we examined the effect of the indenting velocity on the hardness value. The material used and testing equipment are the same as described in the preceding section. Five different diameter balls were indented at velocities of 0.5, 1, 2, 5, and 10 mm/min. Brinell's hardness was calculated when the indentation depth equaled $1/2\pi$ (about 0.16 mm), $1/\pi$, and $2/\pi$ mm (the last condition was omitted for the 1 mm diameter ball).

Figure 3 shows the relations between the indenting velocity and Brinell's hardness. From this figure, we can see that the value for Brinell's hardness changes with the indenting velocity for the ball of 1 mm diameter, whereas it is almost constant for those more than 2 mm diameter. Therefore, we thought it convenient to drive the plunging part under hand control. In the following experiments, we employed the mean indenting velocity of 2 mm/min, which is roughly controllable by hand.

Outline of our handy Brinell's hardness tester

Based on the results obtained by the above-mentioned examinations, we developed a handy-type Brinell's

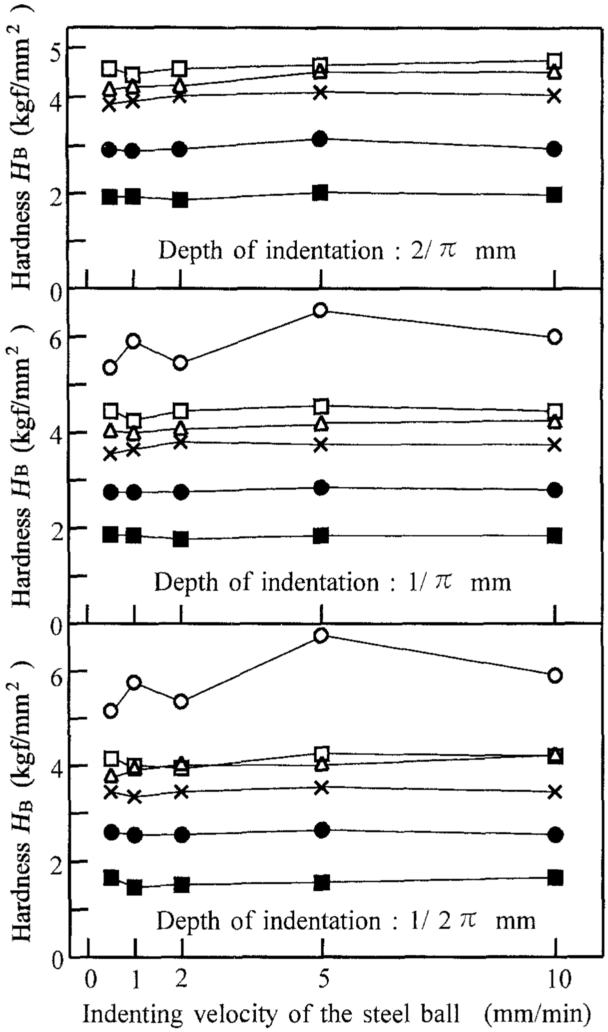


Fig. 3. Relations between indenting velocity of the steel ball and Brinell's hardness for MDF. Symbols are the same as in Fig. 1

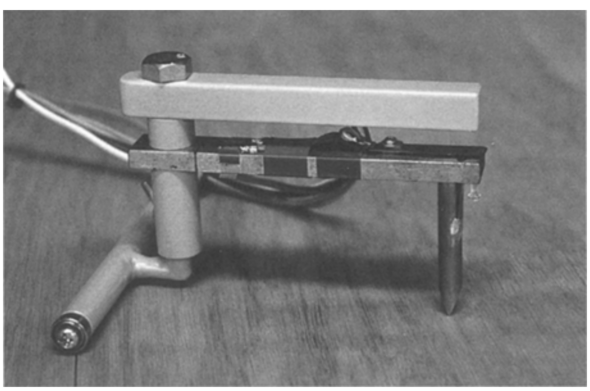


Fig. 4. Main body of the hardness tester made for this research

hardness tester by improving the prototype model presented in the previous report.[3] Figure 4 shows the main body[3,4] of the Brinell's hardness tester. The working principles, using the detecting mechanism of the load P and indenting depth h, are identical to those of the previous report. The required load is applied by hand

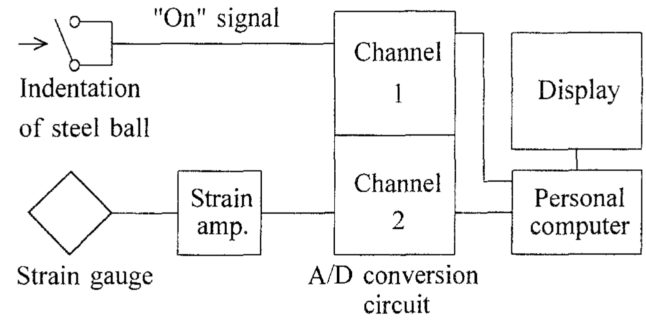


Fig. 5. Block diagram of the hardness tester

power. To measure the hardness distribution minutely, we decided to use a 2mm diameter ball tip and indentation depth of $1/\pi$mm. This tester can also use a 10mm diameter ball.

Figure 5 shows the block diagram used to calculate and indicate Brinell's hardness value. Both the voltage signal of load P and the "on" signal generated by a defined indentation depth h are converted to digital signals by an A/D conversion circuit. The two signals are processed in a personal computer, and the value of Brinell's hardness appears on the display screen. The processing code was written by a BASIC language.

Measurement of the hardness distribution on wood surface

First, the possibility of measuring the hardness difference in an annual ring between the earlywood and latewood was examined using a 2mm diameter ball. The species used were sugi (*Cryptomeria japonica* D. Don, density 0.39g/cm^3), akamatsu (*Pinus densiflora* SIEB. et ZUCC., density 0.69g/cm^3), and Douglas fir (*Pseudotsuga menziesii* FRANCO, density 0.55g/cm^3). Measurements were made on the transverse and tangential surfaces of the test blocks.

Second, the hardness distribution patterns measured by 10 and 2mm diameter balls were compared. The species used was sugi (density 0.34g/cm^3). The test blocks were two air-dried flat-grain boards, including heartwood and sapwood. Their size was 150 × 200 × 20mm.

Brinell's hardness was measured in 100 × 50 and 100 × 20mm rectangular areas by 10 and 2mm diameter balls, respectively. The measurement was made on the cross points of the grid lines drawn along the fiber and tangential directions. The grid intervals were 10mm for a 10mm ball and 2.5mm for a 2mm ball.

Following the above-mentioned experiments, hardness distribution patterns were measured in several species by the 2mm diameter ball system. The measurement area was 50 × 50mm rectangular, and the grid distance was 2.5mm. The species used were agathis [*Agathis* spp., density 0.53g/cm^3 (LR specimen) and 0.47g/cm^3 (LT specimen)], hinoki [*Chamaecyparis obtusa* Endl., density 0.50g/cm^3 (LT specimen)], and katsura [*Cercidiphyllum japonicum* Sieb.

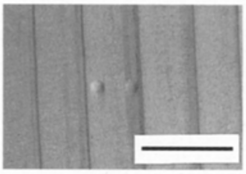
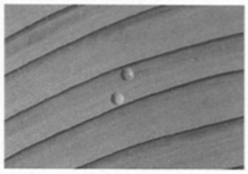
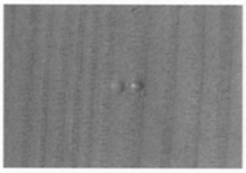
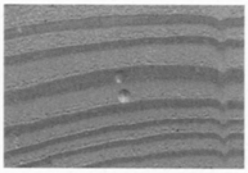
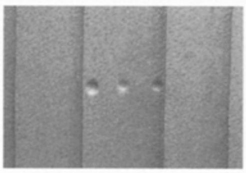
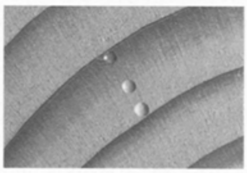
	Edge grain (kgf/mm²)	End grain (kgf/mm²)
Sugi	 earlywood: 0.32 latewood: 2.49	 earlywood: 1.85 latewood: 4.11
Aka-matsu	 earlywood: 1.92 latewood: 7.02	 earlywood: 3.87 latewood: 10.49
Doug-las fir	 earlywood: 0.78 intermediate wood: 1.68 latewood: 7.58	 earlywood: 2.98 intermediate wood: 4.42 latewood: 11.56

Fig. 6. Examples of hardness on radial and transverse sections. All photographs are of the same magnification. Tip diameter is 2mm. *Bar* 10-mm

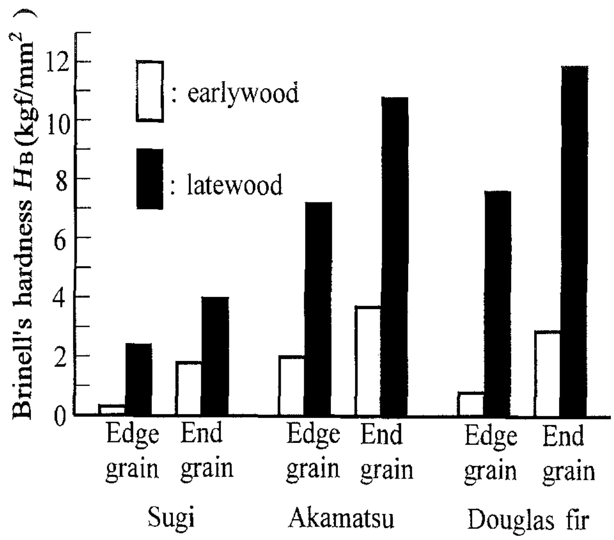


Fig. 7. Average hardness of earlywood and latewood

et Zucc., density 0.47g/cm³ (LT specimen)]. Specimen thickness was 15mm. Agathis was measured in both radial and tangential sections, but hinoki and katsura were measured only in tangential sections.

Results and discussion

Hardness of earlywood and latewood in each annual ring

Figure 6 shows examples of the obtained results. By using a small diameter ball, we could measure Brinell's hardness and distinguish earlywood and latewood in an annual ring. If the annual ring is wide enough, the hardness of the intermediate wood is also measurable (e.g., Douglas fir). Figure 7 shows the averages of hardness obtained from ten measurement points.

Comparison of the hardness distribution patterns obtained by 2 and 10mm diameter ball tips

Figures 8 and 9 show the results with the 10 and 2mm diameter ball tips, respectively. The test block surface, hardness distribution, and averages of the hardness on grid lines are shown in both figures. Comparing the two figures, we can see that the distribution pattern of Fig. 8 is flatter than that of Fig. 9. In Fig. 9 the difference of the hardness between the earlywood and latewood is clear, whereas in Fig. 8 the difference is modest. The former's distribution pattern resembles the density distribution pattern obtained by X-ray densitometry.[5] The scatter of hardness distribution along the fiber direction is smaller than that in the tangential direction.

From this experiment, we can conclude that our minute hardness distribution measuring method is highly efficient for obtaining useful information on the surface quality of wood.

Hardness distribution patterns

In this section, we show other results obtained by the 2mm ball system. Figures 10 and 11 show the hardness distributions of agathis in radial and tangential sections, respectively. As agathis is a tropical coniferous wood, it has no clear growth ring, and there is no large variation in the hardness. It is seen that the scatter of hardness in the fiber direction is somewhat smaller than that in the radial direction in radial sections (Fig. 10). The difference in the hardness values for the radial and tangential sections seems to depend on the difference of the specimen's density.

Hardness distribution patterns of hinoki, which is a coniferous wood of the temperate zone, are shown in Fig. 12. This pattern is similar to that of sugi, seen in Fig. 9, but its hardness variation is less than that of sugi because hinoki has a milder transition from earlywood to latewood than sugi.[6]

Figure 13 shows the results in katsura, which is a Japanese diffuse porous hardwood. Generally, we do not distinguish latewood from earlywood in katsura, because this wood is so homogeneous. However, seeing the dis-

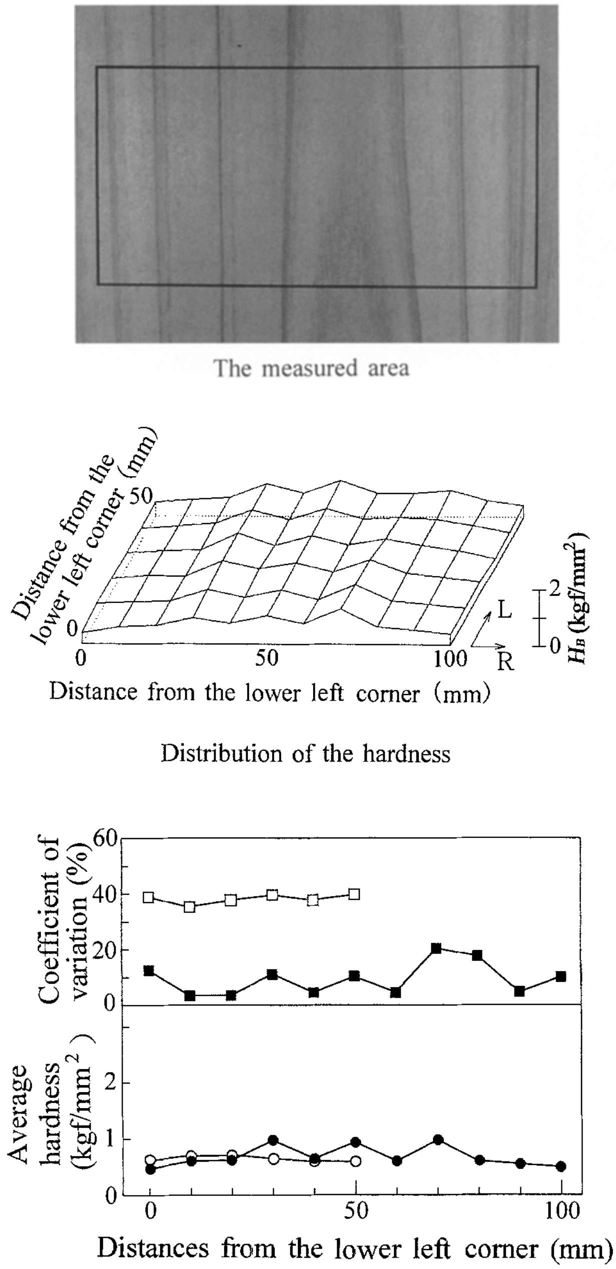


Fig. 8. Measured results of sugi in a tangential section of a 10 mm diameter steel ball. Grid distance is 10 mm. *Open symbols*, measurements in tangential direction; *filled symbols*, measurements in fiber direction

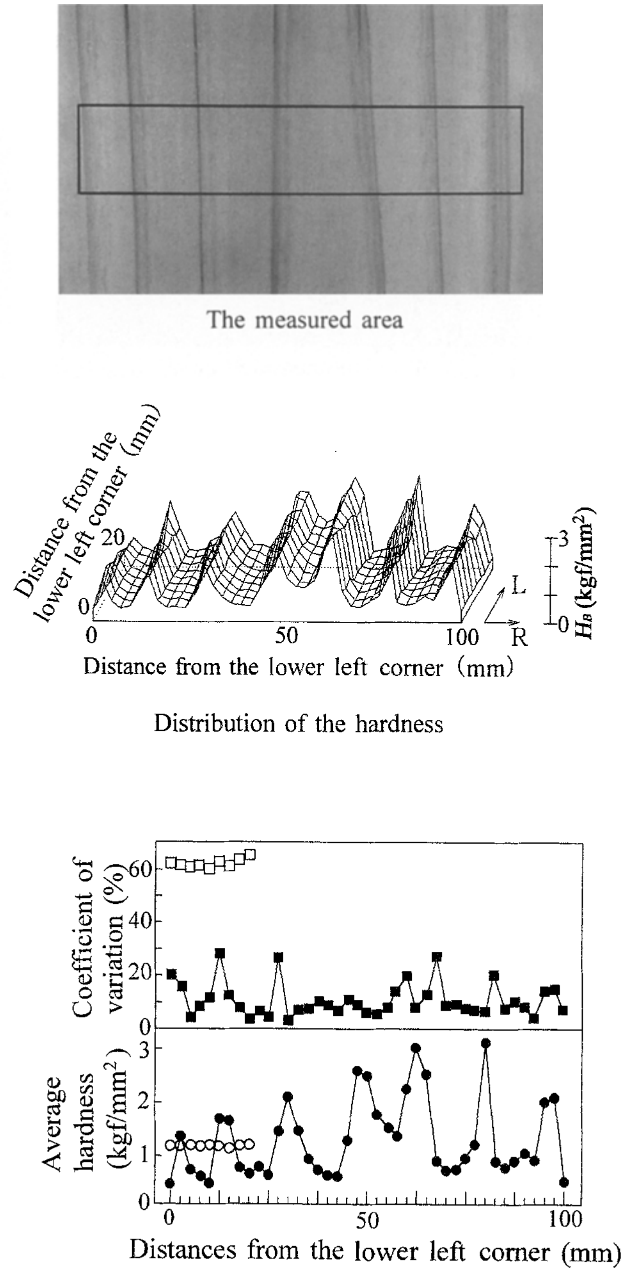


Fig. 9. Measured results of sugi in a tangential section of a 2 mm diameter steel ball. Grid distance is 2.5 mm. Symbols are the same as in Fig. 8.

tribution patterns, we can find good agreement between this pattern and the grain pattern seen in Fig. 13.

Based on these results, we believe that our method for measuring hardness provides us with new information on wood surface properties.

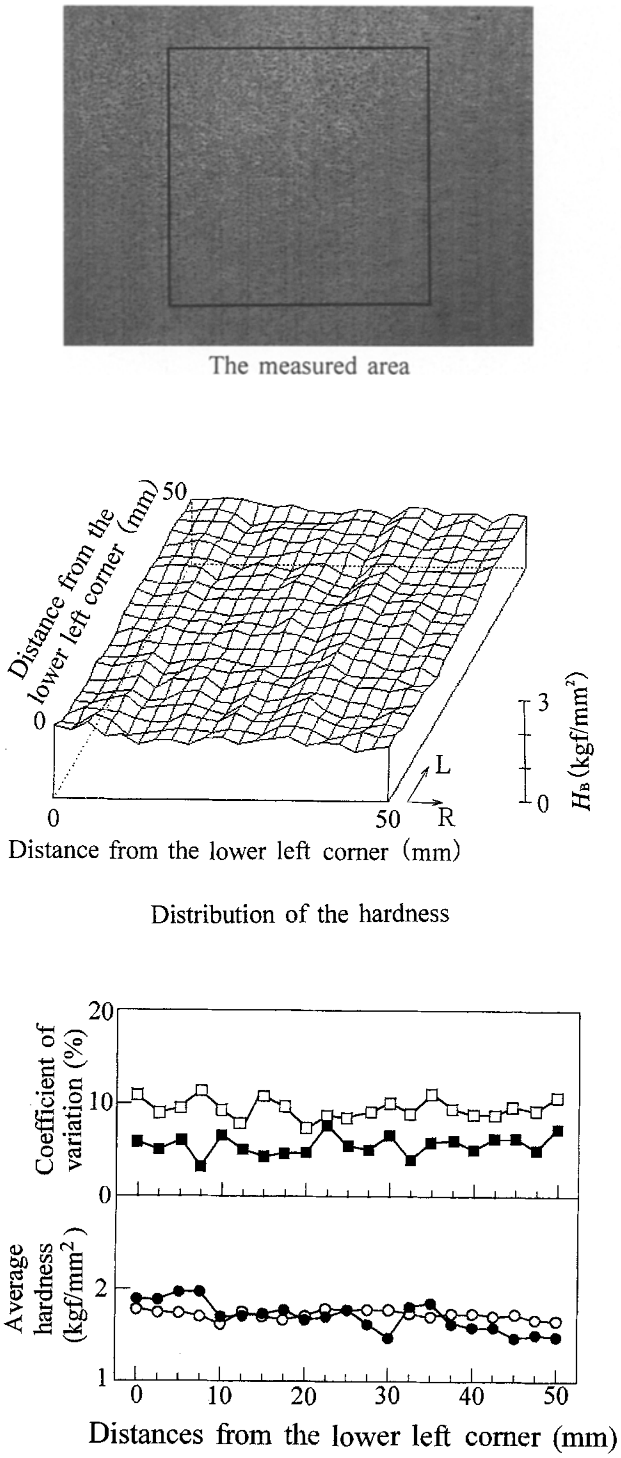
Conclusions

For better understanding of wood hardness, we developed a new hand-operated hardness tester that works with Brinell's method. With this tester, we investigated the hardness distribution of wood minutely using a 2 mm diameter ball tip. The following results were obtained.

1. In preliminary examination with MDF, we found that the value of the Brinell's hardness decreases with the increase in the tip ball's diameter, but that it is almost constant with the indentation velocity.

2. By using a small diameter tip, the difference in the hardness of earlywood and latewood became clearer.

3. We obtained hardness distribution patterns in radial and tangential sections that were similar to those of wood grain. It seems that the hardness distribution reflects the distribution of density on wood surfaces.



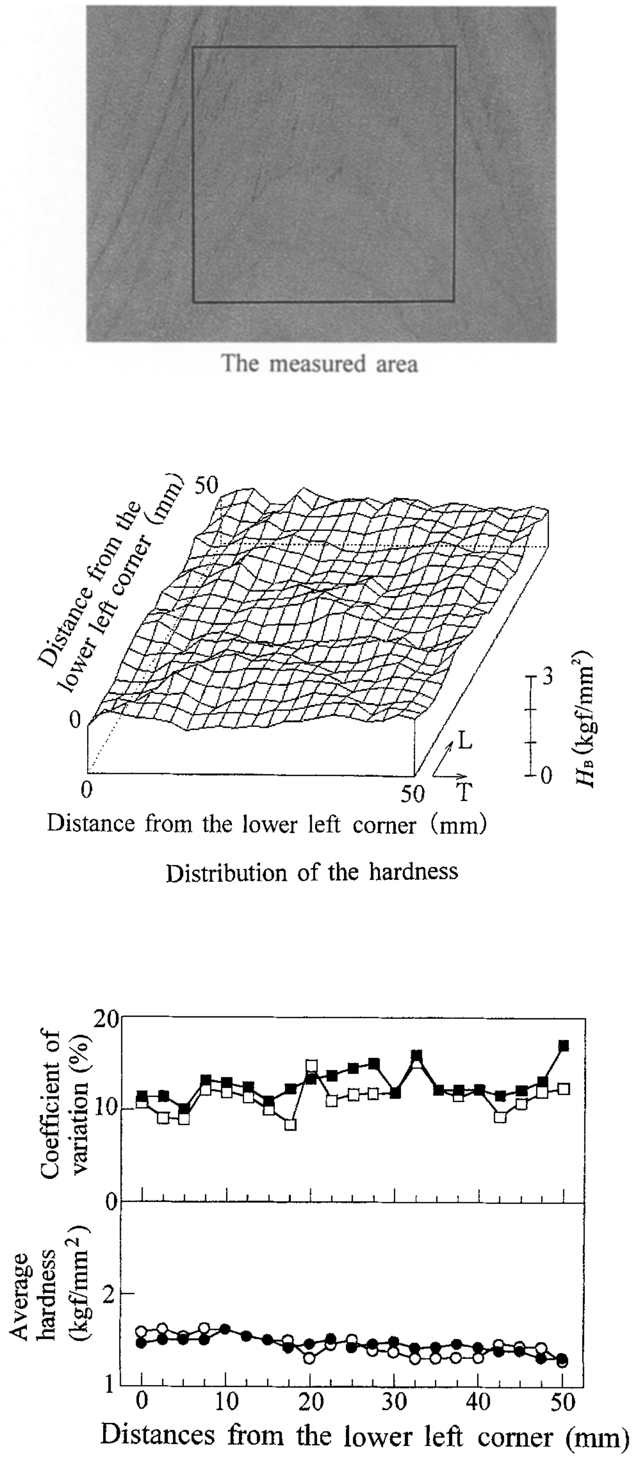


Fig. 10. Measured results of agathis in a radial section of a 2 mm diameter steel ball. Grid distance is 2.5 mm. *Open symbols*, measured in the radial direction; *filled symbols*, measured in the fiber direction

Fig. 11. Measured results of agathis in a tangential section of a 2 mm diameter steel ball. Grid distance is 2.5 mm. Symbols are the same as in Fig. 8

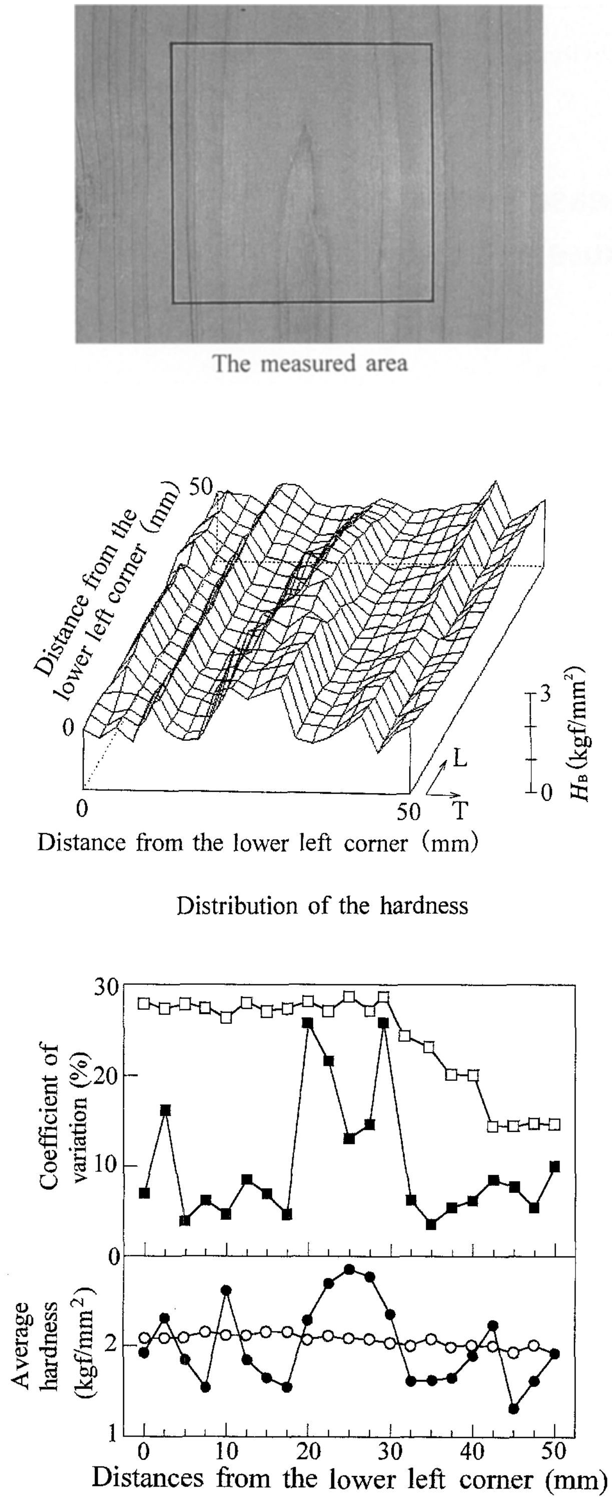


Fig. 12. Measured results of hinoki in a tangential section of a 2 mm diameter steel ball. Grid distance is 2.5 mm. Symbols are the same as in Fig. 8

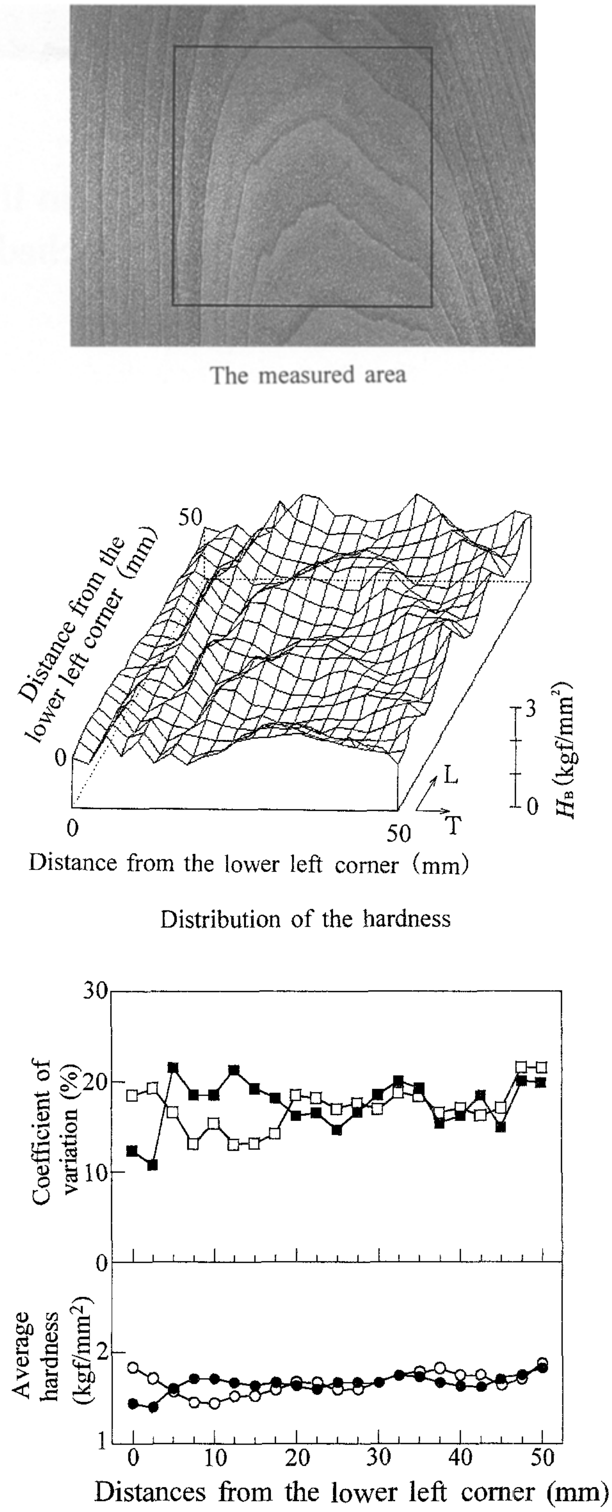


Fig. 13. Measured results of katsura in tangential section of a 2 mm diameter steel ball. Grid distance is 2.5 mm. Symbols are same as in Fig. 8

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